Title

Investigating the Relations Between Elementary School Teachers’ Spatial Cognition, Affect, and Preferences for Spatial Pedagogical Practices

Author

Rocha, Kelsey

Publication Date

2023

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Investigating the Relations Between Elementary School Teachers' Spatial Cognition, Affect, and Preferences for Spatial Pedagogical Practices

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Education

by

Kelsey R. Rocha

June 2023

Dissertation Committee:
Dr. Kinnari Atit, Co-Chairperson
Dr. Catherine Lussier, Co-Chairperson
Dr. Marsha Ing
Dr. Anthony Muro Villa III

The Dissertation of Kelsey R. Rocha is approved:

____

____

____
Committee Co-Chairperson

____
Committee Co-Chairperson

University of California, Riverside

Acknowledgements

Thank you to both of my advisors – Kinnari Atit and Catherine Lussier. I am grateful for your guidance and the support you both gave me every step of the way. Thank you for making me a better writer and researcher.

Thank you, also, to my committee members – Marsha Ing and Anthony Muro Villa III. I appreciate the time and perspective you both gave me and my dissertation.

Thank you to my colleagues from the STEM Teaching and Learning Lab. Thank you all for always being great collaborators and great friends.

ABSTRACT OF THE DISSERTATION

Investigating the Relations Between Elementary School Teachers' Spatial Cognition, Affect, and Preferences for Spatial Pedagogical Practices

by

Kelsey R. Rocha

Doctorate in Philosophy, Graduate Program in Education
University of California, Riverside, June 2023
Dr. Kinnari Atit & Dr. Catherine Lussier, Co-Chairpersons

Spatial skills, the set of cognitive skills that are responsible for our understanding of objects in real and imagined spaces, have been identified as a potential gate-keeper for STEM success. Because of the recent emphasis on improving education to prepare for the increasing demand for workers in STEM fields, there is a rising interest in bolstering students' spatial skills to address this challenge. Given the evidence that teachers' skills and attitudes toward a domain can affect their pedagogical practice within that domain and in turn affect their students' learning and achievement, some researchers have focused their attention on understanding how to best support teachers. This study seeks to understand how specifically elementary school teachers' spatial cognition and spatial affect impact their preference for implementing pedagogical devices that would promote the development of their students' spatial thinking skills. It is imperative to study this particular sample of teachers because of the well-established presence of spatial reasoning in childhood and in the elementary school curriculum. Eighty elementary school teachers completed measures of spatial skills, spatial anxiety, spatial habits of mind, preferences for spatial pedagogy, general anxiety, and general reasoning. Results indicate that elementary school teachers' spatial skills were negatively associated with their spatial anxiety, and teachers who display higher levels of spatial skills reported greater preferences for using spatial pedagogy in hypothetical teaching situations. These findings have implications for teacher professional development related to supporting students’ spatial skills during science and math instruction in elementary school.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In the United States, the number of jobs within science, technology, engineering, and mathematics (STEM) fields are increasing; thus, producing an ever-expanding need to prepare students for a college career in the STEM disciplines (Executive Office of the President, 2018; U.S. Department of Education, 2013). Yet recent data indicates that many K-12 students in the United States are not being adequately prepared for such an undertaking (NCES, 2019). As early as fourth grade, students in the United States are falling behind in learning STEM content. The 2017 National Assessment of Educational Progress (NAEP) shows that only 40% of fourth-grade students in the United States score proficient or above in mathematics (NCES, 2017).

Further, it has been shown that once students who are interested in pursuing STEM at the postsecondary level reach college and begin the coursework required by the major, only about half are successful in reaching that goal (Chen & Soldner, 2013). Moreover, a closer examination of the kinds of students leaving STEM disciplines reveals that the greatest rates of attrition are occurring among women and students from underrepresented minority (URM) backgrounds (Seymour et al., 2019). Therefore, despite the national focus to increase the number of students that pursue STEM professions, Blacks, Hispanics, and women are still underrepresented among those earning STEM bachelor's degrees (National Science Foundation, 2022). Recent research conducted by the National Science Foundation (2022) found that women are awarded 57% of bachelor’s degrees; however, less than half of these degrees (49.4%) are from the science and engineering disciplines. Additionally, Black/African American and

Hispanic/Latino individuals make up approximately 35% of the population in the United States, yet they are only awarded 25% of the undergraduate degrees in science and engineering (National Science Foundation, 2022). Advancing diversity in STEM has many potential benefits. First, increasing diversity is likely to expand the level of creativity, innovation and quality of STEM products and services (Burke & Mattis, 2007). Additionally, increasing diversity may help to alleviate the projected shortage of students pursuing STEM careers. Attrition rates of women and URM students from undergraduate STEM majors impedes progress on goals pertaining to "economic strength, national security, global competitiveness, environment, and health of the United States" (NASEM, 2016, p. 7).

In its current state, K-12 STEM education in the United States is not adequately preparing all students for success in pursuing a STEM career - particularly women and students from URM backgrounds. Research shows that the ramifications of students ending their pursuit of higher education in STEM majors include a variety of consequences on both an individual and community level, including the waste of skills and aptitude, a compromise or change of career goals, a waste of time and resources, an increase in student debt, and a loss of confidence, self-esteem and sense of direction (Seymour & Hewitt, 1997; Seymour et al., 2019). Thus, it is essential that K-12 STEM education is improved in order to (1) increase the overall number of workers in STEM careers and (2) reduce barriers of entry to pursuing higher STEM education for diverse populations.

LITERATURE REVIEW

Dimensions of Spatial Cognition & Affect in STEM Learning

Considering the negative consequences of low performers in STEM fields at individual, community, and national levels, much research has been dedicated to understanding how to improve U.S. student outcomes. Prior research suggests that spatial skills, the set of cognitive skills that are responsible for our understanding of objects in real and imagined spaces (Uttal et al., 2013), may be a gatekeeper for STEM success (Steiff & Uttal, 2015; Uttal & Cohen, 2012). We use our spatial skills everyday doing a variety of tasks, such as navigating shortcuts around traffic, organizing groceries into our refrigerators, and parallel parking. Not only are these skills essential in day-to-day life, but they have been found to predict STEM success at every level of education (Hodgkiss et al., 2018; Lubinski & Benbow, 2006). Therefore, it is imperative that students develop strong spatial skills, and one place the development of these skills is impacted is the classroom.

Spatial Skills

"Spatial skills" as a term refers to the set of related cognitive abilities that revolve around the thought processes that guide our experiences pertaining to objects and the spaces they inhabit (Verdine et al., 2017; Uttal et al., 2013). We use our spatial skills in many everyday activities such as parallel parking a car, arranging as many dishes as possible into our dishwasher, navigating our way to our favorite stores in a new mall by using the directory, or putting together new furniture from Ikea. The study of spatial skills is relatively new and the introduction of spatial skills into educational research is equally recent (Verdine et al., 2017).

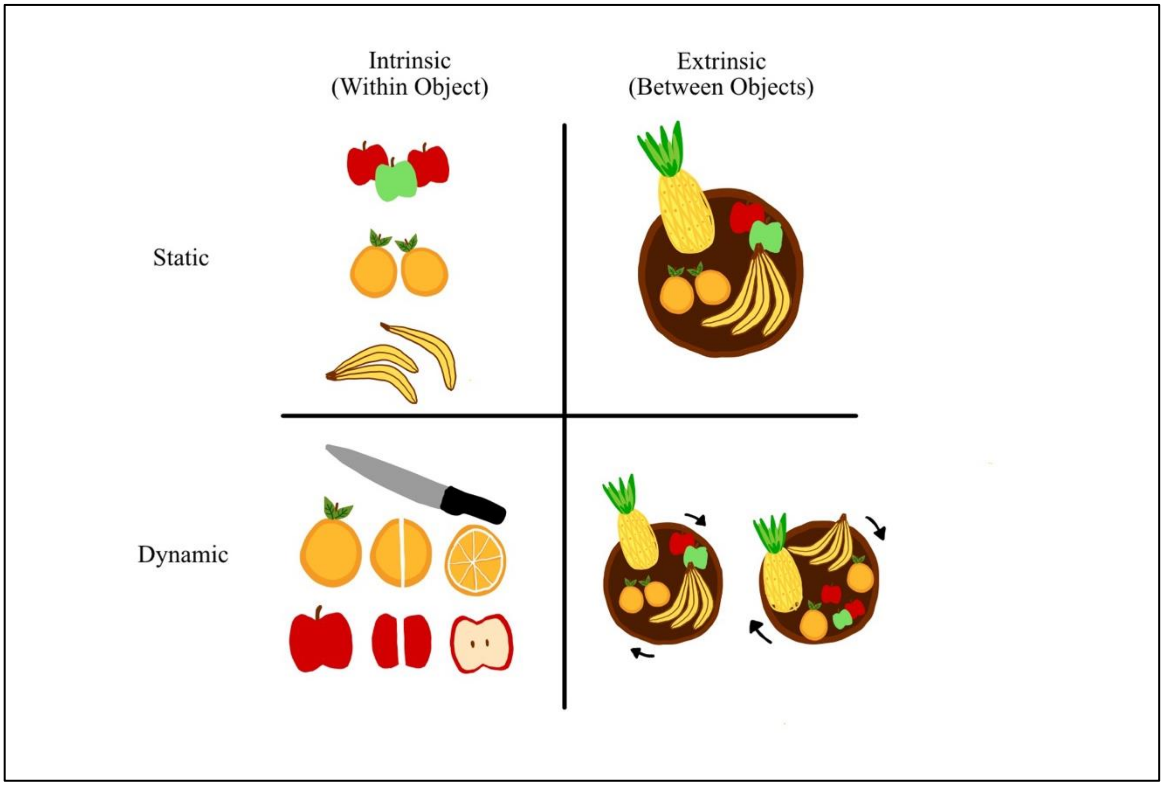
How are spatial skills defined and measured? Using a factor-analytic approach is how most researchers first attempted to characterize the cognitive structures or spatial abilities included within spatial skills. One such notable attempt was put forward by Carroll (1993). He suggested that there are six domains to consider in spatial intelligence by describing six cognitive tasks: (1) spatial visualization, (2) spatial relations, (3) closure speed, (4) flexibility of closure, (5) perceptual speed and (6) visual memory. Spatial visualization refers to the ability to mentally visualize something, or "see" objects in your minds' eye. The spatial relations domain goes one step beyond spatial visualization as it classifies the ability to mentally see how objects are related to one another in space or mentally manipulate objects that are being visualized. Closure speed refers to the length of time it takes for you to discriminate and identify what something is with limited visual information. Whereas flexibility of closure is the ability to alter or adapt discriminations made with visual information, such as when viewing an optical illusion which can present multiple different "correct" images. Perceptual speed refers to the ability to match figures, make comparisons and carry out simple tasks using visual perception. And finally, visual memory indicates the ability to recall or hold visual information about an object or figure in your mind's eye in its absence. Since Carroll's (1993) study, there have been many attempts to separate out the different classes of spatial skills; however, there has not been much consistency in the results of these attempts. Thus, there is no consensus on the categorical structures of the different kinds of spatial skills (Uttal et al., 2013).

In contrast to Carrol's taxonomy of spatial skills, Uttal et al. (2013) has re-defined the structural organization of these spatial skills using a theoretical framework with four distinct classifications. As informed by multidisciplinary research (from Chatterjee, 2008; Palmer, 1978; Talmy, 2000), Uttal et al. (2013) posited that there are four categories of spatial skills in human cognition which are made up by crossing two separate dimensions that specify the nature of how given spatial information is processed--these dimensions are intrinsic/extrinsic and static/dynamic. Intrinsic spatial information refers to an entity's specific properties, such as how it takes up space or methods that predicate its movement. In contrast, extrinsic information refers to relations existing between entities, such as how close they are located relative to one another. In terms of the static and dynamic dimension, entities that remain in one state would be referred to as static and ones that change in some way are dynamic (e.g., a whole apple and an apple that has been cut into pieces). These dimensions cross in such a way that four combinations are made - static intrinsic, static extrinsic, dynamic intrinsic, and dynamic extrinsic. Figure 1 depicts these spatial classifications.

To explain the figure, the spatial information necessary to sort out apples, bananas, and oranges in a fruit basket would be in the intrinsic category; whereas, the spatial relations between the fruits would be extrinsic in nature. Identifying apples, oranges and bananas on their own involves intrinsic static spatial cognition. Thinking about how to cut fruits (for example, considering which way to cut into an orange to create slices versus wedges) requires intrinsic dynamic spatial cognition. By contrast, the spatial information revolving around viewing a fruit basket (for instance noticing the apples are behind the bananas, which are to the right of the oranges) employs static extrinsic spatial cognition. And should it become necessary to add another apple to the fruit basket, changing the arrangement of the fruit and spinning the basket around on a display would be a task that demands dynamic extrinsic spatial cognition.

Figure 1.1

Four classifications of spatial cognition



Note: The figure depicts the four classifications of spatial cognition as proposed by Uttal et al. (2013)

After many attempts over the years to rigidly define "spatial skills" and what exactly is encompassed by this term, there is still no consensus; however, there is a broad agreement that spatial skills encompass more than one categorical skill or ability of this type.

With regard to spatial cognition, research has provided some evidence that different types of processing are happening or that different sets of cognitive skills are being taxed when dealing with the four categories of spatial information that are proposed by Uttal and colleagues (2013). For example, findings from Kozhevnikov and colleagues (2002; 2005), revealed that those who excel on tasks that tax object visualization skills are distinct from those who excel on tasks that tax spatial visualization skills. In real world application, it is observed that artists are very likely to have a propensity for object visualization (which would require intrinsic-static processing abilities); whereas, scientists are very likely to have a propensity for spatial visualization (which would require intrinsic-dynamic processing abilities; Uttal et al., 2013).

Malleability of spatial skills. Importantly, in contrast to other cognitive functions such as working memory, meta-analytic data has shown that spatial skills are malleable (Uttal et al., 2013), meaning that these skills can be bolstered with training and practice. Furthermore, results of this analysis showed that practice effects are not limited just to the spatial task which was trained and that the effects were lasting beyond the duration of the training. Any learning that was gained through training on one type of task was found to transfer to other similar spatial tasks (Uttal et al., 2013). For example, training on the Mental Rotation Test (which is an intrinsic dynamic spatial task) was found to transfer to the Paper Folding Test (another intrinsic dynamic spatial task) as well as transferring to a task that does not fall into the same spatial category, the Water Level Test (which is an extrinsic static spatial task) (Uttal et al., 2013). Further, spatial skills have been shown to be improved through engagement with STEM content (e.g., Clements et al., 1997; Lowrie & Logan, 2007; Sinclair & Bruce, 2015) and through carrying out leisure activities that heavily engage spatial skills, such as playing video games and sports (Contero et al., 2005; Quaiser-Pohl et al., 2006; Subrahmanyam & Greenfield, 1997; Voyer & Jansen, 2017).

Gender differences in spatial skills. Another point that is worth noting is the gender gap which has a history of being observed on tests of spatial thinking skills. Results of a meta-analysis conducted by Voyer et al. (1995) showed that on some tests of spatial skills, there was a significant difference in performance between men and women, with men outperforming women. To further elaborate, gender differences were present in tests of mental rotation and spatial perception; however, not on tests of spatial visualization. In 2019, these findings were replicated by Lauer and colleagues. In their meta-analysis of over 300 studies, they found that the small advantage for men in mental rotation performance is first exhibited in childhood and that it only increases with age, reaching a moderate effect size in adolescence. While the gender gap in spatial skills does not seem to have been erased since Voyer and colleagues (1995) reported their findings over twenty-five years ago, it is important to remember that spatial skills are malleable and can be improved with practice (Uttal et al., 2013). These findings suggest that building an understanding of how K-12 learning experience can be leveraged to bolster students' spatial skills may have broader implications for mitigating the gender gap in this skillset.

Why are spatial skills important in STEM learning? Despite ample evidence underlining the importance of developing spatial thinking skills in K-12 education, they are often overlooked in K-12 curricula (Bodzin, 2010; National Research Council, 2006; Verdine et al., 2014). The lack of emphasis on developing K-12 students' spatial skills as part of their formal education is certainly an oversight, given they are not only important for successful day to day functioning, but they have proven to be especially critical for success in STEM domains (Cheng & Mix, 2014; Gilligan et al., 2017). In fact, longitudinal data from a representative sample of over 400,000 people found that spatial thinking skills exhibited during adolescence were found to be a strong predictor of achieving advanced STEM educational credentials or occupations, even when controlling for mathematics and verbal reasoning skills (Wai et al., 2009). There is even evidence to suggest that spatial skills exhibited in middle school predict STEM degree attainment and STEM employment, more than a decade later (Shea et al., 2001). Further studies have revealed that at both the primary (e.g., Geer et al., 2019; Gunderson et al., 2013; Hodgkiss et al., 2018) and secondary (Ganley et al., 2014; Stavridou & Kakana, 2008) grade levels, spatial skills are predictive of mathematics and science understanding. Such findings suggest that spatial skills are crucial for advancement of STEM knowledge across all stages of K-12 learning.

Further cementing the positive association between spatial skills and STEM learning and attainment is evidence to suggest a connection between practicing spatial tasks and students' improvement in STEM learning (Cheng & Mix, 2014; Miller & Halpern, 2013). Though several studies establishing the causal relation between spatial skills and STEM attainment has been conducted in secondary or postsecondary samples (Miller & Halpern, 2013; Sorby et al., 2018), there is research to suggest the relation also holds true at the elementary educational level. One such experimental study, completed by Cheng and Mix (2014) found that 6- to 8-year old students' calculation skills significantly improved after mental rotation task training. By contrast, students in the control group for this experiment completed crossword puzzles in place of mental rotation task training and did not improve on any of the tested outcomes.

Further evidence is provided by meta-analytic research indicating that improving spatial skills transfers to improved mathematics performance (Hawes et al., 2022). Hawes and colleagues synthesized the findings from 29 studies examining the effects of training spatial skills on pre and post mathematics achievement. Results replicated findings from Uttal and colleagues (2013) showing that spatial skills are malleable, and also established that the average effect of training when compared to control was an improvement in mathematics of 0.28 (Hedges's *g*). Moreover, findings of the meta-analysis revealed that age moderated the impact of spatial training on mathematics outcomes, such that the older the participants were, the greater the impact of spatial training (Hawes et al., 2022). While this research supports the claim that the relations between spatial skills and mathematics performance are causal (Hawes et al., 2022), the mechanism underlying the transfer of skills is not well understood. Some studies have found that training spatial skills does not transfer to STEM outcomes (Cornu et al., 2019; Hawes et al., 2015). Thus, more nuanced and theoretically rooted research is needed to identify the details of if, when, and how improving spatial skills results in better STEM performance in students.

Spatial Anxiety

Spatial anxiety is an important factor that relates to spatial thinking skills–both how they are developed, and subsequently how individuals perform on tasks that require the application of spatial cognition. Spatial anxiety is known as fear and apprehension that is induced while performing tasks that require spatial processing (Lyons et al., 2018). For example, if you find yourself nervous about navigating to a place you've never been before, worried about fitting large objects (like televisions or appliances) into the back of your car, or have been concerned about your ability to parallel park, you may have experienced some spatial anxiety. It is thought that spatial anxiety can inhibit the pursuit of experiences and opportunities that might promote practice and further development of spatial skills (Lyons et al., 2018). Because of its potential negative effects on students' spatial learning, there has been a recent spike in educational researchers' interest in examining the role of spatial anxiety on students' STEM learning (Alvarez-Vargas et al., 2020; Lyons et al., 2018).

How is spatial anxiety defined and measured? Foundational research on spatial anxiety defines this construct as "anxiety about environmental navigation" (Lawton, 1994). In Lawton's (1994) measure, participants are asked to rate their level of spatial anxiety when imagining themselves in a variety of distinct navigation-related scenarios. For example, one item asks participants to rate their anxiety while "locating your car in a very large parking lot or parking garage". In researching the historically apparent gender differences on navigational spatial tasks, Lawton (1994) found that women displayed higher levels of spatial anxiety than men which could account for reported differences in strategy-use in navigational orienting. Only recently has Lyons and colleagues (2018) expanded the accepted definition of spatial anxiety to now include anxiety that is induced in spatial tasks beyond navigational tasks.

In addition to re-defining the scope of the definition of spatial anxiety, Lyons et al. (2018) called for a revision of Lawton’s (1994) measure of spatial anxiety - noting that while it was the most widely used measure of spatial anxiety to that date, it only measured one dimension of spatial processing. As previously discussed, it is not entirely clear the exact processes that encompass the whole of spatial skills; however, it is clear that spatial skills are used in a number of different activities that go beyond navigation. Thus, Lyons and colleagues (2018) concluded that a valid measure of spatial anxiety would need to account for the multifaceted nature of spatial skills, consistent with the modern typology that characterizes spatial processing.

The measurement of spatial anxiety developed by Lyons and colleagues (2018) was informed by Uttal et al.’s (2013) framework of the four category classification system of spatial skills. In the measure, participants were asked to imagine completing a variety of different spatial tasks and then rate their level of anxiety for each task. For example, items asked participants to rate their anxiety while “recreating their favorite artist's signature from memory” or if they were “asked to determine how a series of pulleys will interact given only a 2D diagram”. Using a factor-analytic approach, the researchers were able to identify three subcategories of spatial anxiety that were consistent with the categories of spatial abilities that are commonly accepted in the broader literature. These spatial ability subcategories were (1) navigation, (2) mental-manipulation, and (3) imagery. The researchers were able to establish good external validity on measures of the navigation and mental-manipulation subscales and acceptable external validity on the imagery subscale.

Diverging from the method used by Lawton (1994) and Lyons and colleagues (2018), Gagnier and colleagues (2022) introduced a different way of measuring *teachers'* spatial anxiety - one that does not rely on self-reported ratings of their feelings of anxiety in a variety of imagined spatial tasks. The authors point out that measuring teachers' spatial anxiety with the existing instruments (such as the Spatial Anxiety Scale developed by Lyons et al., 2018) may not directly assess the types of spatial skills that teachers will encounter/use while teaching math and science. To address this discrepancy, these researchers administered a novel measure where participants would solve spatial problems on which success has been linked to performance in STEM (see Uttal & Cohen, 2012) followed by a prompt to rate the level of anxiety they experienced while solving the problem. This method of measuring spatial anxiety was specifically designed to assess teachers' spatial anxiety that would be relevant for the context of teaching math and science content.

Why is spatial anxiety important for early STEM learning? Much is known about the impact of spatial skills on STEM achievement; however, exploration into the affective correlates of children's spatial performance - such as spatial anxiety - is a relatively new area of study. The previously mentioned study conducted by Lawton (1994) provided a basis for the connection between spatial anxiety and performance on spatial measures in adults. It is only more recently, years after Lawton's (1994) findings, that a handful of studies have begun to explore the extent of this connection, and the subsequent connection of spatial anxiety to STEM achievement, in school age children.

A 2012 study conducted by Ramirez and colleagues examined the relationship between young children's performance on a mental rotation task and their spatial anxiety. Interestingly, this study demonstrated that even young children experience anxiety about engaging in spatial activities. Additionally, the researchers found an association between spatial anxiety and reduced mental rotation ability, but this relationship was only maintained in children who displayed higher working memory. Moreover, this interaction between working memory and spatial anxiety was only evident amongst girls.

Further evidence on this topic from Lauer and colleagues (2018) indicates that domain specific anxieties (i.e., math anxiety, reading anxiety, verbal anxiety) are distinct in their relation to cognitive performance, meaning that the anxieties displayed were correlated with performance on respective cognitive tasks. Additionally, the study showed that gender differences in math and spatial anxiety were also domain-specific. In the study of 394 elementary school children (ages 6-12), girls reported significantly greater math and spatial anxiety, but not verbal anxiety. Results of the study demonstrate that math and spatial anxiety represent unique constructs, even from early in childhood, and they exhibit specificity in their associations with gender and cognitive performance during elementary school.

Relating the impacts of spatial anxiety to STEM performance, Ouyang et al. (2022) notes the moderating effects of children's spatial anxiety on advancement of early numeracy skills. In their longitudinal study, the authors found that children with lower levels of spatial anxiety displayed a stronger positive association between early spatial perception (i.e., identifying spatial relations according to body orientation) and later subitizing (i.e., the ability to instantly recognize the number of items without needing to count them out) and number line skills. This study provides evidence that spatial perception (one facet of spatial cognition) is not the only prerequisite for advancing mathematical performance in early childhood, but that spatial affect (e.g., spatial anxiety) may also impact this process.

Thus far, research on the impact of children's spatial anxiety on spatial performance and STEM learning is in its infancy. However, when considering the findings of the available studies in addition to the impact of teachers' spatial anxiety on students' spatial learning (as discussed in the Teachers' Spatial Cognition and Affect section), it is evident that further exploration of this construct could lead to a better understanding of how to mitigate its negative effects.

Spatial Habits of Mind

Efforts to study spatial skills have also led researchers to study other aspects of spatial cognition/affect in order to understand additional factors that may impact our interactions with spatial thinking. The ppatial habits of mind construct is one such facet of spatial cognition that may be related to STEM learning that researchers are beginning to attempt to study in educational contexts.

How are spatial habits of mind defined and measured? Some researchers refer to general "habits of mind" more vaguely, and describe them as being characterized by the patterns that we cognitively select when attending to stimuli, interacting with problem-solving tasks or otherwise navigating novel or recognized phenomena (Costa & Kallick, 2008). Other researchers argue that habits of mind are linked to more specific processes of thought (Cuoco et al., 1996). Regardless, recent research conducted by Kim and Bednarz (2013), defines spatial habits of mind as "an internalized thinking process that uses spatial ways of thinking…and the spatial representation of ideas (e.g., visualization)." Measurement of spatial habits of mind provides a distinct piece of data, separate from spatial skills and spatial anxiety, about cognitive processing, and aims to assess the internal inclinations used in processing information (Kim & Bednarz, 2013).

Kim & Bednarz (2013) note studying spatial habits of mind is relevant for practitioners who are interested in spatial literacy, which Lane and colleagues (2019) define as the "skills involved in visualizing, reasoning, and communicating about 2D and 3D spatial information". Bednarz and Kemp (2011) describe spatial literacy as being tantamount to mathematical and classic literacy. But thus far, not much research that has sought to understand spatial cognition/affect in educational settings has included the spatial habits of mind construct.

Kim and Bednarz (2013), the creators of the Spatial Habits of Mind Inventory (SHOMI), identified the following five subdimensions of spatial habits of mind:

(1) pattern recognition - a habit of mind concerned with noticing spatial patterns, being able to describe them and predict them,

(2) spatial description - which refers to the proficient use of spatial vocabulary, such as terms that describe location, direction and/or diffusion,

(3) visualization - the practice of converting information conveyed in verbal format to a visual format in order to increase comprehension,

(4) spatial concept use - refers to the habit of using spatial concepts to perform and understand various tasks,

and (5) spatial tool use - the habit of utilizing spatial representations or tools, such as drawing and maps.

Each of the five subdimensions of the SHOMI assess proclivities to engage in practices that support spatial cognition and provide evidence of overall spatial literacy. Items used in the SHOMI have previously been validated through factor analysis which identified appropriate inclusion within the subdimensions they were assigned to by the researchers (Kim & Bednarz, 2013).

Why are spatial habits of mind important for STEM learning? Measuring spatial habits of mind can contribute important information for improving STEM learning by providing researchers with additional insight about further aspects of spatial cognition that relate to successful learning outcomes for STEM domain topics. Utilizing the SHOMI, Kim & Bednarz (2013) studied college students' spatial habits of mind upon enrollment in, and subsequently after completing, a geographic information system (GIS) course. Some experts in the field argue that GIS courses can be beneficial to spatial learning (Kerski, 2003; Lee & Bednarz, 2009; Milson & Curtis, 2009). Thus, measuring the change in spatial habits of mind from before the GIS course to after completing it gives some insight into the way that cognition is impacted by engagement with highly spatial material. Results of this study indicated that what the researchers expected was true, that spatial habits of mind were enhanced from pre to post. These findings were recently replicated in a study implementing a similar course called “The Geospatial Semester” (Cortes et al., 2022). The results of this study indicated that students enrolled in the geospatial course improved on a measure of spatial skills in addition to exhibiting greater spatial habits of mind at the end of the term. Taken together, these findings provide evidence that spatial habits of mind are malleable and can be enhanced through students’ engagement with spatially demanding STEM content.

Teachers’ Spatial Cognition and Affect

Thus far, many attempts at bolstering students’ spatial skills in STEM learning have taken the form of direct, student-centered interventions. This approach leaves out an important component: the teachers who are expected to implement the interventions. This is an oversight considering the abundance of evidence that shows teachers play a critical role in students' educational experiences and outcomes that exceeds direct delivery of content (e.g., Ball et al., 2005; den Brok et al., 2004; Perera & John, 2020). Teachers’ skills and attitudes toward a domain can affect their pedagogical practice within that domain and in turn affect their students’ learning and achievement (Ball et al., 2005; Beilock et al., 2010). To elaborate, curriculum standards are similar across the same grade and from one school to the next (e.g., Next Generation Science Standards; Common Core State Standards), but the methods and strategies that teachers elect to use to convey that same content can vary greatly. For instance, consider an elementary school teacher conveying the concept of mathematical equivalence to their students. This concept, that the two sides of an equation are equal, can be taught visually by demonstrating equality on a balanced scale. It could also be taught numerically by focusing on the numerical results of an equation and their equality.

Evidence suggests that teachers' pedagogical practices are influenced by a combination of teachers' domain knowledge, feelings about that domain, and their pedagogical content knowledge (Shulman, 1986; Fennema et al., 1990; Nespor, 1987). Teachers who possess lower understanding of a domain's content utilize more didactic practices and rely more on their students' learning from textbooks (McLaughlin & Talbert, 1993). It has also been found that teachers with a low self-concept in performing within a given domain report using more didactic approaches to teaching it and, further, report that they do not pursue trying new teaching strategies because they lack the time, interest or motivation necessary (e.g., Relich, 1996). By contrast, teachers with greater understanding for a topic and/or a higher self-concept for performing in a given domain tend to encourage more questions from their students and utilize a wider variety of teaching strategies that promote active and student-centered learning (e.g., Grossman, 1990; Harlen, 1997; Osborne & Simon, 1996). With this in mind, it is important to explore the impact that teachers' spatial cognition and affect may have on students' STEM learning and performance.

One challenge of assessing the impact on student's learning of teachers' spatial cognition and affect is that most of the focus of research to date has centered around teacher knowledge and attitude about domains that are formally taught in K-12 curriculum, such as mathematics (Beilock et al., 2010; Hill et al., 2005). This leaves out the study of more informal domains and process skills which are not directly addressed in the K-12 curriculum but have an important impact on their outcome, such as spatial skills. To this point, there are a limited amount of studies that have examined the teachers' role in student spatial learning (e.g., Atit & Rocha, 2020; Gagnier et al., 2021; Gunderson et al., 2013; Otumfuor & Carr, 2017). One such study by Otumfuor & Carr (2017) found that middle school teachers' spatial skills were positively related to their use of spatial instructional practices. To elaborate, these teachers' spatial skills, in addition to their domain and pedagogical content knowledge, was related to their use of graphs, diagrams and representational gestures while teaching.

Perhaps more impactful than even teachers' cognitive skills, is the ample evidence of the influence of teachers' affect on their students' learning outcomes especially when teaching within STEM domains. Evidence from research on such topics in formal curriculum areas, such as math, support the hypothesis that anxiety about a STEM domain can influence teachers practice and student achievement (Bates et al., 2011; Beilock et al., 2010; McLean, et al., 2023; Schaeffer et al., 2021). For example, one study that examined the impacts of elementary school teachers' math anxiety found the greater math-anxiety a teacher who was a woman exhibited, the more likely her students that were girls were to endorse math and gender stereotypes and, subsequently, the lower their math achievement would be at the end of the year (Beilock et al., 2010). In another study, McLean and colleagues (2023) found that fourth-grade teachers' mathematics and science anxiety was positively associated with mathematics and science anxiety in their students from low-socioeconomic (SES) backgrounds.

There is a pattern of evidence to support a parallel, but distinct, relationship in the association between teachers' spatial anxiety and their students' spatial performance. Gunderson and colleagues (2013) found that teachers' spatial anxiety was significantly predictive of their students' spatial learning. Specifically, students from the classes of primary school teachers with higher levels of spatial anxiety exhibited lower scores on a measure of spatial skills, a mental rotation test, at the end of the year. This difference remained significant even after controlling for students' spatial skill levels at the beginning of the year, their phonological working memory, grade level, and teachers' general math anxiety. This finding is important given that spatial skills are not among the formal academic process skills taught, and teachers who exhibit higher levels of spatial anxiety may avoid utilizing spatial instructional strategies. This would limit their students' opportunities to practice spatial thinking (Gunderson et al., 2013). Gagnier and colleagues (2022) suggest that teachers who fall into this category (of possessing high spatial anxiety) may also incorporate fewer spatial activities into their STEM lesson planning or utilize spatial activities with less effectiveness than their low spatial anxiety counterparts.

Further validating the link between teachers' affect and their pedagogical practice, Burte et al., (2020) found that teachers with lower spatial anxiety were also more likely to display overall lower levels of anxiety about teaching math, greater efficacy in teaching spatial concepts in math, and their beliefs about requirements to effectively teach various math content standards were best aligned with the research on how children learn math. Therefore, gaining a better understanding of how teachers' spatial anxiety is related to their preferences for using spatial instructional practices is crucial for bolstering students' spatial learning in K-12 classrooms. Moreover, this information would provide teacher training programs insight in how to best support and prepare future teachers to implement teaching practices that engage students' spatial thinking.

More recently, building on the work by Gunderson and colleagues (2013) and Otumfuor and Carr (2017), my own research (conducted in Atit & Rocha, 2020 and Rocha et al., 2022) attempted to examine the relationships between teachers' spatial skills, spatial anxiety, and their reported use of spatial teaching practices, such as using diagrams/graphs, drawing/sketching, and/or gesturing – both as part of in-person and online teaching environments. In both studies, K-12 teachers completed the Spatial Anxiety Scale (Lyons et al., 2018), a mental rotation task, and a teaching activities questionnaire. Overall, the findings of the studies were mixed. However, one outcome that was replicated between both Atit and Rocha (2020) and Rocha and colleagues (2022) was the manifestation of the relationship between spatial skills and spatial anxiety. In both studies we found that scores on the mental manipulation subscale of the Spatial Anxiety Scale were negatively predictive of mental rotation test scores. Thus, stronger mental rotation skills were associated with lower spatial anxiety for mental manipulation tasks. However, findings of Atit and Rocha (2020) revealed that teachers' mental rotation skills were not only associated with spatial anxiety for mental manipulation tasks but positively associated with their self-reported use of spatial teaching practices. In contrast, Rocha and colleagues (2022) found that K-12 teachers with weaker spatial skills but lower anxiety for mental manipulation tasks reported more frequently using spatial teaching practices. However, it is worth mentioning that Rocha et al. (2022) examined teachers' practices while teaching remotely due to the COVID-19 pandemic when preferred or typical teaching strategy selection may have been impacted.

The limitations and research questions left unanswered by prior studies informed the development of the current study. Results from Rocha et al. (2022) indicate that there were no significant differences between primary and secondary teachers on measures of spatial skills, spatial anxiety or reported implementation of spatial teaching strategies; however, these results contradicted the results of the study conducted by Atit and colleagues (2018), which found differences in spatial abilities between primary and secondary teachers. The difference between the findings of these two studies could be attributed to the fact that the data utilized in Atit and colleagues (2018) study originated from high school students in the 1960s who were future teachers. Whereas in the study conducted by Rocha and colleagues (2022), the data examined was collected from practicing teachers. Further, Rocha and colleagues (2022) posit that the differences could also be associated with the large time gap and systematic changes to standards within educational practice that have been adopted during the large gap in time. To elaborate, since the data used in Atit et al. (2018) was collected, the incorporation of the multi-state K-12 Next Generation Standards (NGSS; NGSS Lead States, 2013) has encouraged the usage of spatial tools (such as manipulatives and diagrams) in teaching STEM, particularly at the primary level. Even though spatial learning has not been actively integrated as a formal skill to be taught explicitly by teachers, spatial pedagogical strategies/tools (such as developing and using models and diagrams) appear throughout the disciplinary core ideas forming the framework of the NGSS standards. Given much prior research on spatial skills has indicated that spatial skills are malleable and can be improved through training and practice (Uttal et al., 2013), it is possible that experience teaching primary STEM content using spatial tools may have resulted in the diminished differences between primary and secondary teachers' spatial skills in the study conducted by Rocha and colleagues (2022).

Taken together, the findings from these studies examining how K-12 teachers' spatial cognition and affect impact their spatial pedagogy has left an unclear picture of the differences between primary and secondary teachers. Rather than examining the differences between these classifications of teachers, the current study focuses specifically on how PreK-6 (elementary) teachers' spatial cognition is related to their preferences for employing spatial pedagogy in STEM domain-specific contexts. While exploring the differences between primary and secondary teachers' spatial cognition, spatial affect and spatial pedagogy may be worthwhile, understanding the relationship between these variables within individual categories of teachers (e.g., primary versus secondary) is more practical for informing teacher training and curriculum/resource support.

The current study was developed to narrow in specifically on elementary school (PreK-6) teachers for many reasons. First, this population should be considered crucial given the impact that spatial skills developed in these early years have on later STEM achievement (Lubinski & Benbow, 2006; Wai et al., 2009) and STEM persistence (Atit et al., 2021). Additionally, though spatial reasoning is considered to be critical to elementary math instruction (Lowrie & Logan, 2018) and science instruction (Hodgkiss, et al., 2018; Newcombe, 2010; Zimmerman et al., 2019), there is a lack of guidance to teachers on how to formally cultivate their students' development of these skills (Gilligan-Lee et al., 2022). Further, research conducted by Gagnier and colleagues (2022) suggests that elementary school teachers are likely to hold the inaccurate belief that spatial thinking skills are more important for older students compared to younger students, and that elementary teachers display significantly lower self-efficacy in their capacity to cultivate their students' spatial thinking skills when teaching in general and during science instruction specifically. This highlights the need for generating more nuanced information that can be used to better inform elementary school teachers' spatial pedagogy, beyond current guidance provided to them on math and science instruction.

Another limitation of the prior studies I conducted that the current study seeks to reconcile is that the prior studies examined teachers' use of spatial practices using a measure employing self-report (Atit & Rocha, 2020; Rocha et al., 2022). Although commonly used to initially explore important pedagogical topics, some suggest that self-report measures may not produce an outcome with the strongest validity because there is evidence that teachers' self-reported recollections may be inaccurate (Koziol & Burns, 1986; Mayer, 1999) and can be misrepresentative of their actual teaching practices. In the current study, to better understand and obtain a more precise assessment of how teachers' spatial cognition/affect relates to their spatial pedagogy, I developed a measure aimed at assessing teachers' level of preference for employing spatial pedagogy during planning of hypothetical STEM teaching situations. This measure serves to eliminate the potential misrepresentation of reflecting back on prior teaching practices. Measuring teachers' preference for engaging in spatial teaching strategies will provide us with knowledge of teachers' contextualized preferences for using specific spatial pedagogical tools during instruction, which is currently missing in the literature. Additionally, exploring teachers' preferences for engaging in spatial pedagogy will provide insight into a teachers' comfort with such practices - when, to this point, much research has only focused on if/how often teachers apply spatial pedagogy.

The overall lack of research in this area is concerning because one of the few available studies found that many K-12 teachers reported feeling unprepared to facilitate spatial learning in their classrooms (Power & Sorby, 2020). Further, this indicates that efforts at improving K-12 students' spatial skills by exposing them to classroom experiences with spatial instructional tools and practice with spatial thinking (e.g., Lowrie et al., 2017; Sorby, 2009) may have limited effects. Additionally, we can only assume that these effects are even more negative in elementary school teacher populations, given the finding that they tend to exhibit lower levels of spatial skills compared to their colleagues teaching at the secondary level (Atit et al., 2018). Findings from this research has implications for teacher development training or pre-service teacher training and for the development of students' spatial skills from their classroom experiences.

Engaging in Spatial Pedagogy

The operational definition that I have assigned to "spatial pedagogy" is the inclusion of strategies and methods for delivery of material that can be used to inform, guide, or assist students in spatial thinking while teaching a subject topic (e.g., mathematical equivalence, solar system, water cycle) which will bolster students' development of spatial skills. Some examples of such pedagogical tools would include incorporating visual diagrams or graphs, physical models, gestures, drawing/sketching. In the following section, I will describe what these tools are and how they theoretically and empirically support elementary students' spatial reasoning development and STEM learning.

Visual diagrams. According to Lowe (1993), a visual diagram is a "graphic portrayal of the subject matter they represent". Displays of graphic representations of information are common and utilized in a variety of outlets (i.e., scientific journals, textbooks, online sources) and because of their popularity, it is imperative that students understand how to extract relevant information from them (McTigue & Flowers, 2011). According to prior research, visual diagrams appear to be most effective when they are specifically designed to support cognitive processes necessary for deepening comprehension (Butcher, 2006).

Both multimedia learning theory and cognitive learning theories support the notion that visual representations can bolster student learning because they make abstract concepts accessible (Rau, 2017; Schnotz 2014; Uttal and O'Doherty 2008). On a cognitive level, visual diagrams are a stimulus that provides different affordances for learning that textual and verbal stimuli cannot (Gates, 2018). Cognitive offloading, in the context of visual diagrams, operates by spreading out the cognitive requirements necessary to process information from only taking place in the verbal/auditory memory store to also include the visuospatial memory store. In addition to supporting initial encoding of information, visual diagrams are also thought to help speed up information retrieval, as information may be recalled from both the verbal and visual memory stores (Gates, 2018).

Existing research confirms that many teachers report displaying visual diagrams in their teaching (Coleman et al., 2011). However, some researchers have identified that many teachers do not provide much opportunity for students' active engagement with the diagrams (Coleman et al., 2011; Gates, 2018). To elaborate on this problem, Gates (2018) suggests that the act of simply displaying visual diagrams gives it a "wallpaper" quality. It is suggested that teachers should employ strategies to connect visual diagrams with verbal/textual information and tangible sensory experiences in order to make visual diagrams most effective for learning from and enhancing the development of visuospatial cognition (Dawe, 1993; Gates, 2018).

Prior research indicates that the incorporation of visual diagrams in teaching is most effective in cultivating a better understanding of scientific concepts when students' engagement with them is supported actively through a variety of pedagogical strategies (e.g., Padalkar & Ramadas, 2011; Tytler, et al., 2009; Waldrip & Prain, 2012). One study explored the role of creating visual diagrams in supporting learning, reasoning and exploration with 5th and 6th grade students learning about animal diversity (Tytler et al., 2009). Students in the study were prompted to create diagrams on a variety of topics while learning about diversity in their school "habitat". This study reported qualitative evidence of sufficient learning gains attained by the students in the class. The visual diagrams that the students in the study produced illustrated a deep understanding of relevant science concepts (Tytler, et al., 2009). Another study, conducted by Padalkar & Ramadas (2011), found that diagrams, in conjunction with other spatial instructional tools, strengthened students' astronomy understanding, which the authors note is heavily reliant upon spatial thinking. Further, a study examining the implementation of "Think3d!", an embodied spatial training program that includes diagram interpretation, in elementary schools led to gains in students' spatial thinking and mathematics outcomes (Burte et al., 2017)

There is ample prior research that provides evidence that visual diagrams can be a useful tool for informing students' understanding of spatial domain-specific concepts, especially when paired with additional spatial instructional tools (e.g., Gates, 2018; Padalkar & Ramadas, 2011; Tytler et al.,2009; Waldrip & Prain, 2012). Additionally, it is clear that visual diagrams are used abundantly in teaching and textbooks; however, it is not clear how often teachers actively choose to utilize visual diagrams in their teaching. Ascertaining teachers' preferences for engaging students' spatial learning through the use of visual diagrams is essential for informing teacher training for STEM teaching.

Physical models. Physical models are tools that students can touch/interact with and that allow teachers to present abstract concepts more concretely. It is theorized that physical models afford students' ability to more readily construct mental images that can be used to scaffold and build new knowledge (Newman et al., 2018; Wu et al., 2001). Similar to the theoretical framework that justifies the use of visual diagrams while teaching, physical models also act as a cognitive offload. Including physical models in learning opportunities reduces the demand on students' working memory, often freeing them from the cognitive processing work of holding/manipulating mental visualizations (e.g., unit cubes, Cuisenaire fraction rods). Both teachers and researchers believe that concrete physical models afford children the ability to make connections between their interactive experiences of the world around them and their budding knowledge of STEM concepts and symbols (e.g., Uttal et al., 1997).

Research suggests that physical models are effective for facilitating understanding of abstract, invisible, and spatially demanding science concepts (Atit et al., 2015; Stieff et al., 2016a; Stieff et al., 2016b). For example, manipulatives (such as unit cubes, Cuisenaire rods, tangrams), which are a type of physical models, have been regarded as an effective tool for teaching mathematics (Ball, 1992). A meta-analysis of 55 studies found that the use of manipulatives in teaching mathematics in elementary school had a moderate effect on student learning (Carbonneau et al., 2012).

Unfortunately, there has been little attention given to assisting teachers with ensuring their students have correctly connected these physical materials with their underlying abstract concepts (Ball, 1992). There is a need for guidance in the curriculum to aid teachers in their successful implementation of these bridging strategies/tools. The current study will provide foundational insight that may be used to help develop such resources by informing the baseline knowledge on teachers' preferences for using these types of instructional tools, in relation to spatial cognition and affect. Similar to the research on visual diagrams, more attention should be focused on how comfortable teachers are with using physical models and what supports they may need to capitalize on their effectiveness for helping students achieve understanding of STEM concepts and developing spatial skills.

Gestures . Gestures are known as meaningful movements of the hands made when engaging in spatial thoughts or spatial activities (Alibali, 2005). Gestures have been found to be an effective scaffold for spatial thinking in many different topic areas. It is theorized that there are two ways that gestures influence learning, (1) gestures we see others produce have the potential to change our thoughts and draw our focus to concepts that are not (or cannot be) conveyed in speech, and (2) gestures that we ourselves produce have the potential to change our thoughts, perhaps by spatializing ideas that are not inherently spatial (Goldin-Meadow, 2014). Again, learning is bolstered by the use of gestures through cognitive offloading. Similar to visual diagrams and physical models, gestures engage cognition in the visuospatial processing stores, spreading out the cognitive demand from the verbal/auditory processing stores.

Overall, research suggests that learners are more likely to profit from instruction that is accompanied by gesture than instruction that is not accompanied by gesture (e.g., Church et al, 2004; Perry et al., 1995; Valenzo et al., 2003). One study that illustrates students' increased ability to learn concepts when teachers use gestures during instruction is Valenzeno et al. (2003). This study showed that students given a verbal and gesture instructional video on symmetry performed significantly better on a test of symmetry knowledge than students given a verbal only instructional video. Another STEM-based study that examined elementary school students' understanding of mathematical equivalence found that when students were taught utilizing an abstract gesture, they displayed greater mastery of the math problems and were (unique from other interventions) additionally capable of solving math problems that required generalized use of the equivalence knowledge (Novack et al., 2014).

It is well established that teachers naturally gesture while teaching (Crowder & Newman, 1993; Flevares & Perry, 2001; Neill, 1991; Roth & Welzel, 2001; Zukow-Goldring et al., 1994) and some research suggests that teachers' gesture use is influenced by their spatial cognition (Otumfuor & Carr, 2013). The aforementioned study found that middle school geometry teachers' spatial skills and pedagogical content knowledge were positively related to their use of representational gestures, in addition to graphs and diagrams. Findings such as these provide further basis for the hypothesis that elementary school teachers' spatial cognition may relate to their preferences for engaging in spatial pedagogical practices. The current study explores this connection, seeking to replicate the findings from Otumfuor & Carr's (2013) study within a different population of teachers.

Drawing/sketching. Research that examines the effectiveness of instruction that incorporates student generated drawing/sketching has shown that it is a promising instructional tool for facilitating learning for spatially demanding science content (e.g., Tytler et al., 2009; Van Meter et al., 2006; Waldrip et al., 2010). To clarify what is meant by the practice of drawing/sketching, Hare (2004) describes the practice as an act that can include student's performing "observational drawing, idea generation, diagramming, design working drawing and doodling". It has been surmised from prior research that drawing/sketching affords learners with the opportunity to extend and simultaneously transform understanding (Hare, 2004), resulting in a higher quality of learning. Similar to all of the other strategies discussed previously, drawing/sketching enhances learning through reducing cognitive load on verbal/auditory processing stores and spreading it to include visuospatial processing stores.

One example of the effects of drawing/sketching in STEM education can be seen in the study conducted by Van Meter and colleagues (2006). These researchers found that learner-generated drawings were more effective for sixth-grade students understanding the structure of bird wings than non-drawing content instruction. Another example of a topic where sketching has often been utilized to assist students spatial thinking (3D visualizing) is within the geology domain as fostering understanding of complex geological concepts (e.g., earthquake faults, plate tectonics, lava flow in volcanoes) relies on students' ability to visualize structures that are not physically visible (Gagnier et al., 2013).

Given the potential of drawing/sketching as an instructional tool, the National Council on Teachers of Mathematics calls for increased implementation of the use of this strategy. They indicate the importance of drawing to learning by stating "many authors have expressed the opinion that children perform better in mathematics problem-solving situations when diagrams or pictures of the problems are provided by the teacher to elicit appropriate mental images (e.g., Driscoll, 1979; Nelson, 1975; Riedesel 1969; Threadgill-Sowder & Sowder, 1982)." While this call provides further evidence that drawing/sketching is an effective tool for supporting students' STEM learning and development of spatial thinking skills and should be included in STEM teaching considerations, it does not address how teachers' spatial cognition and affect is related to their preference for incorporating these tools or heeding this call.

In sum, evidence suggests that engaging in spatial pedagogy supports students' learning for STEM content and may bolster the development of students' spatial skills (Burte et al., 2017; Gagnier et al., 2013; Padalkar & Ramadas, 2011; Valenzeno et al., 2003). Prior research suggests that both of these objectives can be accomplished when teachers integrate spatial pedagogy into their lessons and curriculum delivery (Burte et al., 2017; Gagnier et al., 2013; Novack et al., 2014; Van Meter et al., 2006). Further, showing that spatial pedagogy used in STEM classroom instruction both improve students' domain knowledge and spatial skills, Lowrie et al. (2017) found that a long-term visuospatial training program implemented collaboratively with teacher participation in sixth grade classrooms led to increased mathematics content understanding and improved spatial reasoning abilities. The intervention included components of spatial pedagogy in the form of manipulatives, drawing, and visual diagrams. Further, lessons were specifically designed to have teachers participate in exposing students to practicing skills from three spatial reasoning constructs - mental rotation, spatial visualization, and spatial orientation (Lowrie et al., 2017). The accomplishments of this study highlight the potential for spatial pedagogy. However, more research is needed to fully corroborate the case for spatial instructional tools improving both students' spatial skills and relevant STEM domain knowledge. Additionally, understanding teachers' preferences for spatial pedagogy and how their cognition and affect is related to these preferences is important for obtaining their support and cooperation with any future interventions aimed at improving students' spatial skills that are to be administered as part of teacher training and wider implementation.

The Current Study

The current study focuses on the relations between elementary school teachers' spatial cognition/affect and their preference for spatial pedagogy. This study was conducted using online survey methodology. Participants completed a survey via Qualtrics that included measures of spatial skills, spatial anxiety, spatial habits of mind and preference for using spatial pedagogy in addition to measures of general reasoning ability and general anxiety. In the following paragraphs is an explanation of the features of the current study which methodologically seeks to contribute new information to the existing body of knowledge in this research domain.

Notably, few other studies examining the teachers' role on students' spatial learning have specifically focused on the *elementary* school teacher population despite the established importance for students' development of STEM understanding and spatial thinking in these grades. Of the few available studies that examine this population, Gagnier and colleagues (2022) found that K-5 teachers are readily able to identify the types of problems students could be presented with which require spatial problem-solving skills. Additionally, this study revealed that elementary school teachers consistently exhibit low spatial anxiety when solving spatial problems themselves, and believe in their own ability to get better at solving spatial problems. However, the findings of this study also elucidate that while the teachers of this population have high self-efficacy for their general and science teaching abilities, they report lower efficacy in their ability to cultivate students' spatial thinking skills during science instruction. Further, Gilligan-Lee and colleagues (2022) surveyed reception teachers (the first year of primary education in the United Kingdom) and found that their valuation of spatial and numeracy activities to be of less importance than literacy activities. These findings reveal some potential mechanisms which could shape the way elementary teachers approach formal/informal STEM education and spatial skill building; however, it is still unclear how individuals' spatial cognition/affect relates to spatial pedagogy within this population.

Another aspect of the study that is novel is the aim to empirically explore teachers' spatial skills through a *battery* of measures. This is important as most previous research has only been able to employ a narrow examination of spatial skills with measures that only look at one or two dimension(s) of spatial thinking skills at a time, such as mental rotation or spatial visualization (e.g., Otumfuor & Carr, 2017; Gunderson et al., 2013; Atit & Rocha, 2021; Rocha et al., 2022). For example, Atit and Rocha (2021) administered the timed version of the MRT (Vandenburg & Kuse, 1978) and found that participants' scores were significantly related to their spatial anxiety for mental manipulation, but not their spatial anxiety overall. In order to further validate claims about teachers' spatial skills, however, it is necessary to administer a measure that more fully encompasses the different types of spatial thinking (emphasis on the plurality in spatial skills) as opposed to only looking at one spatial skill.

Further, this study contributes methodological choices to broaden what is known about teachers' spatial anxiety. Instead of administering the Spatial Anxiety Scale (Lyons et al., 2018), as much of the previous research examining teachers' spatial anxiety have done before (e.g., Atit & Rocha, 2020; Rocha et al., 2022), the current study will instead utilize the conventions introduced by Gagnier and colleagues (2022). This method of measuring spatial anxiety entails assessing participants' level of anxiety when engaging with spatial problems they are likely to encounter when teaching math and science. In the current study, participants are asked to solve a variety of spatial problems on which performance has been linked to STEM learning and attainment (Uttal & Cohen, 2012) and then rate their anxiety level after completing each problem. This method of measuring teachers' spatial anxiety will provide insight that is more directly applicable to the experiences they might have while teaching, as opposed to the more general spatial anxiety they would display through the Spatial Anxiety Scale (Lyons et al., 2018).

Additionally, a *spatial habits of mind* measure was administered. To my knowledge, spatial habits of mind have never been measured in studies that examine teachers' spatial cognition. Spatial habits of mind is a construct of interest because prior studies have shown that engagement with spatially-intense material can significantly improve students' spatial habits of mind (Kim & Bednarz, 2013; Cortes et al., 2022). However, prior studies have not examined if *teachers'* spatial habits of mind impact their pedagogy. Understanding how teachers' spatial habits of mind relate to their preference for implementing spatially intense material in their teaching practice will provide insight relevant for strengthening STEM teacher education programs.

And finally, the current study's assessment of teachers' *preferences for using spatial pedagogy* is novel within this research field. Measuring the scope of teachers' preferences, as opposed to the commonly used method of attempting to measure their use of spatial instructional strategies through self-report (i.e., Atit & Rocha, 2020; Rocha et al., 2022), is advantageous for many reasons. First, measuring teachers' preferences is distinct because it speaks to the desire to use a teaching methodology in opposition to actual use. The findings of Gagnier et al. (2022) elucidate that K-5 teachers exhibit a lower self-efficacy for cultivating students' spatial skills during science instruction than their overall self-efficacy for teaching and even their self-efficacy for teaching science. This finding highlights that there may be nuances pertaining to teachers' feelings about their capabilities to conduct instruction using spatial pedagogy. Assessing teachers' preferences for engaging in spatial pedagogy will contribute toward a greater ability to draw conclusions about educators' motivation to engage in spatial teaching practices than previous research (Gagnier et al., 2022). Additionally, the composition of the measure (which is detailed in greater length in the Methods section) allowed for all participants, regardless of grade level/associated STEM curriculum they currently teach, to be compared by their projected preferences. This also introduces greater rigor by seeking to reduce the level of potential inaccuracy that can be introduced when using ex post facto self-reporting measures when surveying teachers (Koziol & Burns, 1986; Mayer, 1999).

Overall, the participants and assessment methods used contribute a new perspective to the nature of the relations between teachers' spatial cognition and their use of spatial instructional practices in STEM education.

Research Questions & Hypotheses

1. Do elementary school teachers' spatial cognition/affect (spatial skills, spatial anxiety, spatial habits of mind) or preferences for using spatial pedagogy in STEM instruction differ by educational attainment or teaching experience? As mentioned previously, there are few studies that have looked specifically at elementary teachers' spatial cognition/affect (Gagnier et al., 2022). Of the constructs that the current research is concerned with, Gagnier and colleagues' (2022) study only addresses teachers' spatial anxiety. When examining teachers' spatial anxiety, they did not find any significant differences on this measure by teachers' experience. Given this information and additionally informed by my previous research that has examined K-12 teachers' spatial cognition and affect (Atit & Rocha, 2020; Rocha et al., 2022), it is hypothesized that there will no significant differences in teachers' spatial cognition/affect or preference for spatial pedagogy by educational attainment or teaching experience.
2. How are elementary school teachers' spatial skills related to their spatial anxiety and spatial habits of mind? Atit and Rocha's (2020) prior investigation into teachers' spatial skills and spatial anxiety showed that they are inversely related, such that as spatial skills increase, spatial anxiety scores decrease and a negative correlation was specifically noted between spatial skills and spatial anxiety for mental manipulation tasks. Atit and Rocha's (2020) study examined these relations amongst aggregated K-12 teachers, not specifically elementary school teachers; however, there is not any evidence to suggest that these relations will

manifest themselves any differently in elementary school teachers. Thus, it is hypothesized that elementary school teachers' spatial skills and spatial anxiety will display similar relations - spatial anxiety will be negatively predictive of spatial skills. As for spatial habits of mind, I predict that they will be highly correlated with spatial skills considering how the constructs are theoretically related (Kim & Bednarz, 2013). Additionally, if someone reports a higher propensity for spatial habits of mind, they likely would not be made anxious by spatial problems and thus will also display lower levels of spatial anxiety.

3. How are the measured factors of elementary school teachers' spatial cognition/affect (spatial skills, spatial anxiety, and spatial habits of mind) related to their preferences for using spatial instructional practices while teaching STEM content? Supported by the findings of Atit & Rocha (2020), which elucidated a significantly predictive relationship between K-12 teachers' spatial skills and reported use of spatial teaching practices, I hypothesize that spatial skills will be positively associated with elementary school teachers' preferences for using spatial instructional practices. Additionally, given that Kim and Bednarz (2013) found that spatial habits of mind were enhanced after students took a GIS course (a course that would expose students to many spatial concepts), I hypothesize that teachers' spatial habits of mind will be positively associated with their preference for using spatial instructional practices.

METHODS

Participants

A total of 80 elementary school teachers were recruited to participate in this study. An a priori power analysis indicated that, while using an alpha of 0.05, 77 participants was a sufficient number of participants to generate an 80% power to detect a medium effect size (f^2 = 0.15) for a linear multiple regression for a fixed model examining R^2 increasing, with three tested predictors and eight total predictors. Participants were recruited for this study on the basis that they held, or were currently in pursuit of obtaining, a multiple-subject California Teaching Credential. This credential certifies individuals to teach in K-6 public schools in California. Recruitment of participants took place through advertising at the California STEAM Symposium (which is an annual state-wide conference for educators that takes place in Southern California), via social media posts made by the research team, and by reaching out directly to past eligible participants, other credentialed teachers, and pre-service teachers in the research team's professional network. Upon completion of the approximate 45-minute survey, participants received a $50 e-gift card to Target for their participation.

Measures and Materials

Spatial Skills and Spatial Anxiety (adapted)

This measure was adapted from Gagnier and colleagues (2022). The measure used here consists of two parts: (1) measure participants' spatial skills, and (2) measure participants' anxiety for completing the spatial tasks. In the spatial skills portion of the measure, the selected problems were pulled from assessments of spatial thinking on which performance has been linked to STEM performance (Gagnier et al., 2022; Uttal & Cohen, 2012). Included items examined participants' mental rotation, perspective taking, visualizing cross-sections, paper-folding, disembedding, and understanding of isometric projection. To summarize the composition of the adapted measure, there were four mental rotation items, three perspective taking items, three visualizing cross-sections items, three paper-folding items, three disembedding items, and one item that evaluated participants' understanding of isometric projections.

To measure participants' spatial anxiety, after each spatial skills item, participants were asked to respond to the following question: "How anxious did you feel when asked to solve this problem?" Response options included (0) not at all, (1) slightly, (2) moderately, (3) very, or (4) extremely.

Scores were computed for both parts of the measure (i.e., spatial skills and spatial anxiety) separately. Scores on the spatial skills portion of the measure was the sum of the amount of correctly answered items–awarding one point to each of the ten items. Thus, with seventeen items, scores on this portion of the measure can range from 0-17. Cronbach's (alpha) for internal reliability was calculated for the whole spatial skills subsection and showed the measure exhibited acceptable reliability ($a = 0.73$).

As for the spatial anxiety portion, scores were computed by summing the indicated values for each of the eighteen items. Scores on this portion of the measure can range from 0-72 points. Cronbach's a for internal reliability was calculated for the whole spatial anxiety portion of the measure and showed the measure exhibited excellent reliability ($a = 0.91$).

Spatial Habits of Mind Inventory (adapted)

Spatial habits of mind are thought of as the internal processes that are used for thinking spatially, for example representing thoughts in a spatial way (i.e., visualizing) (National Research Council, 2006; Kim & Bednarz, 2013). This measure was adapted from Kim & Bednarz's (2013) Spatial Habits of Mind Inventory for geography students. In the version used here, items specific to geography were adapted or removed to make the measure accessible to a more general audience. Four of the five original subscales were used: (1) pattern recognition, (2) spatial recognition, (3) visualization, (4) spatial concept usage. Additionally, some of the wording was changed to provide elaboration/examples to contextualize the items. For a full comparison of the original measure and the adapted version, see Appendix A.

The measure includes 23 items and the instructions ask participants to "Please indicate which response for each item best describes your thoughts, beliefs, and/or actions. There are no wrong answers." The response options were "SD = Strongly Disagree", "D = Disagree", "N = Neutral", "A = Agree", "SA = Strongly Agree". The measure was coded to give participants a score of 0-4 on each item (note: some items were reverse coded because of the wording of the item). Participants' summed scores were used in the analyses.

Additionally, prior to administration in the study, this measure was piloted on a group of undergraduate students (n = 131) to ensure the comprehensibility and validity of the adapted version. Analysis of the data from the pilot shows that the overall measure has a good level of internal reliability. According to Cohen's (1988) conventions, the measure in undergraduate students had an alpha of 0.83. Cronbach's *a* for internal reliability was also calculated for the measure with the scores from the teacher participants and showed the measure exhibited excellent reliability (*a* = 0.92).

Preferences for Spatial Pedagogy Survey

This measure is a researcher-created instrument that seeks to gauge teachers' preferences for using spatial versus non-spatial instructional tools in specified teaching contexts. In each item, participants rated how likely they were to utilize the four listed tools in described teaching contexts. For example, one item asked teachers to think about the following teaching context:

"To teach students about mathematical equivalence and the meaning of the 'equal' (=) sign,"

And then asked them to rate how likely they would be to utilize the following four instructional tools:

(1) vocabulary prompting to emphasize the definition of "equal",

(2) a drawing/sketch of what each side of an equation represents (i.e., drawing four stars plus five stars being equal to three stars plus six stars),

(3) a physical scale to show equal manipulative units on each side creating a balance,

(4) a mnemonic or song that helps students to remember that both sides of the equation have to be equal.

The available ratings they had to choose from are on a scale of one to four, with one representing “not rely on it at all”, two representing “rely on it very little”, three representing “rely on it moderately”, and four representing “rely on it heavily”.

The creation of this measure was informed by the California Frameworks for Mathematics and Science (Frameworks) from the California State Board of Education (2015, 2016). The Frameworks provide statewide recommendations and vignettes that highlight exemplary teaching practices for K-12 California teachers. The instructional tools that are listed for teachers to rate in the instrument were chosen based on the examples given in the Frameworks. To ensure the validity of the measure, seven scholars who study spatial cognition in K-12 STEM education were asked to independently rate the given instructional tools for how spatial they were (meaning how much they would cultivate spatial thinking). The responses that they were asked to choose from ranged from (0) not spatial at all to (5) extremely spatial. These ratings were then used to classify the tools/strategies as more spatial/less spatial. Any tools/strategies that had an average rating below a 2.5 were considered “less spatial” and any tools/strategies that had an average rating above a 2.5 were considered “more spatial”. The “less spatial” instructional tools/strategies were reverse coded. Given this scoring method, teachers who exhibit a higher score can be said to display a greater preference for spatial tool use while teaching elementary STEM topics.

International Cognitive Ability Resource (ICAR) - Verbal Reasoning & Matrix Reasoning.

The Verbal Reasoning and Matrix Reasoning measures were administered to assess participants' general reasoning ability (Kyllonen & Christal, 1990; Kyllonen & Dennis, 1996). The selected measures come from a collection of open-source assessments created for public-use by the International Cognitive Ability Resource Project (ICAR; Condon & Revelle, 2014). The ICAR project website reports an acceptable level of reliability ($\alpha = 0.77$) for the Verbal Reasoning measure and a questionable level of reliability ($\alpha = 0.66$) for the Matrix Reasoning measure. Reports of reliability for these measures within the data collected for this study are reported in the sections to follow.

Verbal Reasoning. This measure consists of 16 items made up of a variety of logic, vocabulary, and general knowledge multiple choice items such as, "If the day after tomorrow is two days before Thursday, then what day is it today?" Participants had to choose the correct answer from the following response choices: "(A) Friday (B) Monday (C) Wednesday (D) Saturday (E) Tuesday (F) Sunday". Participants' score on this assessment was calculated from the sum of the number of correct responses (ICAR, 2014). The reliability of this measure for this study's sample was questionable ($\alpha = 0.69$).

Matrix Reasoning. The Matrix Reasoning assessment consists of 11 items that contain stimuli similar to those used in Raven's Progressive Matrices (ICAR, 2014). In each item, participants were presented with a 3x3 array of geometric shapes where one of the nine shapes is missing. The instructions asked participants to respond by selecting one of six presented geometric shapes to best complete the array. Participants' score on this assessment was the sum of the number of correct responses. The reliability of this measure in this study's sample was acceptable (α = 0.70).

Trait Anxiety Inventory.

The Trait Anxiety Inventory (Spielberger et al., 1970) is a 20-item measure of participants' general level of anxiety. Participants were asked to read each statement and select the response that corresponded to how frequently they experience general feelings of anxiety. One example of an item from the measure reads, "I worry too much over something that really doesn't matter". The response options were (0) almost never, (1) sometimes, (2) often, (3) almost always. Responses on each item were scored from 0 to 3 and total scores for the measure were calculated by taking the sum of the responses for all items. Possible scores range from 0 to 60. Higher scores indicate higher levels of general anxiety. Spielberger and colleagues (1970) report high level median alpha coefficients ($a = 0.90$) for the reliability of this measure. Likewise, the data collected from the participants of this study reflected an excellent level of reliability ($a = 0.93$).

Demographics Questionnaire

This questionnaire included items asking for participants to identify their gender, duration of overall teaching career, duration of elementary teaching career, credentials and educational background, and grade level(s) taught. The full measure can be seen in Appendix B.

Procedure

After recruitment, participants were directed to the survey through a link that was provided to them. The survey was administered through Qualtrics (Qualtrics, Provo, UT).

Participants first were prompted to enter a password that was provided to them by the research team to enter the Qualtrics portal. This protocol eliminated the possibility that intrusive ‘bots’ could access the survey and provide irrelevant data. Each participant then went through the informed consent process prior to beginning all the measures of the survey. The measures that were administered in the following order: Spatial Skills and Spatial Anxiety, Spatial Habits of Mind Inventory, Teachers’ Preferences for Spatial Pedagogy Survey, ICAR Verbal Reasoning, ICAR Matrix Reasoning, Trait Anxiety Inventory, and the Demographics Questionnaire. Demographic questions were administered last in order to reduce introducing the effects of stereotype threat (Spencer et al., 1999; Steele & Aronson, 1995), given that a majority of the participants of this study were women and research indicates their performance on the spatial skills measure could be negatively influenced by asking for demographic information at the beginning of the study.

CHAPTER 4: RESULTS

All analyses were conducted in IBM SPSS Statistics (Version 28). Before conducting analyses, all data collected was screened for invalid or unreliable entries. Participants' data were removed if the time elapsed while completing the survey was less than 20 minutes, as data from these participants was heavily incomplete and likely did not represent thoughtful responses. The median duration for study completion was 72 minutes; thus, participants who took 20 minutes or less to complete the study spent less than a third of the time the majority of the other participants spent on the survey. Further, only measures with complete responses were included in the analyses conducted throughout.

Preliminary Analyses

Table 4.1 represents the descriptive statistics computed for the Spatial Skills and Spatial Anxiety Battery (adapted), Spatial Habits of Mind Inventory adapted (SHOMI-a), Teachers' Preferences for Spatial Pedagogy Survey, Verbal Reasoning, Matrix Reasoning, and Trait Anxiety Inventory.

To examine the relations between the variables, Pearson's correlations between all administered measures, educational attainment, and teaching experience were conducted (presented in Table 2). Following Cohen's (1988) conventions, results indicated that there was a significant positive association between educational attainment and Matrix Reasoning (r = 0.28). Further, there was a positive association between participants' teaching experience and their scores on the Spatial Skills Battery (r = 0.34), Preferences for Spatial Pedagogy Survey (r = 0.32), and Matrix Reasoning performance (*r* = 0.52); however, participants' teaching experience was negatively associated with Spatial Anxiety (*r* = -0.29) and with Trait Anxiety (*r* = -0.48).

Participants' performance on the Spatial Skills Battery was negatively associated with their reported Spatial Anxiety (*r* = -0.25), but positively associated with their Preference for Spatial Pedagogy (*r* = 0.28), Spatial Habits of Mind Inventory (*r* = 0.428), and general reasoning skills. Specifically, participants' Spatial Skills Battery scores were strongly associated with their Verbal Reasoning skills (*r* = 0.623) and Matrix Reasoning skills (*r* = 0.633).

Contrary to the Spatial Skills Battery, participants' Spatial Anxiety scores were negatively correlated with Trait Anxiety (*r* = -0.28), Matrix Reasoning performance (*r* = -0.25), and SHOMI-a (r = -0.36). And participants' scores on the SHOMI-a were positively correlated with their scores on the Preference for Spatial Pedagogy Survey *(r* = 0.30), and negatively correlated with Trait Anxiety (*r* = -0.26) and Matrix Reasoning (*r* = -0.25).

Table 4.1

Descriptive statistics for all measures

Measure	*M* (SD)	*n*
Spatial Skills Battery	10.06 (3.18)	77
Spatial Anxiety	35.09 (10.09)	75
SHOMI-a	76.08 (14.76)	72
Spatial Pedagogy	76.78 (6.92)	73
Verbal Reasoning	9.56 (2.69)	73
Matrix Reasoning	5.99 (2.65)	77
Trait Anxiety	38.91 (9.65)	74

Note. SHOMI-a denotes the Spatial Habits of Mind Inventory (adapted), Spatial Pedagogy refers to the Preferences for Spatial Pedagogy Survey

Table 2

Correlational data among all examined variables

	1	2	3	4	5	6	7	8	9
1. SSB									
2. SA	**-0.25**								
3. SHOMI-a	**0.43**	**-0.36**							
4. PSP	**0.28**	-0.14	**0.30**						
5. Verbal	**0.62**	-0.15	0.16	0.14					
6. Matrix	**0.63**	**-0.25**	**0.26**	0.14	**0.56**				
7. TAI	-0.05	**0.28**	**-0.26**	-0.21	-0.06	-0.22			
8. Exp	**0.34**	**-0.29**	0.14	**0.32**	**0.26**	**0.52**	**-0.49**		
9. Educ	0.15	-0.01	-0.08	0.01	0.28	**0.28**	0.03	0.22	

Note. Significant correlations (p<.05) are bolded. SSB denotes Spatial Skills Battery (adapted). SA denotes Spatial Anxiety. SHOMI-a denotes Spatial Habits of Mind Inventory (adapted). PSP denotes Preference for Spatial Pedagogy Survey. Verbal denotes Verbal Reasoning measure. Matrix denotes the Matrix Reasoning measure. TAI indicates Trait Anxiety Inventory. Exp refers to teachers' reported experience in teaching at the elementary level (measured in years). Educ denotes the highest level of education that participants reported complet

Do elementary school teachers' spatial cognition and affect differ based on educational attainment or teaching experience?

To identify if elementary school teachers' spatial cognition and affect varied based on educational level, I conducted *t*-tests examining the differences between the two levels of educational attainment, (1) bachelors' degree holders and (2) masters' degree holders. Independent samples *t*-tests were run for all of the measures, with the exception of the SHOMI-a because a Levene's test of Homogeneity of Variance indicated that the variance between the groups was not homogeneous for that particular measure. In place of the independent samples *t*-test, a Kruskal Wallis test was used to evaluate if there were significant differences on the SHOMI-a based on educational attainment. The results of these tests, shown in Table 4.3, indicated only significant differences on the general reasoning measures (both Verbal and Matrix Reasoning) between levels of educational attainment ($p < 0.05$ for Verbal Reasoning, $p < 0.01$ for Matrix Reasoning), indicating that elementary school teachers who possess a masters' degree displayed greater general reasoning abilities than teachers who had only obtained a bachelor's degree. No further significant differences based on teachers' educational attainment were found.

To identify if elementary school teachers' spatial cognition and affect varied based on teaching experience, I conducted a one-way ANOVA examining the differences between the six levels of teaching experience (pre-service teachers, 0-5 years of experience, 6-10 years of experience, 11-15 years of experience, 16-20 years of experience and more than 20 years of experience). Results of the test, shown in Table 4.4, indicate significant differences on measures of spatial skills, preferences for spatial pedagogy, matrix reasoning and trait anxiety by level of teaching experience.

Table 4.3

Results of t-tests/Kruskal Wallis test examining differences by educational attainment on all measures

	Bachelors' Degree		Masters' Degree			
Measure	*M*	*SD*	*M*	*SD*	*t*	*d*
Spatial Skills Battery	9.50	3.28	10.47	3.08	-1.32	-0.31
Spatial Anxiety	35.19	9.70	35.02	10.47	0.07	0.02
Spatial Pedagogy	73.10	5.92	73.25	7.84	-0.09	-0.02
Verbal Reasoning	8.88	2.72	10.10	2.58	-1.97*	-0.46
Matrix Reasoning	5.13	2.85	6.60	2.34	-2.49**	-0.58
Trait Anxiety	38.52	10.05	39.19	9.46	-0.29	-0.07
SHOMI-a	77.40	14.79	75.15	14.84	0.00	-0.03

Note. Spatial Pedagogy denotes the Preferences for Spatial Pedagogy Survey. Reported statistics for the SHOMI-a measure are results from a Kruskall Wallis one-way analysis of variance test, the effect size for this measure is given as an $\eta 2$.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 4.4

Results of one-way ANOVA test examining differences by teaching experience on all measures

Measure	*SS*		*df*	*MS*	*F*	*Sig*
Spatial Skills	Between	120.83	5	24.17	2.59	.033*
	Within	634.16	68	9.33		
	Total	754.99	73			
Spatial Anxiety	Between	943.79	5	188.76	1.95	.097
	Within	6378.21	66	96.64		
	Total	7322.00	71			
SHOMI-a	Between	299.23	5	59.85	.257	.935
	Within	14677.58	63	232.98		
	Total	14976.81	68			
Spatial Pedagogy	Between	632.98	5	126.60	2.86	.021*
	Within	2873.33	65	44.21		
	Total	3506.31	70			
Verbal Reasoning	Between	38.91	5	7.78	1.10	.372
	Within	454.57	64	7.10		
	Total	493.49	69			
Matrix Reasoning	Between	146.73	5	29.35	5.35	<.001**
	Within	372.78	68	5.48		
	Total	519.51	73			
Trait Anxiety	Between	2542.14	5	508.43	8.05	<.001**
	Within	4106.17	65	63.17		
	Total	6648.31	70			

Note. Spatial Pedagogy denotes the Preferences for Spatial Pedagogy Survey. SHOMI-a denotes the Spatial Habits of Mind Inventory (adapted).
*p < 0.05, **p < 0.01, ***p < 0.001

How are elementary school teachers' spatial skills, spatial anxiety and spatial habits of mind related?

To explore how the various elements of elementary school teachers' spatial cognition and affect (spatial skills, spatial anxiety and spatial habits of mind) are related, I ran three multiple linear regressions with fixed models. Model 1 examines if elementary school teachers' spatial anxiety and spatial habits of mind predict their spatial skills. Model 2 examines if elementary school teachers' spatial skills and spatial habits of mind predict their spatial anxiety. Model 3 examines if elementary school teachers' spatial skills and spatial anxiety predict their spatial habits of mind. Following the analytical methods used by Sokolowski et al. (2019), to ensure that the relations between these variables were not driven by their general reasoning skills, or their base level of general anxiety, I controlled for Verbal and Matrix Reasoning scores, and the Trait Anxiety Inventory score in all three models.

Results, as shown in Table 4, indicated that after controlling for general reasoning ability and general anxiety, elementary school teachers' spatial habits of mind significantly predict their spatial skills. Further, the results indicated that elementary school teachers' spatial skills significantly predict their spatial habits of mind, while controlling for general reasoning ability and general anxiety. The results also indicated that elementary school teachers' spatial skills and spatial habits of mind do not predict their spatial anxiety.

Table 4.5

Linear Regression Models Examining Predictive Relationships Between Factors of Elementary School Teachers' Spatial Cognition and Affect

	Model 1	Model 2	Model 3
Outcome Variable	Spatial Skills	Spatial Anxiety	Spatial Habits of Mind
Intercept	-0.32 (2.64)	41.19 (9.84)	88.11 (11.98)
Spatial Skills		-0.67 (0.57)	2.03* (0.79)
Spatial Anxiety	-0.04 (0.03)		-0.36 (0.18)
SHOM	0.05 (0.02)*	-0.18 (0.09)	
Verbal Reasoning	0.40 (0.12)**	0.16 (0.57)	-0.57 (0.82)
Matrix Reasoning	0.53 (0.13)***	-0.04 (0.67)	-0.65 (0.95)
Trait Anxiety	0.02 (0.03)	0.20 (0.14)	-0.26 (0.20)
R^2	0.60***	0.21*	0.27**

Note. Reported statistics are unstandardized coefficients. Numbers in parentheses are standard errors.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

How do elementary school teachers' spatial skills, spatial anxiety and spatial habits of mind relate to their preferences for spatial pedagogy?

Regression analyses were conducted to determine if teachers' spatial skills, spatial anxiety and/or spatial habits of mind are predictive of their preferences for spatial pedagogy. In line with the previous analyses, I controlled for general reasoning abilities and general anxiety. Further, I controlled for teachers' educational attainment to ensure that the explored relations are not driven by educational attainment. And because correlational data indicated an association between teachers' preferences for spatial pedagogy and teaching experience, I controlled for teaching experience in the analyses. Model 4 examined if elementary school teachers' spatial skills predict their preference for spatial pedagogy while controlling for general reasoning, general anxiety, educational attainment, and teaching experience. Model 5 examined if elementary school teachers' spatial skills and spatial anxiety predict their preference for spatial pedagogy while controlling for general reasoning, general anxiety, educational attainment, and teaching experience. Model 6 examined if elementary school teachers' spatial skills, spatial anxiety, and spatial habits of mind predict their preference for spatial pedagogy while controlling for general reasoning, general anxiety, educational attainment and teaching experience.

Results, as displayed in Table 5, indicate that only Model 4 was statistically significant.

This model indicated that spatial skills were a significant predictor of teacher's preference for spatial pedagogy. Neither spatial anxiety nor spatial habits of mind were significant predictors of elementary school teachers' spatial pedagogy.

Table 4.6

Linear regression models examining if spatial skills, spatial anxiety and spatial habits of mind display a predictive relationship to elementary teachers' preferences for spatial pedagogy.

	Model 4	Model 5	Model 6
Intercept	70.00**(5.78)	68.93**(6.81)	59.74**(10.11)
Spatial Skills Battery	0.93*(0.38)	0.97*(0.40)	0.90*(0.43)
Spatial Anxiety		0.03(0.09)	0.08(0.07)
SHOM			0.06(0.10)
Verbal Reasoning	-0.04(0.46)	0.03(0.46)	-0.12(0.47)
Matrix Reasoning	-1.01(0.53)	-1.02(0.54)	-1.00(0.55)
Trait Anxiety	-0.07(0.10)	-0.06(0.11)	-0.00(0.11)
Teaching Exp	1.12(0.63)	1.09(0.64)	1.16(0.65)
Educ Attainment	-1.42(1.81)	-1.59(1.84)	-1.43(1.86)
R^2	.20*	.20	.23

Note. Reported statistics are unstandardized coefficients. Numbers in parentheses are standard errors.
*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

CHAPTER 5: DISCUSSION

Teachers are an integral component of childrens' educational experiences and shape their students' learning outcomes (e.g., den Brok et al., 2004; Perera & John, 2020). Given the established importance of spatial skills for STEM learning, the present study sought to understand how teachers' spatial cognition relates to their affect regarding spatial tasks, and how these factors impact their preferences for implementing pedagogical strategies that would promote the development of their students' spatial thinking skills.

The results of this study show that elementary school teachers with stronger spatial skills were generally less anxious when contemplating solving spatial problems, and that these teachers also showed greater preference for using spatial pedagogy in hypothetical teaching situations. However, neither spatial anxiety nor spatial habits of mind significantly predicted preferences for spatial pedagogy.

Building on the findings of other studies that examine the impact of teachers' skills on their pedagogy (Atit & Rocha, 2020; Otumfuor & Carr, 2017), the present study identified that pre-service and in-service elementary school teachers' spatial skills were predictive of their preference for spatial pedagogy. These findings align with the results of Atit and Rocha (2020) that indicate teachers' who exhibit higher levels of spatial skills also reported higher frequency of using spatial teaching strategies. However, unlike Atit and Rocha (2020) whose sample included teachers at both the primary and secondary levels, the present study focused on pre-service and in-service elementary school teachers (PreK-6). This study focused on elementary teachers to narrow the variation of the topics/content that those in the study encounter in their everyday teaching practice and more closely examine the role of a specific population of teachers' spatial skills and affect on their practice. Investigation of this portion of the population of teachers is especially critical because of the established presence of spatial reasoning developing early in childhood (Newcombe & Frick, 2010) and its importance to improving understanding of elementary STEM curriculum (Lowrie & Logan, 2018). Further, this study extended prior findings by introducing a more robust measure of spatial skills. Previous studies in this field (Atit & Rocha, 2020; Rocha et al., 2022) have only administered the Vandenburg & Kuse (1978) version of the Mental Rotation Task; whereas, in the present study a battery measure of spatial skills was administered providing for a more nuanced picture. This allowed for the conclusion to be drawn that elementary school teachers' spatial skills, as exhibited on a variety of spatial tasks, were predictive of their preferences for spatial pedagogy.

There was somewhat conflicting evidence from prior studies about the impact of teachers' spatial anxiety on spatial skills and spatial pedagogy. Atit and Rocha (2020) found that spatial anxiety for tasks such as mental rotation was negatively predictive of mental rotation ability; however, it was also determined that neither spatial anxiety as a whole, nor either of the subscales of the spatial anxiety scale, were predictive of teachers' reported frequency of using spatial pedagogy. By contrast, Rocha and colleagues (2022) found that teachers' spatial (mental rotation) skills and their anxiety for mental manipulation tasks were negatively related to their reported use of spatial pedagogy in remote (online) settings. To elaborate, these findings highlight that teachers with weaker mental rotation skills and lower mental manipulation anxiety reported more frequently using spatial teaching practices while teaching in remote settings. Further, a study conducted by Gunderson and colleagues (2013) found that teachers' spatial anxiety significantly predicted students' end-of-the-year spatial skills, even after accounting for student's beginning of the year spatial skills - illustrating that there is a potential for spatial anxiety to impact teacher preferences for certain pedagogical techniques, given it is directly linked to their students' spatial skill development.

Taking into account the prior findings, it was hypothesized that (1) elementary school teachers would not exhibit significant differences on any of the measures due to varying levels of educational attainment or teaching experience, (2) spatial skills and spatial anxiety would display an inverse relationship, spatial skills and spatial habits of minf would be strongly correlated, and spatial anxiety and spatial habits of mind would be negatively associated with one another, and (3) spatial skills would be positively associated with elementary school teachers' preferences for using spatial instructional practices.

The findings of the current study showed that elementary school teachers' spatial anxiety was not significantly related to their spatial skills nor were they predictive of their preferences for spatial pedagogy. A key difference which could account for this discrepancy was the way in which spatial anxiety was measured within this study. In all of the other studies mentioned here (Atit & Rocha, 2020; Gunderson et al., 2013; Rocha et al., 2022), spatial anxiety was measured with a formal instrument – either the Spatial Anxiety Scale (Lyons et al., 2018) or the Spatial Anxiety Questionnaire (Lawton, 1994).

Future research should compare methods of measuring spatial anxiety because survey methodology is often employed to collect data on this construct (Atit & Rocha, 2020; Gunderson et al., 2013; Rocha et al., 2022). Identifying the most precise method for measuring affective traits is crucial for the advancement of this research.

Currently, all other studies that have examined spatial habits of mind have assessed them in students; however, in this study it was posited that this construct may provide further insight to the factors that impact elementary school teachers' preferences for implementing spatial pedagogy. However, results of the present study found that spatial habits of mind was not significantly predictive of teachers' preference for using spatial pedagogy. While there was not a significant predictive relationship, spatial habits of mind did display positive correlational relationships with teachers' spatial skills and preference for using spatial pedagogy. Further, teachers' spatial habits of mind were predictive of their spatial skills, while controlling for general reasoning (verbal and matrix) ability and general anxiety. However, it was also shown that spatial skills were predictive of spatial habits of mind. Thus, the nature of the direction of the relation between spatial skills and spatial habits of mind remains unclear; however, the results of this study do seem to strongly indicate that these variables are related. There is a potential that spatial habits of mind indirectly contributed to teachers' preferences for spatial pedagogy (or their actual use of spatial pedagogical strategies), but this was not considered in the scope of this study. Knowing that prior studies have shown that students' spatial habits of minf can be improved by instruction (Cortes et al., 2022; Kim & Bednarz, 2013), future research concerned with informing teacher training and resource/curriculum development should consider examining teachers' spatial habits of mind to continue to build an understanding of how this facet of spatial cognition impacts pedagogy.

The use of self-report measures to draw conclusions about teachers' propensity to use spatial pedagogy in their practice will always have some limitations. Research on teachers' accuracy when reflecting on prior instructional practices has been mixed (Koziol & Burns, 1986; Mayer, 1999), thus conclusions drawn from self-report measures will always be subject to some scrutiny. The measure used in this present study attempted to somewhat address these concerns by asking teachers to report their preference for utilizing various spatial and non-spatial pedagogical strategies/tools during hypothetical teaching situations. This was attempted as an improvement over asking them to reflect back and recall previous utilization of spatial pedagogy during classroom instruction. However, it still remains unclear how closely these more contemporaneous preference selections relate to their actual use of spatial pedagogy during teaching. Given the need to confirm the rate of strategy preference with actual pedagogical performance, it is evident that observational methods should be incorporated in future studies to allow for stronger claims about the relations between teachers' spatial cognition/affect and spatial pedagogy.

A second limitation of the study is that the findings cannot be generalized beyond pre-service and in-service elementary school teachers from California. All participants were from this population; thus, generalizing to a national population would be inappropriate due to variations in teacher credentialing requirements from state to state.

Though this constraint on the sample imposed an inherent limitation on generalizability, it also allowed for greater control. While it is true that many states do utilize the same Common Core State Standards in Mathematics and the same Next Generation Science Standards (National Governors Association Center for Best Practices and Council of Chief State School Officers, 2010; NGSS Lead States, 2013) to guide pedagogical practices, teacher performance expectations as part of obtaining educator credentialing is not standardized from state to state (US Department of Education, 2008). Thus, due to the fact that all of the participants of the study possessed the same credentials and teaching performance expectations (TPE) under the guidelines of the California Department of Education (cde.ca.gov), this limits the impact that varying credential and teaching requirements could have upon the results. Further, this population was chosen because students from California have scored in the lowest quartile nationally in the standardized math assessment of 4th and 8th graders for numerous years (including, most recently, 2019) (nationsreportcard.gov).

Additionally, California possesses the largest population of K-5 students in the country (California Department of Education). Therefore, understanding how to support California elementary educators has the greatest potential impact with regards to bolstering elementary students' spatial learning. Future studies should seek to include nationally representative data in order to make claims with greater generalizability.

CHAPTER 6: CONCLUSION

In conclusion, the results of this study indicate the need to further research the role of elementary school teachers' spatial cognition and affect when considering how to improve students' spatial thinking skills and elementary STEM education. To this point, research on elementary school teachers' role in the development of students' spatial skills has provided evidence that teachers' spatial cognition and affect impacts their students' learning outcomes. The results of the current study revealed that elementary school teachers with stronger spatial skills generally possessed less anxiety about solving spatial problems and these teachers displayed greater preferences for using spatial pedagogy. These findings underscore that enhancing the development of students' spatial learning requires efforts that consider relevant teacher characteristics (i.e., spatial skills).

APPENDIX A: SPATIAL HABITS OF MIND INVENTORY ADAPTATIONS

Subscale	Item Original	Item Adapted
Pattern Recognition	I tend to see patterns among things, for example, an arrangement of tables in a restaurant or cars in a parking lot.	I tend to see patterns among things, for example, an arrangement of tables in a restaurant or cars in a parking lot
Pattern Recognition	I tend to see and/or search for regularity in everyday life when viewing objects or phenomena.	I tend to see and/or search for patterns in everyday life when viewing objects or phenomena
Pattern Recognition	*I do not pay attention to reading and interpreting spatial patterns such as locations of cars in a parking lot.	I do not pay attention to patterned arrangements of things, such as cars in a parking lot
Pattern Recognition	When I use maps to find a route, I tend to notice overall patterns in the road network.	When I use maps to find a route, I tend to notice overall patterns in the road network
Pattern Recognition	I am curious about patterns in information or data, that is, where things are and why they are where they are.	I am curious about patterns in information or data, that is, where things are and why they are there
Pattern Recognition	When I use maps showing things such as population density, election results, or highways, I try to recognize patterns.	When I see maps that show such things as population density, election results, or highways, I try to recognize patterns
Spatial Recognition	*I rarely use spatial vocabulary such as location, direction, diffusion, and network.	I rarely use words that describe location, direction, diffusion or network (such as "near"/"far", "left"/"right", "above"/"below")
Spatial Recognition	I use spatial terms such as scale, distribution, pattern, and arrangement.	I use terms that describte scale, distrubution, pattern and arrangement (such as "bigger"/"smaller", "density", "alternate")
Spatial Recognition	Using spatial terms enables me to describe certain things more efficiently and effectively.	Using spatial terms (words that help describe location, direction, pattern, distribution) enables me to describe certain things more efficiently and effectively
	*I have difficulty in describing patterns using spatial terms, such as patterns in bus routes or in the weather.	I have a difficulty in describing patterns using spatial terms, such as patterns in bus routes or in the weather

Spatial Recognition	I tend to use spatial terms such as location, pattern, or diffusion to describe phenomena.	I tend to use spatial terms such as location, pattern, or diffusion to describe phenomena
Visualization	When I am thinking about a complex idea, I use diagrams, maps, and/or graphics to help me understand.	When I am thinking about a complex idea, I use diagrams, pictures, maps, and or graphics to help me understand
Visualization	*It is difficult for me to construct diagrams or maps to communicate or analyze a problem.	It is difficult for me to construct diagrams or maps to communicate or analyze a problem
Visualization	When a problem is given in written or verbal form, I try to transform it into visual or graphic representation.	When a problem is given in written or verbal from, I try to transform it into visual or graphic representation
Visualization	*When I assemble something such as furniture, a bicycle, or a computer, written instructions are more helpful to me than pictorial instructions.	When I assemble something, such as furniture or a bicycle, written instructions are more helpful to me than instructions through pictures
Visualization	I find that graphs, charts, or maps help me learn new concepts.	I find that graphs, charts or maps help me learn new concepts
Visualization	It is helpful for me to visualize physical phenomena such as hurricanes or weather fronts to understand them.	It is helpful for me to visualize physical phenomena, such as the earth's elliptical orbit around the sun or weather fronts on a map, to understand them
Visualization	I like to support my arguments/presentations using maps and diagrams.	I like to support my arguments/presentations using maps, charts and/or diagrams
Visualization	I like to study data or information with the help of graphics such as charts or diagrams.	I like to study data or information with the help of graphics such as maps, charts or diagrams
Spatial Concept Usage	When trying to solve some types of problems, I tend to consider location and other spatial factors.	When trying to solve some types of probelms, I tend to consider location, patterns, distribution or other spatial factors
Spatial Concept Usage	*I have difficulty in explaining spatial concepts such as scale and map projection to my friends.	I have difficulty in explaining spatial concepts such as patterns, arrangements, or location of objects to my friends
Spatial Concept Usage	When reading a newspaper or watching news on television, I often consider spatial concepts	When reading a newspaper or watching news on television, I often consider such concepts as location of

	such as location of the places featured in the news story.	the places featured in the news story and their distance from me or my family members
Spatial Concept Usage	*Spatial concepts, such as location and scale, do not help me solve problems.	Spatial concepts, such as location, scale, arrangement, do not help me solve problems
Spatial Tool Use	I use maps and atlases (including digital versions) frequently.	Omitted
Spatial Tool Use	*I do not like using maps and atlases (including digital versions).	Omitted
Spatial Tool Use	I enjoy looking at maps and exploring with mapping software such as Google Earth and GIS.	Omitted
Spatial Tool Use	*Activities that use maps are difficult and discourage me.	Omitted
Spatial Tool Use	I like to use spatial tools such as maps, Google Earth, or GPS.	Omitted

*indicates reverse coded

APPENDIX B: DEMOGRAPHIC QUESTIONNAIRE

1. Please select the gender you identify with:
    1. Male
    2. Female
    3. Non-Binary
    4. Rather Not Say
    5. Other (fill in option)
2. How long have you been teaching for?
    1. I am a preservice teacher
    2. 0-5 years
    3. 6-10 years
    4. 11-15 years
    5. 16-20 years
    6. More than 20 years
3. Please select all of the degree(s) that you hold
    1. Bachelor of Arts
    2. Bachelor of Science
    3. Master of Arts (M.A.)
    4. Master of Education
    5. Master of Science (M.S.)
    6. Master of Business Administration (MBA)
    7. Doctor of Education (EdD)
    8. Juris Doctor (J.D)
    9. PhD
4. Please select the option(s) that best describe your teaching credentials
    1. Special Education
    2. Multi-Subject Teaching Credential
    3. Single Subject Teaching Credential (option to indicate)
    4. Other Teaching Credential (please specify)
    5. I do not possess a Teaching Credential
    6. I am in the process of obtaining a Teaching Credential
5. What grade level(s) do you currently teach?
    1. TK/Preschool
    2. Kindergarten
    3. 1st Grade
    4. 2nd Grade
    5. 3rd Grade
    6. 4th Grade
    7. 5th Grade
    8. 6th Grade
    9. Other (option to indicate)

6. Have you taught any other grade levels (excluding substitute teaching experience)? Please list them and the approximate amount of time you taught that grade.

References

Alibali, M. W. (2005). Gesture in spatial cognition: Expressing, communicating, and thinking about spatial information. Spatial cognition and computation, 5(4), 307-331.

Alvarez-Vargas, D., Abad, C., & Pruden, S. M. (2020). Spatial anxiety mediates the sex difference in adult mental rotation test performance. Cognitive research: principles and implications, 5, 1-17.

Atit, K., Gagnier, K., & Shipley, T. F. (2015). Student Gestures Aid Penetrative Thinking. Journal of Geoscience Education, 63(1), 66–72.

Atit, K., Miller, D. I., Newcombe, N. S., & Uttal, D. H. (2018). Teachers' spatial skills across disciplines and education levels: Exploring nationally representative data. Archives of Scientific Psychology, 6(1), 130-137. https://doi.org/10.1037/arc0000041

Atit, K., Ramey, K. E., Uttal, D. H., & Olszewski-Kubilius, P. M. (2021). Integrating Engineering Into K-8 Classrooms A Method of Identifying and Developing Strong Spatial Skills. In Engineering Instruction for High-Ability Learners in K-8 Classrooms (pp. 189-203). Routledge.

Atit, K., & Rocha, K. (2021). Examining the Relations Between Spatial Skills, Spatial Anxiety, and K-12 Teacher Practice. Mind, Brain, and Education, 15(1), 139-148.

Ball, D. L. (1992). Magical hopes: Manipulatives and the reform of math education. American Educator: the professional journal of the American Federation of Teachers, 16(2).

Ball, D. L., Hill, H. C., & Bass, H. (2005). Knowing mathematics for teaching: Who knows mathematics well enough to teach third grade, and how can we decide? American Educator, 29(1), 14-17. https://deepblue.lib.umich.edu/handle/2027.42/65072

Bates, A. B., Latham, N., & Kim, J. A. (2011). Linking preservice teachers' mathematics Self-Efficacy and mathematics teaching efficacy to their mathematical performance. School Science and Mathematics, 111(7), 325-333.

Bednarz, S. W., & Kemp, K. (2011). Understanding and nurturing spatial literacy. Procedia-Social and Behavioral Sciences, 21, 18-23.

Beilock, S. L., Gunderson, E. A., Ramirez, G., & Levine, S. C. (2010). Female teachers' math anxiety affects girls' math achievement. *Proceedings of the National*

Academy of Sciences of the United States of America, *107*(5), 1860–1863. https://doi.org/10.1073/pnas.0910967107

Bodzin, A. M. (2011). The implementation of a geospatial information technology (GIT)-supported land use change curriculum with urban middle school learners to promote spatial thinking. Journal of Research in Science Teaching, 48(3), 281-300.

Burke, R. J., & Mattis, M. C. (Eds.). (2007). Women and minorities in science, technology, engineering, and mathematics: Upping the numbers. Edward Elgar Publishing.

Burte, H., Gardony, A. L., Hutton, A., & Taylor, H. A. (2017). Think3d!: Improving mathematics learning through embodied spatial training. Cognitive Research: Principles and Implications, 2, 1-18.

Burte, H., Gardony, A. L., Hutton, A., & Taylor, H. A. (2020). Elementary teachers' attitudes and beliefs about spatial thinking and mathematics. Cognitive Research: Principles and implications, 5(1), 17. https://doi.org/10.1186/s41235-020-00221-w

Butcher, K. R. (2006). Learning from text with diagrams: Promoting mental model development and inference generation. Journal of educational psychology, 98(1), 182.

California State Board of Education. (2015) Mathematics Frameworks for California Public Schools: Kindergarten through Grade Twelve. California Department of Education.

California State Board of Education. (2016) Science Frameworks for California Public Schools: Kindergarten through Grade Twelve. California Department of Education.

Carbonneau, K. J., Marley, S. C., & Selig, J. P. (2013). A meta-analysis of the efficacy of teaching mathematics with concrete manipulatives. Journal of Educational Psychology, 105(2), 380.

Carroll, J. B. (1993). Human cognitive abilities: A survey of factor-analytic studies (No. 1). Cambridge University Press.

Chatterjee, A. (2008, August). The neural organization of spatial thought and language. In *Seminars in speech and language* (Vol. 29, No. 03, pp. 226-238). © Thieme Medical Publishers.

Cheng, Y.-L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. Journal of Cognition and Development: Official Journal of the Cognitive Development Society, 15(1), 2–11. https://www.tandfonline.com/doi/abs/10.1080/15248372.2012.725186

Chen, X., & Soldner, M. (2013). STEM attrition: College students' paths into and out of STEM fields (NCES 2014-001). Washington, DC: National Center for Education Statistics, Institute of Education Sciences, US Department of Education. Institute for Education Sciences, US Department of Education.

Church, R. B., Ayman-Nolley, S., & Mahootian, S. (2004). The role of gesture in bilingual education: Does gesture enhance learning?. International Journal of Bilingual Education and Bilingualism, 7(4), 303-319.

Clements, D. H., Battista, M. T., Sarama, J., & Swaminathan, S. (1997). Development of students' spatial thinking in a unit on geometric motions and area. The Elementary School Journal, 98(2), 171-186.

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. Academic Press.

Coleman, J. M., McTigue, E. M., & Smolkin, L. B. (2011). Elementary teachers' use of graphical representations in science teaching. Journal of Science Teacher Education, 22(7), 613-643.

Common Core State Standards Initiative. (2010). National governors association center for best practices and council of chief state school officers. Retrieved December, 11, 2012.

Condon, D. M., & Revelle, W. (2014). The International Cognitive Ability Resource: Development and initial validation of a public-domain measure. Intelligence, 43, 52–64. https://doi.org/10.1016/j.intell.2014.01.004

Contero, M., Naya, F., Company, P., Saorín, J. L., & Conesa, J. (2005). Improving visualization skills in engineering education. IEEE Computer Graphics and Applications, 25(5), 24-31.

Cornu, V., Schiltz, C., Pazouki, T., & Martin, R. (2019). Training early visuo-spatial abilities: A controlled classroom-based intervention study. Applied Developmental Science, 23(1), 1–21. https://doi.org/10.1080/10888691.2016.1276835

Cortes, R. A., Peterson, E. G., Kraemer, D. J., Kolvoord, R. A., Uttal, D. H., Dinh, N., ... & Green, A. E. (2022). Transfer from spatial education to verbal reasoning and prediction of transfer from learning-related neural change. Science advances, 8(31), eabo3555.

Costa, A. L., & Kallick, B. (2008). Habits of mind in the curriculum. Learning and leading with habits of mind, 16, 42-58.

Crowder, E. M., & Newman, D. (1993). Telling what they know: The role of gesture and language in children's science explanations. Pragmatics & Cognition, 1(2), 341-376.

Cuoco, A., Goldenberg, E. P., & Mark, J.(1996). Habits of mind: An organizing principle for mathematics curricula. The Journal of Mathematical Behavior, 15(4), 375-402.

Dawe, L. (1993). Visual imagery and communication in the mathematics classroom. In M. Stevens, A. Waywood, D. Clarke, & J. Izard (Eds.), Communicating mathematics: Perspectives from classroom practice and research (pp. 60–76). Hawthorne, VIC: Australian Council for Educational Research.

den Brok, P., Brekelmans, M., & Wubbels, T. (2004). Interpersonal teacher behaviour and student outcomes. School Effectiveness and School Improvement : An International Journal of Research, Policy and Practice, 15(3-4), 407–442. https://doi.org/10.1080/09243450512331383262

Driscoll, Mark J. (1979) Mathematical Problem- Solving: Not Just a Matter of Words. Washington, D.C.: National Institute of Education.

Ehrlich, S., Levine, S., & Goldin-Meadow, S. (2006). The importance of gestures in children's spatial reasoning. Developmental Psychology, 42, 1259–1268. https://doi.org/10.1037/0012-1649.42.6.1259

Executive Office of the President. (2018). *Charting a course of success: America's strategy for STEM education.* Committee on STEM Education of the National Science & Technology Council. http://files.eric.ed.gov/fulltext/ED590474.pdf

Fennema, E., Peterson, P. L., Carpenter, T. P., & Lubinski, C. A. (1990). Teachers' attributions and beliefs about girls, boys, and mathematics. *Educational Studies in Mathematics*, *21*(1), 55–69. https://doi.org/10.1007/BF00311015

Flevares, L. M., & Perry, M. (2001). How many do you see? The use of nonspoken representations in first-grade mathematics lessons. Journal of educational psychology, 93(2), 330.

Gagnier, K. M., Atit, K., Ormand, C. J., & Shipley, T. F. (2017). Comprehending 3D diagrams: Sketching to support spatial reasoning. Topics in cognitive science, 9(4), 883-901.

Gagnier, K. M., Holochwost, S. J., & Fisher, K. R. (2022). Spatial thinking in science, technology, engineering, and mathematics: Elementary teachers' beliefs, perceptions, and self-efficacy. Journal of Research in Science Teaching, 59(1), 95-126.

Ganley, C. M., & Vasilyeva, M. (2011). Sex differences in the relation between math performance, spatial skills, and attitudes. Journal of Applied Developmental Psychology, 32(4), 235–242. https://doi.org/10.1016/j.appdev.2011.04.001

Ganley, C. M., Vasilyeva, M., & Dulaney, A. (2014). Spatial ability mediates the gender difference in middle school students' science performance. Child Development, 85(4), 1419–1432. https://doi.org/10.1111/cdev.12230

Gates, P. (2018). The importance of diagrams, graphics and other visual representations in STEM teaching. In STEM education in the junior secondary (pp. 169-196). Springer, Singapore.

Geer, E. A., Quinn, J. M., & Ganley, C. M. (2019). Relations between spatial skills and math performance in elementary school children: A longitudinal investigation. Developmental Psychology, 55(3), 637–652. https://doi.org/10.1037/dev0000649

Gilligan, K., Hodgkiss, A., Thomas, M., & Farran, E. (2017). The role of spatial skills in mathematics cognition: Evidence from children aged 5-10 years. In: Gunzelmann, G and Howes, A and Tenbrink, T and Davelaar, EJ, (eds.) Proceedings of Annual Meeting of the Cognitive Science Society. https://discovery.ucl.ac.uk/id/eprint/10052265/

Gilligan-Lee, K. A., Bradbury, A., Bradley, C., Farran, E. K., Van Herwegen, J., Wyse, D., & Outhwaite, L. A. (2022). Spatial Thinking in Practice: A Snapshot of teacher's Spatial Activity Use in the Early Years' Classroom. Mind, Brain, and Education.

Gilligan-Lee, K. A., Hawes, Z. C., & Mix, K. S. (2022). Spatial thinking as the missing piece in mathematics curricula. npj Science of Learning, 7(1), 10.

Grossman, P. L. (1990). The Making of a Teacher: Teacher knowledge and teacher education. Teachers College Press.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2013). Teachers' spatial anxiety relates to 1st-and 2nd-graders' spatial learning. Mind, Brain and Education: The official Journal of the International Mind, Brain, and Education

Society, 7(3), 196–199. https://onlinelibrary.wiley.com/doi/abs/10.1111/mbe.12027

Hare, R. (2004). The Act of Sketching in Learning and Teaching the Design of Environments: A total skill for complex expression. Leeds Metropolitan University.

Harlen, W. (1997). Primary teachers' understanding in science and its impact in the classroom. Research in Science Education, 27(3), 323. https://doi.org/10.1007/BF02461757

Hawes, Z., Moss, J., Caswell, B., & Poliszczuk, D. (2015). Effects of mental rotation training on children's spatial and mathematics performance: A randomized controlled study. Trends in Neuroscience and Education, 4(3), 60–68. https://www.sciencedirect.com/science/article/pii/S2211949315000083

Hawes, Z. C., Gilligan-Lee, K. A., & Mix, K. S. (2022). Effects of spatial training on mathematics performance: A meta-analysis. Developmental Psychology, 58(1), 112.

Hill, H. C., Rowan, B., & Ball, D. L. (2005). Effects of teachers' mathematical knowledge for teaching on student achievement. American Educational Research Journal, 42(2), 371–406. https://journals.sagepub.com/doi/abs/10.3102/00028312042002371

Hodgkiss, A., Gilligan, K. A., Tolmie, A. K., Thomas, M. S. C., & Farran, E. K. (2018). Spatial cognition and science achievement: The contribution of intrinsic and extrinsic spatial skills from 7 to 11 years. *The British Journal of Educational Psychology*, *88*(4), 675–697. https://doi.org/10.1111/bjep.12211

Jirout, J. J., & Newcombe, N. S. (2015). Building blocks for developing spatial skills: evidence from a large, representative U.S. sample. Psychological Science, 26(3), 302–310. https://doi.org/10.1177/0956797614563338

Jordan, N. C., Glutting, J., & Ramineni, C. (2010). The importance of number sense to mathematics achievement in first and third grades. Learning and Individual Differences, 20(2), 82-88. https://doi.org/10.1016/j.lindif.2009.07.004

Kerski, J. J. (2003). The implementation and effectiveness of geographic information systems technology and methods in secondary education. Journal of Geography, 102(3), 128-137.

Kim, M., & Bednarz, R. (2013). Effects of a GIS course on self-assessment of spatial habits of mind (SHOM). Journal of Geography, 112(4), 165-177.

Kozhevnikov, M., Hegarty, M., & Mayer, R. E. (2002). Revising the visualizer-verbalizer dimension: Evidence for two types of visualizers. *Cognition and instruction*, *20*(1), 47-77.

Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & Cognition*, *33*(4), 710-726.

Koziol Jr, S. M., & Burns, P. (1986). Teachers' accuracy in self-reporting about instructional practices using a focused self-report inventory. The Journal of Educational Research, 79(4), 205-209.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! Intelligence, 14(4), 389–433.

Kyllonen, P. C., & Dennis, A. (1996). Is working memory capacity Spearman's g. Human abilities: Their nature and measurement (pp. 49–76). Lawrence Erlbaum Associates, Inc.

Lane, D., Lynch, R., & McGarr, O. (2019). Problematizing spatial literacy within the school curriculum. International Journal of Technology and Design Education, 29(4), 685-700.

Lauer, J. E., Esposito, A. G., & Bauer, P. J. (2018). Domain-specific anxiety relates to children's math and spatial performance. Developmental psychology, 54(11), 2126.

Lauer, J. E., Yhang, E., & Lourenco, S. F. (2019). The development of gender differences in spatial reasoning: A meta-analytic review. Psychological bulletin, 145(6), 537.

Lawton, C. A. (1994). Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. Sex roles, 30, 765-779.

Lee, J., & Bednarz, R. (2009). Effect of GIS learning on spatial thinking. Journal of Geography in Higher Education, 33(2), 183-198.

Levine, S. C., Ratliff, K. R., Huttenlocher, J., & Cannon, J. (2012). Early puzzle play: A predictor of preschoolers' spatial transformation skill. Developmental Psychology, 48(2), 530–542. https://doi.org/10.1037/a0025913

Li, Y., Wang, K., Xiao, Y., & Froyd, J. E. (2020). Research and trends in STEM education: A systematic review of journal publications. International Journal of STEM Education, 7(1), 1-16.

Lowe, Richard K. (1993). "Diagrammatic information: techniques for exploring its mental representation and processing". Information Design Journal. 7 (1): 3–18. doi:10.1075/idj.7.1.01low

Lowrie, T., & Logan, T. (2007). Using spatial skills to interpret maps: Problem solving in realistic contexts. Australian Primary Mathematics Classroom, 12(4), 14-19.

Lowrie, T., & Logan, T. (2018). The interaction between spatial reasoning constructs and mathematics understandings in elementary classrooms. In Visualizing mathematics (pp. 253-276). Springer, Cham.

Lowrie, T., Logan, T., & Ramful, A. (2017). Visuospatial training improves elementary students' mathematics performance. British Journal of Educational Technology: Journal of the Council for Educational Technology. https://onlinelibrary.wiley.com/doi/abs/10.1111/bjep.12142

Lubinski, D., & Benbow, C. P. (2006). Study of mathematically precocious youth after 35 years: Uncovering antecedents for the development of math-science expertise. Perspectives on psychological science, 1(4), 316-345.

Lyons, I. M., Ramirez, G., & Maloney, E. A. (2018). Spatial Anxiety: A novel questionnaire with subscales for measuring three aspects of spatial anxiety. Journal of Numerical Mathematics, 4(3) 526-553. https://jnc.psychopen.eu/article/view/154

Mayer, D. P. (1999). Measuring instructional practice: Can policymakers trust survey data? Educational Evaluation and Policy Analysis, 21(1), 29–45.

McLaughlin, M. W., & Talbert, J. E. (1993). Contexts that matter for teaching and learning: Strategic opportunities for meeting the nation's educational goals.

McLean, L., Janssen, J., Espinoza, P., Lindstrom Johnson, S., & Jimenez, M. (2023). Associations between teacher and student mathematics, science, and literacy anxiety in fourth grade. Journal of Educational Psychology.

McTigue, E. M., & Flowers, A. C. (2011). Science visual literacy: Learners' perceptions and knowledge of diagrams. The Reading Teacher, 64(8), 578-589.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM undergraduates? Learning and Individual Differences. https://www.sciencedirect.com/science/article/pii/S1041608012000386

Milson, A. J., & Curtis, M. D. (2009). Spatial Visualization and Analysis with GIS in High School Geography.

National Academies of Sciences, Engineering, and Medicine. 2016. Barriers and Opportunities for 2-Year and 4-Year STEM Degrees: Systemic Change to Support Students' Diverse Pathways. Washington, DC: The National Academies Press.

National Center for Education Statistics. (2015). *The Condition of Education 2015.* National Center for Education Statistics. https://nces.ed.gov/pubs2015/2015144.pdf

National Center for Education Statistics. (2017). *The Condition of Education 2017*. National Center for Education Statistics. https://nces.ed.gov/pubs2017/2017144.pdf

National Center for Education Statistics. (2019). *The Condition of Education 2019.* National Center for Education Statistics. https://files.eric.ed.gov/fulltext/ED594978.pdf

National Research Council. 2006. Learning to Think Spatially. Washington, DC: The National Academies Press. https://doi.org/10.17226/11019.

National Research Council. (2013). Monitoring progress toward successful K-12 STEM education: A nation advancing?. National Academies Press.

National Science Board, National Science Foundation. 2022. Science and Engineering Indicators 2022: The State of U.S. Science and Engineering. NSB-2022-1. Alexandria, VA. Available at https://ncses.nsf.gov/pubs/nsb20221

Neill, S. (1991) Classroom nonverbal communication. London: Routledge

Nelson, Glenn T. (1975) The Effects of Diagram Drawing and Translation on Pupils' Mathematics Problem Solving Performance. Ph.D. diss., University of Iowa, 1974. Dissertation Abstracts International 35 (1975):4149A

Nespor, J. (1987). The role of beliefs in the practice of teaching. Journal of Curriculum Studies, 19(4), 317–328. https://www.tandfonline.com/doi/pdf/10.1080/0022027870190403

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. American educator, 34(2), 29.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. Mind, Brain, and Education, 4(3), 102-111.

Newman, D. L., Stefkovich, M., Clasen, C., Franzen, M. A., & Wright, L. K. (2018). Physical models can provide superior learning opportunities beyond the benefits of active engagements. Biochemistry and Molecular Biology Education, 46(5), 435-444.

NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States.* The

National Academies Press.

Novack, M. A., Congdon, E. L., Hemani-Lopez, N., & Goldin-Meadow, S. (2014). From action to abstraction: Using the hands to learn math. Psychological science, 25(4), 903-910.

Osborne, J., & Simon, S. (1996). Primary science: Past and future directions. Studies in Science Education, 27(1), 99–147. https://doi.org/10.1080/03057269608560079

Otumfuor, B. A., & Carr, M. (2017). Teacher spatial skills are linked to differences in geometry instruction. *British Journal of Educational Psychology*, *87*(4), 683-699. https://doi.org/10.1111/bjep.12172

Ouyang, X., Zhang, X., & Zhang, Q. (2022). Spatial skills and number skills in preschool children: The moderating role of spatial anxiety. Cognition, 225, 105165.

Palmer, S. (1978). Fundamental aspects of cognitive representation.

Padalkar, S. & Ramadas, J. (2011). Using diagrams as an effective pedagogic tool in elementary astronomy. In Chunawala, S. and Kharatmal, M. (Eds.) Proceedings ofepiSTEME-4 Conference, Mumbai, India, Jan 5-9, 2011, pp. 159-164.

Perera, H. N., & John, J. E. (2020). Teachers' self-efficacy beliefs for teaching math: Relations with teacher and student outcomes. Contemporary Educational Psychology, 61(101842), 101842. https://doi.org/10.1016/j.cedpsych.2020.101842

Perry, M., Berch, D., & Singleton, J. (1995). Constructing shared understanding: The role of nonverbal input in learning contexts. J. Contemp. Legal Issues, 6, 213.

Pew Research Center, April, 2021, "STEM Jobs See Uneven Progress in Increasing Gender, Racial and Ethnic Diversity"

Power, J. R., & Sorby, S. A. (2020). Spatial development program for middle school: Teacher perceptions of effectiveness. International Journal of Technology and Design Education. https://doi.org/10.1007/s10798-020-09587-w

Quaiser-Pohl, C., Geiser, C., & Lehmann, W. (2006). The relationship between computer-game preference, gender, and mental-rotation ability. Personality and Individual differences, 40(3), 609-619.

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2012). Spatial anxiety relates to spatial abilities as a function of working memory in children. The Quarterly Journal of Experimental Psychology, 65(3), 474-487.

Rau, M. A. (2017). Conditions for the effectiveness of multiple visual representations in enhancing STEM learning. Educational Psychology Review, 29, 717-761.

Relich, J. (1996). Gender, self-concept and teachers of mathematics: Effects on attitudes to teaching and learning. Educational Studies in Mathematics, 30(2), 179–195. https://doi.org/10.1007/BF00302629

Riedesel, C. Allen. (1969) "Problem Solving: Some Suggestions from Research." Arithmetic Teacher 16 (54)

Rocha, K., Lussier, C. M., & Atit, K. (2022). What makes online teaching spatial? Examining the connections between K-12 teachers' spatial skills, affect, and their use of spatial pedagogy during remote instruction. Cognitive Research: Principles and Implications, 7(1), 1-19.

Roth, W. M., & Welzel, M. (2001). From activity to gestures and scientific language. Journal of research in science teaching, 38(1), 103-136.

Schaeffer, M. W., Rozek, C. S., Maloney, E. A., Berkowitz, T., Levine, S. C., & Beilock, S. L. (2021). Elementary school teachers' math anxiety and students' math learning: A large-scale replication. Developmental science, 24(4), e13080.

Schnotz, W., Ludewig, U., Ullrich, M., Horz, H., McElvany, N., & Baumert, J. (2014). Strategy shifts during learning from texts and pictures. Journal of Educational psychology, 106(4), 974.

Seymour, E., & Hewitt, N. M. (1997). Talking about leaving (Vol. 34). Westview Press, Boulder, CO.

Seymour, E., Hunter, A. B., & Weston, T. J. (2019). Why we are still talking about leaving. Talking about leaving revisited: Persistence, relocation, and loss in undergraduate STEM education, 1-53.

Shea, D. L., Lubinski, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. Journal of Educational Psychology, 93(3), 604–614. https://doi.org/10.1037/0022-0663.93.3.604

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. Educational Researcher , 15(2), 4–14. https://doi.org/10.3102/0013189X015002004

Simmons, F., Singleton, C., & Horne, J. (2008). Brief report—Phonological awareness and visual-spatial sketchpad functioning predict early arithmetic attainment: Evidence from a longitudinal study. European Journal of Cognitive Psychology, 20(4), 711-722. https://doi.org/10.1080/09541440701614922

Sinclair, N., & Bruce, C. D. (2015). New opportunities in geometry education at the primary school. ZDM, 47, 319-329.

Sorby, S. (2009). Developing spatial cognitive skills among middle school students. Cognitive Processing, 10, 312–S315. https://doi.org/10.1007/s10339-009-0310-y

Sorby, S. A., Drummer, T., Hungwe, K., Parolini, L., & Molzan, R. (2006). Preparing for engineering studies: Improving the 3-D spatial skills of K-12 students. Science, 88(73), 65.

Sorby, S., Veurink, N., & Streiner, S. (2018). Does spatial skills instruction improve STEM outcomes? The answer is "yes." Learning and Individual Differences, 67, 209–222. https://www.sciencedirect.com/science/article/pii/S1041608018301456

Spencer, S. J., Steele, C. M., & Quinn, D. M. (1999). Stereotype threat and women's math performance. Journal of Experimental Social Psychology, 35(1), 4–28. https://doi.org/10.1006/jesp.1998.1373

Spielberger, C. D., Gorsuch, R., & Lushene, R. (1970). The State-Trait Anxiety Inventory (STAI): Test manual form X. Consulting Psychologists Press.

Stavridou, F., & Kakana, D. (2008). Graphic abilities in relation to mathematical and scientific ability in adolescents. Educational Research, 50(1), 75–93. https://doi.org/10.1080/00131880801920429

Steele, C. M., & Aronson, J. (1995). Stereotype threat and the intellectual test performance of African Americans. Journal of Personality and Social Psychology, 69(5), 797–811. https://doi.org/10.1037//0022-3514.69.5.797

Stieff, M., Lira, M. E., & Scopelitis, S. A. (2016a). Gesture supports spatial thinking in STEM. Cognition and Instruction, 34(2), 80-99.

Stieff, M., Scopelitis, S., Lira, M. E., & Desutter, D. (2016b). Improving representational competence with concrete models. Science Education, 100(2), 344-363.

Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement?. Educational Psychology Review, 27(4), 607-615.

Subrahmanyam, K., & Greenfield, P. M. (1998). Computer games for girls: What makes them play. From Barbie to Mortal Kombat: gender and computer games, 46-71.

Swartz, R., Costa, A., Beyer, B., Reagan, R., & Kallick, B. (2007). Thinking based learning. Norwood, EE. UU.: Christopher-Gordon.

Talmy, L. (2000). Toward a cognitive semantics (Vol. 2). MIT press.

Threadgill-Sowder, J. & Sowder, L. (1982) "Drawn vs. Verbal Formats for Mathematical Story Problems." Journal for Research in Mathematics Education 13, 324-31

Tytler, R., Haslam, F., Prain, V., & Hubber, P. (2009). An explicit representational focus for teaching and learning about animals in the environment. Teaching Science, 55(4), 21-27.

U.S. Department of Education. (2008). Organization of U.S. Education: The School Level.

U.S. Department of Education (2013). *STEM attrition: College students' paths into and out of STEM fields. Statistical analysis report (NCES 2014-001).* National Center for Education Statistics. https://files.eric.ed.gov/fulltext/ED544470.pdf

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how?. In Psychology of learning and motivation (Vol. 57, pp. 147-181). Academic Press.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402. https://doi.org/10.1037/a0028446

Uttal, D. H., & Doherty, K. O. (2008). Comprehending and learning from ‘visualizations’: A developmental perspective. Visualization: Theory and practice in science education, 53-72.

Uttal, D. H., Scudder, K. V., & DeLoache, J. S. (1997). Manipulatives as symbols: A new perspective on the use of concrete objects to teach mathematics. Journal of applied developmental psychology, 18(1), 37-54.

Valenzeno, L., Alibali, M. W., & Klatzky, R. (2003). Teachers’ gestures facilitate students’ learning: A lesson in symmetry. Contemporary Educational Psychology, 28(2), 187-204.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. Perceptual and Motor Skills, 47(2), 599–604.

Van Meter, P., Aleksic, M., Schwartz, A., & Garner, J. (2006). Learner-generated drawing as a strategy for learning from content area text. Contemporary Educational Psychology, 31(2), 142-166.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., Newcombe, N. S., Filipowicz, A. T., & Chang, A. (2014). Deconstructing building blocks: Preschoolers' spatial assembly performance relates to early mathematical skills. Child development, 85(3), 1062-1076.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. (2017). Links between spatial and mathematical skills across the preschool years. Hoboken: Wiley.

Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. Human Movement Science, 54, 110-124.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. Psychological bulletin, 117(2), 250.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835. https://doi.org/10.1037/a0016127

Waldrip, B., Prain, V., & Carolan, J. (2010). Using multi-modal representations to improve learning in junior secondary science. Research in science education, 40(1), 65-80.

Wang, S., Hu, B. Y., & Zhang, X. (2021). Kindergarteners’ spatial skills and their reading and math achievement in second grade. Early Childhood Research Quarterly, 57, 156-166.

Wechsler, D. (2012). Wechsler Preschool and Primary Scale of Intelligence. Psychological Corporation.

Wu, H. K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching, 38(7), 821-842.

Yancey, A. V., Thompson, C. S., & Yancey, J. S. (1989). Children must learn to draw diagrams. The Arithmetic Teacher, 36(7), 15-19.

Zukow-Goldring, P., Romo, L., & Duncan, K. R. (1994). Gestures speak louder than words: Achieving consensus in Latino classrooms. Education as cultural construction: Exploration in socio-cultural studies, 4,