The Pennsylvania State University

The Graduate School

THE ROLE OF SENSEMAKING PRACTICES IN SUPPORTING SPATIAL COGNITION

A Dissertation in

Curriculum and Instruction

by

Abha Vaishampayan

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Doctor of Philosophy

August, 2020

The dissertation of Abha Vaishampayan was reviewed and approved by the following:

Julia D. Plummer
Associate Professor of Science Education
Director of Curriculum
Dissertation Advisor
Chair of Committee

Lynn S. Liben
Evan Pugh University Professor
Professor of Psychology; Human Development; and Education
Director, Cognitive and Social Development Lab

Christopher Palma
Associate Dean for Undergraduate Students, Eberly College of Science

Scott McDonald
Associate Professor of Education (Science Education)
Director, Krause Innovation Studio

Rose Mary Zbiek
Department Head, Curriculum and Instruction
Professor of Education (Mathematics Education)

ABSTRACT

Spatial thinking is important in predicting students' success in STEM fields. However, there is limited knowledge about *how* students learn spatial skills during classroom instruction by using strategies that support their cognition. This dissertation addresses this gap as I explored *spatial sensemaking practices* that supported learners in using *perspective-taking skill* (PT skill) – a skill that enables navigating between frames of references. To achieve this, I analyzed classroom interactions and individual student interviews (N=22) to uncover their use of spatial sensemaking practices when learning lunar phases and seasons. I used *embodied cognition* to interpret how spatial sensemaking practices may have supported learners' cognition. *Conjecture mapping,* a methodology for identifying the most salient features of a learning environment, revealed that physical and virtual models from the classroom environment were important in giving rise to a variety of spatial sensemaking practices that supported students' PT skill. I also found that teacher's in-the-moment prompts were key in facilitating students' perspective taking. Thematic analysis of interviews suggested that use of spatial sensemaking practices during classroom instruction may have become a part of an individual students' repertoire of practices irrespective of their PT skill. In conclusion, this study demonstrates how developing sensemaking practices during classroom instruction might be important in supporting spatial skills like perspective taking. This research also highlights how embodied ways of learning can be leveraged by promoting use of spatial sensemaking practices in understanding complex spatial phenomena.

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ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Julia Plummer, for advising me on my dissertation research. I am grateful to her for supporting me in taking on new directions in spatial thinking research, pushing me to write critically, and helping me hone academic writing. I'm thankful to her for always prioritizing student advising, for always being accessible, and providing a productive space for graduate students like me.

I thank my committee members, Lynn Liben, Scott McDonald, and Christopher Palma for asking me critical questions, bringing their unique expertise from their fields to guide my thinking, and providing insights about utilizing interdisciplinary ideas about teaching and learning in my own research.

I would like to thank *ThinkSpace* research team members Patricia Udomprasert, Susan Sunbury, Erin Johnson, Henry Houghton, Erika Wright, and Alyssa Goodman for partnering with me on this project and supporting me in taking it in a new direction for research.

I thank my fellow graduate colleagues Carmen Vanderhoof, Kyungjin Cho, Jonathan Bell, Dhvani Toprani, Sagun Giri, Jonathan McCausland, Katheryn Bateman, and Starlette Sharp for always asking me tough questions, and providing constructive feedback, and most of all, making my "grad student" life an unforgettable experience by offering me their friendship. A very special thanks to my friends and writing companions Hong-En Chen and Anuradha Anantharaman for spending hours writing with me at Wegmans, for helping me brainstorm research ideas, and for always being my cheerleaders.

I'm grateful to my loving family, Aai, Baba, Adya, and Shru, who made sure to check-in on me even when we were on the opposite sides of the globe. Their constant love and encouragement kept me moving forward. Most of all, I would like to thank my husband, Arthur

Kauffman, who has been my constant source of light throughout my journey as a graduate student. Without his confidence and belief in my abilities, it's hard to say this dissertation would have seen the light of day.

Note: Research conducted for this dissertation was supported by the National Science Foundation under Grant nos.. DRL-1502798 and 1503395. Findings and conclusions of the study do not necessarily reflect the view of the funding agency.

Chapter 1

Introduction

Spatial thinking is an important factor related to achievement in many professions such as mechanics, architecture, and meteorology. Mechanics have to infer what to fix by visualizing movement of the parts of an engine; architects and engineers depend on drawings of cross sections and plans before building structures; meteorologists have to rely on satellite and infrared imagery to make sense of weather patterns; chemists have to understand the stereochemical structure of molecules to compose complex compounds. In general, spatial reasoning and representations are fundamental to reasoning in all of Science, Technology, Engineering and Mathematics (STEM) domains (National Report Council; NRC, 2006)

Even though applications of spatial thinking are evident in learning many disciplines, our educational system often fails to recognize the importance of spatial thinking (Hegarty, 2014; Newcombe, 2017). According to National Research Council Report *Learning to Think Spatially* (NRC; NRC, 2006) spatial intelligence is “not just under-supported but underappreciated, undervalued, and therefore under-instructed” (p. 5). To understand implications of spatial thinking to achievement in STEM disciplines, we need research studies that include spatial training in school curricula and show how it can potentially inform designing classroom environments rich with opportunities for students to exercise their spatial reasoning. However, there is a lack of literature on what spatial thinking looks like in practice or how spatial skills can be exercised at K-12 level. There is also a gap in literature about how we can facilitate learning spatial thinking through different practices.

The focus of this dissertation is to explore what kinds of sensemaking practices students use when engaged in a spatially-enriched middle-school astronomy curriculum. To achieve this, I looked at students' engagement in spatial thinking through the perspective of embodied cognition, which attributes parts of learning processes to bodily actions (Alibali & Nathan, 2012; Barsalou, 2008; Wilson, 2002). I also examined whether there are differences in spatial practices of students with different spatial skills.

To achieve this, I used the conceptual framework of *spatial sensemaking practices* – practices that students use that leads to their engagement in solving spatial problems using their perspective taking skill (Liben & Downs, 1993). This framework was adapted from the one developed by Ramey and Uttal (2017) for understanding students' use of spatial skills in learning engineering design.

The goal of this dissertation study is to explore the implications for designing spatially-enriched, discipline-specific curricula and to explore new ways of teaching spatial skills that support student learning. This dissertation is an extended part of an ongoing research project called *ThinkSpace* funded by *National Science Foundation* (DRL 1503395 and 1503395). ThinkSpace research is an active partnership between Harvard-Smithsonian Center for Astrophysics and The Pennsylvania State University. I have been member of the ThinkSpace research collaboration since it received funding.

The first chapter is meant to situate my dissertation study in the broader research on spatial thinking and show importance of spatial thinking in STEM. I will first give a brief introduction of spatial thinking and the terminology commonly used in research literature. Second, I will present rationale for my study followed by a brief discussion of the frameworks and research questions.

Spatial Thinking

According to NRC (2006), spatial thinking is a combination of three basic components – concepts of space, tools of representations, and process of reasoning. This definition treats space as the basic analytical framework within which information and knowledge can be integrated, built, processed, and reasoned into a whole. Any kind of internal, external, graphic, physical or linguistic representations provide a vehicle for storing the information and communicating it with others. Reasoning provides means for manipulation, interpretation, and explanation of the structured information stored in representation. According to this definition, spatial thinking goes beyond "mental" representations and it can manifest in different forms. In the rest of my proposal, I will adhere to this holistic definition of spatial thinking presented by NRC (2006).

An important concept in spatial reasoning is spatial *skill*, which is construed as "a way of characterizing a person's ability to perform mentally such operations as rotation, perspective change, and so forth" (NRC, 2006, p. 26). In broader sense, spatial skill is related to the mental transformations a learner is able to perform in order to make sense of space. Spatial thinking differs from spatial skill in that spatial thinking is a combination of domain-specific content knowledge and different types of spatial skills.

Rationale for the study

The rationale for this dissertation study is manifold. First, a growing body of research studies have shown that spatial thinking is important in predicting success in STEM fields (e.g., Hsi, Linn & Bell, 1997; Newcombe, 2010; Shea et al., 2001; Wai, Lubinski & Benbow, 2009). For example, a substantial amount of research on correlational studies have shown that spatial skills strongly predict students' performance in college engineering (e.g., Sorby & Baartmans, 2000; Sorby, Casey, Veurink, & Dulaney, 2013). Heyer and colleagues (2013) found that there is a moderate to strong relationship between college students' mental rotation skill and spatial transformation skill to their astronomy conceptual knowledge scores.

The correlation between students' spatial skills and their achievement in STEM fields is mainly attributed to the fact that STEM fields require analyzing and transforming spatial relations (Uttal, Miller, & Newcombe, 2013). Spatial thinking is extensively used by scientists and experts to figure out relationships between concrete and abstract entities of their studies, to understand spatial-dynamic relationships between objects, and how those relationships give rise to macroscopic behaviors of systems (DeSutter & Stieff, 2017). Application of spatial thinking in STEM fields has engendered great advancements in the field of science such as the conceptualization of double-helix structure of DNA by Watson and Crick or the discovery of the presence of nucleus by Rutherford (NRC, 2006). Therefore, exploring how application of spatial thinking might be activated during early years of schooling might be beneficial.

Uttal and colleagues (2013) carried out a meta-analysis of 217 research studies investigating the effects of spatial skills training on students' considering how those results are generalizable. They found that training effects are not only stable and enduring over longer period but are also transferable to other spatial tasks that were not trained. Their analysis showed that spatial skills are moderately malleable and can lead to meaningful improvement through a wide range of training programs. If positive effects are shown through spatial training then new research studies should be designed to give promising evidence of the training. But there exists much less clarity about whether and how improving spatial skills affect students' STEM outcomes in positive ways. Stieff and Uttal (2015) argue that we lack enough evidence of the relationship between spatial training and STEM achievement because spatial thinking research lacks focused studies that use rigorous methodologies. There is a dearth of research literature about assessments that tell us what factors affect improvements in students' achievement. Knowledge about useful practices in improving students' spatial skills through curriculum and instruction is limited.

Second, most spatial thinking research studies are contextualized in higher education such as at undergraduate level. There is little research on effects of spatial training and interventions at K-12 level. Few studies have looked at students' discipline-specific spatial thinking at K-12 school level (e.g., Bodzin, 2011; Lowrie et al., 2017; Plummer, Bower, Liben, 2016; Wilhelm J., Jackson, Sullivan, & Wilhelm R., 2013). Both introductory and advanced curricula require students to reason about complex spatial relationships. For instance, finding distance between three points in a Cartesian coordinate system, visualizing a three-dimensional structure of a cell, or visualizing movements of tectonic plates are some of the examples of complex spatial tasks that students often deal with in schools. Therefore, research at K-12 level might be useful in understanding how complex spatial reasoning can be facilitated.

Moreover, research studies have shown that psychometrically assessed spatial skills become less significant as students participate in their STEM coursework and start narrowing down their specializations (Hambrick et al., 2011; Kozhevnikov, Motes & Hegarty, 2007). Experts in STEM fields develop analytical strategies to solve problems through practice. For example, Stieff (2007) found that expert chemists depend on visuospatial skills along with deeper analytical skills for understanding chirality of molecules. While students, at an earlier age, depend on visuospatial skills alone to perform mental transformations of the molecules as they lack expertise in the field. This suggests that spatial skills might be more useful at novice level than at an advanced learning stage, when domain-specific conceptual knowledge, familiarity with the semantics, and analytical strategies become dominant in the process of learning (Hegarty, 2014; Stieff, 2007).

There is another potential setback in not training spatial thinking at an early stage - students who are interested in STEM disciplines but have lower spatial skills may not be able to perform mental operations that are required to understand topics such as molecular chemistry, geology, or engineering design (Uttal & Cohen, 2012). They may also face challenges in interpreting rich paper- or computer-based representations that are used to communicate this information with students. Resonating with their argument, DeSutter and Stieff (2017) posit that if research suggests that students' spatial skill is, in fact, a factor that determines their immediate performance in STEM disciplines or their future career choice, then students with lower spatial ability are disadvantaged by default with the current state of STEM curricula.

Third, even though research studies have shown importance of spatial training in STEM curriculum, broad development of learning environments that support domain-specific spatial learning is lacking (DeSutter & Stieff, 2017). Many research studies on spatial thinking have shown that certain spatial skills are useful in understanding discipline-specific content knowledge. For example, mental rotation is useful in learning stereochemistry (Stieff, 2007), spatial visualization of 3D shapes is important in engineering design studies (Sorby, 1999, 2009), and visualization of cross-sections is important in studying medicine (Hegarty & Cohen, 2012). Therefore, training of specific spatial skills can be useful in learning discipline-specific content knowledge.

One skill identified as being useful in understanding certain astronomical phenomena, such as daily celestial motion, is perspective-taking (Plummer, 2014; Plummer et al., 2016). Perspective-taking skill (PT skill hereafter) is the skill to determine how a scene might look like to an observer from a different perspective or a different line-of-sight (Liben & Downs, 1993). For example, making sense of an event like the daily motion of the Sun across the sky involves visualizing and connecting space- and Earth-based views to fully grasp how the Sun appears to move for a viewer on Earth. Plummer and colleagues (2016) found that individual differences in students' PT skill are useful in predicting differences in accuracy of their explanations.

In this study, I focused on examining students' usage of PT skill through a variety sensemaking practices for learning seasons and lunar phases. As a part of ThinkSpace project, my colleagues and I developed astronomy curricula on seasons and lunar phases, which were taught in various public schools in New England. Seasons and lunar phases are two phenomena that require learners to make connections between space- and Earth-based perspectives to understand complex spatial nature of the two phenomena. The curricula were designed to be spatially-enriched in that the two phenomena were taught by including explicit training of PT skill during instruction. This was achieved by providing different kinds of physical and virtual models, animations, and tools to learn discipline-specific content knowledge through spatial thinking. Students were assessed across three dimensions before and after their participation in the curricula – 1. content knowledge (multiple-choice assessment) 2. PT skill, and 3. explanations of the phenomena (open-ended interview). Students' data were collected through testing and video-based interviewing. By analyzing the data collected from first two years of research, we found the following results (Plummer et al., 2018; Plummer et al., (in progress); Vaishampayan et al., 2018):

1. A correlational analysis showed that students' PT skill is moderately correlated (Lunar phases: $r\ (399) = .487$, $p < 0.001$, Seasons: $r\ (293) = .470$, $p < 0.05$) to their content

knowledge and also to their usage of accurate PT skill during open-ended explanations (Lunar phases: r (45) = 0.430, p < 0.001; Seasons r (29) = .411, p<0.05).

2. Students of all PT skill scores (low or high) who participated in the curriculum showed significant improvement across all three dimensions of assessments (Lunar phases - Content knowledge: t (399) = -25.545, p < 0.001; PT skill: t (399) = 7.643, p < 0.001; Explanations: t (45) = 6.045, p < 0.001). Seasons – Content knowledge: t (293) = -25.81, p < 0.001; PT-skill: t (291) = 4.810, p < 0.001; Explanations: t (53) = 8.412, p < 0.001)).
3. From interview analysis, students with high PT-scores were found to make high proportion of accurate connections between Earth- and space-based perspective in their post-interviews than those with low PT-scores.

These results suggest that the ThinkSpace curriculum may have played an important role in improving students' overall spatial thinking relevant to understanding seasons and lunar phases and PT skill might be important in learning those phenomena. However, these findings are based on analysis of the data collected from students' assessments; *how* the curriculum may have supported students to improve their spatial thinking still remains a question to investigate. All the three assessments suggest that PT skill might have played a role in students' learning of seasons and lunar phases; however, these assessments did not provide information about what kinds of practices students used to exercise PT skill during their participation in the curricula.

Understanding how different components of the ThinkSpace curricula engage students in spatial thinking, how the tools and materials of the classroom environment facilitate students' application of PT skill, and how their social interactions with their peers and the instructor might play a role in shaping their spatial thinking are important questions in understanding the mediating processes that shape students' spatial thinking. Finding out *what* may have supported students' spatial thinking demands a deeper analysis of the curriculum enactment and students' classroom interactions.

To dive deeper into which practices might be useful in supporting students' spatial reasoning about seasons and lunar phases, I analyzed students' classroom interactions during their participation in the curriculum and their explanations of the two phenomena from their qualitative interviews. This included examining students' sensemaking practices related to spatial problems that may have emerged while learning seasons and lunar phases. These practices were adapted from Ramey and Uttal's (2017) *spatial sensemaking practices* framework. However, I focused only on those practices that students used when engaged in application of their PT skill. To analyze the spatial sensemaking practices, I applied the theoretical foundations of embodied cognition to make sense of students' bodily actions, their use of materials from the environment, and their social interactions with their peers and the instructor. In other words, I examined how the particular context of teaching ThinkSpace curriculum shaped students' spatial sensemaking about seasons and lunar phases.

Conceptual framework – Spatial Sensemaking Practices

Ramey and Uttal (2017) defined Interactions between internal cognitive spatial processes and the ways in which they are realized in the material environment are defined as *spatial sensemaking practices*. The word *spatial* was used by the researchers to refer to problems pertaining to interpreting spatial relationships when learning engineering design. Examples of spatial problems included hypothesizing the appropriate shape of a roof, or figuring out the direction of the motion of a gear. Examples of spatial sensemaking practices that were identified as useful for solving spatial problems included spatial talk (discussing shape, orientation, position of the objects), gestures, bodily movements, manipulation of material objects, hypothesis testing, and even students' interactions with their instructor that supported their engagement in spatial thinking. The researchers primarily assessed students' sensemaking practices in solving design-related issues of building structures involving spatial skills such as disembedding, 2D to 3D translation, cross-sectioning, mental rotation etc.

ThinkSpace curriculum was specifically designed to engage students through physical and virtual models, computer animations and various spatial tasks with a focus on the spatial skill of perspective taking. Therefore, instead of focusing on all the spatial skills that Ramey and Uttal examined, I focused only on those practices that showed evidence of supporting students' PT skill.

The curriculum inherently created opportunities for students to manipulate their environmental resources such as physical and virtual models. Throughout the course of instruction, the teacher consistently provided verbal cues and targeted questions to activate students' use of PT skill. Students were paired up or divided into small groups to collaboratively make sense of the seasons and lunar phases. Animations and virtual tours about seasons and lunar phases engaged students in both perceptual as well as sensorimotor experiences. Thus, students were given many opportunities for tool-use and collaborative problem-solving to facilitate their process of sensemaking through different modes of learning. All these elements were intentionally aimed at honing students' PT skill. However, a framework to analyze how these spatially-enriched components supported students' PT skill remained unexplored. Therefore, in this dissertation, I used the conceptual framework of spatial sensemaking practices to analyze students' interactions during instruction. In Chapter 3, I further elaborate on how I identified spatial sensemaking practices and created a codebook for analyzing data. To establish a link between students' use of spatial sensemaking practices and how they learn from them, I applied principles of embodied cognition.

Theoretical framework - Embodied cognition

Many scholars believe that cognition and mental processes are embodied by body-based activities including gestures, movement, and even engaging one's neural network in action planning (Alibali & Nathan, 2012). Human cognition and linguistic processes are inherently grounded in physical interactions of the human body with its physical environment (Barsalou, 2008; Wilson, 2002). By doing actions through physical manipulation rather than doing them mentally reduces cognitive load (Kirsh & Maglio, 1994). In other words, our body creates pathways for us to learn by helping us create physical representations of abstract conceptual knowledge.

As explained earlier, ThinkSpace curriculum and instruction was enriched to develop students' spatial skill of perspective taking through different modalities. Therefore, to examine how students may have learned from spatial sensemaking practices, assessing affordances of the learning environment was indispensable. Finding out which components of the ThinkSpace curriculum and instruction may have supported students' spatial thinking called for analysis of students' gestures, individual actions, their social interactions, and how they utilize all these resources for learning. Therefore, I used three fundamental principles of embodied cognition to ground my data analysis – *we offload cognitive work onto the environment; offline cognition is body-based; and embodied cognition can manifest in social interactions* (Abrahamson & Lindgren, 2014; Wilson, 2002).

The first principle suggests that we use our body to reduce cognitive load by using material resources from the environment. This principle was applicable in the context of this study because students were given material resources so that they do not have to rely entirely on their mental imagery for perspective-taking tasks. For example, students were given a model of the Earth to explicitly highlight how the tilt of its axis might change its spatial orientation with respect to the Sun. Therefore, students did not have to mentally visualize Earth's motion in its orbit and its orientation simultaneously. In this manner, the first principle seemed applicable in the context of this study in a variety of ways as students used material resources while learning.

According to the second principle, embodiment is a brain-based phenomenon, where the function of the body is to simulate a physical aspect of the world that are not present in the immediate learning environment (Wilson, 2002). DeSutter and Stieff (2017) interpreted this principle to suggest that embodied actions may provide students ways of representing and structuring information for problem solving. They argue that these body-based activities such as gesturing can become a part of the learner's "toolbox" providing new ways to organize information and knowledge to assist their thinking. Performing actions with body such as gesturing may serve as a way to refine existing spatial representations. Consistent with these suggestions, research has shown that students with higher PT skill are able to make better connections between different perspectives and they use certain iconic gestures more frequently (Plummer et al., 2016). Therefore, this principle of embodied cognition was useful in providing insight about how students spontaneously and/or actively recruit their body in facilitating their own spatial thinking.

The third principle of embodiment – embodied cognition can manifest in social interactions – suggests that using our body to facilitate learning and conceptual development may not be an intuitive process (Abrahamson & Lindgren, 2014). "Students will often need guidance to take actions and move their bodies in ways that simulate the core mechanism and spatial relations" (Abrahamson & Lindgren, 2014, p. 7) Therefore, scaffolding or guided instruction might be necessary for some learners to activate their body-based actions. The teacher and students' peers participating in the ThinkSpace curriculum must have played an important role in shaping students' sensemaking processes. As the teacher guided students to exercise their PT skill, the third principle was useful in assessing how her support may have facilitated students to take some actions. Therefore, this principle was useful in gaining insight about how students were facilitated in the process of sensemaking through application of PT skill.

Therefore, embodied cognition provided ways to look at students' observable actions and interactions to establish a connection between students' spatial sensemaking practices and improvement in their spatial thinking. Embodied cognition provided a lens for interpreting how students' gestures, model manipulations, and collaborative actions shape their spatial thinking.

Based on the conceptual framework of spatial sensemaking practices and embodied cognition, I researched two questions for this dissertation study. The main goal of these questions was to gain insight about how learning environments, curriculum, and instruction facilitate learning of discipline-specific spatial skills such as PT skill in this study.

Research questions

The research questions I addressed in this dissertation are:

1. *How might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?*
2. *What are the differences between the range/use of spatial sensemaking practices used by students with low PT skill and those with high PT skill?*

For answering my first research question, I explored the nature of students' engagement in ThinkSpace astronomy curriculum. I first identified the spatial sensemaking practices that emerged during instruction and then identified the most salient features of the curriculum based on my interaction analysis.

From the earlier iterations of the ThinkSpace project, we found that students with higher PT skill showed greater gain on both their content knowledge and explanations in comparison to those with lower PT skill (Plummer, 2018; Vaishampayan et al., 2018). Therefore, to answer the second research question, I examined similarities and/or differences in students' use of spatial sensemaking practices while explaining seasons and lunar phases. In the following chapter, I present the literature review including the role of spatial thinking research in education, embodied cognition, and spatial sensemaking practices framework.

Chapter 2

Literature review

Spatial Thinking

We are surrounded by space and we often take for granted how we interact with it. Many simple actions from day-to-day life such as driving and navigating through a cognitive map of the town we live in, estimating how far the ball will travel while playing baseball, or even looking for objects in the dark without stumbling are all space-related actions that require us to use the spatial representations and knowledge stored in our memory. In many ways, spatial thinking affects human life and its role in human life is pervasive.

Spatial thinking is a collection of cognitive skills required to navigate space (NRC, 2006). However, in the spatial thinking literature, there is no singular definition of spatial thinking that is used synonymously. *Learning to Think Spatially* (NRC, 2006) defines spatial thinking as a combination of concepts of space, using tools of representation, and reasoning processes. Spatial thinking provides a way to store and manipulate internal and externals representations of information. The *Learning to Think Spatially* (NRC, 2006) further explains that spatial thinking is a collection of cognitive skills consisting of declarative and perceptual knowledge and cognitive operations that can be used to transform this knowledge in order to make it applicable.

Therefore, the first component – space – provides the foundation for spatial thinking. Spatial relationships between static or dynamic objects give a way to structure knowledge. The second component – tools of representation – provides a way to create representation of spatial knowledge stored in memory. The third component – reasoning – is useful in establishing relationships between spatial components and choosing how to make use of the spatial knowledge stored in representations. As Liben (2006) clarifies, the component of space is related to knowing the declarative knowledge (knowing "what"). The component of reasoning is related to the procedural knowledge (knowing "how"). However, the second component – representation – is identified more closely with spatial thinking as it highlights how different forms of representation play a significant role in showing interpretation of spatial information.

Spatial Skills

One important component of spatial reasoning is *spatial ability* or *spatial skill*. These two terms have been used interchangeably in the spatial thinking literature. I use the term spatial skill for consistency throughout this dissertation. According to NRC (2006), spatial skill is conceptualized as "a trait that a person has and a way of characterizing a person's ability to perform mentally such operations as rotation, perspective change, and so forth." (p. 26). According to Linn and Petersen (1985), spatial skills are classified into groups fundamentally based on spatial perception, mental rotation, and spatial visualization. But more broadly, spatial skill is related to the mental transformations a learner is able to perform in order to make sense of space – the "how" of spatial thinking. Many research studies on spatial thinking depend on measuring spatial skill as an indicator of the outcomes of their interventions (e.g.,, Kozhevnikov & Thronton, 2006). However, spatial thinking differs from spatial skill in that spatial thinking is a combination of domain-specific content knowledge and different types of spatial skills (Plummer, 2014).

Importance of spatial thinking in STEM fields

Spatial nature of STEM domains

Spatial thinking is important in understanding concepts in the domains of Science, Technology, Engineering, and Mathematics (STEM) because of the inherently spatial nature of these fields. For instance, physicists often reason about dynamic motion of objects in space for problem solving, chemists study chirality of molecules to determine properties of materials; geologists reason about physical and temporal processes that enable them to study different geological forms and structures such as mountains and outcrops. Learning geoscience and practicing geoscience as a profession requires interpretation of spatial data and spatial representations (Ishikawa & Kastens, 2005; Liben & Titus, 2012). Engineers and architects often project three-dimensional features of a structure onto two-dimensional plan to work on the details of constructing a building. In all these cases, the process of knowledge-building takes place by solving inherently spatial problems.

Professionals from STEM fields use a variety of spatial representations such as diagrams, plots, maps and graphs to characterize the objects or phenomena they study to capture abstract data in their respective fields. For example, the motion of a projectile can be represented as a graph of its trajectory across time and space; or a concept map is a way to show connections between different entities even if they are not inherently spatial. As Hegarty (2014) points out - "as part of science instruction, students need to develop skills in constructing, interpreting, transforming, and coordinating these domain-specific external representations" (p. 152). Therefore, spatial thinking that is manifested in representation of abstract concepts is an important component of spatial reasoning.

Application of spatial thinking in STEM

Daily actions involve manipulating space either mentally or physically. Beyond that, spatial thinking is also an indispensable part of learning of STEM fields. Spatial thinking is applied by scientists for the purpose of problem-solving or visualization by making use of complex relationships between space and physical properties of nature. One of the most versatile examples of application of spatial thinking is the representation of the structure of DNA developed by Watson and Crick. Their three-dimensional double-helix model of DNA represents intertwined and complementary sugar phosphate chains. The double-helix structure accurately represents not only the experimental data, but also accounts for other complex information related to chemical structure and stereochemical arguments (NRC, 2006). The double helix and the information it encodes is an example of Watson and Crick's spatial thinking as it represents a perfect combination of use of space, representation and reasoning.

Application of scientists' spatial thinking is also fundamental to many discoveries in science. For example, Rutherford's deduction of presence of a nucleus at the center of an atom, early astronomers' deductions about geocentric or heliocentric nature of the solar system, interpreting motion of the planets, or even figuring out behavior of enzyme molecules regarding how they fold to interact with other molecules are all examples of scientists' spatial thinking. All these discoveries involve visualization of space and its relationship to static and dynamic elements in the space. Thus, these examples show that spatial thinking is necessary in deriving complex relationships between different components of nature, which are not directly visible to the naked eyes (DeSutter & Stieff, 2017; NRC, 2006). Thus, looking closely at STEM domains, one can argue that applications of spatial thinking are myriad in understanding different disciplinary subjects or even navigating everyday-life processes.

Spatial thinking and success in STEM

A large body of literature has shown that spatial skills are important in predicting success in STEM domains (Hegarty, 2014; Hsi, Linn & Bell, 1997; Shea, Lubinski & Benbow, 2001; Wai, Lubinski & Benbow, 2009). A meta-analysis of 217 studies on training of spatial skills showed that the effects of the training were stable and persisted over long period of time (Uttal et al., 2013). Enriching educational experiences could make a substantial impact on increasing participation in STEM domains (Uttal et al., 2013). In general, a number of skills have been identified to be useful in learning discipline-specific content knowledge. Mental rotation is shown to be useful in learning stereochemistry (Stieff, 2007); mental visualization and mental rotation are useful skills in learning engineering (Sorby, 1997, 2009); spatial visualization has shown to have a correlation with students' ability to solve mechanics problems in physics (Kozhevnikov & Thronton, 2006); spatial visualization of cross-sections and perspective taking are important skills in studying medicine (Cohen & Hegarty, 2007).

The skill that has been identified to be relevant in learning astronomical phenomena is perspective-taking skill (Plummer, 2014). Perspective-taking skill is defined as the skill of identifying how a scene might look like from a viewpoint other than one's own perspective or line-of-sight (Liben & Downs, 1993). Considering learners' spatial skills may predict their success in domain-specific spatial thinking, further insight into how students learn to apply PT skill might be useful in informing ways in which astronomy can be taught.

The role of perspective-taking skill in learning astronomy

In the context of K-12 education, many studies have been carried out to understand spatial thinking related to topics such as day/night cycle (e.g., Kikas, 2000), daily celestial motion (e.g., Plummer, 2014; Plummer et al., 2016), lunar phases (e.g., Parnafes, 2012; Wilhelm, 2009), seasons (e.g., Plummer & Maynard, 2014; Sung & Oh, 2017), and general astronomy (e.g., Wilhelm et al., 2013). The common thread between topics like daily celestial motion, lunar phases and seasons is that they are observable from Earth. Children learn to construct explanations based on their observations of celestial objects, which is an *Earth-based perspective* (Plummer, 2014). For example, students can learn to construct explanations of daily motion of the Sun or the Moon across the sky based on their observations. However, to fully make sense of an observable celestial phenomenon, students need to connect their observations to a *space-based perspective*. For example, how the Sun appears to move across the sky can be understood if one can visualize the rotational motion of the Earth. Thus, mentally navigating Earth-and space-based perspectives is fundamentally important in understanding celestial phenomena (Plummer, 2014). Mentally navigating these perspectives may be supported by developing students' PT skill. Therefore, spatial perspective-taking skill has is important in building explanations of celestial phenomena.

Crowder (1996) analyzed students' sensemaking about seasons through analysis of their gestures and different ways in which they engage in perspective taking. The researcher assessed learners' use of perspective-taking by observing their gesture stance, movements and eye-gaze. She found that students used an 'inside-observer perspective' while explaining their model of changing seasons. An 'inside-observer perspective' meant that even though they held the Earth in their hands to explain the seasons, they still gestured and made use of the space around their model to explain seasons. This kind of 'inside-perspective' taking helped students in explaining and revising their own models of changing seasons.

Plummer, Bower and Liben (2016) carried out a study for investigating the role of PT skill in students' explanations of phenomena such as daily celestial motion of Sun and stars and seasonal changes in constellations. The researchers found that students with higher PT skill were able to connect the Earth- and space-based perspective explicitly by using gestures; while those with lower PT skill may require support in making these connections. The researchers suggested that students with lower PT skill may need additional scaffolding when teaching complex astronomical phenomena. Thus, PT skill plays a significant role in shaping students' explanations of the celestial phenomenon.

Lunar phases and seasons are two topics that require PT skill to understand how those phenomena take place. In addition to that, these two topics are often included as parts of the mainstream Earth Science and Astronomy curricula at middle school level, which made it a natural choice to further investigate how these phenomena can be learned through spatial thinking.

Lunar Phases

The first phenomenon – lunar phases – refers to the apparent change in the shape of the Moon over a period of about 28 days. To be able to understand lunar phases, one must first observe the phase of the Moon as it appears from Earth (Earth-based perspective); second, visualize how the Moon is lit up by the Sun (space-based perspective), and then use their PT skill to visualize the portion of the lit-up Moon that will be visible to an observer on the Earth by connecting the two perspectives.

For example, in Figure 1, the outer ring of Moon phases represents the phases seen by an observer on the Earth with the respective position of the Moon as it revolves around Earth. The inner ring represents the overhead perspective or the space-based view showing the position of the Moon in its orbit around the Earth, lit up due to the Sun's rays hitting it. This diagram is helpful in visualizing how the side of the Moon that faces the Sun is always half lit, and the other half of the Moon appears to be dark. Therefore, from a space-based perspective, the Moon would appear to be half lit and half dark. However, how the Moon appears to an observer on the Earth is different depending on the position of the Moon in its orbit around the Earth – represented by the outer ring. An observer on the Earth will see only a portion of the half-lit Moon as the Moon moves in its orbit. Thus, perspective taking is an important skill that is useful in making the connections between Earth-based view and the space-based view (Plummer et al., 2016).

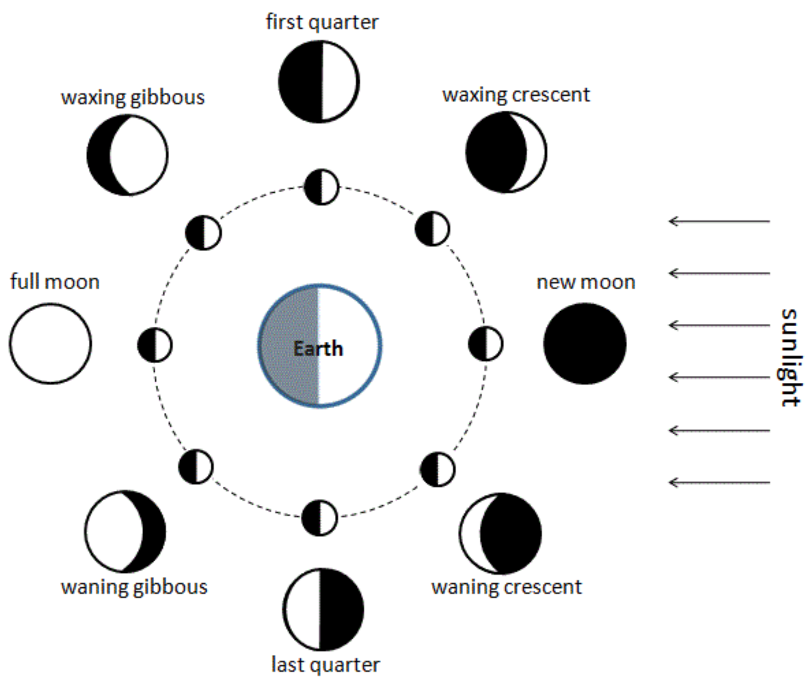


Figure 1. Cycle of lunar phases explained (source: creative commons)

Studies have shown that students' explanations of lunar phases vary greatly in sophistication. Without focused instruction, students tend to explain the change in lunar phases only from an Earth-based perspective (Plummer, 2014). One of the most prevalent explanation that students have for lunar phases is the blocking mechanism, wherein students believe that the Earth's shadow covers parts of the Moon in different ways (Baxter, 1989). In some cases, students explain the lunar phases as an effect of being covered by the clouds based on their observations from Earth (Baxter, 1989).

A study about 10 to 14-year-old students' explanations of lunar phases showed that children considered only a certain position of the Moon when explaining the phases, instead of talking about the cycle of changing lunar phases (Parnafes, 2012). Parnafes also showed that students assume that observers from different locations on Earth see different phase of the Moon. One of the students from the study also explained lunar phases by explaining that Moon phase gets smaller as it moves away from the Sun, and bigger as it moves closer to the Sun. This shows that the student had a basic understanding that the phase depends on Moon's position in space. However, she did not show evidence of making connection between how the position affects the way an observer on Earth will see a phase. All these concepts are challenging elements of spatial thinking in building explanations of lunar phases. This may suggest that the student was not able to make a connection between space- and Earth-based perspectives. In summary, teaching lunar phases might be facilitated if students are actively engaged in exercising their PT skill. PT skill might be useful in making the Earth-based and space-based connections explicit.

Seasons

Seasons change because Earth's axis of rotation is tilted thereby causing it to orient itself differently relative to the Sun as it revolves in its orbit. The concepts that are difficult to visualize and connect to the seasons are the Sun's apparent motion in the sky, the height of the local meridian (the highest point Sun reaches in the sky), and how that affects the amount of energy reaching different places on the Earth. All these factors affect the length of the day and the sun-angle at different places on the Earth. The Sun seems to have a higher altitude in Summer, and the incoming solar energy per unit area is greater in comparison to that in winter. Therefore, we feel hot in summer. In winter, the conditions are opposite, thereby causing the sun-angle to be very low. A low sun-angle causes the Sunlight to spread across a larger surface area, thereby decreasing the amount of energy per unit area. Therefore, we experience cold weather in winter.

Many studies have shown that children as well as adults are not naturally able to connect all the different components of the reasoning thereby leading them to develop inaccurate knowledge or misconceptions. For instance, research has shown that the most predominant misconception why students think seasons change is due to the change Earth's distance from the Sun (Baxter, 1989; Chae, 1992; Sung & Oh, 2017). Students believe that winter on Earth is caused when Earth is farther away from the Sun as opposed to the summer when it is closer. Kikas (1998a) found that many students confused the conceptual knowledge and reasoning for seasons with that of day-night cycles. For instance, students believe that one side of the Earth lights up more or receives more light causing summer due to Earth's rotation around its axis. Thus, a deeper understanding of seasonal changes might be developed by supporting students' ability to connect different perspectives and explore relationship different spatial components of this complex phenomenon.

In essence, understanding of lunar phases and seasons requires spatial thinking – especially application of PT skill. Uttal and colleagues (2013) argued that students' spatial skills are moderately malleable and that they are transferable to different contexts. There have been research studies that have shown improvement in students' spatial skills through curriculum and instruction in the context of discipline-specific interventions. In the following section, I review a few studies and their implications to embedding spatial thinking in K-12 education.

Learning spatial thinking through curriculum and instruction

Even though spatial thinking has been shown to be an important factor in learning different STEM disciplines, our education system has often failed to recognize its importance in K-12 curriculum and instruction (Hegarty, 2014). Spatial thinking has often been relegated to being a skill that remains underappreciated, undervalued, and therefore underutilized (NRC, 2006, p. 5). A part of the problem might be that schools place more focus on basic skills such as literacy and mathematics. Therefore, teaching of spatial thinking will have to be achieved within the context of teaching content of different disciplines.

Spatial thinking researchers use psychometric tests to study spatial thinking among students in K-12 settings. However, psychometric testing tends to focus on measuring particular cognitive skills that are decontextualized and thereby promote a deficit model of spatial thinking by assessing students through standardized tests (Ramey & Uttal, 2017). Therefore, spatial thinking needs to be assessed in contextualized ways, embedded within content knowledge of disciplines being taught at school.

There are a few research studies college level in which researchers have embedded spatial training in the content knowledge of the specific discipline. Small and Morton (1983) trained students from organic chemistry by giving them tasks involving manipulation of 3D molecular models and interpreting diagrams outside of their regular class. The researchers found that the trained group of students performed 12% higher on the spatial tests than those who were not trained.

The most extensive spatial training program in engineering was led by Sorby and colleagues, who developed semester-long courses to focus on engineering-specific skills such as imagining projections, cross-sections, and translations to train students with low spatial skills (Gerson, Sorby, Wysocki, & Baartmans, 2001; Sorby, 1999; 2009). In their studies college students were given a variety of engineering design-related tasks through spatial training tests. The coursework included tasks such as working on CAD software modules for learning spatial manipulations of 2D and 3D surfaces, cutting planes and cross-sections, and multi-view drawings (Sorby, 1998, 2007). All the tests were focused on developing students' spatial visualization. Students who participated in the spatial coursework performed significantly better than those who participated in the traditional coursework.

In a medicine-related study, 30 students performed a task that required them to draw the cross-section of a 3D egg-shaped object with duct-like canals (Cohen & Hegarty, 2007). The stimulus (Figure 2) was designed such that it resembled the complexity of the shape and structure of biliary ducts of a human liver. The horizontal line on the image at left indicated where participants should imagine the object had been sliced. The arrow in the left stimulus indicates the participants should visualize the cross-section. The image on the right shows the solution to the stimulus on the left.

This test used for training students' spatial visualization was based on discipline-specific content knowledge of medicine. To perform this task, participants were allowed to interactively manipulate the digital image of the object. The researchers found that use of interactive visualization was predictive of performance on cross-section task and that students' spatial visualization is correlated to their performance.

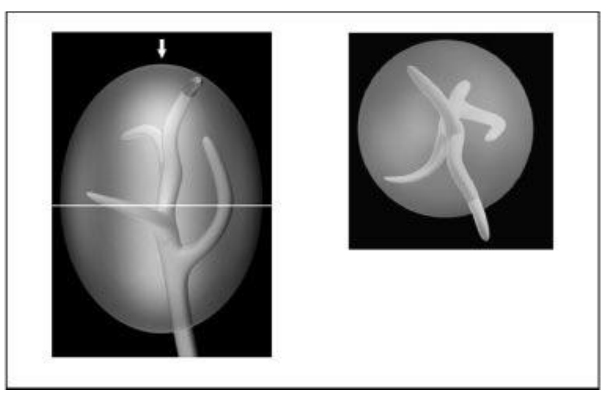


Figure 2. Stimulus (left) and arrow view (right) for a stimulus trial (Cohen & Hegarty, 2007)

The studies presented above show that students' spatial skills improved at the end of interventions, which support the argument that discipline-specific training is helpful in honing students' spatial skills. Spatial training was included in the curriculum itself and the spatial training tasks were based on discipline-specific content knowledge. However, all the studies used spatial tests as the method of training as well as a measurement of improvement in spatial skills. Psychometric testing methods are insufficient in explaining *how* spatial thinking is learned and applied. The studies do not provide substantial knowledge about how spatial skills are learned. Even though the training was embedded in the respective curricula, these studies were not designed to provide insight about what strategies or practices students used that may have led to improvement in spatial skills. Another problem with training through testing is that just by taking the test twice, students can improve their performance (Uttal et al., 2013). In addition to these shortcomings, the studies do not inform how to develop instruction enriched with spatial thinking. Thus, current spatial training is unlikely to make any impact on curricula as the training is not embedded within classroom practices (Lowrie, Logan & Ramful, 2017). However, we can embed training of spatial skills during instruction by focusing attention to classroom practices that might be useful in supporting students' spatial thinking. This might entail observing students when they are involved in solving spatial tasks and understanding what elements shape their spatial thinking.

Contexts shape a person's thinking and learning through interactions with the participants as well as the artifacts of the environment (Lave & Wenger, 1991; Rogoff, 2003). Embedding spatial thinking in the design of the curriculum and developing students' spatial training within classroom instruction might be helpful in developing their spatial thinking as their experiences are grounded in a context. However, there is limited literature on how spatial thinking can be integrated within curriculum as well as instruction, much less on how integrated curriculum shapes students' spatial thinking. Therefore, understanding how students' spatial thinking can be supported within classroom instruction would be important in further enhancing research on spatial thinking.

In the next section, I review a few studies from different disciplines in K-12 education that have not only used psychometric testing for training students' spatial thinking but also included spatial thinking in curriculum and instruction.

Spatial thinking in K-12 education

Geology

Bodzin (2011) investigated how a Geospatial Information Technology (GIT) – enhanced science curriculum supported eight-grade middle school students' understanding of land use change (LUC) concepts, which are important in making decisions about modeling our environment. Concepts related to LUC and Geographic Information System (GIS) mapping are foundational in understanding environmental maps and are applicable in the context of sustainable urban planning and management (Liu & Yang, 2015). Interpreting LUC requires different abilities of learners such as identifying patterns, colors, shapes, textures, sites etc. By teaching those concepts through use of spatial tools, Bodzin not only contextualized spatial thinking in an important middle-school topic, but also highlighted its importance in practical, job-embedded applications.

In Bodzin's (2011) study, teachers were trained to teach spatial thinking through easy-to-use geospatial technology, by doing activities to elicit students' spatial skills such as spatial visualizations and giving them opportunities to exercise their spatial skills through meaningful everyday examples. Instructional features such as scaffolding, modeling and guided practice were used to support student learning. Students' performance was measured before and after curriculum implementation through a 32-item multiple choice questionnaire that included both content knowledge and spatial thinking items. Using LUC as a context for teaching geoscience showed high effect sizes on lower and middle track learners.

Bodzin's (2011) study provides a model of a spatial training study that not only uses pre- and post- assessments for spatial training, but also focuses on guided instruction. The study investigated the role of teachers as well as tools provided to students in enhancing their spatial thinking. However, the study was not designed to examine *how* students' engagement with the technology and tools led to productive learning. The end results were measured through testing.

Mathematics

Research has shown that those who perform better on spatial skill tests seem to perform better in mathematics (Homes, Adams, & Hamilton, 2008). Research perspectives on spatial thinking in mathematics are varied in that some researchers think that mathematics is spatial in nature (Jones, 2002) and others think that similar areas in the brain are activated when performing spatial functions or numeric tasks (Hubbard, Piazza, Pinel, & Dehaene, 2005). However, research studies have shown that higher level of thinking in mathematics is aided by spatial visualization and that spatial skill of visualization predicts students' success in mathematics (Shea, Lubinski & Benbow, 2001).

Embedding spatial skills training in mathematics teaching has been mainly limited to discipline-general spatial tasks such as mental rotation test and spatial relations test (e.g., Cheng & Mix, 2014; Hawes, Moss, Caswell & Poliszczuk, 2015). Studies based on spatial skills training typically involve giving students' timed tests. However, these kinds of studies are conducted in laboratory settings and more research needs to be done to develop different methods of training that can be done within classrooms.

Lowrie and colleagues (2017) designed an intervention to improve students' mathematical skills by embedding spatial training within a sixth-grade classroom setting. They achieved this by collaborating with teachers and training them to embed spatial training in their teaching of mathematics. For example, the normal math tests included geometry-based items such as figuring out the number of colored cubes when a colored 3D object is cut up in certain number of cubes. These kinds of problems require spatial visualization more than mathematical knowledge. The intervention was implemented over a duration of 10 weeks, during which students were given visuospatial reasoning (VSR) tasks for two hours per week. The training involved administering two kinds of tests – Spatial Reasoning Instrument (SRI) to train skills of mental rotation, spatial orientation and spatial visualization, and MathT test that included both spatial skills and content knowledge to solve the problems rather than the mechanized drill-and-practice procedures. In this way, students were trained to improve their spatial skills simultaneously along with their knowledge of mathematics during regular classroom teaching hours. Along with the regular training, teachers also focused on fostering spatial reasoning through their instruction by using concrete materials, focusing on key spatial constructs, and promoting students' reasoning.

Lowrie and colleagues (2017) found that the program with explicit spatial reasoning through instruction had significantly higher spatial reasoning scores than students from the control group. The researchers also found a significant improvement in students' learning across mathematical concepts in comparison to the control group. However, they also found that activities should go beyond physical manipulation of concrete objects and towards helping students mentally visualize spatial orientation for problem solving. In summary, explicit spatial training embedded in classroom instruction was useful in improving students' spatial skills as well as math content knowledge. Thus, this study represents an example of benefits of embedding spatial thinking in the mathematics curriculum.

Astronomy

Wilhelm (2009) explored difference in performance of seventh-grade male and female students on understanding lunar phases. Students' performance was measured through pre- and post-test results on Lunar Phases Concept Inventory (LPCI) and Geometric Spatial Assessment (GSA). The curriculum involved teaching of lunar phases through observations, journaling, sketching, two- and three-dimensional modeling, and classroom discussions. This study offered learning of lunar phases in different modalities. The author found that males gained significantly more than females. On the other hand, females scored higher on the GSA assessment in comparison to the males. The researcher attributed this gain to practicing two-and three-dimensional modeling that may have developed their spatial skill of visualization. Thus, the study showed that scientific and mathematical understanding can be improved for both sexes through guided instruction. However, the study does not explain which aspects of the curriculum were helpful in shaping students' spatial thinking or how the two- and three- dimensional modeling may have been useful for females in developing spatial skills that are relevant in studying astronomy.

Engineering

Ramey and Uttal (2017) investigated spatial thinking in engineering education at middle-school level to explore students' interactions in their learning environment to engage in spatially challenging tasks. The researchers developed a *distributed spatial sensemaking* framework to refer to interactions between students' cognitive processes and the ways in which these processes influence their spatial thinking. The distributed spatial sensemaking framework emphasized the role of both social and material resources in the classroom, which divide the sensemaking work between different actors (human or non-human) in the classrooms. In their study, the researchers argue that when engaged in a spatial task, learners use their internal cognitive spatial processes and draw on available external resources (such as materials or peers) to engage in what the researchers called *spatial sensemaking practices.*

Ramey and Uttal (2017) focused on identifying various spatial sensemaking practices related to solving engineering design tasks. In their study, they observed a class of 26 middle-school students over a period of six weeks to understand the kinds of spatial sensemaking practices that students used to make sense of spatial problems arising in engineering design. Some examples of the sensemaking practices identified were spatial talk, hypothesis testing, object manipulation, and gesturing. The researchers hypothesized that no one person or one representational medium is sufficient in doing spatial sensemaking work – it is distributed between participants and the materials. They found in their study that the process of sensemaking is inherently collaborative as different participants brought different repertoires of sensemaking practices and cognitive processes to solve the engineering design activity. More importantly, the researchers found that the students depended on both their spatial cognitive processes and spatial sensemaking practices to build and revise mental models of scientific phenomena and consequently their engineering designs. Thus, this study shows that identifying students' spatial sensemaking practices is a useful way of understanding how students engage in spatial reasoning.

The studies reviewed above give a brief account of different ways in which curriculum and instruction was used such that students exercise their spatial skills and develop spatial thinking. These research studies set themselves apart from other spatial thinking studies as all of them show efforts taken to develop students' spatial thinking through guided instruction and curricular support. This was achieved by keeping the spatial skills training close to the discipline-specific content knowledge and by embedding training in regular classroom settings. All the studies presented above suggest that teaching disciplinary content knowledge by integrating spatial training within curriculum and instruction may be helpful in improving students' overall performance. Bodzin (2011) made an argument that spatial competency can be developed through use of tools that support students' spatial thinking and that these tools are useful in solving real-life applications. Lowrie and colleagues (2015) showed the importance of explicitly teaching spatial skills and how that improved students' learning of mathematics. In conclusion, studies presented above suggest that integrating spatial thinking within disciplinary content knowledge may support students' content learning as well as spatial thinking.

However, with the exception of Ramey and Uttal (2017), most of the studies presented from each discipline were not designed to explain the nature of students' interactions and how they might contribute to shaping students' spatial thinking. Even though the studies included spatial training embedded within the curriculum and guided instruction, most of them depended on measuring students' gains in spatial skills associated with the specific discipline. This was achieved by administering psychometric tests before and after the intervention. However, psychometric tests act as summative assessments that are limited to representing cumulative end-results. They are insufficient in providing insight about what might have influenced students to improve or about factors causing hindrance to improvement. Therefore, these studies are not useful in informing development of spatially-enriched curriculum and instruction.

Ramey and Uttal (2017) delved deeper into understanding what practices might be helpful in improving students' spatial thinking and how that helps students' conceptual understanding of engineering design. In their study, the researchers focused on analyzing the underlying cognitive and physical processes that led students to solve engineering problems. Even though the study was not designed to train students' spatial skills, it gave insight into how learning engineering design might benefit from students' spatial thinking. By using a cognitive ethnography approach, Ramey and Uttal (2017) investigated students' actions and collaborative interactions with their peers that supported their learning. As their study was carried out in an informal summer camp setting, the design and results of this research study are not entirely comparable to studies that take place during regular teaching time during a school year. However, the study provides important knowledge about students' sensemaking practices that are useful in learning engineering design.

Therefore, research in spatial thinking at K-12 education could benefit from further exploration about what kinds of practices are useful in fostering students' spatial skills and spatial thinking through curriculum and instruction. We need more studies like that of Ramey & Uttal (2017) in order to inform how we can bring spatial thinking in mainstream curriculum and instruction because such studies would help us in understanding what kinds of efforts need to be taken to foster students' spatial thinking other than drill-and-practice methods.

In summary, I have identified the following gaps in current literature in spatial thinking, which I addressed through this dissertation study.

- There is limited literature on discipline-specific training studies in spatial thinking, including in astronomy.
- There are few studies that integrate spatial thinking within classroom settings. Spatial thinking is often taught in domain-general and de-contextualized manner.
- Psychometric tests give a summative measure of students' spatial skills rather than formative. These tests are also insufficient in providing details of *how* students learn to think spatially.
- We have limited knowledge about how students' interactions with their teacher, their peers, and the physical environment influence their spatial thinking.
- There is a lack of literature about how students develop spatial thinking through actions and interactions in their physical environment.

One step towards filling these gaps is by examining what is happening in the classrooms when students are engaged in spatial activities. In my research, I studied how spatial thinking can be learned from actions and interactions with the learning environment that had students use their bodily actions to represent spatial concepts, discipline-specific conceptual knowledge, and reasoning. Therefore, I used the framework of embodied cognition that explains how learning takes place through bodily actions and movement.

Theoretical Framework

Introduction

From the moment humans are born, they interact with the environment with the help of their bodies through multiple senses. Babies start making internal representations of the outside world through closely coupled feedback loops between actions and perceptions (DeSutter & Stieff, 2017; Wellsby & Pexman, 2014). For example, if babies push on a wall with their hands or feet, they learn the consequence of their action through their eyes and sense of touch. Similarly, humans learn to construct knowledge through their actions and physical interactions even before developing language. Embodiment is defined as "the process by which physical action in the world generates, stores and reactivates mental representations abstracted from bodily experiences" (DeSutter & Stieff, 2017, p.4). In other words, bodily actions help in creating physical representations of abstract cognitive mental imagery built in our minds. This phenomenon is called *embodied cognition.* According to embodied cognition theory, all cognition is grounded in bodily actions (Barsalou, 2008).

Theoretical principles of embodied cognition might give a perspective on interpreting how students learn spatial thinking from gesturing, from their use of tools and materials, and their collaborative social interactions. In addition to that, embodied cognition provides a way to examine not only learners' discrete actions taken in the service of learning, but also how the physical environment shapes learning experiences. Therefore, I used the embodied cognition framework to make a connection between students' actions and how they might lead to development of spatial thinking.

Embodied Cognition

Embodied cognition researchers believe that cognition and mental processes are facilitated by body-based activities including gestures, movement, and even engaging one's neural network in action planning (Alibali & Nathan, 2012). The theory of embodied cognition suggests that motor and perceptual processes are not only useful for physical interactions with the world but also important in developing mental representations of the physical world (Hosteller & Alibali, 2007). "Embodiment is characterized by a shared assumption that the body, its particular form, and its sensory capacities supply a cognitive system with a rich input stream that shapes knowledge representation and later cognitive processing of those representations" (DeSutter & Stieff, 2017, p. 4). Our body including the brain and its capacity to store information in short term or long-term memory, its capacity to perceive through visual and physical stimuli create pathways for us to comprehend and represent knowledge in different ways (Wilson, 2002).

Embodied cognition, in general, is an umbrella term that considers many different aspects of how our body shapes our cognition. However, to address questions about how students' interactions with their physical environment, their individual bodily actions, and social interactions shape their spatial thinking, I will mainly focus on using three principles of embodied cognition – 1. we offload cognitive work onto environment; 2. offline cognition is body-based (Wilson, 2002) and, 3. embodied cognition can manifest in social interactions (Abrahamson & Lindgren, 2014).

We off-load cognitive work onto the environment

Embodied cognition suggests that human cognition and linguistic processes are inherently grounded in physical interactions of the human body with its physical environment (Alibali & Nathan, 2012; Barsalou, 2008; Wilson, 2002). The meaning of the term "environment" encompasses material resources, digital or virtual resources as well as the space in which learning activity takes place. Off-loading on the environment is thus a "minimal memory strategy" that humans use to do cognitive work more efficiently (Ballard, Hayhoe, Pook, & Rao, 1997).

Kirsh and Maglio (1994) support this argument by examining students' *epistemic actions* in playing the game of Tetris. The researchers defined epistemic actions as the actions taken by humans to manipulate their physical environment with an intent of gathering information and facilitating cognition for problem-solving. The researchers studied students' actions while playing Tetris – a game in which falling blocks of different shapes must be rotated and translated to fit compactly with the blocks that have already fallen. They found that students actually rotate and translate the blocks to find the best fit before they fall, instead of mentally computing the matching orientation. This action facilitates them to partially off-load the cognitive work on the virtual environment (the gaming console in this case) by manipulating different shapes to find the best fit.

Kastens, Liben and Agarwal (2008) explored how college students gathered and recorded spatial information related to outcrops scattered in a field and then made mental models of the geological structure by visualizing its components buried under the ground. Some epistemic actions taken by the students were identified as moving rejected models of outcrops out of sight, juxtaposing two models for comparison, and rotating models for alignment with referents. The researchers argued that one way of understanding students' cognitive processes is by studying their epistemic actions. Kastens and colleagues claim that a close examination of students' epistemic actions can give us insight into how scientists or experts manipulate objects in the physical world to solve problems and puzzles. This study was useful in learning more about what students do to help reduce their cognitive load and thereby facilitate their spatial reasoning.

Ramey and Uttal (2017) considered the role of material resources in facilitating students' epistemic actions (helping them work through their ideas) and instructive/ explanatory actions (using models to convey meaning to someone else). In their analysis of observing students' interactions with their physical environment, they found that students tinker with materials for the purpose of problem-solving, hypothesizing and planning. For instance, students used material resources for simulating a rough imagery of the design of a structure that they were planning to build. Thus, epistemic actions like these can serve different purposes through a combination of bodily actions and use of different materials. In this particular study, students used material resources to explain and communicate spatial relationships.

In all the three studies presented above, rather than attempting to *mentally* store and manipulate relevant information, students *physically* stored and manipulated those details out in the environment. The process of problem solving was related to explicitly spatial information that was manipulated to solve tasks related to that information. In the study involving Tetris (Kirsh & Maglio, 1994), the physical elements (blocks) being manipulated do not serve as proxy or tokens for anything but themselves, and their manipulation serves the goal of problem-solving through trial and error. However, Wilson (2002) argued that off-loading is useful even for those tasks which are not explicitly spatial in nature. For instance, tasks such as doing mathematical calculations with a pencil and paper or drawing Venn diagrams are examples of activities that require manipulation of spatial relationships among different components in the environment. But in doing so, physical manipulation of the environment is done for the goal of solving an external task not directly related to the components themselves. By doing these actions through physical manipulation reduces the cognitive work of mentally doing calculations. However, unlike in the Tetris example, these actions are carried out in the environment for the purpose of solving an activity that was external to the environment. Thus, off-loading on environment through manipulation of objects can help improve students' understanding of abstract tasks and may help them in developing representations of the physical world. This form of action is called as "symbolic off-loading" (Wilson, 2002).

A few other examples of how cognition is offloaded on materials or tools in the environment is explained through use of computer technology to help cognition. Virtual interfaces, visualizations tools, and animations have been used to design learning environment based on embodied cognition. Chan and Black (2006) found that graphic simulations that emulate physical actions through virtual movements or animation were effective in learning functional relationship between system entities. For instance, replicating action of a gear by physically moving a joystick helps students in understanding how input force is related to output force by moving a gear. The immediate sensorimotor feedback received through motion of the hand can be transferred to working memory. By grounding students' actions through a physical movement of joystick and connecting its effect to the motion of the gear through a computer simulation enabled better understanding of the underlying concepts in mechanics. The researchers also found that interactive graphic animation of a roller coaster led students to understand the relationships between different heights and changes in kinetic and potential energy. Students interacted on the graphic with a virtual slider that helped them navigate the roller coaster through peaks and valleys. The researchers claim that engaging students in direct manipulation of animation helps their active engagement and participation in the process of meaning making.

A study showed that use of multimodal sensing and incorporating tactile feedback help students understand functioning of simple machines (Han & Black, 2011). Tools that support manipulation of digital entities (such as gears) that provide a haptic feedback grounds students' experiences in embodied actions. Furthermore, Han and Black (2011) showed that the haptic simulation group performed better than those who did not have access to haptic channel. Thus, using digital or virtual tools help in shaping students' meaning-making experiences by providing sensory input and feedback systems that ground their experiences in physical actions. In summary, embodiment extends beyond the individual actions as it is activated through digital and technological tools.

Offline cognition is body-based

The second principle of the embodied cognition framework suggests that offline cognition is body-based (Wilson, 2002). The word offline refers to the ability to depend on mental representations of the world that are removed from the situational context such as planning, recall and mental simulations (Nathan, 2008; Wilson 2002). In this view, embodiment is a brain-based phenomenon, where "function of the sensorimotor resources is to run a simulation of some aspect of the physical world, as a means of representing information or drawing inferences" (Wilson, 2002, p.633). DeSutter and Stieff (2017) suggest that embodied actions may provide students ways of representing and structuring information for problem solving. These body-based activities can become a part of the learner's "toolbox" providing new ways to organize information and knowledge to assist their thinking. For example, using fingers to count numbers or for doing numerical calculation is useful in externalizing the cognitive function of counting. Another function of bodily actions may be to sharpen learners' spatial schemas or representations that they might already possess (DeSutter & Stieff, 2017).

One way in which thinking is externalized as bodily actions is through gestures and movement (Alibali & Nathan, 2012). "Gestures enact symbols and provide grounding of novel and abstract ideas and representations" (Nathan, 2008, p. 377). McNeill's (1992) typology describes four major types of gestures – *pointing* (deictic) gestures, which serve the purpose of indicating objects or locations; *iconic* gestures, which are used to show semantic content directly via motion of shape of hand(s); *metaphoric* gestures, which show the semantic content with a metaphor (e.g., cupping hands as if to hold an idea; and *beat* gestures, which convey rhythm and sounds (not meaning). Use of different kinds of gestures often add to verbal communication by enhancing its meaning.

Alibali and Nathan (2012) focused on analyzing gestures that both teachers and students produced during explanations of mathematical concepts. The researchers found evidence of two claims, in particular, that are prevalent in embodied cognition– *pointing* (deictic) gestures display grounding in physical or imagined (off-line) environment and *representational* (iconic/ metaphorical) gestures display mental simulations of action and perception. For example, they observed that an elementary student used his left index finger to point to left side of the equation and the right one to point to the right side of the equation, suggesting his awareness of the two distinct sides of the equality. The researchers argue that such gestures can reveal the "leading edge" of a learner's knowledge.

Roth and Welzel (2001) argued that gestures can provide the means for bridging scientific laboratory experiences to scientific discourse about abstract quantities. The researchers examined gestures of 10th graders as they explained concepts in electrostatics. They found that students' gestures provide a pivotal role in constructing multimodal representations of their explanations. The study showed that gestures may arise in laboratory/classroom activities because they provide a rather fluid way of linking activity to scientific discourse, especially if they are limited by their unfamiliarity with the appropriate scientific language.

Crowder (1996) argued that students' gestures serve different purpose in different discourse modes. The researcher found that students use gesturing to help predict, revise and coordinate different components of their models of the phenomena they were learning. The researcher observed that 6th grade students actively used gestures to explain their models about shadows and changing seasons. The findings of the study showed that gestures used by the students for the purpose of explanation of a model were significantly different from those used for the purpose of making description of the same. While describing their models, students used redundant non-iconic gestures that added little new information to their models; while students used iconic gestures to enhance meaning of their explanations and used them to their advantage of refining their models. This tells us that analyzing gestures can be a way for us to understand students' thinking and learning more deeply, which might be helpful during instruction to aid students in making spatial relationships.

Plummer, Bower and Liben (2016) examined how 7 to 9-year-old students used gestures in their explanation of apparent motion of stars and seasonal changes. The researchers found that the connections between students' mental imagery and the physical environment was apparent in students' use of gestures. For example, in making explicit connection between different frames of references, students used pointing gestures to support their verbal explanations. Students were also found using pointing and iconic gestures to refer to imagined aspects of their mental imagery. For example, they used gestures to refer to the location of a constellation or for referring to position of the Earth in its orbit. Thus, the researchers found that students' used gestures to support their explanations of the phenomena suggesting that their knowledge was embodied in significant ways.

However, bodily actions and movements that might help conceptual development may not come naturally to all the learners (Abrahamson & Lindgren, 2014). Students may need scaffolding for simulating actions, making spatial relationships, and using their bodies in the service of developing spatial thinking. Therefore, extending the embodied cognition to go beyond individual actions and to accommodate for social interactions is indispensable.

Embodied cognition can manifest in social interactions

In general, classroom environments are communicative spaces. Students as well as teachers are constantly producing and comprehending language, notations, and symbolic representations such as texts and curricular materials in their classrooms. Instructional settings are particularly rich with opportunities for providing meaning to abstract signs and symbols, since these are sensorially demanding contexts, where novel ideas and conceptual knowledge is formally introduced by the teacher (Nathan, 2008). Therefore, understanding the role of teachers in facilitating students' embodied actions and how they create pathways for students' embodiment through different pedagogical practices is important. How students can be guided to make embodied representations of knowledge might be useful in understanding how students learn meaning of symbols and signs. This may include practices such as teachers' use of gestures, use of verbal prompts, or modeling. Abrahamson and Lindgren (2014) suggest that effective pedagogical practices might include modeling by the facilitator, co-production, hands-on coaching and using media-technology to present ideas through audiovisual animations.

Nathan (2008) considered the principle of embodied cognition – *offline cognition is body-based* – to incorporate the influence of social interactions along with sensorimotor processes as mediating cognitive behaviors of students. Nathan analyzed how a teacher's gestures ground students' meaning-making processes. The researcher observed how teachers' pointing gestures are helpful in students' sensemaking even if they do not have the vocabulary to express their thinking. For instance, the teacher made linking gestures between a students' idea of 'timesing' (multiplying) by pointing to the multiplication sign in an expression written out on a board. The teacher, instead of interrupting student thinking, used gestures to ground meaning of that word to a symbolic sign. Thus, Nathan makes a case that teachers' gestures play a significant role in grounding students' ideas and conceptual knowledge.

Alibali and Nathan (2012) observed teachers' constant use of gestures in explaining mathematical concepts. They observed that while re-voicing a students' explanation of how two rectangles are similar, the teacher used both her index fingers to show the similar sides of the rectangles under consideration. The researchers argue that instructional pointing like this can help students' uptake of the content knowledge. Their study also highlighted teachers' usage of representational gestures in depicting a variety of mathematical constructs such as slope of lines, orientation of triangles, and shape of angles. The teachers' used gestures to represent these abstract mathematical concepts for the purpose of clarification and for reinforcing the meaning of those concepts.

Alibali and Nathan (2012) also found that teachers' gestures are useful for students in

Figure 3 Representational gesture by the teacher (from Alibali & Nathan, 2012)

understanding spatial nature of some mathematical terms. For example, a teacher showed the difference in slopes of different lines by moving his forearm at different angles (figure 3).

In this case, the teacher anchored the meaning of an abstract mathematical concept – slope – in concrete action by representing it spatially with hand gesture. The researchers argued that gesture played an important role in making thinking visible and in adding meaning to the conceptual knowledge being learned by the student. Thus, this kind of activity becomes a part of students' sensemaking repertoires. Thus, support from teacher is an important aspect of embodied cognition in that it adds to students' repertoire of knowledge and practices for further exploration of the phenomena.

Black, Segal, Vitale, and Cameron (2012) introduced a concept called *instructional embodiment*, which is "the use of embodiment as an engaging activity for the student that may be modeled by the teacher but is fundamentally designed to engage the student in a sequence or system of movement, imagination, and exploration." (p. 215). The same concept was evident in a study by Padalkar and Ramadas (2012) who found that intentionally thinking of gestures as a part of pedagogy may help students in internalizing natural phenomena, a model, or general characteristics of space. The two researchers intentionally prepared elaborate list of gestures that they further used for teaching elementary astronomy. They found that gestures can be used to internalize patterns in astronomical phenomena, to enact spatial characteristics and dynamic properties of astronomical models, and to internalize space in general. Through development of a pedagogical model that is based on intentional use of gestures, the researchers attempted to integrate the spatial and temporal interactions between body and environment, thereby following the principles of embodied cognition. Both these studies are examples of instructional embodiment that explain the role of a teacher in modeling embodied actions to guide students to use their bodies to enact sequences or statements necessary in problem-solving tasks.

Ramey and Uttal (2017) analyzed the role of the instructor in guiding students' sensemaking activities while involved in solving engineering designs tasks. In their study, the students were asked to make designs of buildings by taking into consideration different weather patterns. In this study, the instructor facilitated student conversations and prompted them to make explicit representations of their knowledge through sketching as a way to think through their designs. The instructor's role in this case was to enable students to offload their cognition and make use of physical representations to aid their spatial thinking.

In summary, all the research studies reviewed here give a perspective on using embodied cognition as a framework to analyze how our bodies experience and interpret different sensorimotor experiences from our learning environment. A general consensus seems to be that embodiment of knowledge supports cognitive work and shapes learning experiences by grounding them in concrete actions. The process of embodiment comes naturally to most humans; however, further support from facilitator to activate embodied actions for the purpose of problem-solving is also crucial. Therefore, I use the theory of embodied cognition to understand how students' and teacher's observable actions and interactions are useful in grounding students' spatial thinking in concrete experiences.

Students' as well as the instructor's actions can be examined to see how they come about while constructing explanations of different phenomena or novel concepts introduced in their classrooms. An analysis of students' gestures, how they manipulate external physical tools, technological tools, and materials to create spatial representations, how they use their bodies to physically interact with their learning environment, and teacher's role in eliciting students' bodily actions to aid cognition was be useful in understanding how all these elements support their spatial reasoning. In the context of learning spatial thinking, principles of embodied cognition were helpful in giving insight about how different elements from students' classroom environment are helpful in supporting their understanding of complex spatial relationships and representations.

For this study, students were taught a combined astronomy curriculum on seasons and lunar phases with special emphasis on the perspective-taking skill. Understanding these two phenomena entails constant navigation between visualizing an Earth-based and space-based perspective (Plummer, 2014; Plummer & Maynard, 2014). Therefore, the curriculum was designed to explicitly include training of students' spatial PT skill simultaneously to learn the conceptual knowledge related to seasons and lunar phases. Therefore, I used the theoretical framework of embodied cognition to specifically observe and analyze students' actions and social interactions in the process of engaging in perspective taking. The purpose of analysis using embodied cognition is to understand the ways in which spatial sensemaking practices were used by learners to engage in spatial thinking. To fully understand how students exercise their PT skill and how that leads to spatial thinking, I considered individual as well as social aspects of the classroom environments.

In the next section, I introduce the concept of spatial sensemaking practices and how I used it to understand which practices students recruited to support their PT skill to understand seasons and lunar phases.

Conceptual framework - Spatial sensemaking practices

To examine how embodied cognition can be applied to students' engagement in perspective taking, I identified practices that are called *spatial sensemaking practices* adapted from those identified by Ramey and Uttal (2017). Ramey and Uttal (2017) carried out a study to examine students' use of spatial skills in learning engineering design. In their research study, they observed middle-school students' interactions during a six-week long afterschool program, which focused on learning engineering design through hands-on activities. The researchers identified episodes in students' interactions when spatial problems arose and observed the cognitive processes that were used by students to solve them. They called these processes as spatial sensemaking practices, which included students' cognitive processes and social interactions with peers, and students' manipulation of materials and tools from their learning environment. The word 'spatial' was used to refer to the sensemaking practices related to spatial problems. Thus, spatial sensemaking practices were defined as "strategies for making sense of spatial information that relied on communication with individuals (learners or instructors) or interactions with external objects and representations" (Ramey & Uttal, 2017, p. 12)

Ramey and Uttal (2017) identified seven different spatial sensemaking practices based on students' interactions either with other individuals or interactions with external objects and representations when learning engineering design. These practices were: 1. spatial talk, 2. hypothesis testing, 3. object manipulation (epistemic, pragmatic, or instructive/explanatory), 4. gesture (static, dynamic, or pointing), 5. working from diagrams, 6. analogical or spatial relational comparison, and 7. sketching. Examples of spatial talk included students' discussions about shape or orientation of materials; gestures included students simulating an Earthquake by moving their hand sideways; object manipulation included students tinkering with different parts of the kit-based engineering design materials to make their design decisions; sketching included students drawing a sketch of a climate house before starting to build it. In broader sense, these practices represented moments when students were engaged in solving spatial tasks such as visualization, visual simulation, and spatial representations. Thus, these sensemaking practices were categorized depending on how students solved spatial problems to progress toward their end goals of solving engineering design problems.

The seven sensemaking practices mentioned above take into consideration all the possible types of spatial cognitive processes along intrinsic-extrinsic and static-dynamic matrix

(Uttal et al., 2013). Ramey and Uttal identified all the episodes concerning students' use of different types of spatial skills such as mental rotation, 2D-3D translation, and perspective taking, each one of which represents a different cognitive process. Mental rotation and translational skill are intrinsic-dynamic cognitive processes; while perspective taking is extrinsic-dynamic.

However, for learning astronomical phenomena such as lunar phases and seasons, the spatial skill of perspective taking has been identified key in interpreting spatial information because navigating different perspectives allows learners to construct explanations of these phenomena (Plummer, 2014; Plummer, Bower, & Liben, 2016). As the ThinkSpace curriculum was based on seasons and lunar phases, I focused on identifying spatial sensemaking practices that supported students' use of PT skill as they are involved in mentally navigating between reference frames to explain these phenomena.

PT skill includes imagining a different orientation from a stationary point of view other than that of one's own ego-centric perspective (Liben & Downs, 1993). PT skill is classified as the extrinsic-dynamic skill. Extrinsic because it requires manipulation of information about multiple objects (self and object or self and multiple objects) and dynamic because it involves visualizing different orientations and navigating relationships between them with changing orientation (Kozhevnikov & Hegarty, 2001).

The distinction I made from the spatial sensemaking practices that Ramey and Uttal (2017) used is that I identified and analyzed the practices that took place when making sense of astronomical phenomena of seasons and lunar phases as opposed to engineering. Thus, this study is fundamentally different in the context it provides for learning. The second major distinction I made was that I identified those practices that students used to visualize Earth- or space-based perspectives for learning those phenomena. Being able to connect the Earth- and space-perspectives is an important step in understanding seasons and lunar phases. An individual spatial sensemaking practice may not show evidence of the navigation between two perspectives. But a combination of spatial sensemaking practices showed students taking various approaches in connecting multiple perspectives. Therefore, I focused on spatial sensemaking practices that make students' Earth- and space-based visualizations explicit, which further support them in making connections between the two using their PT skill.

An example of a spatial task related to perspective-taking or visualizing a singular perspective is when a student is visualizing how the Moon is lit up when viewed from a space-based view. In this example, the student has to interpret the relationship between the Sun and the Moon (extrinsic characteristics) as well as the effect of their motion (dynamic characteristics). In this example, the student must use PT skill to figure out how the system affects the way the Moon is lit up as viewed from space. So, if student uses a model of the Moon to support visualization of the space-based perspective, that action was interpreted as the spatial sensemaking practice of either explanatory or epistemic object manipulation. Epistemic because the student offloads his/her cognition on the material resource by using a physical object.

Examples of spatial sensemaking practices from literature

Plummer, Bower, and Liben (2016) investigated how children from elementary grades used PT skill to communicate their explanations about astronomical phenomena and how they learn to construct reasoning for their explanations. The researchers found that when students are required to coordinate mental navigation between Earth- and space-based perspectives, they used gestures and materials from their environment to help cognitive work. When asked about Sun's apparent motion across the sky, 9-yr old Richard answered - 'it looks like the Sun goes across the sky' (p. 353) with an iconic gesture of a curved arc with his arm. This can be classified as a spatial sensemaking practice as the student used gestures to connect his verbal explanation to a physical representation to clearly communicate his usage of Earth-based perspective taking. In another instance, 7-yr old Ashley used a paper with a drawing of stars and a model of globe to explain how our location on Earth matters in deciding whether we will see certain constellations in the sky depending on our local time. In her explanations, Ashley communicated her understanding by using physical props to navigate between Earth-based perspective and space-based perspective. Her explanation showed a clear use of PT skill that was used for sensemaking with the help of object manipulation. Both these examples can be categorized as spatial sensemaking practices as the students use their PT skill to make sense of spatial relationships between multiple objects.

These examples show how students learned by using bodily actions such as gestures and from off-loading their cognition on physical materials.

One of Crowder's (1996) observations was students' use of foreshadowing gestures while explaining seasonal changes and celestial motion. Foreshadowing gestures show evidence of sensemaking as foreshadowing happens when meaning-carrying gestures are used by learners before using speech representing the same meaning. For example, Gail, a middle school student was trying to decide where the Sun would shine on the surface of the Earth. In the process of sensemaking, she took a space-based perspective by first gesturing how the Sunlight might shine on the Earth by tracing an imaginary line between the Sun and the Earth with a gesture, and then refining her verbal explanation. She was also actively involved in visualizing a space-based perspective while figuring out how the Sun would shine. Thus, these actions might be classified as spatial sensemaking practices as they involve gesturing and verbal sensemaking through revisions of mental models.

In summary, I identified spatial sensemaking practices as one of the first steps to answer the research questions of this study. In the following chapter, I explain the conjecture mapping, the methods I use for collecting data, analyzing it, and for making sense of it from the lens of embodied cognition.

Chapter 3

Methodology

Introduction

In this chapter, I explain the methodological approach of conjecture mapping (Sandoval, 2014) to layout theoretically-driven connections between elements of this dissertation and explain different methods for data collection and analysis. Through this research study, I answer the following research questions about spatial thinking from the perspective of embodied cognition:

1. *How might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?*
2. *What are the differences in the range/use of spatial sensemaking practices used by students with low PT skill and those used by high PT skill?*

First, I use conjecture mapping to explain the research design, the decisions for collecting data and to test how embodied cognition might be useful in developing spatial thinking when engaged in a spatially-enriched curriculum. Next, I explain the method of interaction analysis (Jordan & Henderson, 1995) to answer the first research question about identifying spatial sensemaking practices when learning seasons and lunar phases. I explain the method of inductive coding (Thomas, 2006) to answer second question regarding students' explanations about seasons and lunar phases from their interviews.

Conjecture mapping

Conjecture mapping is "a means of specifying theoretically salient features of a learning environment design and mapping out how they are predicted to work together to produce design outcomes" (Sandoval, 2014, p.19). The main purpose of conjecture mapping is to carry out research *on* intentionally designed learning environments. The ThinkSpace curriculum was designed to create a specific learning environment that focused on improving students' PT skill. Therefore, conjecture mapping is an appropriate approach to test how different elements of the learning environment may have worked together to create a positive impact on student outcomes as seen in the findings from previous iterations of the ThinkSpace project (Plummer et al., in progress; Vaishampayan et al., 2018).

Conjecture mapping also allows simultaneous assessment of the design and testing of a theory. In other words, conjecture mapping provides a systematic approach for practical improvements in the design and their implications to theoretical refinement. This approach assumes that learning environments inherently include theoretical activity that guides the process of learning in specific context (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2013; Sandoval, 2014). Elements from the learning environments give rise to specific mediating processes that contribute to the learning outcomes.

In this research study, I focused on identifying *spatial sensemaking practices*, which represent the *mediating processes* that took shape in the learning environment during the enactment of ThinkSpace curriculum. In the following section, I introduce components of the conjecture map specific to this study - *the high-level conjecture, components of the embodiment, mediating processes*, and *outcomes* from previous iteration of the ThinkSpace project.

Initial conjecture map

High-Level Conjecture

A conjecture map begins with a theoretical conjecture about "how to support the kind of learning we are interested in supporting in that context" (Sandoval, 2014, p. 21). The learning goal for the ThinkSpace curriculum was enhancing students' spatial thinking in the context of seasons and lunar phases, especially by leveraging their perspective-taking skill. While participating in the ThinkSpace curriculum, students were intentionally engaged in different spatial tasks allowing students to exercise their perspective-taking skill. This was achieved by using physical and virtual materials, technological tools, and giving them opportunities to solve problems collaboratively. Thus, students were engaged in active learning by maximizing their interactions with the learning environment and their peers.

According to embodied cognition, physical interaction with the environment concretizes abstract experiences by grounding them in physical representations (Barsalou, 2008; Wilson, 2002). Physical actions in the world generate, store and reactivate mental representations abstracted from bodily experiences (DeSutter & Stieff, 2017). Therefore, based on embodied cognition, I proposed an initial high-level conjecture about how the ThinkSpace curriculum supported students' spatial thinking: *ThinkSpace curriculum engages students' PT skill through spatial sensemaking practices such as use of gestures, tools and materials from the learning environment, along with social interactions between peers and instructor*. This conjecture was initially kept broad and was then refined according to the findings from data analysis in Chapter 4.

Figure 4 shows the initial conjecture map starting with the conjecture I am proposing to test with this research. In the following sections, I explain what each one of the elements of the conjecture map include and their relationship to each other.

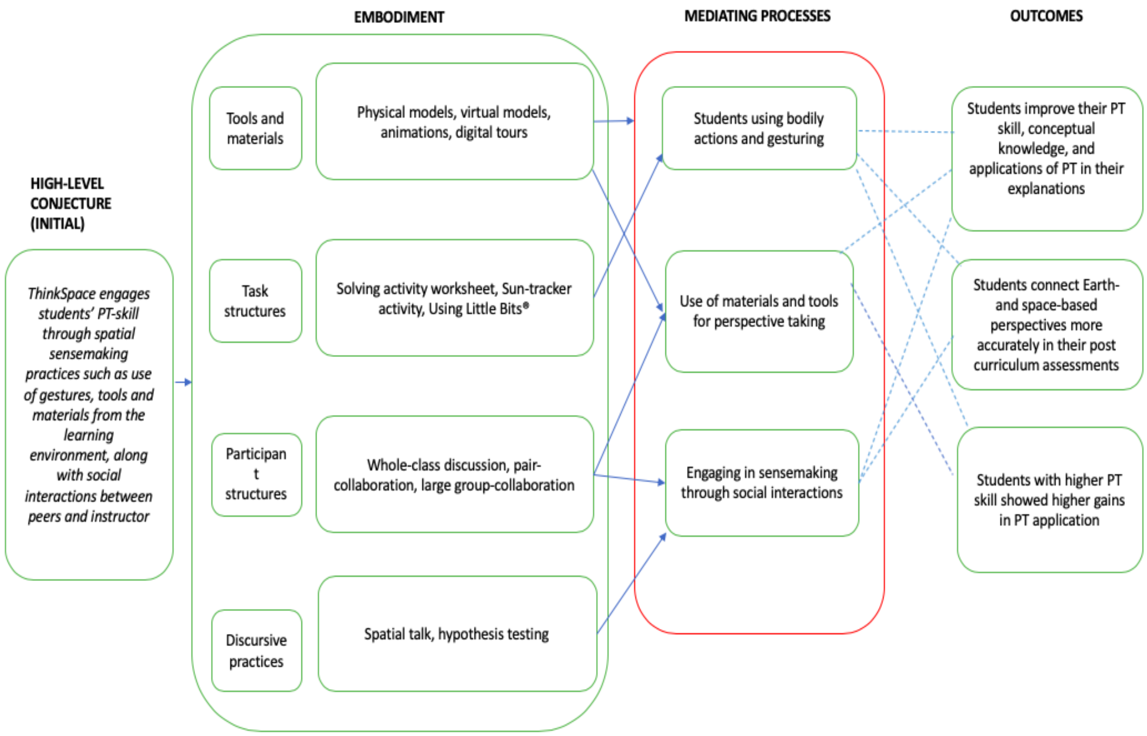


Figure 4. Initial conjecture map

Embodiment

A conjecture takes shape within *embodiment,* which represents different elements of the research design within which the high-level conjecture is reified. These elements are roughly categorized in four different environmental components: tools and materials, task structures, participant structures and discursive practices (Sandoval, 2014). A combination of these four components together shape spatial sensemaking practices that emerge from the learning environment. The second column of the Figure 4 shows elements of the embodiment relevant to this study.

The *tools and materials*, used for teaching seasons and lunar phases were carefully brought in with a specific goal of leveraging students' PT skill that allowed them to understand a variety of spatially complex concepts more deeply than by rote learning. The tools and materials included physical and virtual models, digital animations and tours, which included specific training tasks designed to engage students in using their PT skill. *Task structures* refer "to the structure of tasks learners are expected to do" (Sandoval, 2014, p. 22) such as solving worksheets and using models. *Participant structure* refers to "how participants are expected to participate in the tasks" (Sandoval, 2014, p. 22) including the roles and responsibilities. For example, students were required to work in pairs to solve the worksheets instead of solving individually. *Discursive practices* refer to ways of talking. Although discursive practices cannot be predetermined in the design of a learning environment, they can at least be partially designed (Sandoval, 2014). For example, while teaching the curriculum, the teacher intentionally asked questions to elicit students' perspective taking skill in order to support their problem-solving tasks.

Mediating processes

Design features of a learning environment represented in the embodiment do not lead to the outcomes directly; instead they give rise to particular types of activities and interactions that lead to intended outcomes (Sandoval, 2014). These activities and interactions are called as the *mediating processes,* which represent the link between components of the learning environment (embodiment) and the desired outcomes. In the context of this research study, the spatial sensemaking practices *are* the mediating processes. Initially hypothesized mediating processes are indicated by the red box in Figure 4. The dotted lines represent possible connections between the mediating processes and the learning outcomes, which were revised after data analysis.

The goal of this research study was to examine what kinds of mediating processes – spatial sensemaking practices – contributed to the desired outcomes of the ThinkSpace curriculum. Therefore, before delving into spatial sensemaking practices, a discussion about outcomes of the previous iterations of the ThinkSpace project is important.

Outcomes

I must highlight that initial conjecture map is developed by taking into consideration data analysis from first two years of the ThinkSpace study. The “Outcomes” section in Figure 4 represents the high-level outcomes from those analyses.

Findings from the first two years of the ThinkSpace project showed that:

1. Students’ PT skill is moderately correlated to their content knowledge about seasons and lunar phases as well as to their accurate use of PT skill in explaining those phenomena (Vaishampayan et al., 2018).
2. Regardless of their pre-PT skill scores (low or high) students who participated in the ThinkSpace curriculum showed significant improvement in their content knowledge of seasons and lunar phases and in making accurate connections between Earth-and space-based perspective in their explanations of the phenomena (Plummer et al., 2018; Plummer et al., in progress).
3. Students with higher PT skill have higher gains in their use of PT skill in their explanations of seasons after participating in the curriculum. (Plummer et al., in progress).

In summary, the findings suggest that the ThinkSpace curriculum and instruction played an important role in improving students’ understanding of astronomical phenomena as well as in improving spatial skill of perspective taking. However, these findings are derived only from the results of analysis of students’ psychometric and written assessment data gathered before and after the curriculum. These findings do not reflect how students’ engagement in the curriculum may have led to improvement in their spatial thinking. In other words, the findings do not inform us about the kind of sensemaking practices that may have shaped these outcomes.

Therefore, I examined *how* students used their PT skill when making sense of the spatial tasks related to learning seasons and lunar phases. I focused on analyzing the enactment of ThinkSpace curriculum and instruction to gain insight about which mediating processes related to PT skill may have led to improvement in students' spatial thinking.

The third column in Figure 4 are the hypothesized mediating processes from embodied cognition perspective. Based on prior literature, I predicted the mediating processes to be gestures, students' use of the tools and materials from the learning environment, and social interactions (Plummer et al., 2016; Ramey & Uttal, 2017).

Regression model from the previous years' data from ThinkSpace project predicted that students with high PT skill may have had a higher gain in using PT skill successfully in their explanations for post-interviews than those with low PT skill (Plummer et al., 2018; Plummer et al., in progress). Therefore, in the second question, I examined whether there is a difference in terms of their use of spatial sensemaking practices. In the following sections, I will give an overview of the research setting, ThinkSpace curriculum, data collection and analysis methods for this study.

Setting

A 10-day spatially-enriched curriculum on Seasons and Lunar phases titled ThinkSpace was taught to sixth-grade students from a public middle school in New England area. The school district to which the school belongs to has a population of 74.6% White, 11.4% Asian, 5.4% Hispanic, 4.7% multi-race, 3.6 African-American, 0.2% Hawaiian, and 0.1% Native American according to the latest report on demographics (obtained from the district website).

Curriculum

ThinkSpace was developed by a team of researchers to teach middle-school astronomy by supporting students' spatial reasoning, especially their spatial skill of perspective taking. The goal of the ThinkSpace curriculum was to engage students in discipline-specific, spatially-demanding activities that promote deep understanding of science practices such as modeling, explanation, and argumentation through spatial thinking. ThinkSpace curriculum was taught by one member of the research team over 10 days. The researcher, Dr. Paula[1], has a Ph.D. in Astrophysics and has experience teaching in a private school for five years.

ThinkSpace curriculum supported students' conceptual understanding by making use of multimodal approaches and engaging students in perspective taking. Students were engaged in spatial thinking through different activities including a variety of physical and digital resources. To introduce students to the concept of PT skill, the teacher demonstrated perspective taking by placing physical objects in a classroom and having students experience how their perspective changes with respect to different locations in the classroom space. Students were also given models of Sun, Earth, and Moon to support spatial visualization of extrinsic relationships between multiple objects. Physical models were also given to students to understand lunar phases as they themselves acted as the Earth while holding a Moon ball in their hand against a light source. Students then observed parts of the Moon being lit up by the light source (Sun) and those visible from their (Earth-based) perspective to understand lunar phases. Additionally, the teacher also made use of a hula-hoop to represent the tilted orbit of the Moon to teach Eclipses.

A large portion of the curricula was taught through an interactive software called the *WorldWide Telescope* (WWT), which is a virtual interface that enables students to explore astronomical phenomena. WWT interface showed accurate representations of scales and

[1] Real names are replaced by pseudonyms

distances between different celestial objects – a task otherwise impossible to replicate in a classroom space. WWT facilitated students' spatial visualization by demonstrating these concepts through virtual tours. In summary, both physical and virtual models together created opportunities for students to apply their PT skill and explore these two phenomena. Some portion of the curriculum was also taught through preset virtual tours and animations to introduce students to basic conceptual knowledge.

Table 1 provides a day-to-day description of the ThinkSpace curricula. Even though the phenomenon of lunar phases was taught on the last two days, a lot of concepts taught during day-1 and day-2 were applicable to both seasons and lunar phases.

Table 1

Day-by-day description of ThinkSpace curriculum tasks

ThinkSpace curriculum days	Description of tasks
Day 1	Modelling of Sun-Earth system through physical and virtual models, Introduction to concepts of rotation vs. revolution
Day 2	Introduction to cardinal directions, sky angles, apparent path of the Sun using Sun-tracker
Day 3	Observation of Sun path in different montååhs, using Sun-trackers for prediction
Day 4	Understanding how different sun-angle affects the temperature on Earth, activity using Little Bits® to measure change in intensity of light with different angle of inclination
Day 5	Introduction to the concept of Earth's tilt and its effect on sun-angle on different days of the year
Day 6	Continuation from day 5: understanding sun-angle in summer, winter by using WWT
Day 7	Understanding change in hours of daylight throughout the year using WWT

Day 8	Understanding shape of Earth's orbit and whether it affects the change in seasons – addressing misconceptions about distance mechanism
Day 9	Lunar phases – introduction to changing phases using physical models and virtual tours
Day 10	Review of lunar phases, solving worksheets to practice perspective taking, Explanation of eclipses

Participants

A total of 185 students (ages 11-12 yrs) from five different 6th grade classrooms participated in the curriculum and took pre- and post-assessments. The pre- and post-assessments included two written assessments – PT- skill test and MOSART test (Sadler et al., 2010). A total of 24 (11 males, 13 females) students participated in the individual interviews before and after instruction, of which 22 students' interview data was used for analysis.

Data Collection

Classroom instruction

To understand which spatial sensemaking practices manifest during instruction, I collected video-data on students' interactions in their classrooms. According to conjecture mapping (Sandoval, 2004), examining the nature of students' participation is the key to establishing the link between the mediating processes and learning outcomes. Therefore, I chose to video-record the enactment of the ThinkSpace curriculum during the 10 days of instruction to analyze students' physical and social interactions.

Video-recording provides a mechanism to capture sequential organization of talk, actions such as blinks or gaze, or turn transitions, which are otherwise likely to be missed through data collection techniques like field notes (Jordan & Henderson, 1995). Gestures and body-positioning or micro-behaviors such as gaze-shifting normally take place out-of-awareness

(Jordan & Henderson, 1995). Therefore, to capture students' actions such as gestures and movements, their interactions with their peers, and the teacher's role in engaging students in spatial tasks, video-recording was the most appropriate method for data recording as it provided continuity in data collection process. This data set was used to examine which spatial sensemaking practices may have supported students' perspective taking.

To capture interactions between participants more closely, a handheld camera was used to record videos of classroom interactions as I moved between participants. Another stationary camera was placed in one corner of the classroom to capture an unobstructed view. Each recorded class period lasted for about 45 minutes every day of the instruction. Video-recording was done in two classrooms (out of five) wherein the same curriculum was taught. One set of classroom instruction was recorded as a primary data set, while the second one was recorded as a backup. A total of 90 minutes of classroom interactions was recorded each day making up about 900 minutes (15 hours) of total instructional data.

Student Data

Qualitative interviews

To identify the differences in high and low PT skill students' explanations, I needed data about individual students' use of spatial sensemaking practices for comparison. Therefore, I collected data on students' explanations through semi-structured qualitative interviews carefully worded to elicit students' responses by enabling their use of PT skill. The interview protocol included six questions on seasons and six questions on lunar phases (see Appendix A). For responding to questions on seasons, students were given foam-models of the Sun and the Earth (with a pin stuck on it indicating the observer's location) to support their explanations. The questions on seasons included concepts such as effects of Sun's apparent motion, effects on the change in temperature in different seasons, and the role of the Sun's altitude in a given location. Students were provided photos of the lunar phases for reference if they were unfamiliar with the scientific terminology for each phase such as *gibbous* or *first quarter*. Students were encouraged to use gestures and movement to support their explanations. Follow-up questions were asked by the interviewer in case the students misunderstood a question or gave incomplete responses. This data set was used to analyze the difference in the range or use of spatial sensemaking practices students with high and low pre-PT scores. The following section shows the binning of student scores to determine the low, medium, and high PT-score bins.

PT skill assessment

Determining students' spatial skill of perspective taking was an important part of this research study to answer the second research question. From earlier iterations of the ThinkSpace study, we found a correlation between students' PT skill and their explanations of the two phenomena (Plummer et al.. in progress; Vaishampayan et al., 2018). Therefore, students' PT skill was measured to further investigate whether there are observable differences between explanations of students with low PT skill and those of high PT skill.

Students' perspective-taking skill was measured by administering a 16-item PT skill test (Liben, 2012) to students before and after the curriculum that determines their ability of perspective taking. One of the items from the test was used for demonstration. Therefore, the PT skill test given to students was a 15-item test. In the test, students were shown a picture of a doll looking at two colorful dots from different angles. Students were asked to visualize what the doll would see from her perspective. They were given eight choices to choose the correct answer from (see Figure 5). Students were given 15 seconds to solve each item.

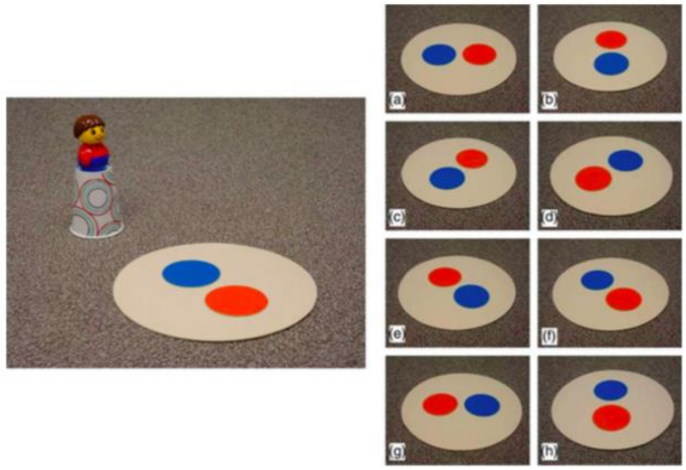


Figure 5. Sample item from PT skill test (Liben, 2012), modified from Liben & Downs (1993)

Out of 185 students who participated in the ThinkSpace curriculum, 24 were selected to do interviews based on approximately equal distribution of students with low, medium, and high pre-PT scores. The lowest third of the students were binned as low PT, the middle third were binned as medium PT, and the highest third were binned in high PT skill. As a result, students who scored between 0-10 were binned as low PT skill group (n = 8), students scoring between 10-13 were binned as medium PT skill group (n = 8), and those who scored 14-15 were scored as high-PT skill group (n=6).

MOSART assessment

Students were given a 15-item MOSART (Misconceptions-Oriented Standards-based Assessment Research for Teachers; Sadler et al., 2010) test to measure their conceptual knowledge about lunar phases and seasons before the curriculum was taught. Items with high discrimination were chosen to assess students' non-normative ideas about the two phenomena. Students who were selected for interviewing obtained a score of 7 or below (with one exception) to ensure that most of them had a similar level of conceptual understanding irrespective of their PT skill.

In summary, to answer the research questions, four different kinds of data were recorded – students' PT skill before and after instruction, MOSART test scores before instruction, videos from classroom interactions, and videos from qualitative interviews about students' explanations before and after the curriculum. I used a video-data analysis software called *V-Note* to carry out interaction analysis for analyzing data from students' classroom interactions, while I used the inductive and deductive coding approaches (Miles & Huberman, 1994; Thomas, 2006) to analyze students' pre-and post-interviews.

Data Analysis

Instruction Analysis

I applied the method of *interaction analysis* to answer the first research question about spatial sensemaking practices. Interaction analysis, as the name suggests, is an interdisciplinary approach for analyzing interactions between people and their environments in naturally occurring settings (Jordan & Henderson, 1995). The main focus of the interaction analysis is on "human activities, such as talk, nonverbal interactions, and the use of artifacts and technologies, identifying routine practices and problems and the resources for their solution" (Jordan & Henderson, 1995, p. 39). The key to interaction analysis is observing how social order is achieved in everyday settings to understand how and why certain actions take place in a social environment. Therefore, this method provided a practical approach to analyzing different aspects of interactions such as the temporal organization of activities, participant structures, talk moves (verbal and non-verbal), and turn-taking that take place as different participants engage in the activities (Jordan & Henderson, 1995). This method was helpful in identifying spatial sensemaking practices emerging in students' classroom interactions.

First cycle of coding

I took the approach of general inductive coding to understand the core mediating processes evident in the video-data relevant to the research questions (Thomas, 2006). The first step in analyzing classroom instruction data was to map events from each day of instruction that are relevant for answering the first research question (Jordan & Henderson, 1995; Kelly & Chan, 2011). These events were named as *PT sensemaking* episodes. PT sensemaking episodes were identified as chunks of video-data related to explanation of seasons or lunar phases but also involved participants' usage of PT skill. This allowed me to distinguish those instances in the instruction that are not directly relevant to application of PT skill from those that involve students' engagement in PT skill.

The beginning of a PT sensemaking episode was marked by a problem that required students' use of PT skill for solving or a perspective-related question asked by a teacher. The end of the sensemaking episode was marked when the problem or the question was answered. For example, one PT sensemaking episode began when the teacher asked the students to predict the direction of the rotation of the Earth (clockwise or counterclockwise). This question required students to use the model of the Earth to simulate the motion and then connect Earth's rotation to their visualization of Earth-based perspective. This episode required students' use of PT skill to connect the two perspectives. Therefore, this qualified as a PT sensemaking episode. Within this PT sensemaking episode, students used a variety of spatial sensemaking practices.

The processes such as event mapping and identifying the PT sensemaking episodes were helpful in filtering only the events relevant to perspective taking. For example, a discussion about whether southern hemisphere has different names of the seasons was *not* marked as an event, as it has relevance neither to spatial thinking nor perspective taking. Therefore, event mapping was useful in identifying chronological order of different events that took place in a day-to-day instruction time, which were then used for the process of inductive coding. A total of 43 PT sensemaking episodes were identified within 10 days of instruction.

Second cycle of coding

According to Miles, Huberman, and Saldaña (2014, p.72), "coding *is* analysis", as the process of coding initiates the process of finding meaning of the data and its interpretation. Therefore, I began the process of analysis of PT sensemaking episodes by starting to identify spatial sensemaking practices within those episodes. First, I created codes for categorizing the type of perspective used by a participant within an instance into three categories – space-based perspective, Earth-based perspective, multiple-perspective, and disconnected perspective (see Appendix B).

Identifying perspective-based codes created chunks of data to zoom-in and to further identify actions and interactions associated with those codes. Thereafter, I coded all the perspective codes with overlapping *process* codes that showed students' observable actions and interactions with other participants in the classroom (Saldaña, 2015). For example, once identified as an Earth-based perspective instance, I went back to see the same segment of video and coded for actions such as *pointing gesturing, iconic gesturing*, and so on.

Examples of process codes included both verbal and non-verbal processes such as *gesturing* or *perspective-related questioning*. For example, gesturing was coded if a student used her arm to show the motion of the Sun. Only the gestures meaningful to sensemaking were coded. As ThinkSpace curriculum included use of technological tools such as the WWT software, the interaction analysis also included students' interactions with virtual tools when they used WWT to solve their worksheets as the part of the curriculum design. For example, while solving worksheets using virtual models, I coded the instances when students were panning the display to navigate space-based perspective to see different locations on the Earth from multiple viewpoints or manipulating virtual imagery to support their spatial thinking.

Process coding enabled observation of patterns in the data associated with different perspectives that students were engaged in. I coded a set of videos from different days of instruction to cover all types of activities. In other words, to identify spatial sensemaking practices relevant to perspective taking, I coded PT sensemaking episodes that represented the most variety of tools and materials, participant structures, task structures, and discursive structures. As a result, I coded approximately 30% of the instruction video-data for finalizing the spatial sensemaking practices.

After the second cycle of coding, I compared my process codes to the coding system used by Ramey and Uttal (2017) to finalize spatial sensemaking practices. I found that some of the sensemaking practices used by Ramey and Uttal (2017) were overlapping with the codes from my interaction analysis. So, I created a codebook of spatial sensemaking practices based on the guidelines from Ramey and Uttal (2017) and creating new codes to accommodate some additional patterns, which were not included in their framework. The most prominent spatial sensemaking practices identified and coded at the end of the coding process were – *iconic gesturing, pointing gesturing, use of body-movement, explanatory object manipulation, epistemic object manipulation, use of fixed objects for referencing, explanatory sketching, and epistemic sketching* (see Appendix B).

Figure 6 illustrates a snapshot of timeline with code labels. The left side of the image shows the process codes nested under a single PT sensemaking episode along with the type of perspective taking. The codebook was used to do inter-rater reliability and to further analyze the rest of the instruction videos.

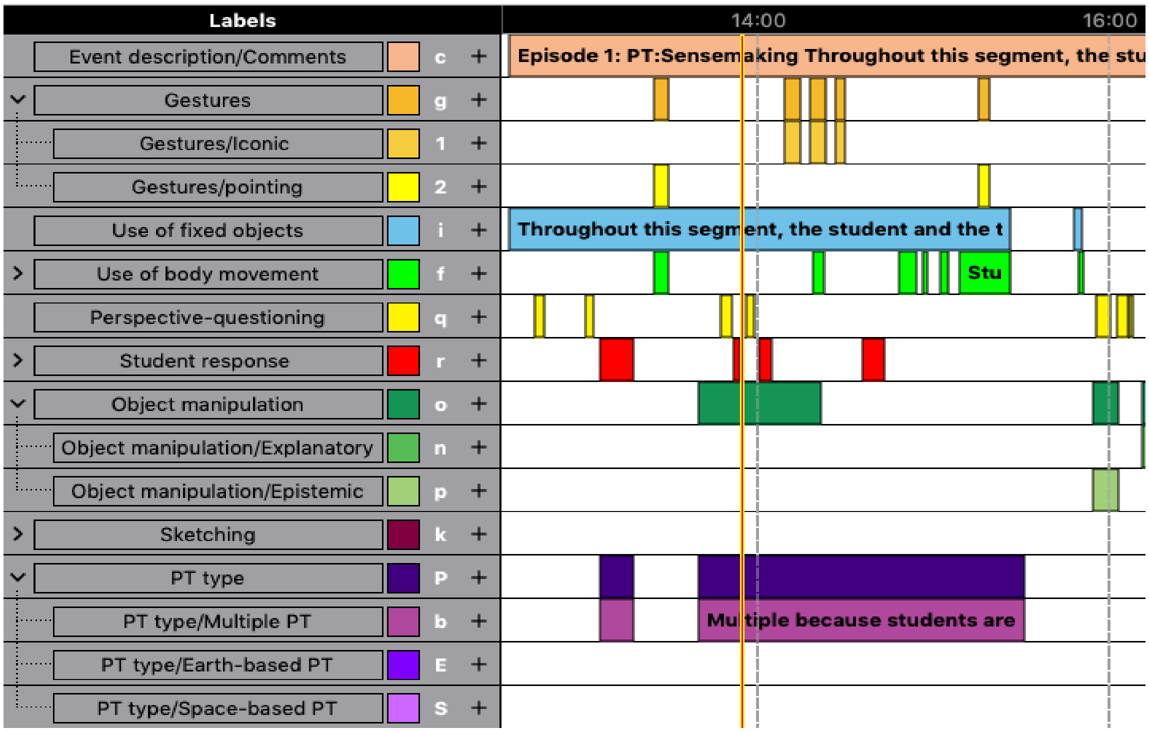


Figure 6 Snapshot of a coded timeline from instruction data

Third cycle of coding

A portion of all the instructional videos (about 25% of total duration for classroom data) was coded by two coders including me and an independent rater to establish inter-rater agreement about identification of types of spatial sensemaking practices. Multiple rounds of coding were carried out until substantial agreement was achieved between me and another coder who independently coded the data. Establishing inter-rater reliability was important in order to minimize the researcher bias in analyzing students' explanations. The agreement between the coders was based according to Cohen's Kappa reliability measurement (Landis & Koch, 1977).

The agreement or *Kappa* value for gesturing (pointing or iconic) was 0.616, for object manipulation (explanatory or epistemic) was 0.767, for sketching (explanatory or epistemic) was

0.750, and use of fixed objects for referencing was 0.5. The *kappa* value for perspective type was 0.645, which was also substantial. All the *kappa* values showed substantial agreement between the independent raters. Use of body movement was a practice rarely observed in the classroom instruction videos. Therefore, its kappa value was not calculated.

Once the agreement was established to be satisfactory, I coded the rest of the instructional data using the revised codebook for identifying spatial sensemaking practices. At the end of this data analysis process, I identified 43 PT sensemaking episodes, each one of which was coded using the spatial sensemaking practices codebook for coding practices students as well as the teacher used for engaging in tasks related to perspective taking skill.

Interview Analysis

Interview analysis was carried out to answer the second question that calls for comparison of individual student's spatial sensemaking practices in the service of perspective taking. For coding spatial sensemaking practices from students' pre- and post- interviews, I used the same codebook developed during interaction analysis with a small modification as interviews did not afford social interactions or practices such as sketching. During interviews, students were given physical models of the Sun, Earth and the Moon to support their explanations and pictures of the lunar phases for reference. Therefore, students' responses included only spatial sensemaking practices such as gesturing, object manipulation, use of fixed objects for referencing, and use of body-movement. For example, if a student used object manipulation to support their verbal explanation, that event was coded as a spatial sensemaking practice. If a student rearranged pictures of the lunar phases to construct explanations of lunar cycle, that event was coded as spatial sensemaking practice related to epistemic object manipulation. Spatial sensemaking practice was coded along with the types of perspective that students used for answering the prompts.

Identifying patterns in data

To compare students' spatial sensemaking practices, all the students were binned according to their pre-PT skill scores. After the initial coding, I compared the coded timelines of the students from low PT skill bin to those with high-PT skill bin to see any visually apparent patterns. Specifically, I looked for patterns of spatial sensemaking practices that are associated with different types of perspective – space, Earth, multiple, or disconnected. This was done by first making visual inspection of the V-note timelines and then zooming-in onto selected chunks of data that showed any apparent pattern.

In summary, the spatial sensemaking practice codebook was developed using thematic analysis along with pattern coding. The same codebook was used for uncovering patterns in instruction as well as interview data. Both data sets were analyzed independently to look for patterns within each one of them. Results from the instruction analysis were used to revise the initial conjecture map and to answer the first research question. Results from the interview analysis were used to answer the second research question.

Validity

There are multiple ways in which I addressed validity of this study. Because a large portion of the findings depend on rich descriptions of the data, a threat to validity is the inaccuracy and incompleteness of the data (Maxwell, 2014). Therefore, methods of data collection help address validity issues in this research study. Both the classroom instruction and students' interviews were comprised of a large set of rich video-data that gave a detailed picture of the events that took place. "Video data provides optimal data when we are interested in what "really" happened rather than in accounts of what happened" (Jordan & Henderson, 1995, p. 51). Video-taping the interactions and the interviews provided a rich dataset that is continuous and reduces researcher bias in comparison to other data collection methods such as field notes.

Second, this research study involves a spatially-enriched curriculum, which was designed to produce certain outcomes about students' spatial engagement. This curriculum was taught by one member of the ThinkSpace research team, who was also a subject in the data analysis. Therefore, member-checking was used as a method of addressing validity by soliciting feedback from her to limit possible misinterpretation of data. Member-checking was useful especially in establishing that the findings from the interaction analysis were not trivial outcomes of the ThinkSpace curriculum and that emergent patterns identified during the curriculum implementation were authentic. Another approach to ensuring validity of the data analysis was by establishing inter-rater reliability for data analysis. Inter-rater reliability provided a way to limit the researcher bias in identifying the spatial sensemaking practices and also helped in identifying the nuanced differences between different practices.

Limitations

Video-recording ensures continuity in the data collection in that it provides a means of continuously observing daily enactment of the curriculum. However, this research study lacked other means of recording such as field notes, which provide essential supplemental information such as in-the-moment reflections (Maxwell, 2013). Since I was the only person recording data from instruction, I took limited field notes during actual instructional time. Hence, there was a lack of documentation about my own thoughts and reflections as a researcher when the study took place and I rely largely on the data gathered from two video cameras for answering my research questions. Another limitation of this study is that the sample size of the students who were interviewed is small ($N = 22$). Therefore, explanations assessed for students in low, medium, and high bin may not be representative of all the students with similar PT skill and may not be generalizable.

This study is designed by taking a particular perspective on students' learning – embodied learning. Thus, the findings from this study were attributed largely to observable patterns emerging from the data, based on principles of embodied cognition. There are many other factors such as students' engagement in classroom, their prior knowledge, SES status, attendance, and even their spatial skills other than perspective taking that may have played a role in determining students' outcomes. Therefore, I want to highlight that through this study, I focused on what engagement in perspective taking might look like. I did not make any analyses to determine causal relationships between the intervention and the outcomes, but merely suggested how certain practices may have implications to developing spatial thinking.

Lastly, I must acknowledge that I was a member of the core ThinkSpace project team for the past four years and I knew the teacher closely. I was involved in analyzing previous years' data, developing codebooks, and conducting literature review. However, all the methods I presented in this section are chosen by carefully examining existing literature in qualitative research to produce reliable findings. In the following two chapters I present the findings from instruction and interview analyses.

Chapter 4

Findings and Analysis: Instruction

Introduction

In this chapter, I present the findings from interaction analysis of the video-data collected during 10 days of instruction. First, I present the spatial sensemaking practices that I found through interaction analysis, which represent the mediating processes manifested from the design of the ThinkSpace curriculum. Second, I present claims highlighting the relationships between components of the embodiment and mediating processes which were the most salient. In the end, I revise the initial conjecture map (Sandoval, 2004) to reflect only the most salient spatial sensemaking practices and the related classroom embodiment. The research question that guided my analysis is: *How might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?*

Spatial sensemaking practices

Spatial sensemaking practices are those practices that students and the teacher use for interpreting spatial information and solving spatial problems (Ramey & Uttal, 2017). I adapted Ramey and Uttal's framework for analyzing how students made use of spatial sensemaking practices in the context of learning seasons and lunar phases by using their PT skill. Overall, I found eight spatial sensemaking practices that both the students and the teacher used for interacting with and communicating spatial information in order to engage in perspective taking– *using pointing gestures, using iconic gestures, use of body movement, explanatory object manipulation, epistemic object manipulation, use of fixed objects for referencing, explanatory sketching,* and *epistemic sketching* (Table *2*).

Table 2

Spatial sensemaking practices and their definitions

Spatial sensemaking practice	Definition
Using iconic gestures	Gesturing to show a dynamic process/arrangement (McNeill, 1992)
Using pointing gestures	Gesturing to direct attention (McNeill, 1992)
Use of body movement	Using one's whole body for simulating a process
Explanatory object manipulation	Using objects for the purpose of explaining something to others (Ramey & Uttal, 2017)
Epistemic object manipulation	Using objects to reduce cognitive load (Kirsh & Maglio, 1994)
Use of fixed objects for referencing	Using an object or artifact for referencing without touching it
Explanatory sketching	Drawing out ideas for the purpose of explaining
Epistemic sketching	Drawing out ideas for the purpose of externalizing mental visualization

To identify spatial sensemaking practices relevant to PT skill, I focused mainly on those episodes when students were showing their engagement in visualizing Earth- or space-based perspectives and learned to navigate those perspectives through use of PT skill. These episodes were called PT sensemaking episodes (adapted from Ramey & Uttal, 2017). In the following section, I will explain the role of each spatial sensemaking practice and a discussion about how embodied cognition might help us understand how that practice helps spatial thinking.

Role of gestures in spatial sensemaking

Use of gestures was the most frequently used spatial sensemaking practice among students and the teacher to communicate spatial information along with using verbal identifiers. The participants used gestures to process spatial information and also to communicate that information to others. The two types of gestures that were used for communicating spatial information were iconic gestures and pointing gestures (McNeill, 1992). Iconic gestures are used by learners to show semantic content by shape, placement, or a motion trajectory. Pointing gestures are used by learners to direct attention to an object or a location (McNeill, 1992). Gestures have been found to convey information in a visuospatial format along with the speech (Crowder, 1996; Singer & Goldin-Meadow, 2006). Both the teacher and students used iconic gestures to simulate the shape, size, or motion of a celestial body. For example, students used iconic gestures to show movement of the Sun across the sky, while they used pointing gestures to show relationship between two or more objects. In the following section, I present examples that illustrate the use of gestures as a spatial sensemaking practice.

Example 1: Teacher's use of gesturing to introduce abstract concepts

Throughout the instruction, the teacher used a combination of iconic and pointing gestures when familiarizing students with the concept of sun-angle (also referred to as sky-angle). Sun-angle is the angular distance of the Sun from the horizon at a given instance of time. This is an important concept in understanding seasons as the effect of sun-angle on the spread of its energy varies depending on its location in the sky – the higher the sun-angle, lower is the surface area over which the Sun's energy is distributed. Therefore, this concept is the basis of connecting the Earth-based perspective to the space-based perspective. However, this concept is abstract in that humans have created the construct of sun-angle to better represent Sun's location with respect to an observer on the Earth. We don't actually see the sun-angle with our naked eyes. Therefore, creating representations of this concept with hand-gestures was key in introducing this concept to students.

Figure 7 and Figure 8 show how the teacher used gesturing as a spatial sensemaking practice to support verbal explanation. As one can see in Figure 7, the teacher started showing the zero-degree angle by eliciting student idea of the horizon first. She made an iconic gesture of

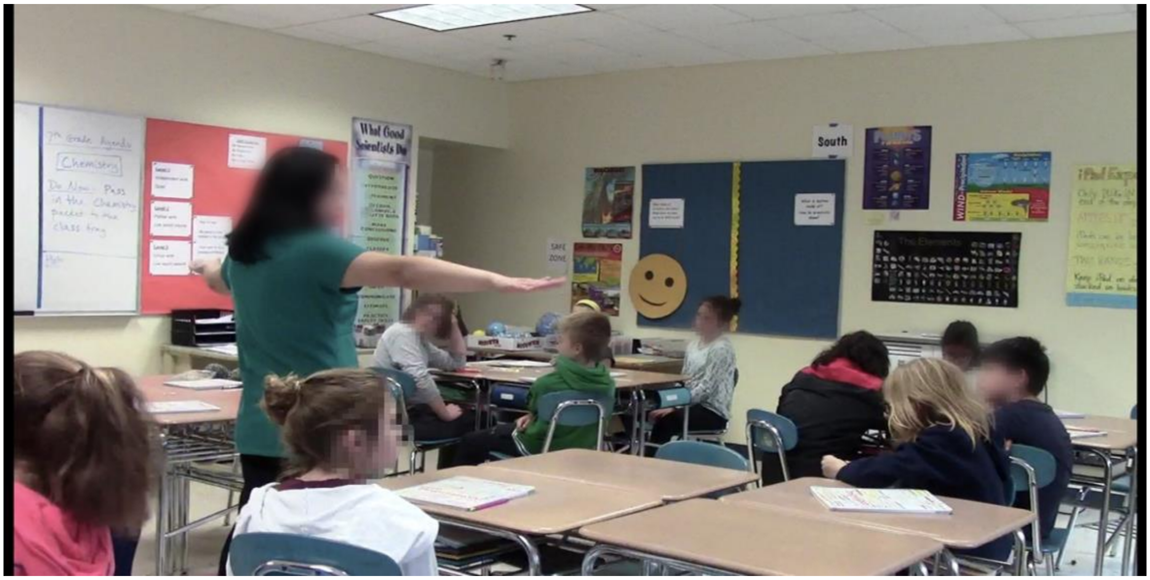


Figure 7 The teacher showing iconic gesture showing horizon

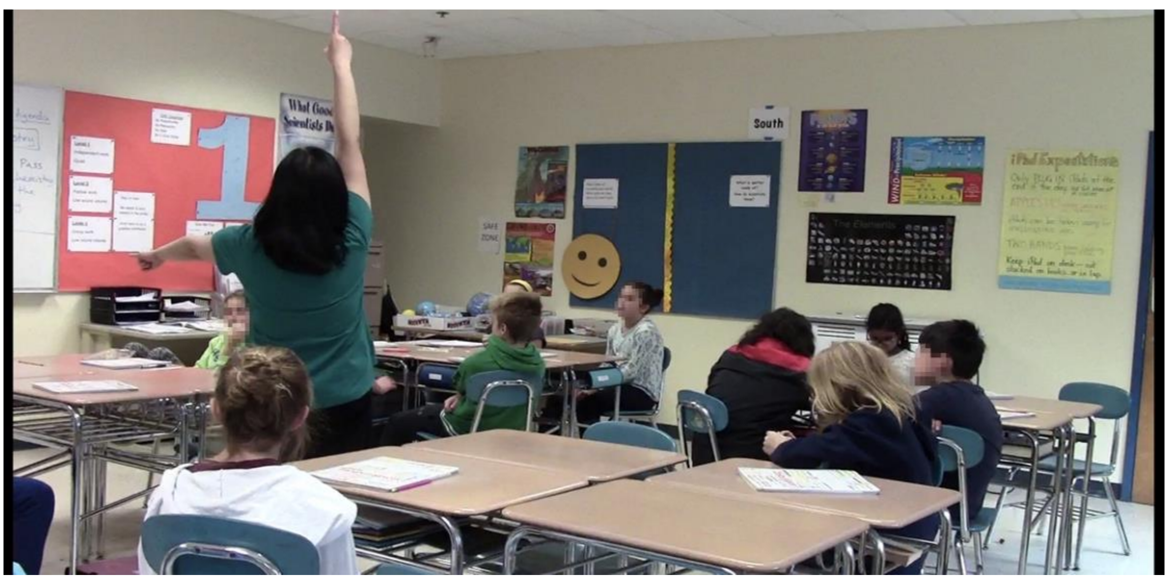


Figure 8 The teacher using iconic gesture to show 90-degree sky-angle

spreading her arms for drawing an imaginary horizontal circle in the space around her and explained, “The horizon is the imaginary line between the sky and the ground. We’re going to call that the zero-point of our scale *[shows a dynamic iconic gesture]*.” Next, the teacher built on this knowledge to ask students how they will describe a location of something that is high up in the sky. She asked, “That’s zero *[points horizontally to a wall with one arm]* and that’s straight above *[points the other arm straight overhead]*; are my arms making something?” (Figure 8).

This example shows that both pointing and iconic gestures were used by the teacher to communicate spatial parameters such as the sun-angle to support students’ Earth-based perspective and conveying meaning in a visuospatial format. In this example, the teacher heavily relied on pointing and iconic gestures for using the space around herself to convey spatial parameters such as the sun-angle. She was also able to show the concept of sun-angle by the movement of her arm to draw an arc-like shape using a dynamic gesture. The use of classroom space in combination with gestures was not only useful but also indispensable in conveying information that may have been ambiguous with only verbal description.

Example 2: Students’ use of gestures for visualizing spatial locations

The next example shows the manifestation of the principle of embodied cognition that off-line cognition is body-based. The word ‘offline’ refers to the entities that are removed from the learning contexts. When predicting the Sun’s path and its apparent motion during the day, the teacher asked students where the Sun will be in the morning, at midday, and at Sunset. In this question, the Sun’s motion was invisible or absent from the immediate learning environment and therefore “offline”. Some students used only pointing gestures to show its location during different times of the day, some students showed with an iconic gesture the Sun’s path from east to west going overhead. Figure 9 shows a student pointing overhead and communicating her visualization of the Sun’s position at midday using pointing gesture. The student used gesturing as a way to externalize her mental simulation of the Sun’s motion.

Figure 9 Student using pointing gesture to show Sun's position

Figure 9 reveals a students’ Earth-based perspective of the Sun at noon on a day in winter. Similarly, other students showed the path by using both spatial position descriptors such as the cardinal directions as well as the shape of the Sun’s path using a dynamic iconic gesture.

Example 3: Students’ use of gestures as tools for problem solving

The following conversation shows an example of how gestures can become a learner’s mental “toolbox” to solve problems (DeSutter & Stieff, 2017). The example shows how a student made use of an iconic gesture as a strategic “tool” to solve a spatial problem by externalizing their mental visualization.

1 Teacher: *[pointing to a sketch on the whiteboard that represented a waning crescent]* Which side of the Moon is actually possible to see? So, half of the Moon is facing Earth and half of the Moon is facing away from Earth. So, how am I going to figure out which side of the Moon is possible to see from Earth?

Figure 10 Student using iconic gesture as a tool

2 Student: I took my hand from the Earth *[shows her right hand dividing the Earth to show day-time and night-time],* from inside the Earth, and then…made a line with it *[moves her hand from the Earth to the Moon]* and then I drew a line there (Figure 10).

3 Teacher: Beautiful! I love that! What she said is that she took her hand from the Earth *[holds a meter scale and shows the same action as the student's iconic gesture]* and kind of dragged it over to the Moon and that makes a line across your Moon that makes to divide it into the side facing the Earth and the side facing away from the Earth.

In this example, the practice of iconic gesturing enabled the student to visualize the side of the Moon facing the Earth and the other side facing away from the Earth. This is an essential step in connecting the Earth-based perspective and space-based perspective. Her gesture also shows her understanding of the spatial orientation of the Moon in relation to the Earth. Thus, this example showcases a student's use of hand-gestures in supporting her own PT skill. This sensemaking episode also shows the manifestation of the embodied cognition principle that offline cognition is body-based – learner, in this case, externalized her mental visualization using bodily actions. Overall, gestures played an important role during instruction in making sense of spatial information and communicating spatial locations.

According to embodied cognition, the use of gestures is a function of our body to externalize abstract concepts (McNeill, 1992). Gestures are manifestations of the principle of embodied cognition that offline cognition is body-based (Wilson, 2002). The teacher's use of gestures was important in conveying the Earth-based view as there are limited ways of showing a sun-angle without using digital tools. Sun-angle is a complex concept that is often used in measuring positions of celestial objects. Understanding of this concept is useful in developing sophisticated knowledge about observational astronomy. The teacher's use of arm-gestures may have helped in concretizing this abstract and otherwise imaginary construct for students to be able to use it for their descriptions without confusion. Therefore, use of gestures as a spatial sensemaking practice was also crucial for the teacher in communicating ideas to students effectively as it enabled her to externalize as well as communicate her own thinking.

Example 2 and 3 showed students' use of gesturing as a sensemaking practice. In example 2, pointing gestures played a dual role of visualizing the sun-angle and communicating spatial relationships. Pointing gestures may also be crucial in communicating the Earth-based view as a majority of students seem to be using their pointing gestures to show the motion of the Sun in the sky. Example 3 illustrated the student's way of using her gesture as a tool to externalize spatial orientation of the celestial objects and using that imagery to solve spatial problems. Overall, gesturing seemed to be a versatile spatial sensemaking practice that played an important role when communicating Earth-and-space-based perspectives, visualizing multiple perspectives, and engaging in making sense of the spatial relationships between Earth, Sun, and Moon.

Role of body movement in spatial sensemaking

Both the teacher and the student used body movement to physically move from place to place to represent spatial information such as the scale, changing relationships between two objects, and changing perspectives. This practice is differentiated from gesturing because in this case, the person involved in communicating spatial information uses their body as a proxy for an object or a motion that they want to simulate. Therefore, the practice of using body movement is defined as using one's body as a whole to make sense of spatial information for solving problems.

Example 4: Use of body movement to embody the motion of a celestial body

The following example shows the students' use of the body movement to simulate the motion of the Earth as it moves around the Sun. On day 6, students were visualizing Earth and space-based perspectives and connecting them to make sense of how the alignment of the Earth's tilt with respect to the Sun's position changes the seasons. To emphasize this relationship and making it explicit for students, the teacher asked a volunteer student to simulate the motion of the Earth's revolution around the Sun (Figure 11). This supported students' visualization of the Earth's position and orientation of its axis as seen from the space-based perspective and how that leads to seasonal changes on the Earth. In Figure 11, you can notice that the student moved around within the classroom space. The physical movement may have supported students' mental imagery of the Earth's orientation in a visuospatial format.

Figure 11 Student representing Earth's position in winter and summer in northern hemisphere

This activity seems to be of special significance as enacting out the rotational and revolving motion of the Earth might clarify confusions for the students who mistake the reasoning for seasons for the daily rotational motion of the Earth. It also helped in reinforcing the idea that the tilt is important as the student kept the tilt fixed while the teacher guided their thinking about sticky-Vicky's perspective.

Example 5: Use of body movement for reducing cognitive load

The following example shows use of the body movement being used by a student as a strategy to simplify perspective taking and to solve a spatial problem. On day 4, students were presented with a problem that required them to exercise their PT skill and solve the problem independently. The WWT program showed a hypothetical scenario – An *Orange Alien* is on the other side of the solar system looking at the Earth and the Sun from his space-based perspective. Students were asked to guess which way the Earth is tilted for the Orange Alien and how the Earth is seen illuminated from the alien's perspective. This required students to use their PT skill as they imagine the Earth's tilt from the Orange Alien's perspective.

To solve this question, a student stood up from his seat and extended his arm aligning with the direction of the tilted axis of the Earth as shown on the screen Figure 12. Then keeping his arm aligned in the same direction as the Earth's axis, he turned his entire body to imagine the Orange Alien's perspective (Figure 12). The rest of the class was sitting while he explained his answer by showing his method. "So, I imagined Polaris *[points to an imaginary spot on the wall]*. Polaris is fixed…I thought. And then…I did that *[turns around facing away from the screen to mimic the Orange Alien's perspective]* … and it's (the tilted axis) still that way *[points to the imaginary north pole]*."

This example shows a strategy that the student used to reduce his cognitive load by using his own body to visualize a frame of reference other than his own. Orienting himself to match the perspective of the Orange Alien might have reduced the cognitive load of having to visualize the position of the North star with respect to the Orange Alien. After which, he only had to use his

PT skill to visualize what Orange Alien would be seeing if he looked at the Earth. Thus, the student effectively used body movement as a practice to simplify the problem.

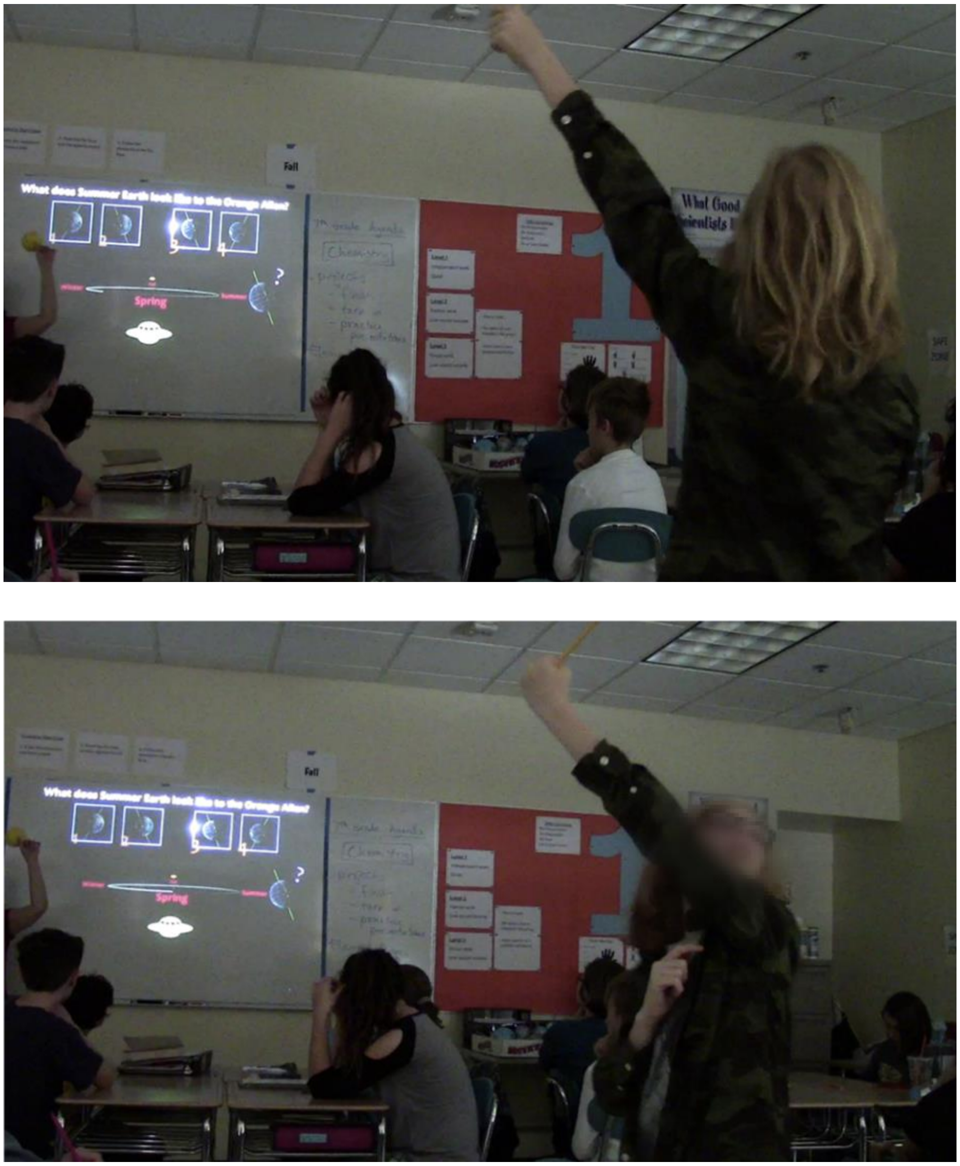


Figure 12 Student simulating a different vantage point using body movement

Examples 4 and 5 show that the practice of using body movement was used for two different purposes – first, moving one's body to recreate or to simulate motion of a celestial body that was not present in the learning environment and second, for ease of mental visualization of a different perspective. Both motions are related to communicating or interpreting spatial configurations by running simulations of events/phenomenon using one's own body. Hence, this was categorized as one of the spatial sensemaking practices.

Embodied cognition suggests that offline cognition is body-based. Offline refers to the ability to use mental representations of the world that are removed from the situational context. These abilities might include planning, recall, or mental simulations. In example 4, the student represented the orbital motion of the Earth around the Sun by simulating it with his own body. The action of representing the orbital motion and actually seeing the Earth-based perspective from different vantage points might have reduced the cognitive load of having to recall a space-based perspective. Moreover, enacting out the revolving motion of the Earth served a dual function – it clarified the Earth's dynamic motion of rotating and revolving at the same time and it helped in making conclusions about the role of Earth's tilt in changing seasons. Therefore, using one's body in simulating Earth's motion created a powerful experience for students to learn about the seasons without room for errors.

In example 5, the student used his body to simulate the perspective of the Orange Alien, who has the opposite vantage point from that of the student. By standing up and turning around to match the Orange Alien's perspective, the student used body movement as a practice to simplify the task of perspective-taking. Thus, the practice of body movement or changing spatial position may be an important spatial sensemaking practice for engaging in perspective taking skill.

Role of object manipulation in spatial sensemaking

The spatial sensemaking practice of object manipulation was also used commonly as the ThinkSpace curriculum provided a variety of physical and virtual resources for students to make sense of the phenomena of seasons and lunar phases. Object manipulation was defined as using objects by physically touching/manipulating them for externalizing spatial representations. I identified two practices related to object manipulation – explanatory and epistemic.

Explanatory object manipulation was defined as the practice of using an object for explaining a phenomenon or a process to others. This practice was used both by the teacher and the students for communicating spatial information for explanatory purposes. However, explanatory object manipulation was more commonly used by the teacher for explaining, for modeling a concept, or for asking students questions related to perspective taking. Explanatory object manipulation also included instances when the teacher used the virtual models from WWT to support students' perspective taking.

On the other hand, epistemic object manipulation was defined as the practice of using physical or virtual objects for externalizing mental processes to reduce the cognitive load (Kirsch & Maglio, 1994). The primary purpose of epistemic object manipulation is to supporting cognitive processing for problem-solving. This practice might include actions such as rotating an object or viewing it from a different angle for ease of mental calculations. This practice was used by both the teacher and the students to support their own engagement in perspective taking.

Example 6: Explanatory object manipulation by the teacher

This example shows how the teacher used explanatory object manipulation to aid students' application of PT skill. On day 1, the teacher used a model of the Earth with a small Lego® person (shown with the arrow) – *sticky Vicky*— sitting on a location in northern hemisphere (Figure 13). The teacher used this model to elicit students' PT skill by using *sticky Vicky* as the observer on the Earth. Instead of using verbal cues, she used this model to guide students to make a connection between what *sticky Vicky* would see from northern hemisphere according to her physical location as seen from a space-based perspective. The teacher used the physical models for eliciting students' PT skill by making them visualize Vicky's perspective.

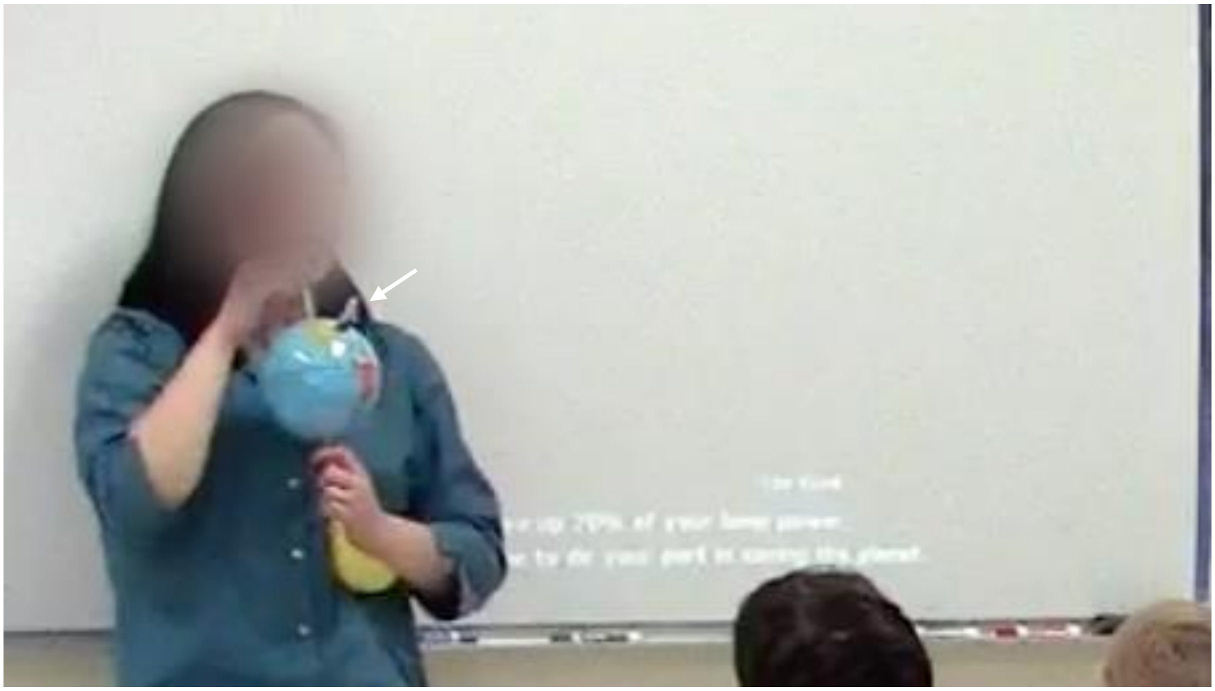


Figure 13 The teacher using model of Earth with a Lego®-person to show Earth-based perspective

The use of physical model made it easier for students to visualize her line-of-sight as an observer on the Earth.

1 Teacher: So, there's the Sun *[uses a pointing gesture to the lamp in the middle of the classroom and faces Vicky toward the Sun]* So, what time of the day is it for Vicky right now?

2 Student: Right now, about midday since the Sun is in the middle of the sky for her.

3 Teacher: Exactly! So, we are going to call this midday *[makes an iconic gesture with her palm to show the half of the Earth facing the Sun]*. We are not going to worry whether it's noon or 1 o'clock, or when it's daylight saving; we're just going to call it midday. And

then… when she is facing the opposite way *[rotates the Earth model such that Vicky is facing away from the Sun]*, which time of the day is that?

4 Student: Midnight.

5 Teacher: *[Makes an iconic gesture to show the daytime side of the Earth]* So, this whole side of the Earth is daytime, *[makes an iconic gesture to show the nighttime side of the Earth]* and this is nighttime, we're turning just like this, *[turns the Earth model counterclockwise so that Vicky is facing sideways with respect to the Sun*], so she's kinda on the line between day and night *[makes an iconic gesture to show the demarcation line between day-time side and night-time side]*, what time is this?

6 Student: If it's daylight saving time, it will be 7.

7 Teacher: Evening or morning?

8 Student: AM

9 Teacher: Right, so we are going to call this sunrise.

In this PT sensemaking episode above, lines 1, 3, 5 show that most of the spatial relationships between the Earth- and space-based perspectives were communicated entirely based on models and using gestures in combination with models. The practice of explanatory object manipulation externalized the process of navigation of the two perspectives, which might have been challenging with use of only verbal descriptors. The use of models for explaining different positions of the observer on the Earth may have been useful for students in visualizing view from Earth.

Embodied cognition framework suggests that we offload cognition onto the environment to help us in problem-solving. Offloading refers to the process of simplification so that our brain does not have to hold all the information in memory (Wilson, 2002). Therefore, we often use strategies that occupy minimum memory such as jotting numbers on a paper while calculating simple arithmetic functions such as divisions or additions. In example 6, rather than attempting to manipulate information mentally, the teacher *stored* the spatial information onto the physical models of the Earth, Sun and the Lego® model, which automatically made the process of perspective-taking easier for students. Using a physical model of the Lego®-person might have made it easier for the teacher to explain an Earth-based perspective and for students to visualize it without having to store all of that spatial information in their memory. The practice of explanatory object manipulation was especially useful in the classroom, where the teacher and the student were viewing the system of Earth and Sun from their own unique point-of-views.

Explanatory object manipulation was also observed using virtual objects from WWT. On day 2 and 3 of the instruction, students were asked to predict the path of the Sun in different seasons. Students first predicted the direction of the path on the Sun-tracker, the maximum Sun angle on solstices and equinoxes, and then viewed a virtual model to test their predictions. Following is an example of how WWT virtual model supported students in visualizing the motion of the Sun in the sky during different seasons.

Example 7: Use of explanatory object manipulation using WWT virtual models

On Day 3, students were asked to predict the Sun’s path in winter and draw it on their plastic Sun-trackers using markers. After students drew a path of the Sun based on their initial prediction, the teacher played a short simulation showing the path of the Sun in the winter sky as viewed from an Earth-based perspective from their actual location. This virtual simulation served as a virtual model that could be manipulated by changing the date and time. Figure 14 shows a snapshot of the screen with the virtual model of the sky and the Sun’s position. The following transcript shows the teacher's use of the explanatory object manipulation and students' interactions within the sensemaking episode.

Teacher: So, I want you to pay attention to which direction the Sun is moving in and how high it gets when it's in the middle of the day. I'm going to stop at mid-day.

[*Starts the animation showing the path of the Sun in winter as seen from northern hemisphere. Students watch the Sun move from East towards south*]

Teacher: [*Pauses the animation*] Ok, so this is the middle of the day.

Student 1: [*Surprised to see the Sun reach its highest point that isn't overhead*] What?!

Student 2: But it's not in the…

Student 3: But in summer, it almost seems like it's…like…directly above you.

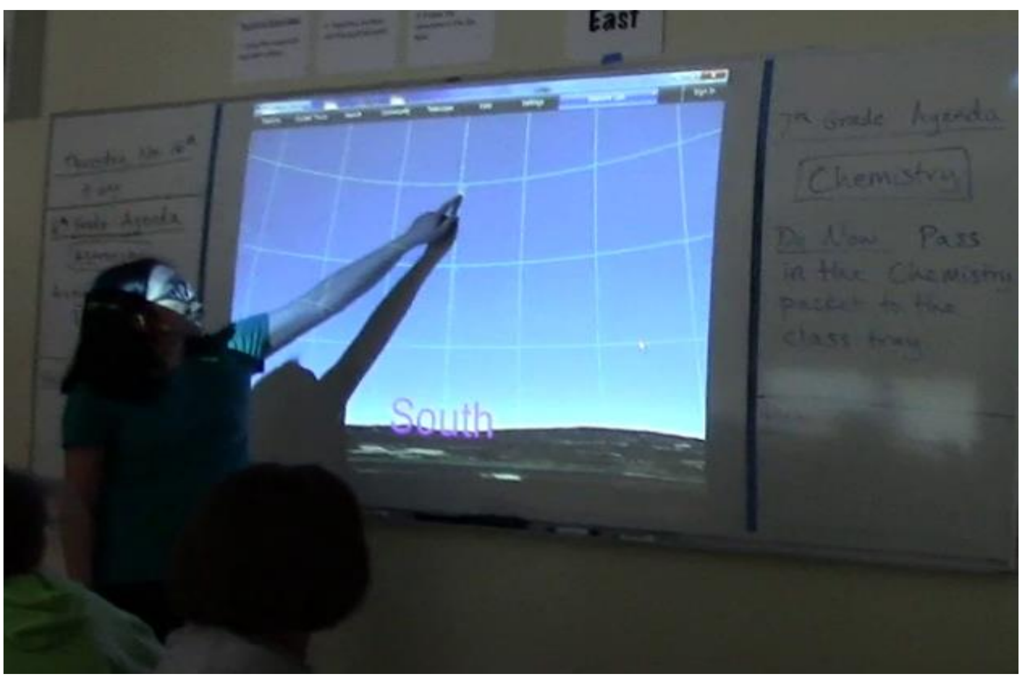


Figure 14 Teacher showing the virtual model of the Sun in local sky

Teacher: [*uses her hand to point out the Sun* (Figure 14)] Ok, so we are looking at south. And we are [*starts counting the Sun angle using pointing gestures*] 10…20…almost 30 degrees above the horizon. So, I want you to take your green marker and put a dot just below the 30 degrees on the south.

[*Students start drawing their path on the Sun-tracker, the teacher is goes around checking on them*]

Teacher: Is it surprising?

Student 4: Yes, it's really surprising.

After this episode, students connected the point of sunrise, mid-day Sun angle (30 degrees) and the point of Sunset after watching the virtual animation. They also mentioned how they were surprised to see the difference in the predicted vs. actual path of the Sun in winter sky.

The object being used for explanation in this example is the virtual model of the Sun moving in the sky, which was manipulated by the teacher to show the path of the Sun and simultaneously engaging students in visualizing Earth-based perspective. The use of virtual model of the local sky provided a way for students to observe different paths of the Sun in different seasons followed by insightful wonderings. This experience might have supported students in building their own models of the Sun-Earth system. The practice of explanatory object manipulation resulted in a sensemaking episode that gave rise to the inquiry about the contradiction between predicted vs. actual paths of the Sun. This practice also appeared to have grounded students' sense of Earth-based perspective as they transferred their visualization from the virtual model onto a concrete physical model of the Sun-tracker.

Example 8: Use of epistemic object manipulation by students

This next example illustrates the use of epistemic object manipulation guided by the teacher. Epistemic refers to making a physical change in the environment to reduce cognitive load (Kirsh & Maglio, 1994). In this example, students made changes in their environment by physically moving the objects to ease their mental visualization for solving a spatial question.

On day 1, students were asked to figure out whether the Earth's rotation is clockwise or counterclockwise. The teacher gave them a model of Earth to support their sensemaking and the following conversation ensued between a pair of students.

1 Student 1: *[picks up the Earth model]* It's a six-hour time difference *[moves index finger between two different locations on the Earth]*.

2 Student 2: Ahead of us?

3 Student 1: The Sun hits *them* first *[points at Europe]* and then hits us.

4 Student 2: *[Rotates the Earth counter-clockwise with one hand and holds her index finger above the Earth at an angle* (Figure 15)*]* Sun is *here.* Sun is *here*.

5 Student 1: Oh, so it's counter-clockwise *[students rotate the Earth slowly on its axis counterclockwise looking at it laterally]*. Wait, is that clockwise?

6 Student 2: *[Changes orientation of the model to face the north pole head-on while rotating the Earth* (Figure 16)*]* No, it's counterclockwise *[Both agree]*.

In this example, lines 3, 4, and 6 show that the students moved the model of the Earth to manipulate it physically in different orientations to support their spatial visualization of the location on the Earth that would see the Sun first. Line 5 shows that the students were looking at Earth from a lateral-view and showed confusion about determining the direction of rotation. Line 6 shows that the students flipped the model on its head to look at the north pole from directly overhead and then confirmed that the direction of rotation will be counter-clockwise (Figure 16).

Figure 15 Students viewing Earth sideways

Figure 16 Students viewing Earth head-on

This PT sensemaking episode is an example of epistemic object manipulation. In this example, the two students moved the orientation of the model-Earth to help them visualize whether the Earth moves clockwise or counterclockwise. This episode shows students' engagement in applying their PT skill as they are visualizing the part of the Earth the Sun hits first and then determining the rotational direction of the Earth. According to embodied cognition, the students may have used their physical materials to simplify the process of mental visualization (Wilson, 2002). Instead of mentally visualizing which countries on the Earth see the Sun first, they used epistemic model manipulation as they physically manipulated the model-Earth to figure out the rotational direction based on their space-based perspective. This whole episode shows students' use of PT skill as they were engaged in using Earth model to make a connection between the Earth-based perspective and a space-based perspective.

Another example of epistemic object manipulation was seen when using virtual models of the Earth on WWT. On day 7, students were asked to solve a worksheet that required them to apply their PT skill to solve questions and make spatial drawings related to seasons. For instance, students were asked to predict the amount of daytime vs. nighttime in different hemispheres. When asked to predict daytime on September 21st, a pair of students first predicted their answer that is equal hours of day and night, and then dragged the virtual model of the Earth to see it head-on to confirm its orientation with respect to the Sun and verify their prediction (Figure 17). This strategy was almost similar to the one used in example above as the students manipulated the virtual model to confirm their predictions.

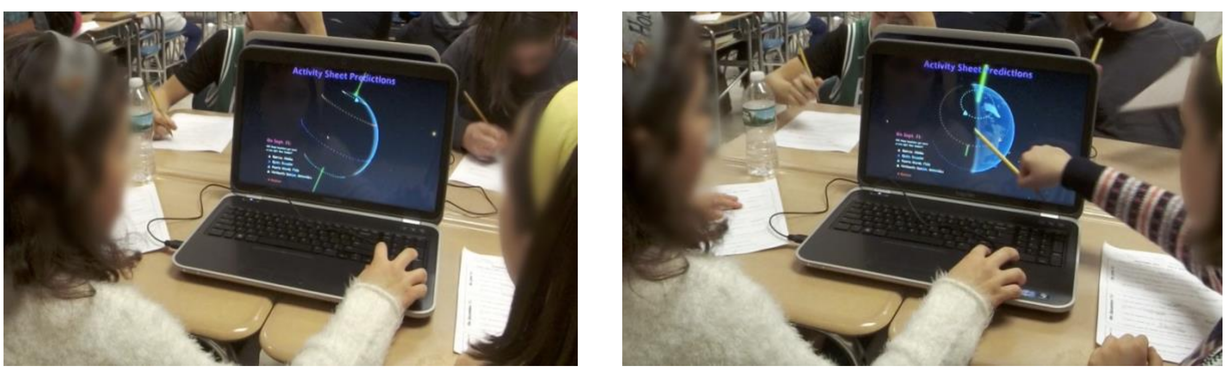


Figure 17 Student using epistemic virtual modeling to test their predictions

Overall, object manipulation was used during instruction as students made physical changes in their learning environment to support their perspective taking.

Role of fixed artifacts for referencing

The practice of using fixed objects for referencing is distinguished from the practice of using object manipulation in that physical materials were not physically manipulated but only used as reference points. The purpose of using fixed objects as references was often used by students to anchor their spatial orientation with respect to a fixed object. This practice was especially useful for perspective taking as the teacher or students organized spatial parameters such as the orientation, direction, or location with respect to particular objects to create a common spatial co-ordinate system when working in groups or as a whole class. This practice was especially useful when students used artifacts from the virtual animation to ground their sense of space.

Example 9: Use of a wall-clock as north star

The following example shows students' use of fixed objects from their classroom to anchor their sense of a reference frame and supporting their space-based perspective taking. On day 5, students were split into groups of four and were given an Earth model with a dowel stuck in it representing the rotational axis. Each group of students was asked to pass the Earth model around in a circle mimicking the revolution of the Earth around the Sun while also focusing on the rotational motion of the Earth. They were asked to keep the axis of rotation pointing towards the north direction. As the groups moved the model-Earth around the Sun, they compared the orientation of the axis and discussed how that will affect seasons.

One of the groups, when performing the activity, struggled to keep the axis tilted in the same direction when passing the Earth around. When one student was getting the tilt of the axis wrong, another student from her group said, "Just say that the clock is our north star" (Figure

18). Another student interjected, “No, that is the north *[points to a wall that has been labeled as ‘north’].”*

Figure 18 Student pointing at a clock for referencing the north star (north direction)

In this example, students used a fixed artifact (a wall-clock or a wall) to fix their north direction. This enabled them to interpret and communicate spatial parameters such as location and relative positions of objects from a common reference point even if they were viewing the same system from different vantage points. The practice of using fixed objects for referencing differs from gesturing as the use of an artifact such as a clock as a proxy for north star may have created an immersive experience for the students to recreate a coordinate system with a common reference point. This is a crucial step in processing spatial information, especially when being engaged in perspective taking, because description of a location from one point-of-view can be different from another. In the example above, students would have had a different sense of direction without a common anchoring point in their reference frame as they were facing in different directions. Hence, using fixed artifacts for referencing was a useful spatial sensemaking practice for effective communication.

The practice of using fixed objects for referencing can be interpreted as a manifestation of the principle that we offload cognition onto the environment (Wilson, 2002). In this case, the students used an object from their environment in the service of communicating spatial information without having to remember or getting confused about the north direction. Once fixed as a concrete object, the system, as a whole, might have been simplified as the students no longer had to remember north direction that determined the tilt of the Earth thereby reducing their cognitive load.

Role of sketching in spatial sensemaking

Sketching was another practice used by both students and the teacher to interact with spatial information and to communicate it with others. Two types of sketching practices were found in the data– explanatory and epistemic. The practice of explanatory sketching was defined as drawing to convey or represent spatial information (adapted from Ramey & Uttal, 2017). Epistemic sketching was defined as the practice of drawing for ease of mental processes or for externalizing thought processes when solving a problem by sketching. The practice of explanatory sketching was used by the teacher more often than the students to explicate her own visualizations.

Example 10: Teacher using explanatory sketching for representing space-based perspective

This example shows how the teacher used the sensemaking practice of explanatory sketching to externalize her representation of a space-based perspective. On day 10, the whole class was collectively making sense of how the Moon is illuminated by the Sun from a space-based perspective and what an observer on Earth would see depending on the Moon’s position in its orbit. To make sure that students understood how the Moon is lit up considering its position with respect to the Sun, the teacher drew a diagram showing the Moon being illuminated half-way by the Sun. In her sketching she showed how the Moon is illuminated by shading the dark side.

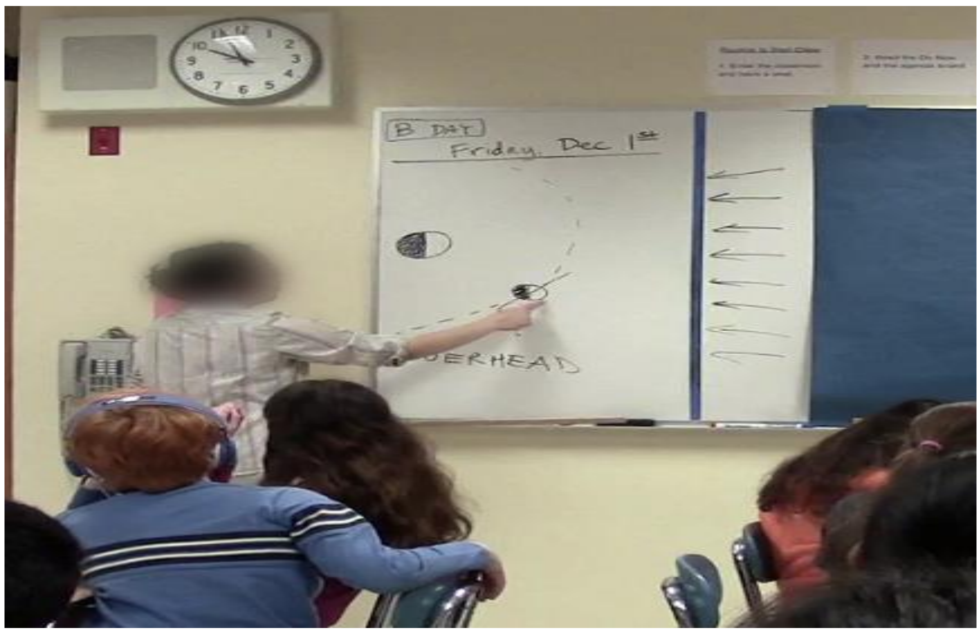


Figure 19 The teacher showing space-based perspective by sketching

As seen in Figure 19, the teacher has captured rich spatial information in her simple drawing. She showed the Moon’s orbit using a dotted line and the Moon in waning crescent position. Additionally, she shaded half of the Moon to distinguish the dark side of the Moon from the light side illustrating how the Moon is always half-lit by the Sun. She then drew another longer line cutting the Moon across showing the part of the lit-up side of the Moon visible from the Earth. This drawing created a space-based view of the Sun-Moon-Earth system and supported students’ visualization of its connection to the Earth-based view.

Example 11: Teacher-led epistemic sketching

The following example showcases use of epistemic sketching – sketching used to reduce cognitive load by leaving spatial details out there in the learning environment to process afterwards. On day 2 of the instruction, students were engaged by the teacher in predicting the apparent motion of the Sun across the sky as seen from their location on the northern hemisphere. The goal of this task was to teach the concept that the Sun's path is shorter or longer depending on the season. To achieve this, students were given an object called the Sun-tracker - a clear plastic half-dome that is useful in visualizing an observer's sky (Figure 20).

As seen in the Figure 20, the half-dome Sun tracker acts as a physical model of the sky as viewed by an observer on the Earth. The numbers on the Sun-tracker indicate the sun-angles (0-90 degrees) and the alphabets on either side of the dome denote the cardinal directions. The teacher used this Sun-tracker to support students' representation of an Earth-based perspective. The teacher gave the students prompts to draw each path in a different color so that they can compare them easily. In this particular sensemaking episode, students were engaged in connecting an Earth-based perspective to a space-based perspective as they were transferring their Earth-based observations on a half-dome sphere as if the sphere was their sky (Figure 20).

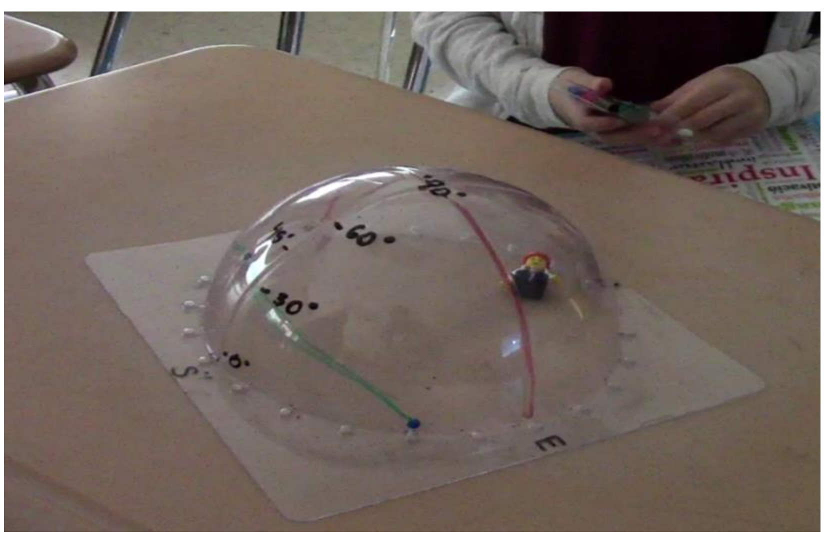


Figure 20 Sun-tracker with the predicted and observed paths

The practice of sketching was coded as epistemic sketching because the students were using sketching as a way to make physical changes in their learning environment to help reduce cognitive load. I infer that the action of sketching on the Sun-tracker and leaving that artifact in the learning environment instead of visualizing might have reduced cognitive load as it simplifies the process of comparison. By sketching on the tracker, students did not have to remember the Sun's paths in different seasons. Sketching on the Sun-trackers supported comparing the Sun's paths in different seasons by readily making representations available for analysis.

Overall, the reason sketching was categorized into explanatory and epistemic practice was because they both served different cognitive functions. Explanatory sketching used by the teacher was used for communicating spatial information efficiently, while epistemic sketching was used to support problem solving. Both these spatial sensemaking practices supported students' PT skill as it engaged them to visualizing either space- or Earth-based perspective to make connections between the two.

Conclusion: Role of all the sensemaking practices

The spatial sensemaking practices presented above were identified by using interactions analysis of the videos collected during the 10 days of instruction. These practices were fundamental to understanding PT sensemaking episodes as each one of the episodes was comprised of a combination of these sensemaking practices. Spatial sensemaking practices were used by students and the teacher to engage in either space-based perspective or an Earth-based perspective or both together. By themselves, each practice in isolation was not associated with connecting multiple perspective, but a combination of these practices was used by the students and the teacher to make connections between perspectives. The teacher used these sensemaking practices herself for honing students' PT skill by consistently engaging them in challenging PT-related tasks. In summary, spatial sensemaking practices provided ways for students to externalize their spatial thinking, communicating their ideas. concretizing their learning using multimodal approaches, and developing their PT skill. In the following section, I present findings about how different components of the ThinkSpace curriculum gave rise to a pattern of spatial sensemaking practices or the mediating processes.

Findings from instruction data analysis

I started the interaction analysis from a broad theoretical conjecture that *ThinkSpace curriculum engages students' PT skill through spatial sensemaking practices such as use of gestures, tools and materials from the learning environment, along with social interactions between peers and instructor.* However, the analysis showed that some parts of the ThinkSpace curriculum were more useful in supporting students' use of PT skill than others. The main goal of the instruction analysis was to uncover the spatial sensemaking practices and to identify the most salient features of the ThinkSpace curriculum that created opportunities for students to use those practices. In the following section, I present claims about the most salient features of the ThinkSpace curriculum that were helpful in engaging students in perspective taking skill. These claims will be used to revise the initial conjecture map.

Finding 1: Physical and virtual models appeared to have supported students' PT skill by giving rise a variety of spatial sensemaking practices. Students made a large number of connections between Earth- and space-based perspectives while using physical or virtual models.

Making a connection between an Earth-based perspective and a space-based perspective is an important step in understanding seasons and lunar phases. In my analysis, I found that students made a large number of successful connections when they were using either physical or virtual models. This might mean that students' use of physical and virtual models may have supported their perspective-taking skill as materials from their environment are useful offloading cognitive load (Wilson, 2002).

The reason for students making a large number of multiple-perspective connections may be attributed to the fact that use of models afforded a large variety of spatial sensemaking practices. Use of physical materials such as the models of the Earth, Sun, and the Moon, Lego®-figures, and Sun-trackers gave rise to practices such as iconic and pointing gesturing, use of epistemic and explanatory object manipulation, and use of fixed objects for referencing. Students used physical models to externalize their spatial thinking by using them for communicating spatial parameters such as locations, orientation, shape, size as well as the relationship between different celestial bodies. Virtual interactive models from WWT acted as tools for navigating different frames of references and gave rise to practices such as pointing gestures, epistemic object manipulation and use of body movement.

Both the teacher and students used physical and virtual models from the classroom to off-load their cognitive processes on to the models instead of using only verbal descriptions. The teacher changed the orientation or location of physical models for communicating her perspective-related questions instead of verbalizing the information about the spatial parameters. Use of virtual models enabled both the teacher and students to be visualize Sun's motion from an Earth-based perspective. Virtual models seemed to ground students' Earth-based perspective that may have supported them to navigate to a space-based perspective. This may also suggest that using physical and virtual models for teaching seasons and lunar phases facilitated students' use of PT skill. Further analysis suggested that students successfully made connections between multiple perspectives, especially when the teacher used perspective-related questioning with the help of models. The following example shows affordances of a material-based activity in giving rise to other spatial sensemaking practices.

On day 5, students started making connections between the orientation of the Earth's tilted axis (space-based perspective) and what an observer on Earth might see based on the tilt being away or towards the Sun (Earth-based perspective). To achieve this, the teacher gave groups of students a model of the Earth with a dowel representing the axis, a Lego®-person named *Sticky-Vicky*, a model of the Sun, and a sheet of paper with seasons written on it (Figure 21). Then the teacher went from group to group asking them perspective-related questions – questions to activate students' PT skill by making connections between the Earth- and space-based perspectives. The following dialogue shows the teacher's interaction with a group of students.

Figure 21 The teacher using object manipulation and PT questioning

1 Teacher (goes to one group of students): Show me daytime.

2 [*One student moves the sticky-Vicky to lean towards the Sun* (Figure 21).*]*

3 Teacher: Now let's think about Vicky or where Vicky has to look to see the Sun right now *[points to Vicky]*

4 (Students observe the orientation of the models of the Earth and the Sun)

5 Teacher: So, looking straight ahead, your Lego® person is seeing the desk, right? *[puts her finger on the desk in front of Vicky's line-of-sight]* So, where would they have to…

6 Student: He has to tilt his head upwards.

7 Teacher: Yeah! *[Bends backwards and shows her head tilting up to look further up to mimic Vicky's movement]* So, is that looking high in the sky or looking low in the sky?

8 Student: High in the sky?

9 Teacher: *[moves the Lego®-person's head showing tilting upwards]* Yes. So, down is further low. Ok, so now pass the ball (Earth) for winter and show us daytime and nighttime (for Vicky). [*Students repeat the same exercise of observing Vicky's line-of-sight and determining that the Sun will be lower in her sky for winter]*.

In this entire episode, students as well as the teacher used the practice of epistemic object manipulation by moving Vicky's position and the Earth with respect to the Sun and creating different spatial configurations to figure out what Vicky would see from the Earth. Thus, physical materials played an important role in eliciting epistemic actions. Lines 1, 3, 5, 7, and 9 show the teacher's use of perspective-questioning to guide students' thinking to connect the two perspectives based on the position of the models and Vicky's orientation. To communicate spatial relationships between the Lego®-person's position and her Earth-based perspective, the teacher used gestures (line 5) to focus students' attention; while the teacher also used her own body to simulate Vicky's perspective from the Earth. This example shows how students and the teacher used a variety of spatial sensemaking practices when they were using physical materials.

A similar pattern was observed during their use of virtual models from WWT. Students were seen using pointing and iconic gesturing and body movement when they were engaged in using virtual models.

Finding 2: Sketching seemed to be an effective way of communicating space-based perspective.

In my analysis, I found that sketching provided a way to represent and process spatial information to apply perspective-taking skill. I found that both students and the teacher often used sketching for communicating or visualizing a space-based perspective that is to represent the view of an object from space. However, explanatory sketching was often used by the teacher as she explained the seasons and lunar phases by creating drawings of the relevant spatial configurations.

For instance, the teacher used a sketch to show how the Earth's tilted axis affects the sun-angle in summer vs. in winter. She drew a stick-figure person standing on the Earth and showed the students how the Sun's rays hit the Earth at his location that makes an angle with respect to the Earth's surface (Figure 22).

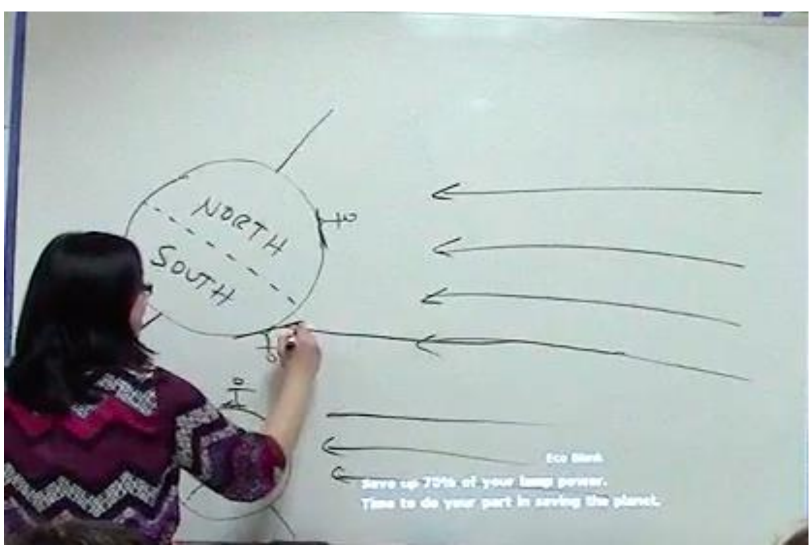


Figure 22 Teacher using sketching to show space-based perspective

In another example, a student created a representation of his own space-based perspective by drawing the Earth in different orientation when asked to explain how the orientation of the axis affects the sun-angle (Figure 23). In his rough drawing, he showed the tilt of the axis in summer and winter as he verbally described to other what he was drawing. However, his drawing alone did not show representation of an Earth-based perspective.

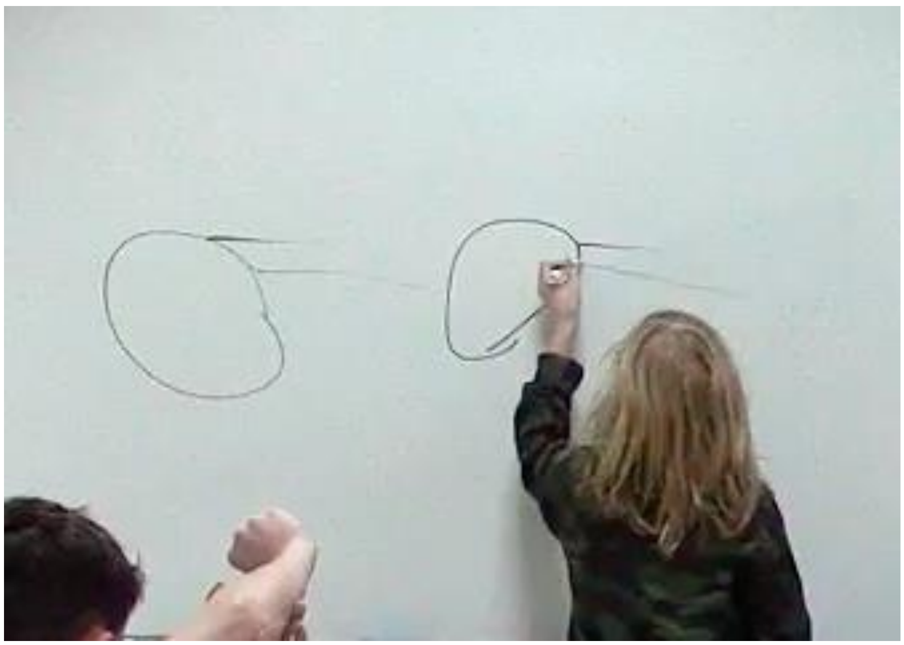


Figure 23 A student showing his space-based perspective through sketching

For making connections between the Earth- and the space-based perspectives using sketching, participants used verbal communication in addition to sketching. On day 10 of the instruction, the teacher drew a diagram of the Earth-Sun-Moon system from a space-based perspective and asked questions about which phase of the Moon will be visible from the Earth when the Moon's location in its orbit is changed. In this example, the teacher showed a technique to determine which phase will be seen from the Earth depending on the configuration of the system (refer to Figure 19). However, the sketches themselves did not represent an Earth-based perspective. Earth-based perspective was made more apparent by using virtual tours from WWT. Earth-based perspective was communicated mainly through use of verbal spatial descriptions, along with use of iconic and pointing gestures based on the drawing.

Sketching appeared to be an efficient way of representing and summarizing spatial information in a single yet detailed diagram. The teacher as well as students used sketching as a way to not only communicate verbal spatial questions but also to clarify space-based perspective.

Finding 3: Use of virtual models along with fixed artifacts for referencing may have created an immersive experience that supported students' Earth-based perspective.

When teaching seasons, the teacher put labels of cardinal directions on the walls of the classroom. These labels were also aligned with the actual cardinal directions. By doing this, each wall of the classroom was used as a reference to a cardinal direction creating an Earth-based frame of reference for all students in the classroom. The same directions on the walls were also carefully matched with the directions shown in the WWT virtual simulation projected on a screen showing the motion and paths of the Sun during changing seasons. In other words, the classroom itself was turned into a real-world simulation of an Earth-based perspective, where the students themselves were observers inside a simulated celestial sphere. During this activity, students were not only watching the simulation of the Sun moving across the sky on the big screen but were also being a part of the simulation. They *were* the simulation. This kind of embodiment is called *participatory simulation*, in which participants collaboratively explore the dynamics of the activity (Colella, 2000). The combination of these two embodied elements – physical materials and virtual simulations – in combination with the practice of using fixed objects for referencing may have created an immersive experience for students in visualizing Earth-based perspective.

Participatory simulation activities are useful in understanding complex and dynamic systems (Colella, 2000). In this case, Earth-Sun system as viewed from the Earth was the complex, dynamic system. As students were collectively immersed in a common reference frame, they were experiencing a shared model of the system from their Earth-based perspective. According to Jaeger et al., (2016),

> when a simulation takes place within a familiar space, such as a students' classroom, it may be easier to begin to represent spatial information than when a simulation is contrived to take place in a less familiar or more abstract other space (p.4).

Therefore, using students' own classroom and creating an immersive frame of reference for them for visualizing Earth-based perspective might have been a powerful learning experience for grounding students' sense of Earth-based perspective. The immersive experience may have supported students' use of PT skill as it helped them in grounding their Earth-based frame of reference in a concrete and externalized representations of space.

Another advantage of creating a unique immersive frame of reference for multiple observers is that it created a common language for communicating spatial information. Example 9 presented earlier showcased how students were seen using the label of the north direction on the wall to anchor their reference point when they were engaged in determining the Earth's orientation as it revolves around the Sun. These immersive experiences have the potential to create strong links between elements of the real world and those of the hypothetical worlds (Jaeger et al., 2016).

Finding 4: The teacher played a crucial role in eliciting students' use of spatial sensemaking practices in ways that may have scaffolded their perspective taking.

Interaction analysis showed that the teacher played a key role in guiding students to use their perspective-taking skill. Her perspective-related questions may have led students to follow a step-by-step procedure for accurately connecting perspectives. This finding emphasizes the role of the teacher in training students to use their PT skill. This pattern also highlighted the discursive practice of perspective-questioning as being salient in the context of the curriculum designed to be spatially enriched for practicing PT skill. The following episode illustrates this finding.

On day 9 of the curriculum, the teacher used a series of perspective-based questions along with the object manipulation to engage students in exercising their PT skill understanding lunar phases.

1 Teacher: Ok, so I want to talk about how we get the full Moon from Earth. When you're doing *this [holds a Moon ball in front of her face between herself and the Sun-lamp simulating a new Moon position]*, I'm here… where is the light shining on the Moon? *[students remain silent]*. By 'light', I mean the Sun that's in the middle of the room. So, I'm holding it here…

2 Student 1: The Sun will be shining on *nearly* the other side of the Earth but not quite. So, probably a crescent?

3 Teacher: Ok. So, the side of the Moon that's facing the Sun is going to be the side that's getting the light, right? *[makes an iconic gesture with her palm showing the side of the Moon that's lit up]* and that's the lit-up part. And if I'm looking down from space, *[makes a pointing gesture to show an overhead perspective looking down on the Moon]* how much of the Moon is lit up at any time?

4 Student 2: Everywhere or half?

5 Teacher: Everywhere *or* half?

6 Student 2: Like…half of it

7 Teacher: Who agrees with *half*?

[many students raise their hand]

8 Teacher: So, half of all the objects in the solar system are lit up by the Sun. So, every object in the solar system has a day-time side and a night-time side. So, which side of the Moon is the day-time side of the Moon? How do you know?

9 Student 3: Well… the Sun is over there on this side *[points to the Sun-lamp in the middle of the classroom]*. So, that's the side facing the Sun *[points to the side of the Moon facing the Sun]*

Figure 24 Teacher explaining lunar phases using object manipulation and perspective-related questioning

10 Teacher: It's always the side that's facing the Sun that's going to be lit up. And you're looking from above *[shows a pointing gesture showing overhead view]*. So, the question is, if I'm bringing it around *here [moves the Moon ball from a new-Moon position to a full-Moon position]*, I can *see* the lit up side *[makes a dynamic gesture in circular motion with her hand to show the lit up side of the Moon]* if I hold my Moon up high. But do you

think that the Moon orbits the Earth in this weird, high, strange angle? *[moves her arm in a circular motion mimicking an exaggerated Moon orbit with an acute tilt]*.

11 Student 4: Yeah, sometimes

12 Teacher: So, it is tilted *[brings out a Hula Hoop from the back of the classroom].* The orbit of the Moon around the Earth is a little bit tilted *[holds the Moon, Earth, and the hula-hoop in an aligned position* (Figure 24)*]*. It's tilted by five degrees. So, if I tilt this hula-hoop by five degrees, is that tilt big enough to get the tilt out of the way?

13 Student (chorus): No

14 Teacher: So, there's a problem with my model.

15 Student 5: It's not to scale

In the PT sensemaking episode above, students and the teacher are making sense of how we see the Moon as the Moon is revolving around the Earth. Figuring this out requires a learner to apply their PT skill to visualize perspective from Earth and then connect it to the space-based view. Lines 1, 3, and 8 show examples of the teacher asking perspective- related questions that led students to gradually visualize a space-based perspective and then connect it to an Earth-based perspective. For example, on lines 3 and 8, the teacher elicits students' space-based perspective as the answer to the question requires students to visualize an overhead space-based perspective. Line 10 shows that the teacher herself connects the space-based perspective to the Earth-based perspective by modeling to her students her perspective from the Earth. Perspective-related questions might have provided students a procedural knowledge for navigating space- and Earth-based perspective.

In summary, spatial sensemaking practices arose from a combination of a variety of elements from the learning environment. These findings are useful in fine-tuning theoretical conjectures about which design features are salient and how they produce learning experiences. The most salient features of the ThinkSpace curriculum are discussed in the following section.

Revision of conjecture map

I used conjecture mapping (Sandoval, 2014) to drive data analysis with the goal of identifying the most salient features of the class environment in shaping students' PT skill. I started with interaction analysis to explore the research question – *How might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?* The initial conjecture hypothesized to answer this question was - *ThinkSpace curriculum engages students' PT skill through spatial sensemaking practices such as use of gestures, tools and materials from the learning environment, along with social interactions between peers and instructor.* I carried out interaction analysis to uncover only the most salient features of the curriculum that mediated students' use of PT skill. The new revised conjecture from the interaction analysis is – *Students' PT skill might be fostered through spatial sensemaking practices such as gesturing, object manipulation, and sketching along with teacher's guided questions related to perspective taking*. The following section presents the new conjecture map and a brief discussion of each one of its salient features.

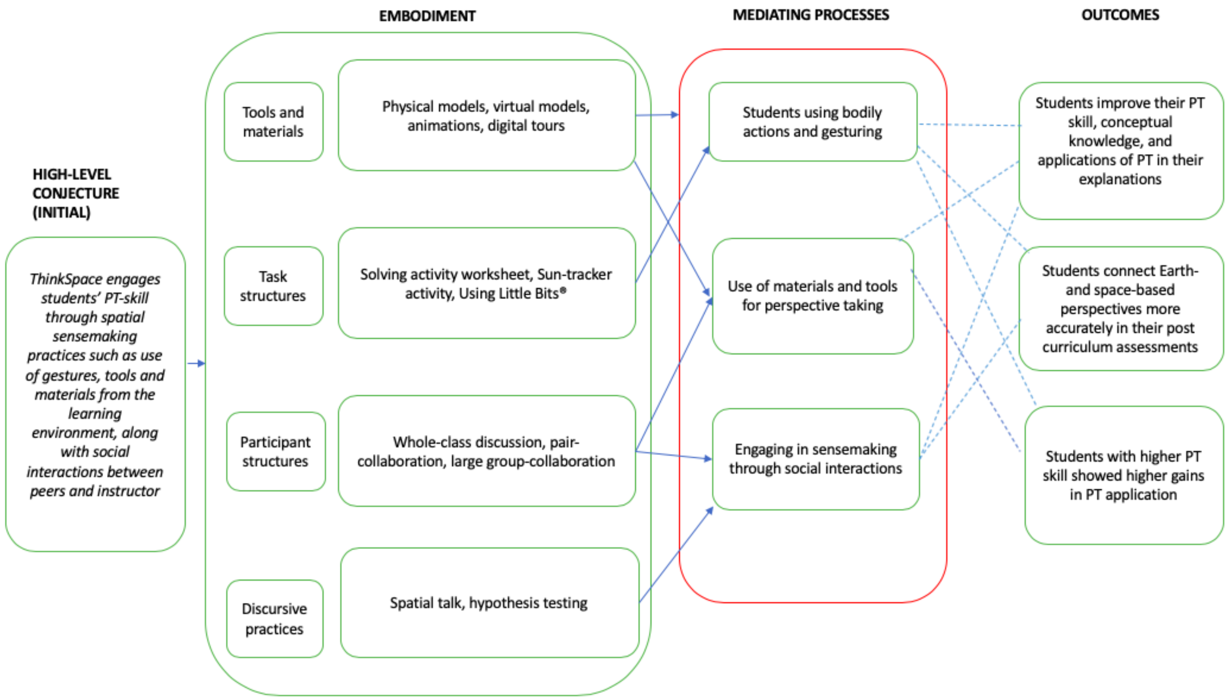


Figure 25 Initial conjecture map

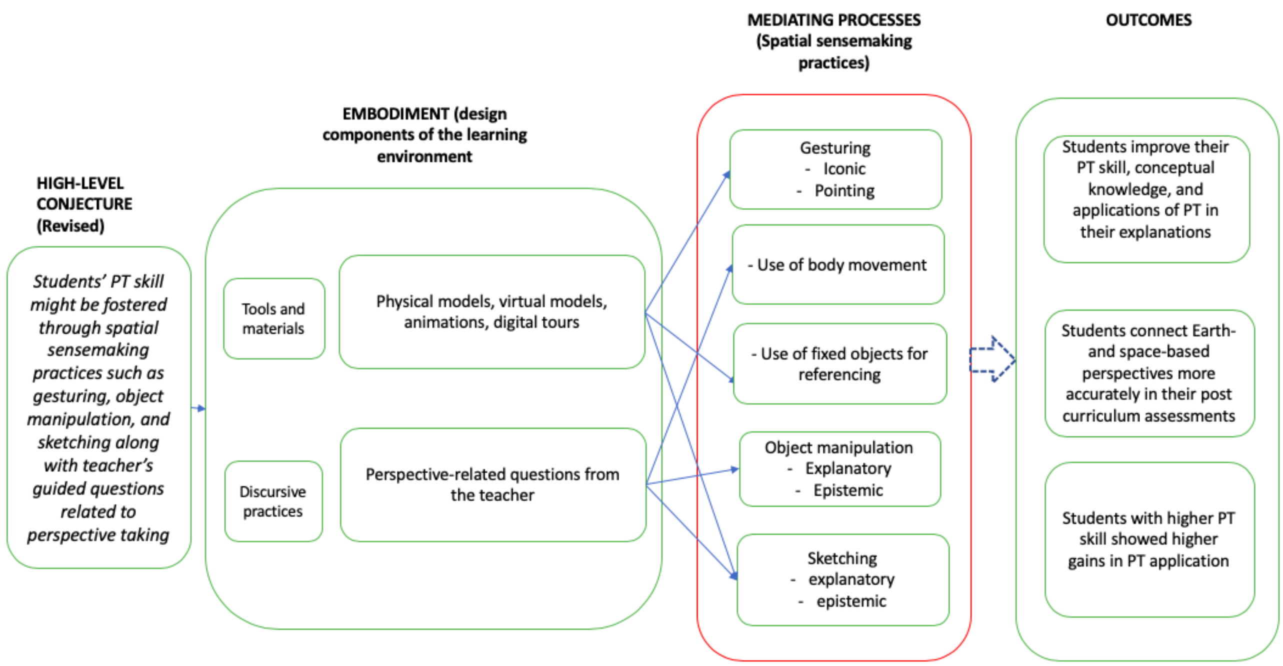


Figure 26 Revised conjecture map after interaction analysis

Figure 25 and Figure 26 show the initial conjecture map and the revised conjecture map respectively. In the following sections, I compare the embodied components of both the initial and revised conjecture map along with a discussion of mediating processes. In the initial conjecture map, the mediating processes were the hypothesized interactions predicted to be mediating the outcomes. In the revised conjecture map, I called these mediating processes as ‘spatial sensemaking practices’ as I argue that these sensemaking practices arose from the most salient features of the learning environment. Therefore, I referred to the mediating processes as the spatial sensemaking practices (Figure 26). In the following section, I present the comparison of the embodiment and the mediating processes from the initial and revised conjecture map.

Embodiment

Tools and materials

In the initial conjecture map, tools and materials such as the physical and virtual models, animations, and digital tours were predicted to be salient in shaping mediating processes such as students’ bodily actions such as gesturing, and their use of materials to support their PT skill. After the interaction analysis, I found that physical models and virtual animation/tours were, in fact, few of the most salient features of the ThinkSpace curriculum in engaging students in perspective-taking activities. As presented in claim 1, physical materials (Sun-trackers, Sticky-Vicky, models of Earth, Sun, Moon etc.) seemed to be eliciting a large variety of spatial sensemaking practices. Virtual tools such as the WWT tours and simulations also played an important role in supporting students’ perspective taking activities by helping create immersive experiences for students. Therefore, in the revised conjecture map (Figure 26), I included the use of tools and materials such as physical and virtual models as salient features.

Task structures

Task structure refers to the structure of activities along with their goals, criteria, standards and so on (Sandoval, 2004). Task structures such as the solving activity worksheets, using Sun-trackers, and using Little Bits® were hypothesized to be salient features of the learning environment. However, the interaction analysis did not reveal any pattern that showed their salience in the ThinkSpace instruction. The tools and materials from specific tasks turned out to be more salient than the structure of the tasks themselves as they gave rise to a variety of mediating processes. As a result, I did not include task structures as salient features of the revised conjecture map (Figure 26).

Participant structure

In the conjecture map, participant structure refers to the specific roles and responsibilities the participants take on. In the initial conjecture map, the participant structures such as whole-class discussion, pair-collaboration, and large-group collaboration were predicted to be important in supporting students' PT skill based on previous literature (Ramey & Uttal, 2017). However, interaction analysis did not show evidence of specific participant structure other than the student-teacher conversations supporting students' PT skill. Therefore, this feature was not included in the revised conjecture map (Figure 26). Teacher-led conversations that supported students' PT skill were considered under discursive practices.

Discursive practices

Discursive practices in conjecture mapping refer to simply "ways of talking" (Sandoval, 2004, p.22). In the initial conjecture map, I hypothesized that discursive practices such as spatial talk (Prudent et al., 2011) or hypothesis testing (Ramey & Uttal, 2017) to be salient discursive practices that will shape students' PT skill based on previous studies. During interaction analysis, I found that the teacher's use of perspective-related questioning seemed to have supported students' engagement in PT skill the most. In other words, the teacher's strategic placement of questions that elicited students' application of their PT skill seemed to be the most salient discursive structure. There was no evidence of spatial talk or hypothesis testing relevant to perspective-taking. Therefore, in the revised conjecture map, *perspective-related questions from the teacher* was added as a salient feature and others were omitted.

All the four design elements – tools and materials, task structures, participant structures, and discursive practices worked together in combination to give rise to specific mediating processes. In the ThinkSpace study, tools and materials along with the discursive structure of perspective-questioning led to a variety of spatial sensemaking practices that led to learning in interactive ways. In the following section, I present the most salient spatial sensemaking practices that may have supported students' PT skill.

Mediating processes (spatial sensemaking practices)

Mediating processes emerge out of learners' interactions with different embodied components (tools and materials, task structures etc.) that lead to desired outcomes. Figure 26 shows mediating processes pertaining to the ThinkSpace curriculum and instruction. I called the mediating processes as the spatial sensemaking practices (adapted from Ramey & Uttal, 2017) to better represent the nature of the interactions as this analysis only focused on participants' use of PT skill. A combination of the salient tools and materials and discursive structures led to students' use of spatial sensemaking practices that facilitated their use of PT skill.

As shown in Figure 25, the hypothesized mediating processes were students' actions such as gesturing, use of materials and tools for perspective taking, and engaging in sensemaking through social interactions. As a result of interaction analysis, the revised mediating practices were use of iconic and pointing gestures, use of body movement, use of fixed object for referencing, use of explanatory and epistemic object manipulation, explanatory sketching, and epistemic sketching as all of them seemed to play a unique role in shaping students' perspective-taking. The arrow connecting the mediating processes and the outcomes has been kept as a single connection as the methods used in the study do not give details about which particular sensemaking practices may have created the outcomes observed in the previous literature. Therefore, unlike the initial conjecture map (Figure 25), there is only one arrow showing a generalized trend that a combination of these spatial sensemaking practices may have contributed to the outcomes.

Only the salient features of the design are expected to lead to mediating processes (Sandoval, 2004). Use of physical and virtual models led to spatial sensemaking practices such as iconic and pointing gesturing, explanatory and epistemic object manipulation, use of fixed objects for referencing, and epistemic sketching. The discursive practice of perspective-related questions led to students' use of all the spatial sensemaking practices that emerged in interaction analysis. It must be noted that the combination of tools and materials and the discursive practice of perspective-related questioning seemed to have been the most productive way of engaging students in perspective taking.

Conclusions

In conclusion, conjecture map (Sandoval, 2004) provided a way to hypothesize and test initial conjecture about students' use of perspective taking in ThinkSpace curriculum. As the outcomes were predetermined from the previous iterations of the study, conjecture mapping helped in understanding which mediating processes – spatial sensemaking practices – led to those outcomes as a result of students' interactions with the learning environment. As a result, I found that the most salient features of the study were the tools and materials such as the physical and virtual models and the discursive practice of perspective-related questioning from the teacher. These two components of ThinkSpace curriculum were salient as they gave rise to a variety of spatial sensemaking practices as shown in the revised conjecture map (Figure 26). More importantly, they both led to students making a number of successful multiple-perspective connections. Spatial sensemaking practices gave insight into students' use of PT skill in learning lunar phases and seasons. Some of the spatial sensemaking practices were also used by the students in their personal interviews. In the following chapter, I discuss the results of the interview analysis.

Chapter 5

Findings and Analysis: Student Interviews

Introduction

In this chapter, I present the analysis of interview data. I started the interview analysis with an initial hypothesis that there will be differences in the approaches in which spatial sensemaking practices are used by students with low PT skill as compared to those used by high PT skill students. This prediction was based on the findings from Plummer and colleagues (2016) that PT skill predicted proportion of hand gestures used by 7-9 year olds when explaining seasonal constellations and stars' apparent motion. Additionally, finding from an earlier iteration of ThinkSpace study showed that students with high PT skill showed a greater accuracy in their explanations of lunar phases and seasons. Therefore, the research question that guided this analysis was: *What are the differences between range/use of spatial sensemaking practices of students with low PT skill and those of high PT skill?* In the following section, I present the findings from the interview analysis and overall trends found in the data.

Overview

Twenty-four students were selected for an interview before and after the curriculum was taught. Students were selected based on two criteria – 1. their MOSART test scores and 2. PT skill scores. The selection of students is elaborated in Chapter 3 (ibid). Based on consistency of data and absent students, interview data of 22 students was used for analysis. There were eight students grouped in low PT skill bin and six in high PT skill bin. The rest were binned as *medium* PT skill, which were not included in this comparative analysis.

The interview protocol (see Appendix A) included questions to elicit responses from students that show their descriptions of a space- or Earth-based perspective and their application of PT skill to explain seasons and lunar phases by connecting the two perspectives. The codebook used for instruction analysis was also used for interview analysis with minor changes as explained in Chapter 3. The code of *sketching* was not applied in the interview coding as students were not allowed to use sketching as a means of explaining their thinking. Therefore, interview videos were limited in their affordances for showing students' spatial sensemaking in comparison to instruction. Therefore, the only spatial sensemaking practices that were coded in the interviews were – 1. *iconic gesturing 2. pointing gesturing 3. use of body movement 4. explanatory object manipulation 5. epistemic object manipulation,* and *6. use of fixed objects for referencing.* In the following section, I present the findings from interview analysis.

Findings from interview analysis

Finding 1: There were no qualitative differences in the range/use of spatial sensemaking practices of students with low PT skill and those of high PT skill except *for epistemic object manipulation*

When comparing students' use of spatial sensemaking practices, I did not find any pattern in the data showing overall differences in the ways they were used by low and high PT skill students. Students from both low and high PT skill bins showed their use of PT skill through similar combinations of sensemaking practices. In other words, the patterns of sensemaking practices associated with a certain type of perspective were similar for students from both low and high PT skill scores in both pre- and post-interviews. For instance, when asked to explain using models how the Earth's position in space affects the temperature on Earth using models, students from both low and high PT skill groups used a combination of epistemic or explanatory object manipulation along with iconic or pointing gestures to show their connections between multiple perspectives.

In their post-interviews, students from both the groups seemed to be using their hand-gestures as a tool for identifying lunar phases. In other words, students from both high and low pre-PT score groups used iconic gestures as a way to externalize their connections between space- and Earth-based perspective for problem solving.

The physical models provided to the students during interviews may have helped both groups of students equally in supporting their perspective taking by enabling them to offload their thinking onto the models. Similarly, use of gestures seemed to have been used by both groups equally as they seamlessly used gestures along with verbal explanations of seasons and lunar phases. Overall, there were no differences in the ways that students used the practices of gesturing, use of body movement, and explanatory object manipulation. However, there were nuanced differences in the pattern of how students from the two groups used epistemic object manipulation.

Finding 2: Epistemic object manipulation used by most students (n=6) with low PT skill in their pre-interviews led to explanations that showed their use of a singular perspective. No such pattern appeared in the data from students with high PT skill.

Students from both low and high PT skill groups used the practice of epistemic object manipulation with the models of the Sun, Moon, and Earth. They used these models for testing different spatial positions and evaluating the most suitable spatial orientations that helped them in explaining seasons or lunar phases. Epistemic object manipulation was distinguished from the explanatory object manipulation by closely observing students' gestures, gaze, their pauses, and their use of models. Learners make physical changes like this in their environment to reduce cognitive load (Kirsh & Maglio, 1994). As epistemic object manipulation is a cognitive task (Kirsh & Maglio, 1994), often the instance when students used this practice did not involve any verbal explanation. If there was any verbal communication between the student and the interviewer, it showed uncertainty or indecisiveness in students' explanation. If students manipulated the objects to checked a number of spatial configurations before starting their explanation about seasons or lunar phases, that instance was coded as epistemic object manipulation.

One example of students' use of epistemic object manipulation is when explaining seasons, a student gazed at the models, changed the angle of the Earth's axis towards the Earth, then away from the Earth, and then started explaining his answer. His actions showed his usage of models to formulate an answer before starting to explain it. Therefore, this instance was coded as epistemic object manipulation as the student physically changed the orientation of the Earth to support his space-based perspective. In case of lunar phases, epistemic object manipulation included some students first revolving the Moon-ball around the Earth presumably to visualize different phases before starting to explain lunar phases.

I observed a trend in pre-interviews that low PT skill students (n=6) used epistemic object manipulation that led to explanations that were singular-perspective. In other words, even though students manipulated their models in order to answer the interview questions, they did not successfully connect Earth- and space-based perspectives. The following examples show low PT skill students' use of epistemic object manipulation. Note that students' explanations were not coded for accuracy. They were coded depending on their use of PT skill whether it showed their singular or multiple perspective.

Example 1

David, scored 7 on 15 in the pre-PT skill test, which was binned as a low score. Following example shows a dialogue between David and the interviewer. David used the models possibly to test out appropriate explanation but did not connect the space- and Earth-based perspectives to explain why it is hot or cold in summer depending on the tilt of the Earth's axis.

1 Interviewer: Can you show me using the models how the Earth is positioned for summer in Massachusetts? Oh, and I forgot to mention, this little pushpin [*points to the pushpin on Earth]* represents where Massachusetts is.

2 David: *[Holding the Earth slightly tilted with pushpin facing the Sun, gaze towards the interviewer* (Figure 27)*]* In summer… I think it'll be facing the Sun a little more than it usually does.

Figure 27 David (low pre-PT score) using epistemic modeling for explaining seasons

3 Interviewer: Can you show me what that would look like? [*points to the model*]

4 Student: [*starts moving the Earth to the other side of the Sun, gaze towards the model*] it…rotate… [*moves the Earth to the other side of the Sun, tilted towards the Sun*]. It will look something like that, I guess…

5 Interviewer: And how does that explain why it is hot in summer?

6 Student: Because when it is closer to the Sun, it's hotter; and when it's further, it's more cold.

In the example above, line 4 shows David's use of epistemic object manipulation for supporting his cognition. Physically moving the model of the Earth from one place to another to mimic its rotation may have helped him in visualizing a space-based perspective. He also seems to have the knowledge about Earth being tilted on its axis. The student started exploring an appropriate configuration using epistemic object manipulation before showing his explanation. However, he still gave an answer that would qualify as space-based explanation because his answer lacks a connection to an Earth-based perspective such as details about Sun's position in the sky as seen from the Earth. After the interviewer asked him how that might explain the hotness in summer, he still attributed the reasoning to the distance of the Earth from the Sun – a space-based perspective explanation. He did not connect it to how the Earth's tilted axis affects the sun-angle for an observer on the Earth to show his connection.

Even though the practice of epistemic object manipulation was observed in this student's repertoire of practice, he did not use it to connect the space- and Earth-based perspectives. The same student used epistemic object manipulation four other times in the interview. However, his explanations were coded as space-based perspective only. This example showed how the student used a spatial sensemaking practice to interpret spatial information by offloading mental workload onto the model. The model may have helped in visualizing the Earth's position around the Sun as it rotates. However, it did not lead the student to make a successful use of PT skill.

Example 2

Melissa scored 9 out of 15 on her pre-PT skill, which was also binned as a low score. She gave an explanation where she used the models actively to change their orientation for sensemaking. However, her descriptions showed only her space-based, singular-perspective. The dialogue below shows how the student used epistemic object manipulation to explain new Moon, but gave a singular perspective explanation.

1 Interviewer: Can you position the models so that a person on Earth would see a new Moon?

2 Melissa: *[places the Moon-ball at the first quarter position]* There.

Figure 28a Figure 28b Figure 28c

Figure 28 Melissa (low pre-PT score) using epistemic object manipulation for explaining new Moon

3 Interviewer: And why did you pick that spot?

4 Melissa: Oh, actually, around *here [moves the model to a waxing crescent position* (Figure 28a)*]*. I picked that spot because…because if the Moon is here *[makes an iconic gesture showing the circular disk of the Moon behind the Earth]*, it has to take…*[moves the Moon-ball at the waning crescent position* (Figure 28*b*)*]* a full turn for it to…[*moves the model to waning gibbous phase*]… become… the…*[points to the photo of the new-Moon* (Figure 28*c*)*]*.

In this example, Melissa's explanations and her use of the Moon-model shows epistemic object manipulation. Learners make changes in their environment to aid their cognition by offloading cognitive load onto the environment (Kirsh & Maglio, 1994). As Melissa changed the position of the Moon, she also changed her explanation with it. But based on her explanation, she is only using relative positions of the lunar phases to make conclusions about Moon's position as seen from the space. Her explanation (line 4) does not show evidence of a connection to an Earth-based perspective. Therefore, it was coded as singular space-based perspective.

In examples 1 and 2, both David and Melissa show use of epistemic object manipulation as a practice to figure out the spatial orientation relevant to spatial problems, but they did not show evidence of connecting the Earth- and space-based perspectives. More students from the low pre-PT skill group seemed to have struggled in making connections between multiple perspectives even though they used epistemic object manipulation. In the next section, I elaborate another minor pattern observed in low PT skill students' post-interviews.

Finding 3: More students from low PT skill bin used epistemic objects manipulation in their post-interview, than those from high PT skill bin. Additionally, most of the low PT skill students' use of epistemic object manipulation in their post-interviews led to successful use of PT skill to explain seasons and lunar phases.

I found that many low PT skill students (n=6), in their post-interviews, used epistemic object manipulation in their post-interviews. However, in their post-interviews, more students made connections between Earth- and space-based perspectives. Not only was the number of students using epistemic object manipulation higher in comparison to high PT skill students, but also the practice led to more students from low-PT bin making multiple-perspective connections. In comparison to the low PT skill students, high PT skill students did not use this practice in their post-interviews as often. However, in both groups, this practice seemed to have led students to explain answers by making connections between Earth- and space-based views. The following examples show changes in a low PT skill student's use of epistemic object manipulation from pre- to post-interview.

Example 3

Mark, who was grouped into low pre-PT score, did not use epistemic object manipulation in his pre-interview as a spatial sensemaking practice. Most of his explanations were coded as singular space-based perspective. However, this student in his post-interview, showed use of the epistemic object manipulation for explaining six different prompts requiring application of PT skill. Use of this practice was also followed by multiple -perspective explanations. In other words, the practice of epistemic object manipulation may have been useful for Mark in making connections between Earth- and space-based perspective. The following episodes show change in his explanations from singular to multiple perspective answers.

In the pre-interview, Mark showed a non-normative understanding of seasons. He showed a disconnect between the Earth-based perspective and space-based perspective that he showed with the models when explaining the Sun's position in the sky in winter.

1 Interviewer: If we look up, in winter, in the middle of the day, where would you see the Sun?

2 Mark: [*points upwards*] may be right above us?

3 Interviewer: Ok, so now can you use these models and position the models to show how… to show me *why* we would see the Sun in that place in the sky?

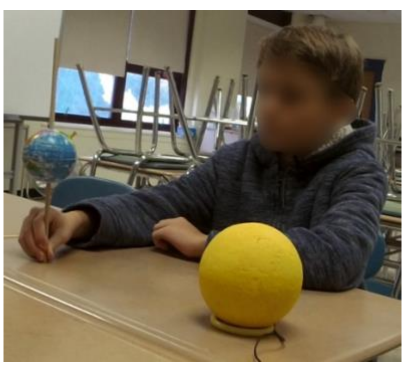


Figure 29a

Figure 29b

Figure 29c

Figure 29 Mark explaining seasons using epistemic object manipulation in pre-interview

4 Mark: *[gazes at the Earth and Sun, and then rotates the Earth so that push pin is towards the Sun and then away from the Sun* (Figure 29a)*]* Actually, I don't think it would be… umm… above us. I think…like… it would be to our left or our right, but still in the sky.

5 Interviewer: Ok. What do you mean by to your left or to you right?

6 Mark: Like…umm… over *there [points his arm upwards and to his left]* or over *there [points his arm upwards and right]*.

7 Interviewer: Oh, ok. So, how does the model explain that?

8 Mark: So, if you were like that [*holds the Earth horizontally on the table with axis facing the Sun* (Figure 29b)] then the Sun would be above us. But like…umm... this way [*holds the Earth upright, pushpin facing sideways*] the Sun could be here [*points finger to the Sun*] or it could be here…umm… the Earth moves around [*places the Earth on the other side of the Sun* (Figure 29c)] and then could be to the left…right.

A broad look at the dialogue and Figure 29 shows Mark's struggle to connect an Earth-based view of the Sun to the space-based orientation of the Earth. When asked to explain Sun's position in the sky using models, he placed the Earth horizontally to show an overhead Sun, which shows a disconnection between the Earth and space-based perspective. Even though lines 4 and 8 show Mark's use of epistemic model manipulation, his use of models did not lead him to connect multiple perspectives.

The following dialogue shows the same student's post-interview after he participated in the ThinkSpace curriculum. In the post-interview, the student used epistemic object manipulation multiple times in the interview. But this time, all his explanations were qualified as multiple-perspective answers, suggesting that he successfully applied his PT skill.

1 Interviewer: Can you show me, using the models, how the Earth would be positioned for summer in Massachusetts?

2 Mark: Umm…the Earth would be [*holds the Earth tilting away from the Sun] …* Massachusetts *(whispers)…*like…that [*tilts the Earth facing towards the Sun]* (Figure 30a).

3 Interviewer: Ok! And how does that explain why it's hot in summer?

4 Mark: Umm…because…wait… [*makes the Earth's axis tilted away from the Sun and then tilts towards the Sun again]…*because…the Sun is higher in the sky and so that would mean the Sun isn't like…spreading the light out as much [*makes an iconic gesture showing the spread from Sun to the Earth* (Figure 30b)*]*…it's just hitting the Earth more directly in one spot [*makes iconic gesture showing a spot*]… and is… when it's spreading out the light [*spreads his palm from Sun to the Earth]*…umm… it's not as hot because it's spreading out the heat.

Figure 30a

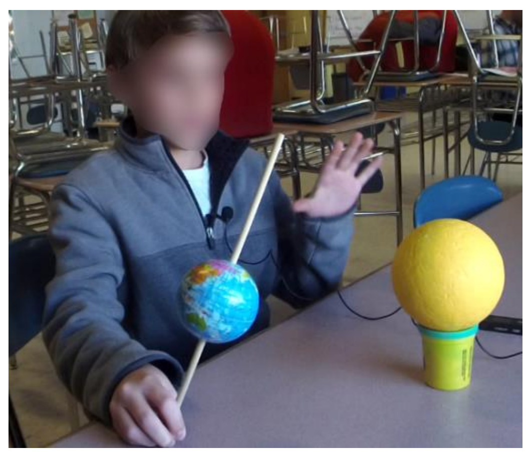


Figure 30b

Figure 30 Mark explaining seasons using epistemic object manipulation in his post-interview

In this episode, Mark, in his post-interview, shows his use of the Earth-model to help his cognition by trying different orientation of the tilt with respect to the Sun. Line 2 and 4 show his use of epistemic object manipulation, where he physically changes the position and orientation of the Earth to visualize the Sun's position in the sky as viewed by an observer on Earth. This also shows how instead of mentally visualizing a space-based perspective, the student offloads his mental visualization on the model before constructing his explanation for how the Earth would be positioned in summer. In line 4 he says “the Sun is higher in the sky”, which shows his connection to the Earth-based perspective.

The same student also used the practice of epistemic object manipulation to explain the Moon's phases. He actively used the Moon-model to first test out different locations of the Moon around the Earth to come up with multiple-perspective explanations for lunar phases. I argue that his use of epistemic object manipulation might have stream-lined the process of visualizing an Earth-based perspective related to Moon's position. As student used the Moon-ball, the model might have freed him from having to store information about Moon's positions in its orbit. Using physical models readily offered him the spatial information necessary to visualize an Earth-based perspective with respect to the physical position of the Moon thereby supporting his PT skill. These examples presented above signify the role of physical objects or materials in shaping cognitive processes such as perspective-taking.

Conclusions

Analysis of student interviews revealed that students from low and high PT skill groups used most of the spatial sensemaking practices in similar ways except for epistemic object manipulation. Students from both groups used practices such as iconic and pointing gesturing, explanatory object manipulation, and use of body movement to show successful use of perspective taking by using these practices simultaneously to connect multiple perspectives. From the embodied cognition standpoint, students from both groups showed embodiment of their visualizations through their use of iconic and pointing gestures. Especially in the post interview, students from both groups showed sophisticated use of gestures to predict lunar phases by using their hands as a “tool” to show connections between Earth- and space-based views (refer to Figure 10). Students from both groups also successfully used explanatory object manipulation to communicate spatial parameters and used them to externalize relationships between Sun, Moon, and Earth for explaining seasons and lunar phases.

However, there were nuanced differences in low and high pre-PT skill groups in their use of epistemic object manipulation. The purpose of epistemic actions is to reduce cognitive load by simplifying processing of information for our brain (Kirsh & Maglio, 1994). Using epistemic object manipulation to test out ideas may have supported students in advancing their thinking and revise their existing mental models. This is the same idea that Crowder (1996) referred to as “running” of a model, where a student is actively explaining a model while simultaneously revising or refining it. Epistemic object manipulation helps learners in bringing their cognitive processing in an external space. Interview analysis revealed that in the pre-interviews, students from low PT skill group used epistemic object manipulation just as much as those in the high PT skill group. However, low PT skill students’ use of epistemic object manipulation still led to explanations, which were coded as *singular*-perspective based. In other words, even though students were seen using the physical models to test out possible explanations of the two phenomena, majority of students did not successfully connect the Earth- and space-based perspective.

On the other hand, I observed a trend in the post-interview data that more students from low PT skill group used epistemic object manipulation as compared to high PT skill group. However, in post-interviews, this practice led them to explain the phenomena successfully by showing multiple connections. High PT skill students did not use this practice as often as those from low PT skill group.

One possible explanation for this trend might be the role teacher played in re-shaping students' sensemaking practices. Even though epistemic object manipulation was in students' repertoire of practices before instruction, the teacher may have fine-tuned their use of the practice by modeling it in her own teaching. Teacher's use of pre-defined gestures during math instruction has been shown to produce an increase in the number of gestures produced by students (Wagner-Cook & Goldin Meadow, 2006). Additionally, children are known to reproduce behaviors performed by others (Meltzoff & Moore, 1977). The practice of using epistemic and explanatory object manipulation was observed being used throughout the instruction both by the teacher as well as students. Based on the findings from pre- and post-interviews, one can argue that the teacher's use of epistemic or explanatory object manipulation during classroom instruction might have been taken on by students in their own practice. This might have improved students' use of epistemic object manipulation in their post-interviews even though they scored low on their PT skill test. Thus, interview analysis revealed the important role of the teacher in shaping students' repertoire of practices and it also showed the salience of physical and material resources in supporting students' engagement in perspective taking.

More importantly, this might imply that spatial sensemaking practices, when used appropriately, can lead students to make successful use of their perspective taking irrespective of their PT skill. As long as students were given opportunities to use models, manipulate them to aid their cognition and mental visualization, they made multiple perspective connections even though they had low PT skill. This further highlights the importance of investigating *how* students learn to apply spatial skills and construct explanations for spatially challenging topics. In the final chapter, I present the key findings from data analyses, and discuss the implications of this dissertation.

Chapter 6

Discussion

This dissertation study sought to understand how middle-school students engage in spatial thinking. Specifically, this study was an effort to understand which spatial sensemaking practices (adapted from Ramey & Uttal, 2017) play a role in shaping students' perspective-taking skill. This is one of the few studies that looked at students' engagement in spatial problem-solving in every-day classroom context and through individual interviews, rather than relying on psychometric testing alone. This research adds to spatial cognition literature by highlighting qualitative details of how spatial sensemaking practices might help in learning discipline-specific content knowledge by applying spatial skill of perspective taking (Liben & Downs, 1993). In this final chapter, I give an overview of conceptual and theoretical frameworks, summarize the key findings, situate this study in the broader literature, discuss implications the field of spatial thinking education and research, and layout future lines of research.

Overview

This dissertation was a two-pronged study with the goal of uncovering *how* students engage in spatial sensemaking activities in every-day classroom context. First, I addressed the research question - *How might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?* For answering this question, I recorded and analyzed classroom interactions to uncover a variety of spatial sensemaking practices that students and the teacher used to engage in perspective taking. In the second part, I addressed the research question - *What are the differences between range/use of spatial sensemaking practices of students with low PT skill and those of high PT skill?* For answering this question, I analyzed students' use of spatial sensemaking practices during individual interviews as they explained the phenomena of seasons and lunar phases.

Spatial sensemaking practices

Understanding *how* students engage spatially entailed analyzing classroom interactions. To achieve this, I developed an analytical framework to identify spatial sensemaking practices emerging in an astronomy class during instruction. For identifying the processes that may have supported students' PT skill, I adopted Ramey and Uttal's (2017) spatial sensemaking practices framework to create an analytical framework. This framework was used to uncover practices that showed participants interpreting and communicating spatial information in order to engage in perspective taking. Therefore, spatial sensemaking practices, in the context of this study, were defined as the strategies used by learners to make sense of spatial problems requiring PT skill. By using interaction analysis (Jordan & Henderson, 1995), I identified eight spatial sensemaking practices relevant to using PT skill - *iconic gesturing, pointing (deictic) gesturing, use of body movement, explanatory object manipulation, epistemic object manipulations, use of fixed objects for referencing, explanatory sketching, and epistemic sketching* (see Appendix B). These practices were identified by analyzing a small portion of the data and then using inter-rater reliability to establish validity of the codes.

Embodied Cognition

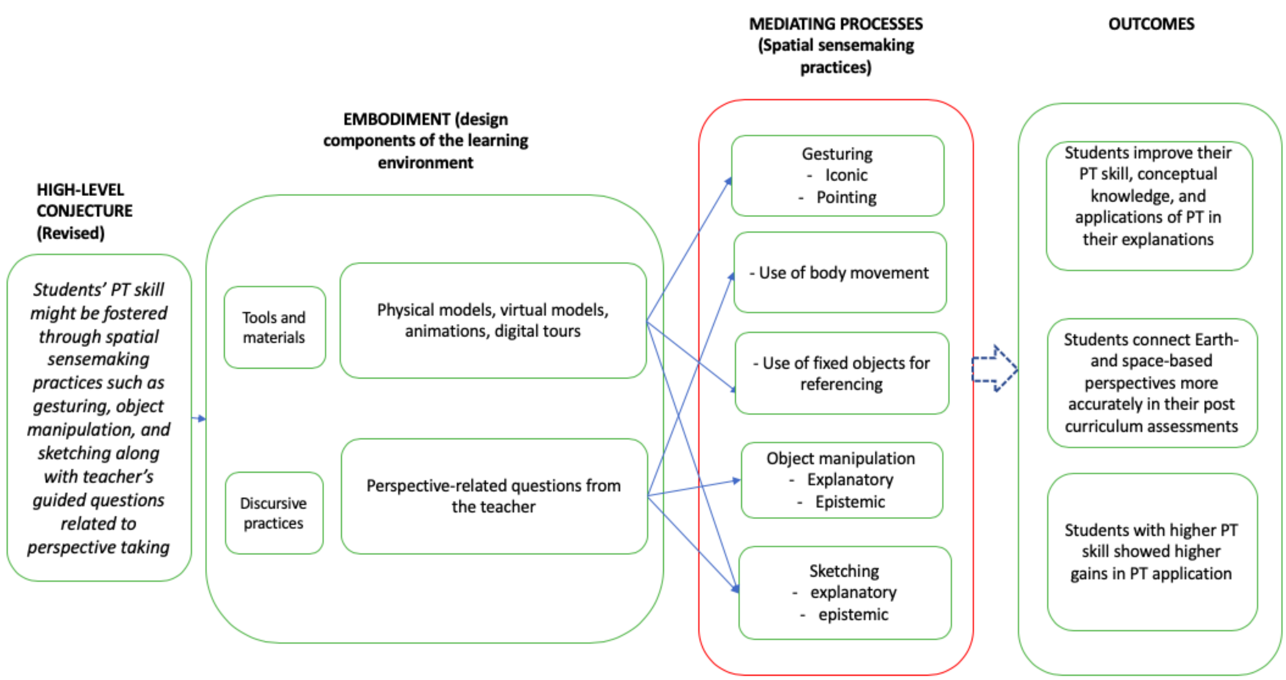
I used the principles of embodied cognition (Alibali & Nathan, 2012; Barsalou, 2008; Wilson, 2002) to draw conclusions about how certain spatial sensemaking practices may have supported students' visualizations of space- and Earth-based perspectives. Specifically, I looked at the data through the lens of three principles that tell us about how learners use their body to create pathways for learning – 1. *we offload cognitive work onto the environment* (Kirsh &

Maglio, 1994), 2. *offline cognition is body-based* (Wilson, 2002); and 3. *embodied cognition can manifest in social interactions* (Abrahamson & Lindgren, 2014; Wilson, 2002). In the following sections, I present the key findings from analysis of classroom instruction and interviews.

Key findings

Key findings from classroom instruction

In this section, I first present key findings from the first research question - *how might a spatially-enriched curriculum engage students in spatial sensemaking practices during instruction?* I used the methodology of conjecture mapping (Sandoval, 2014) to analyze different parts of the ThinkSpace curriculum such as tools and materials, task structures in the curriculum, participant structures, and discursive practices. The following figure shows the revised conjecture map[2].



[2] This conjecture map is the same as Figure 26.

In this revised conjecture map, the outcomes represent results from previous iterations of the ThinkSpace study found by statistical measurement of students' data. High-level conjecture shows potential ways of explaining those results. Embodiment reflects the most salient features of the ThinkSpace study uncovered through interaction analysis (Jordan & Henderson, 1995). Mediating processes are the processes, actions, and interactions taking place in a learning environment that lead to the outcomes (Sandoval, 2014). I re-named the mediating processes as spatial sensemaking practices to emphasize the actions and interactions pertaining to spatial problems arising during classroom instruction. The red box in the map shows the spatial sensemaking practices relevant to perspective taking identified through data analysis. The salience of an element of the embodiment was decided based on how each one of those supported students' perspective-taking skill. A feature was deemed salient when it led to students' successful engagement in connecting Earth- and space-based perspective, also referred to as multiple-perspective-taking. In the following section, I present the findings of the first research question that further elaborate this revised conjecture map.

Finding 1: Physical and virtual models appeared to have supported students' PT skill by giving rise to a variety of spatial sensemaking practices. Students made a large number of connections between Earth- and space-based perspective while using physical and virtual models.

Use of physical models and virtual models from WWT gave rise to a large number of spatial sensemaking practices that may have supported students' use of PT skill to make connections between multiple perspectives. Physical and virtual models create visuospatial representations for learners and create multimodal pathways for learning (Kirsh & Maglio, 1994;

Ramey & Uttal, 2017; Wilson, 2002). In my analyses, students as well as the teacher seemed to have taken advantage of using models as they enabled using other practices such as gestures, body-movement, and epistemic object manipulation to efficiently process spatial information. This can be explained using the principle of embodied cognition that *we offload cognition onto the environment* (Wilson, 2002). Models can be useful in making external representations of information and communicating it as spatial parameters are more readily available for the person to manipulate (Wilson, 2002). Thus, once offloaded, the learner does not have to memorize the information thereby making it efficient to process other spatial information.

Although this finding may seem obvious, use of physical objects in the context of perspective taking was found to be nuanced. Offloading information onto the environment saves the time required for mental calculations and the learner does not have to fully encode information before using it (Wilson, 2002). An exemplar of this was seen in a sensemaking episode when the teacher used a hula-hoop to represent the orbit of the Moon to elicit students' PT skill. Her use of hula-hoop created efficient ways of communicating spatial positions of the Moon with respect to the Earth. The hula hoop additionally represented the concept of Moon's orbit being tilted, which is key in understanding why we see full Moon as opposed to an eclipse every month. Thus, model of the hula-hoop served a dual purpose for the teacher – saving her the effort of communicating spatial information verbally to students and externalizing her own perspective taking. Similarly, virtual models were used to communicate several spatial coordinates related to Sun's motion as seen from an observer on Earth. This enabled students to visualize a broader picture of how low or high the Sun moves in the sky, which affects the variation in temperatures in different seasons. Thus, physical and virtual models enabled both the teacher and students to use other spatial sensemaking practices and also supported their perspective taking.

Because physical and virtual models let learners offload information efficiently, a large portion of their working memory might have been available to engage in other spatial sensemaking practices such as gesturing, sketching, and/or body movement to solve other spatial problems. Therefore, it is not surprising that students used a variety of other spatial sensemaking practices when they were using materials from their learning environment. Overall, use of physical and virtual models was salient in shaping students' perspective taking as it provided ways to navigate between different perspectives.

Finding 2: Sketching seemed to be an effective way of communicating space-based perspective.

Sketching as a spatial sensemaking practice was predominantly used for visualizing and representing space-based view for learning seasons and lunar phases. Sketching was used in visualizing events such as the Moon being lit up by the Sun, or the way Sun's rays hit the Earth depending on the tilt of the Earth's axis. Both these phenomena are not directly observable and hence, sketching facilitated visualization of space-based perspective. The teacher used explanatory sketching as a way to convey her own mental imagery of the space-based perspective when explaining lunar phases. The practice of epistemic sketching was used in combination with epistemic object manipulation by a pair of students in figuring out the direction of the Earth's rotation – another space-cased concept.

According to embodied cognition framework, sketching provides a way for learners to access information by leaving it out there in the learning environment– another way in which learners offload their cognition (Kirsh & Maglio, 1994; Wilson, 2002). Sketching enabled the participants of this study to store spatial information in the form of a sketch to perform mental operations on it. When the teacher drew a sketch of the Earth with an observer in the northern hemisphere, it may have freed her to mentally visualize an Earth-based perspective related to that space-based diagram of the Earth-Sun system. She was then able to ask perspective-related questions as the most important spatial information was left out there in a drawing to access at a later instance. The act of sketching a space-based perspective of Earth-Sun system enabled the teacher as well as the students to more readily visualize the corresponding Earth-based perspective without having to draw another diagram. Sketching was also a powerful strategy in showing distinctive effects of Earth's tilted axis in northern and southern hemisphere. Thus, this research uncovered an important use for sketching in representing space-based perspective.

There are a few studies exploring how sketching can affect students' spatial cognition. Sketching 3-D objects is a key strategy in developing spatial skills in developmental stages of a learner (Sorby & Baartmans, 2000). Sketching has been shown to be an effective way to support 3D-visualizations of objects that are not directly visible to the eyes such as structure of outcrops (Shipley et al., 2013). Jee and colleagues (2014) showed in their study that sketching can reveal the depth and understanding of one's domain knowledge as learners translate their mental representations of the phenomena such as plate tectonics into drawings. In comparison to these studies, my dissertation reveals the unique role sketching plays in representing students' use of perspective-taking skill by revealing how sketching can be an effective sensemaking practice in showing space-based perspective. Sketching seemed to be an effective spatial sensemaking practice in capturing spatial information in two-dimensional representations, which were useful in understanding the Earth-Sun-Moon system.

Finding 3: Use of virtual models along with fixed artifacts for referencing may have created an immersive experience that supported students' Earth-based perspective.

The practice of using fixed objects for referencing seemed to have created pathways for students to fully experience participatory simulation (Colella, 2000). For instance, on day 3 and 4, the teacher used the virtual animation and models from WWT to create an Earth-based reference frame for students. Cardinal directions were pasted on the walls of the classroom such that they aligned with the actual local cardinal directions. This configuration allowed students to visualize their Earth-based perspective from a common frame of reference. As a result, all of them were immersed in a shared model of the Sun's motion in their local sky. In another sensemaking episode, students also referred to a wall-clock as a proxy for north star. Using fixed object as a reference appeared to have enabled them to figure out the orientation of the Earth's axis during its revolution without leaving any room for error. This was especially useful when students were sensemaking in a group setting but had a common language to communicate spatial parameters such as direction, size, shape, and relative position of two objects.

According to Danish et al. (2015), when students talk about a shared model, it refines their understanding of the content. This immersive experience and sharing of common reference frames may have supported students' perspective taking as they collectively attempted to make sense of the seasons and related phenomena. Creating an immersive participatory experience may have enhanced students' visualizations of Earth-based perspective.

Finding 4: The teacher played a crucial role in eliciting students' use of spatial sensemaking practices in ways that may have scaffolded their perspective taking.

As embodied cognition might explain how learners use their own bodies and their learning environment to help their cognition, learners may also need support in guiding embodied ways of thinking. The third principle of embodied cognition that I used as a lens to look at the instruction data was *embodied cognition can manifest in social interactions* (Abramson & Lindgren, 2016). Black, Segal, Vitale, and Cameron (2012) introduced a concept called instructional embodiment, which is “the use of embodiment as an engaging activity for the student that may be modeled by the teacher but is fundamentally designed to engage the student in a sequence or system of movement, imagination, and exploration” (p. 215). Instructional embodiment seemed to become a crucial part of classroom instruction as the teacher used her own embodied actions to convey spatial information relevant to perspective taking. For instance, the teacher used a combination of object manipulation and gestures to show them a procedure to engage in space-based perspective taking. She used her own pointing gestures to show the Earth-based perspective to show the concept of sun-angle thereby creating externalized representation of an abstract concept.

Wagner-Cook and Goldin-Meadow (2006) showed that meaningful gestures used by the teacher increased students’ use of gestures too. They also argued that copying a teacher’s gestures help learners in problem-solving as long as they understand the purpose of those gestures. In this study, the teacher often modeled the spatial sensemaking practices that students took on in their own practice. Use of different spatial sensemaking practices might have eventually become a part of students’ repertoire of practices as they were seen using those practices in their post-interviews. Therefore, the teacher might have played a key role in supporting students’ PT skill by modeling spatial sensemaking practices.

Another pattern observed in the instruction data was the teacher’s use of perspective-related questions. Perspective-related questions were coded as those questions that may have activated students’ PT skill. Even though the ThinkSpace curriculum was embedded with spatially-enriched materials and activities, the teacher played an important role in bringing students to practice their PT skill by interspersing a series of perspective-related questions. In a class that promote learning about seasons and lunar phases by engaging students in PT skill rather than direct instruction, students seemed to be visualizing Earth- or space-based connections specifically by answering the guiding questions asked by the teacher.

As a result, video-analysis of instruction uncovered that discursive structure of *perspective-related questioning* was key in guiding students to engage in PT skill step-by-step. The teacher's questioning was followed by students using spatial sensemaking practices that may have led them to successfully engage in perspective taking. Both the gestures and perspective-related questioning thus illustrated the principle of embodied cognition that *embodied cognition can manifest in social interactions* (Abramson & Lindgren, 2016). As a result, the discursive practice of perspective-related questioning, which was not included in the initial conjecture map, was added as a salient feature in the revised conjecture map.

Thus, the four findings presented above illustrate the revised conjecture map and situate the role of spatial sensemaking practices according to the cognitive functions they provide for perspective-taking. In summary, the four key findings answer the first research question by explaining *how* students engaged in the spatially-enriched ThinkSpace curriculum by using spatial sensemaking practices. How students' may have learned from them is explained by principles of embodied cognition. In the next section, I summarize the key findings from interview data analysis to answer the second research question.

Key findings from student interviews

The interview data analysis was led by the research question - *What are the differences between range/use of spatial sensemaking practices of students with low PT skill and those of* *high PT skill?* This question entailed observing students' unique repertoires of practices and identifying general patterns in the data from the low and high PT skill groups.

Finding 1: There were no qualitative differences in the range/use of spatial sensemaking practices of students with low PT skill and those of high PT skill except for epistemic object manipulation.

The interview data analysis showed that the students from both the low and high PT skill groups seemed to have used all the spatial sensemaking practices in the same capacity. In other words, there were no notable differences in the way students from both groups used iconic and pointing gesturing, explanatory object manipulation, and use of body movement.

Students' explanation to the interview questions were coded for their use of perspective along with the type of spatial sensemaking practices used. The data analysis revealed that most students who successfully made connections between Earth- and space-based perspective often used a combination of spatial sensemaking practices. For instance, successful use of PT skill showed students' explanations using a model as well as using their pointing or iconic gestures. Both groups of students showed use of combination of different practices to support their perspective-taking.

This finding might be a manifestation of the principles that we offload cognition onto the environment and that the offline cognition is body-based (Wilson, 2002). Students made use of the models to externalize their thinking by offloading their cognition onto the models of the Earth, Moon, and the Sun to ease their mental calculation before applying PT skill. Use of gestures afforded students to externalize their thinking with respect to the models. Visualizations of the spatial configurations using models may have helped students in visualizing appropriate reference frames. For instance, many students used the model of the Earth representing their space-based perspective, while they explained their Earth-based perspective using their gestures to show its connection to an Earth-based view. Overall, there were no qualitative differences in the purpose or goal of the use of practices between students with low PT skill and high PT skill.

Finding 2: Epistemic object manipulation used by most students (n=6) with low PT skill in their pre-interviews led to explanations that showed their use of a singular perspective. No such pattern appeared in the data from students with high PT skill.

Interview analysis revealed that many students from the low PT skill group used epistemic object manipulation in their individual pre-interviews. However, their explanations following their use of the practice was still a singular-perspective based. Epistemic object manipulation is a practice used by learners to simplify their mental calculations and facilitate problem solving. In the case of low PT skill students, even though they used this practice, it did not lead them to make successful connections between Earth- and space-based perspectives in their explanations of the two phenomena in pre-interviews. For instance, low PT skill students seemed to be struggling to make a connection between the Earth's tilted axis (a space-based perspective) and the Sun-angle (an Earth-based perspective). However, further analysis showed that there was a shift in their usage of epistemic object manipulation in their post-interviews.

Finding 3: More students from low PT skill bin used epistemic objects manipulation in their post-interview, than those from high PT skill bin. Additionally, most of the low PT skill students' use of epistemic object manipulation in their post-interviews led to successful use of PT skill to explain seasons and lunar phases.

More students from the low PT skill bin used epistemic object manipulation in their post-interviews than those with high PT skill. Students who had not shown use of epistemic object manipulation in their pre-interviews seemed to be using it in their post-interviews. Their answers were not distinguishable from the high PT students as both high and low PT skill students were able to make multiple-perspective connections. I argue that using practices like epistemic object manipulation during classroom instruction may have added those in students' repertoire of practices. Students used the physical models more actively for constructing their explanations of seasons and lunar phases after having used those same models in the classroom. As a result, students from low PT skill seemed to be making more multiple-perspective connection in their post-interviews than their explanations in the pre-interviews. From the perspective of embodied cognition, this may suggest that students started using materials from their environments as tools to construct explanations about lunar phases and seasons (DeSutter & Stieff, 2017).

There were other practices like iconic gesturing adapted by students from their instruction to apply in their interviews. One reason for that might be attributed to the teacher's role in guiding students' perspective taking using her own practices. The teacher, by merely modeling use of different spatial sensemaking practices, may have added sensemaking practices to students' 'toolbox' for problem-solving, providing utility for novel problems such as those asked in the interviews (DeSutter & Stieff, 2017). For example, students from low PT skill groups used iconic gestures to figure out a mechanism to visualize Earth-based perspective of the Moon. Therefore, this finding highlights that even students with low PT skill can practice and apply spatial sensemaking practices in solving problems. In other words, their low PT skill did not seem to be a limitation to constructing explanations as long as they had opportunities to use spatial sensemaking practices.

In summary, there were subtle differences in the range/use of spatial sensemaking practices used by students from low and high PT skill groups. However, interview analysis revealed that students' PT skill may not be a limiting factor in constructing explanations as long as they were given opportunities to use sensemaking practices that supported their perspective taking.

Overall, from both instruction and interview data, a broad theme seemed to be apparent in the analysis that using a variety of spatial sensemaking practices at the same time may have created advantages in applying PT skill as a combination of practices provided different cognitive functions for problem-solving. I found that both the teacher and students used a combination of spatial sensemaking practices in different capacities as they supported visualizations of space- or Earth-based perspectives, or both. For instance, students used their iconic and pointing gestures in combination with object manipulation to make connections between how Sun's rays hit the Earth and how that affects the sun-angle viewed from the Earth. By using a combination of body movement and epistemic object manipulation, students successfully connected multiple perspectives to understand the effects of changing sun-angle on seasons.

Gestures are manifestations of the embodied cognition principle that *offline cognition is body-based* in that participants used gestures as a way to externalize their thinking about objects and events by representing and structuring information with their gestures (Nathan, 2008; Wilson, 2002). Pointing gestures display grounding in physical or imagined space, while iconic gestures display mental simulation of action and perception (Alibali & Nathan, 2012). Gestures play the role of carrier of the scientific meaning or they play the role of enhancing ideas (Crowder, 1996). During instruction, gestures were used majority of the times when the participants were also practicing object manipulation using Sun, Earth, or Moon models. Gestures added meaning to the sensemaking activity by acting as external representations of their mental models (Crowder, 1996; Plummer et al., 2016). They were used by students to explain the dynamic nature of processes that were not conveyed by static models. Students used iconic gestures along with object manipulation to clarify their verbal description thereby enhancing their explanations. Therefore, gestures seem to have played an important role in interpreting spatial information relevant to perspective taking.

On the other hand, spatial sensemaking practices such as the explanatory and epistemic object manipulation or using fixed objects for referencing are manifestations of the principle that *we offload cognition onto the environment*. Learners use physical materials to store and manipulate spatial information rather than attempting to store it mentally for manipulation (Brooks, 1991; Kirsh & Maglio, 1994). In other words, using material resources from the environment such as physical or virtual models helps learners in working through their ideas or conveying meaning to someone else by using the 'minimal memory strategy' (Ballard et al., 1997). When learning about seasons and lunar phases, sensemaking practices such as epistemic or explanatory object manipulation provided ways for students to efficiently manipulate spatial parameters pertaining to the models in order to engage in perspective taking. Using these practices may have simplified students' mental manipulation by reducing their cognitive load by allowing them to offload onto their learning environment.

In conclusion, using combination of these spatial sensemaking practices offered two different cognitive functions for students in order to engage in perspective taking – one that let students offload their cognition onto their learning environment and the other that let them externalize their thinking in embodied actions. A combination of spatial sensemaking practices seemed to play a unique role in supporting participants in solving spatial problems, communicating spatial information, and making connections between different reference frames.

Implications to curriculum and instruction

The results summarized above have implications for future researchers, practitioners, and curriculum designers. I also make a few recommendations for astronomy educators and general STEM disciplines in the context of middle school education based on the findings from this dissertation.

First, I recommend that teachers be informed about the importance of spatial skills training, interventions, and spatially-enriched curricula. Uttal and colleagues (2013) showed a strong correlation between students' spatial skills and predictability of their success in science. However, ways to train students to develop and hone their spatial skill remains elusive (Newcombe, 2017). Spatially-enriched curricula are rare and there is still scope for education research to move in that direction. Lowrie and colleagues (2017) showed how guiding teachers to embed spatial training benefited students' math learning. Bodzin (2011) showed that training teachers to use spatially-enriched technology such as GIS seemed to have positive outcomes on students' learning experiences in geology classrooms. In my research, I found that the teacher played a significant role in shaping students' spatial sensemaking practices that they used for problem-solving. I found that the teacher interspersed perspective-related questions for activating students' PT skill. From the findings of interview analysis, I also found that her use of the spatial sensemaking practices may have played a role in adding certain practices to students' repertoires of practice that led them to successfully use their PT skill in individual interviews.

The conjecture map revealed that the teacher's discursive practices related to using PT skill were key in giving rise to students' use of spatial sensemaking practices. Therefore, first, I recommend creating more opportunities for teachers to learn how to apply spatial cognition research and apply research-based strategies in their own practice. This might entail identifying spatially-challenging topics within STEM curricula and identifying which spatial skills support learning of those topics. This will better prepare teachers to instructionally support broader habits of mind for students to think spatially.

Second, I recommend that the key role of physical materials and virtual models must be considered by practitioners and/or curriculum designers especially when teaching spatially challenging phenomena. The material resources from ThinkSpace curriculum gave rise to a variety of spatial sensemaking practices that were useful in solving spatial problems. According to embodied cognition, physical models avail different cognitive functions to learners by enabling them to offload their cognition onto them (Kirsh & Maglio, 1994, Wilson, 2002). In this study, I found that students as well as the teacher used physical and virtual resources to offload spatial information. For instance, using the model of a Lego®-person stuck on a globe allowed students to successfully visualize an Earth-based perspective as the models encoded rich spatial information without having to verbalize it. This attribute of physical and virtual objects allowed students to manipulate spatial information more readily that might have helped them in constructing explanations using PT skill.

Even in the interviews, when given opportunities to use models, students used them to help their cognition irrespective of their PT skill. Therefore, I suggest that practitioners and curriculum developers give explicit attention to use of physical models to support students' spatial thinking when teaching spatially complex topics. This might entail teachers and curriculum developers doing the metacognitive work of identifying attributes of the material or virtual resources that can be leveraged to support their domain-specific spatial skills. This dissertation provided the framework to think about those aspects of the models that are useful in carrying rich spatial information and using that to support other spatial practices.

Third, specifically for astronomy educators and practitioners, I recommend using virtual models and digital resources as ways to create immersive learning spaces. Supporting learners to think spatially means designing learning spaces that can be leveraged to be used as tools for spatial reasoning (Waller, 2014). One of the challenges of teaching astronomy in school is recreating accurate astronomical events in a classroom/laboratory setting because of the astronomical sizes and scale being so large. However, in my analyses, I found that using virtual models of the Sun-Moon-Earth systems created powerful experiences for students to simulate phenomena like seasons and lunar phases as the tools created a mixed reality, which combined elements of the real world with virtual objects (Danish et al., 2015). Using virtual animation and interactive models from the WWT, students were able to visualize the path of the Sun in different seasons as viewed from their own classroom. This might have concretized their ideas about the Sun's motion in different seasons in an externalized visual. Use of virtual models of the Sun-Moon-Earth systems enabled students to not only visualize an Earth-based perspective but also predict changes in the Sun's position in the local sky at times when the simulation was not present. Therefore, their visualization of the perspectives seemed to have translated beyond just the immersive experience. Additionally, immersing students in a virtual coordinate system not only supported students' visualization of Earth- and space-based phenomena but provided a common language for communicating spatial information and a common frame of reference. This was then leveraged by the teacher to guide their thinking as most of the information was embodied by the participating students, who were able to navigate between Earth- and space-based perspective more readily based on their common experience.

There are other topics in astronomy such as the celestial motion of the stars and seasonal motion of constellations, which can be learned by navigating between Earth- and space-based perspectives. Students learning these topics can potentially benefit from having an immersive experience. Therefore, I recommend astronomy educators to use tools like *WorldWide Telescope, Stellarium*, or *Starry Night,* which can create learner-specific immersive experiences that might lead to successful navigation between different reference frames. Using tools like these in the classroom allows to create two-dimensional projections in the classroom, which can become parts of the learning environment. These virtual models coupled with physical models might enable students to learn astronomical phenomena through embodied learning.

Fourth, I recommend including pre-designed gestures as a part of instruction when teaching spatially challenging topics such as lunar phases and seasons. In my analysis, I observed that gestures created agency for students to show connections between different perspectives and to process spatial information. Gestures have been shown to play an important role in externalizing critical thought (Alibali & Nathan, 2012; Nathan, 2008). Iconic gestures have been shown to be of special importance in connecting reference frames by simulating otherwise invisible mental imagery (Plummer et al., 2016). Padalkar and Ramadas (2011) recommend training students to use gestures as a repertoire of practice as they may be useful in forming mental representations. My dissertation furthers this research by showing that students used gestures as tools to connect different perspective and developed a technique to identify the correct lunar phase from Earth-based perspective. They also seemed to be using their body-movement as a whole to simulate offline processes such as the rotation of the Moon or revolution of the Earth around the Sun. Student used iconic and pointing gestures to communicate spatial parameters throughout classroom instruction as well as in their interviews.

Therefore, I recommend that teachers encourage use of gestures and body movement for simulating spatial processes and possibly utilize them as a means of formative assessment as gestures are useful in supporting meaning-making (Crowder, 1996). Danish et al., (2015) had also showed that using kinesthetic ways of learning through play enables deeper understanding of the content as their body movement acts as a way to externalize their cognitive processes. Therefore, I recommend teachers leverage gestures and body-movement in creating body-based models when teaching spatially complex phenomena.

Fifth, I recommend that teacher use sketching as a tool for assessing students' mental representations of spatially complex phenomena. Visual representations like sketching have attributes that align with mental and visual-spatial demands of science learning (Ainsworth et al., 2011). Learner-generated drawings are also useful in understanding whether certain skills are transferred (Van Meter & Garner, 2005). Embodied cognition (Wilson, 2002) also suggests that sketching is a way to simulate events that are offline or not present in the learning environment.

This study highlighted the role of encoding space-based representation through sketching. It must be noted that visualizing and accurately depicting a space-based perspective is an important step in navigating perspectives. Through this study, I found that the teacher as well as students encoded rich spatial information in simple drawings such as Earth tilted on its axis or a model of the Moon revolving around the Earth. These simple drawings were then used by the students to understand connections between Earth- and space-based perspective when necessary. Additionally, I observed that sensemaking episodes began with a simple drawing that was taken on by the teacher to refine students' thinking by adding details to it. Therefore, I recommend that teachers use sketching as another means of formative assessment.

Middle-school level subjects such as Geography and Earth Sciences demand students' spatial thinking regarding sensitivity to location, scale, movement, and spatial perspective (NRC, 2006), which are attributes of spatial representations also present in understanding seasons and lunar phases. During instruction, students used epistemic sketching to transfer their Earth-based model of the Sun on a Sun-tracker, that showed their visualization of location, movement, and their Earth-based perspective. This then acted as a formative measure for the teacher to guide their Earth-based perspective taking. Therefore, I recommend that sketching be leveraged to capture students' sensemaking during instruction and using sketching as a medium to assess students' spatial visualization, especially when teaching topics such as seasons and lunar phases.

Lastly, I recommend that teachers as well as curriculum developers consider the role of sensemaking practices in addition to the curricular content. An overarching pattern apparent in the instruction and interview analysis was that students used a variety of spatial sensemaking practices when solving problems as they provided different cognitive support. I showed from my analysis that students were processing spatial information to connect multiple perspectives as long as they were given opportunities to use a variety of sensemaking practices. The interview analysis also demonstrated that a successful connection between multiple perspectives may be attributed to students' use of spatial sensemaking practices rather than their PT skill. According to interview findings, the teacher also played a vital role in shaping students' use of spatial sensemaking practices through teacher-led discursive practices specific to perspective taking. Therefore, I recommend intentionally developing strategies that will support students' sensemaking such as use of gestures, use of physical or virtual models, or sketching.

Spatial thinking research has also showed that experts do not always depend on their spatial skills to solve complex spatial problems (e.g., Hambrick et al., 2012; Stieff, 2007). They largely rely on their discipline-specific content knowledge, familiarity with the disciplinary representations, and problem-solving strategies as opposed to spatial skills. In my dissertation, I uncovered the spatial sensemaking practices used as strategies to simplify problems requiring PT skill. Some of these practices were used more often by students with low PT scores than those with high PT scores suggesting that given opportunities to develop sensemaking practices, students can use them to solve spatially challenging practices. Therefore, I recommend that teachers and practitioners think explicitly about sensemaking practices that can be taught and exercised during instruction so that students are trained to use these practices from early on regardless of their spatial skills.

Limitations and future work

My dissertation adds to the spatial thinking literature by providing rich descriptions of actions and interactions that took place when teaching spatially-enriched curriculum. But a few limitations call attention to directions for future research. This study was designed to get a deeper understanding of students' engagement in PT skill and their application of the skill in explaining seasons and lunar phases. Therefore, the spatial sensemaking practices identified in this study are limited to students' engagement in PT skill.

Methods of analyses were limited in their affordances as this research does not offer any causal connections between instruction and interviews. In other words, pinpointing which parts of the classroom instruction may have affected students' use of perspective taking in interviews is difficult to predict with the methods used in this study. Classroom interactions and interviews were video-recorded for exploring a general pattern of spatial sensemaking practices emerging in these two contexts.

There are methodological limitations of this study in gathering video data. The video data were limited to two cameras in a large classroom as it was the least intrusive way of gathering data. Therefore, individual student work, artifacts, and peer interactions were not fully captured for analysis. For future analysis, capturing students' classwork artifacts would be useful in tracking individual student's application of PT skill. Students' sketches and drawings from their worksheet may provide insight into how students use sketching to process information by using their PT skill. This might allow us to see whether there exist any differences in representations created by students with low vs. high PT skill.

As opposed to the classroom setting, interviews were aimed at understanding an individual's use of PT skill. Therefore, the two settings provided fundamentally different data for achieving different goals making it challenging to make any causal connections between findings from classroom instruction and interviews. However, the two buckets of data – a collection of classroom interactions and individual student explanations of seasons and lunar phases – provided an insight about how students might be processing spatial information using spatial sensemaking practices. In the next few paragraphs, I propose new lines of research for refining connections between the spatial sensemaking practices and the outcomes of the ThinkSpace study from previous iterations.

In the revised conjecture map (refer to Figure 26), the dotted blue arrow on the right is an indicator of potential connections between the spatial sensemaking practices and the outcomes of the previous iterations of the ThinkSpace study. Identifying the most significant spatial sensemaking practices leading to those outcomes is beyond the scope of this study. However, to understand which practices might have led to specific outcomes, we need more rigorous methods of evaluating them during instruction and during interviews. It must also be acknowledged that these outcomes are not effects of the spatial sensemaking practices alone and that there might be other variables that affect the outcomes. In the next section, I discuss a few approaches to extend this dissertation research.

The first outcome from the previous iterations of ThinkSpace study (Figure 26) had shown that *students improved their PT skill, conceptual knowledge, and applications of PT skill in their individual explanations of seasons and lunar phases.* One potential way of understanding which specific practices or a combination of practices might be more significant in determining the outcomes than others, we can design a *path analysis* study (Duncan, 1966). Path analysis is a method of multiple regression that also determines the causal inferences about the relationships between multiple variables by taking into consideration the mediators that may have caused those outcomes. Conjecture mapping used in this dissertation already provides *paths* -- hypothesized relationships between different classroom elements, mediators (spatial sensemaking practices) and outcomes. A path analysis might provide a quantitative way to determine which of the eight practices identified in this study have the highest impact on the learning outcomes versus those that have the lowest impact.

A multi-group path analysis model (Sarstedt, Henseler & Ringle, 2011) might also provide ways to discern differences in use of spatial sensemaking practices used by those with high PT scores vs. low PT scores. In such a study, one could potentially use students' PT scores as the grouping variable and identify if students with low vs. high PT scores have different patterns in their path model. However, it must be acknowledged that a variety of independent variables such as the gender, PT skill, prior knowledge, SES etc. may have affected these outcomes and therefore might have to be included as control variables. This method will, however, also require a larger sample of student interviews.

The second outcome from previous iterations (Figure 26) was that *students conceptual understanding of the phenomena, PT skill, and explanations improved significantly post curriculum assessments* (Plummer et al., 2018; Plummer et al., in progress). One limitation of this study is determining which attributes of the ThinkSpace curriculum (embodiment) were tightly correlated to the outcome. This limitation exists mainly because this study was not an experimental or quasi-experimental setup, where another group of students was taught a traditional curriculum as opposed to a spatially-enriched curriculum. Going forward, there is opportunity for researchers to carry out a quasi-experimental study where results from the two setups might be compared for discerning the impact of spatial sensemaking practices from one another.

The third outcome of the previous iteration of the ThinkSpace study was that *students with higher pre-PT score showed higher gains in their use of PT skill than those with low PT-score* (Figure 26). In my dissertation, sample sizes used for drawing conclusions about differences in low and high PT skill students' spatial sensemaking practices were small. Therefore, the claims presented in this study are limited to qualitative descriptions and present only the broad themes observed in the data. A larger sample of students would help us in understanding if there exist any nuanced qualitative differences between explanations of students with low PT score versus those of students with high PT score. A large sample will also help in investigating whether there exists stronger correlation between PT skill and the types of sensemaking practices used by students.

Another approach that might be useful to test whether there are fundamental differences between how students of high and low PT score apply their perspective taking skill is to use a *think-aloud* protocol (Ericsson & Simon, 1979). Think-aloud protocols are used to study mental processes in which participants can be asked to articulate their thinking as they work through a spatial problem. Videos alone enable us to capture participants' actions but they do not allow us to capture an individual's cognitive processes. In this study, I used principles of embodied cognition to make claims about how spatial sensemaking practices might have helped students' cognition when problem-solving. Therefore, a think-aloud protocol will be useful to gain insight about how students apply their PT-skill to solve problems outside of classroom context or even outside of the domain of astronomy. They might be useful in identifying spatial sensemaking practices other than the ones identified in this research study.

Overall, this research study calls forth more studies that zoom-in onto how everyday classroom instruction can be enriched with spatial tasks. While this study was designed around 10 days of curriculum and instruction, delayed observations would allow us to understand long-term effects of training students to think spatially. Because this study highlighted the role of spatially-enriched curriculum and the role of the teacher in promoting spatial thinking in classroom context, more such studies would help us in understanding how we can leverage learning spaces to support spatial thinking. Further research is needed for understanding how our embodied ways of learning and interactions with the learning environment can be leveraged to other spatially-challenging topics in STEM.

Conclusions

Spatial thinking has been shown to be an important predictor of success in STEM fields and that spatial skills are malleable (Newcombe, 2010; Uttal et al., 2013). Spatial skill of perspective taking has been shown to be useful in understanding astronomical phenomena such as daily celestial motion or movement of constellations. However, despite the need to develop spatially-enriched curricula, spatial thinking is an 'epiphenomenon of instruction' (DeSutter & Stieff, 2017). There is still a lack of direct attention to spatial thinking during instruction in classroom settings. The goal of this study was to better address this gap by understanding *how* students engage in spatial skills required to explain spatially challenging phenomena of seasons and lunar phases.

I found that focusing on students' spatial sensemaking practices related to perspective taking provided an insight into how they use their PT skill in constructing explanations. Conjecture mapping (Sandoval, 2004) provided a way to distinguish features of the learning environment that supported students' perspective taking. Theoretical principles of embodied cognition (Abramson & Lindgren, 2015; Barsalou, 2008; Wilson, 2002) provided a lens to analyze students' actions and interactions with their learning environment that emphasized the role of spatial sensemaking practices and how they are operationalized within a learning environment.

The key findings from this dissertation highlight the importance of physical and virtual resources in offering cognitive functions that support spatial problem-solving. The analysis uncovered the pivotal role of gestures in shaping students' problem-solving processes and creating agency to externalize their thinking. Thus, my dissertation creates pathways for researchers to explore different sensemaking practices pertaining to a variety of spatial skills. Lastly, the instruction as well as interview analyses highlighted the crucial role of a teacher in supporting students' perspective taking by modeling use of different spatial sensemaking practices and use of questions that guided students to exercise their PT skill.

The interview analysis showed that students' use of spatial sensemaking practices played a large role in enabling students to construct multiple-perspective explanations rather than their PT skill alone. Therefore, this study brings a refreshing addition in spatial thinking literature that often adheres to psychometric testing for training spatial skill. Lastly, rich descriptions of students' engagement bring us to acknowledge unique repertoires of practices that individual learners bring to their classrooms for problem-solving irrespective of their spatial skills and knowledge. This calls for future research in spatial thinking in how we can foster students' spatial cognition in fields other STEM fields by promoting the use of spatial sensemaking practices.

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Appendix A - Interview protocol

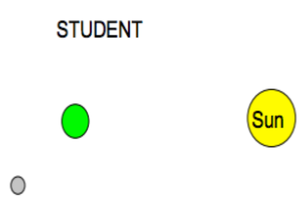
Seasons and Moon phases combined interview

Action:	Question:	
		Thank you again for agreeing to participate in this interview. If there are any questions that you are not sure of the answer to, you can say "I don't know" but we are interested in hearing all of your ideas, so give it your best attempt. **What is your astronomy-word?** **What is your code #?** **How old are you?**
Get model Sun & Earth & give to student	1	Can you show me, using the models, how the Earth would be positioned for **summer in Massachusetts**? **How does that explain why it is hot in Summer?**
	2	**Based on what you just showed me, how and where would you position the Earth for winter?** **How does that explain why it is cold in Winter?**
	3	Now we'll think and talk about how the Sun appears in the sky to someone on Earth. **We're still in MA. Now, imagine it is the middle of the day in <u>winter</u> and you are standing outside. Can you use your hand or arm to show me how high the Sun will appear to be in the sky?** **a. Can you position the models of the Sun and Earth in space to show me why we would see the Sun in that place in the sky?**

	4	**Imagine it is the middle of the day in <u>summer</u> and you are standing outside in Massachusetts. Can you use your hand or arm to show me how high the Sun will appear to be in the sky?** **a. Can you use the models to show me why we would see the Sun in that place in the sky?** [If they seem really confused (and start moving Sun), offer some sort of follow up, such as "OK, but if we are living here on the Earth, why does it look like the Sun is that high in the sky?" or "Oh, is the Sun actually moving in space?"]
	5	**Do you think that the Sun's location in the sky is connected to the temperature difference in Summer and Winter?** a. (If yes) How is it connected? b. (Only if they seem very confused, call back what they said in previous questions. "You said, Sun is high in summer, low in winter. Do you think that is related to temperature"? If they say yes, then say "HOW is it connected.")
	6	**Here is Argentina. Imagine you are in Argentina in July. What season would you experience in July in Argentina.** a. Can you use the models to explain why Argentina is experiencing that season in July? b. (*If brief*) How does that explain why someone in Argentina would experience (the same or different) season than we would experience here in MA in July?

Transition to Moon questions

Action:	Question:		
Get model Earth, moon & Sun	1		*Now we are going to add a model of the Moon to our models of the Earth and Sun for the rest of the interview. We'll use these to explore why the Moon appears to have Phases from Earth. These models are not accurately sized in comparison to the Earth. Remember, you can move these models and yourself around as much as you like.* *Also, here are some photos showing the phases of the moon. [Place 8 photos of the moon in front of the student as a reference. These should not be placed in order.]*

			Can you use these models of the Sun, Moon, and Earth to show me why you think we see different phases of the Moon?
	2		*Now let's connect these models to some photos taken of the Moon on different days.*
Hand photo of Crescent Moon		**A.**	**Can you position the models so that a person on Earth would see a Crescent moon (point to picture)?** **Why did you pick that spot?**
Hand photo of Half Moon		**B.**	**Can you position the models so that a person on Earth would see a Half moon (point to picture)?** **Why did you pick that spot?**
Hand photo of Full Moon		**C.**	**Can you position the models so that a person on Earth would see a Full moon (point to picture)?** **Why did you pick that spot?**
Hand photo of New Moon		**D.**	**Can you position the models so that a person on Earth would see a New moon (point to picture)?** **Why did you pick that spot?**
Position model	3		*Now I'm going to position the models.*
		**A.**	**If you were standing on the Earth looking at the Moon, which phase would you see?** Why would you see that phase? If the student seems unsure how to answer, suggest they can point to a moon phase photo for their answer. If they do not say the name of the phase, state the name of the phase for the camera.

Appendix B – Codebook for data analysis

No.	Main codes	Sub-codes		Examples
1	**Gestures**		Motion of arm or hand to communicate information	
		Iconic/Representational	Gesture that show semantic content by a shape, placement, or motion trajectory	The teacher moves her arm in an arc to show the Sun angle as see from Earth
		Pointing	Gesture that shows a teacher or a student pointing at an object	Students points at the sign on the wall that says "fall" seasons
2	**Use of body movement**	-	An instance when a student or the teacher moves their body or move from one place to another when being engaged in a sensemaking activity	One student showed how she aligned herself with the orange alien on the screen by moving her entire body
3	**Use of fixed objects for referencing**	-	when the student or the teacher uses an object without physically manipulating it. They use this object without really touching it - for example, for using as a reference point etc.	1. The teacher moves around the class to show the motion of the Moon's orbit around the Earth for supporting students' multiple perspective taking. 2. A student refers to the wall-clock clock as a North star

4	**Perspective questioning**	-	An instance when either a student or the teacher (or even the virtual animation program) asks a question related to perspective taking. This can be a question about single or multiple perspective.	"What do you think my helicopter pilot sees to its right?", "Why does the midday Sun angle looks really high in summer but low in winter?"
5	**Object manipulation**		Instances when the participant uses/touches a physical object to use it in relation to PT skill	
		Explanatory	An instance when the teacher or the student physically manipulates an object to show their explanation to others. This object manipulation is for *explaining*.	The teacher uses the models of the Sun and the Earth to show orientation of the Earth when it's winter in northern hemisphere to students
		Epistemic	An instance when the teacher or the student use physical objects to simplify their problem task (by physically manipulating the object). Epistemic object manipulation is done when an individual is using it for themselves. Object manipulation for *thinking*.	A student just holds his pencil out to visualize the Earth's tilted axis.
5	**Sketching**		Any kind of drawing or sketching that students or the teacher do in class	

		Explanatory	An instance when a student or a teacher is drawing diagrams to explain to others: sketching as a way to them to externalize their mental visualization	A student draws a diagram of the Earth's lit up side facing the Sun to show what they mean by summer in northern hemisphere
		Epistemic	An instance when the teacher or a student uses sketching to simplify mental visualization	A student sketches a drawing of the Sun's path when asked to visualize the Sun's motion across the sky; Students draw different paths of the Sun in different colors

Type of perspective (used from Vaishampayan et al., 2018)	Definition	Example
Space-based perspective	An instance when the participant is showing their perspective of an object/system from space	Students use the model of the Earth and mimic the motion of the revolution of the Earth in a group
Earth-based perspective	An instance when the student or the teacher show their of object/system from Earth	Student showing the path of the Sun using their gestures
Multiple-perspective	An instance when the participant is simultaneously uses Earth- and space-based perspective by making the connection between the two	Student showing the Sun angle seen by an observer on the Earth when northern hemisphere is tilted towards the Sun

Abha Vaishampayan
140 Chambers Building, University Park, PA 16802
abv5104@psu.edu | 412.652.7505

EDUCATION

Ph.D., Curriculum and Instruction, The Pennsylvania State University, 2020

M.S. Physics, University of Hyderabad, 2011

B.S. Physics, University of Pune, 2009

RESEARCH AND TEACHING EXPERIENCE

Graduate Assistant, The Pennsylvania State University, 2015-18
Research Support, The Pennsylvania State University, Fall 2018
Research Assistant, The Pennsylvania State University, 2016-17
Graduate Student Instructor, The Pennsylvania State University, Spring 2019

K-12 TEACHING EXPERIENCE

Instructor, Upward Bound Math and Science Program, University Park, Summer 2018
Teaching Intern, Hazleton Area School District, PA, Summer 2017
Science Educator, Hazleton Integration Project, Afterschool Program, Fall 2018
Project Assistant, Homi Bhabha Center for Science Education, 2014-15
High-School Teacher, Dr. Kalmadi Shamarao High School, India, 2012-13
Instructor and Outreach coordinator, IUCAA, India, Summer 2012, 2013

PUBLICATIONS

Zembal-Saul C. & **Vaishampayan A.M.** (2019) Research and Practice on Science Teachers' Continuous Professional Development in Argumentation. In S. Erduran (Ed.) Argumentation in Chemistry Education: Research, Policy and Practice. Royal Society of Chemistry.

Plummer, J.D., **Vaishampayan, A.M**., Udomprasert, P., Sunbury, S., Cho, K., Houghton, H., Johnson, E., Wright, E., Zhang, H., Sadler, P.M. & Goodman, A. (in progress). Learning to think spatially through curricula that embeds spatial training.

AWARDS AND FELLOWSHIPS

Vincent N. and Lois W. Lunetta Fellowship in Science Education, The Pennsylvania State University, Fall 2015.

Graham Robert Ed Scholarship, The Pennsylvania State University, 2015-16

Dean's Graduate Assistantship Award, The Pennsylvania State University, 2015-16

SERVICE

Department Representative, College of Education Graduate Students Council
The Pennsylvania State University, 2017-18
Secretary, Indian Graduate Students Association
The Pennsylvania State University, 2016-17