Spatial thinking as the dimension of progress in an astronomy learning progression

Abstract

The big idea of *celestial motion*, observational astronomy phenomena explained by the relative position and motion of objects in the solar system and beyond, is central to astronomy in primary and secondary education. In this paper, I argue that students' progress in developing productive, scientific explanations for this class of astronomical phenomena can be defined by the increasing sophistication of spatial knowledge and reasoning in the domain. Drawing upon literature on children's ideas about celestial motion, instruction that supports progress in that domain, and literature on spatial thinking, I developed a learning progression framework that integrates cognition, instruction, and assessment to understand student learning in this domain. This framework was applied to a study of children learning to explain the daily celestial motion of the Sun, Moon, and stars and the phases of the Moon. The application of the learning progression framework to analyse teaching sequences in astronomy extends this review by illustrating how progress within these phenomena is shaped by students' ability to visualize the appearance of objects and their motions across moving frames of reference.

Key words: astronomy; learning progressions; primary school; spatial cognition; assessment

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Introduction

Even with instruction, many children and adults cannot construct the scientific explanation for observable astronomical phenomena (e.g. Kikas, 2000, 2003; Mant & Summers, 1993; Plummer, Kocareli, & Slagle, in press; Plummer, Zahm, & Rice, 2010; Trundle et al. 2002, 2006), such as those that are recommended for study in primary and secondary school (e.g. National Research Council [NRC], 2012; Palen & Proctor, 2006; Sharp & Grace, 2004). The instruction students receive is likely to be fragmented and superficial, not helping students see how the explanations for astronomical phenomena are connected (e.g. Kesidou & Roseman, 2002). This is compounded with the limited time dedicated to astronomy in many schools (Plummer & Zahm, 2010). Reform-based education efforts have focused on improving school science by organizing instruction around big ideas with broad explanatory power for multiple phenomena (NRC, 2012; Smith, Wiser, Anderson, & Krajcik, 2006). One such big idea is *celestial motion*: the set of astronomical phenomena whose explanation requires understanding both observations visible from the Earth and how the actual motions and orientations of celestial objects result in those observations (Plummer, 2012; Plummer & Krajcik, 2010).

Learning to construct explanations for celestial motion requires learners to understand sequences of motion across *frames of reference*. The first frame of reference learned by every child is their own *Earth-based perspective*; their understanding of astronomy from this frame of reference is initially based on their own observations of celestial objects in the sky. An Earth-based perspective on a celestial motion phenomenon includes describing the Sun as appearing to rise and set. The explanation for celestial motion phenomena requires understanding the *space-based perspective* in which the student imagines how celestial objects are actually moving in space, such as the Earth's 24-hour rotation. A full explanation for celestial motion phenomena requires understanding both the Earth-based and space-based perspectives and requires the ability to shift between these perspectives to explain why celestial objects appear to move or change as seen from the Earth. These shifts rely on imagining changes over time, different timescales (days, months, and years), and across vast spatial scales. This type of reasoning is necessary for several astronomical phenomena taught in primary and secondary school, such as the day/night cycle, lunar phases, eclipses, tides, planetary motion, and the seasons.

The Framework for K-12 Science Education (*Framework;* NRC, 2012), commissioned as a guide for developing new K-12 science education standards in the U.S., recognizes the centrality of celestial motion as an organizing principle for students' learning in Earth and space science (ESS), as reflected in the *Disciplinary Core Idea ESS1*: 'What are the predictable patterns caused by Earth's movement in the solar system? … These patterns, which are explainable by gravitational forces and conservation laws, in turn explain many large-scale phenomena observed on Earth' (p. 175). The *Framework* goes beyond a focus on content by organizing student learning around the intersection of disciplinary core ideas, practices of science, and crosscutting concepts. This reflects the complexity of what it means to understand and use astronomical explanations; for students to develop knowledge of astronomy that goes beyond superficial memorization requires sophisticated use of shifting perspectives between patterns in observations made from the Earth and the actual motions and orientations of objects in the solar system and beyond. Such an understanding forms the foundation for students' ability to engage in the science of astronomy; the use of scientific practices, such as argumentation, explanation, and modelling, rely on students' ability to make sense of observational data by shifting to a new frame of reference. Progress in astronomy also requires engagement in crosscutting concepts, such as *patterns* and *scale, proportion, and quantity* – elements knowledge and ways of thinking that are included in spatial thinking (NRC, 2012).

In this manuscript, I will argue that it is *spatial thinking* that forms a foundation for students' ability to improve their understanding of astronomy and engage in scientific practices in this domain. The NRC (2006) report *Learning to Think Spatially* defines spatial thinking as:

> … a constructive amalgam of three elements: concepts of space, tools of representation, and process of reasoning. It depends on understanding the meaning of space and using the properties of space as a vehicle for structuring problems, for finding answers, and for expressing solutions. By visualizing the relationships within spatial structures, we can perceive, remember, and analyze the static and via transformations, the dynamic properties of objects and the relationships between objects. We can use representations in a variety of models and media (graphic [text, image, and video], tactile, auditory, and kinesthetic) to describe, explain, and communicate about the structure, operation, and function of those objects and their relationships (p. 3).

While not mentioned explicitly in the *Framework*, spatial thinking spans the domain-based practices, core ideas, and crosscutting concepts explained throughout the document.

Crosscutting concepts are described in the *Framework* as those that bridge 'disciplinary boundaries, having explanatory value throughout much of science and engineering' (NRC, 2012, p. 83). The concepts, practices, and reasoning processes of spatial thinking are integrated across the domains of science in similar ways to how crosscutting concepts are portrayed in the *Framework*. For example, progress in understanding chemistry requires students to learn how to make connections between macroscopic observations of phenomena and the microscopic processes at work. Understanding chemistry requires students to visualize three-dimensional molecules and perform spatial manipulations, such as mental rotation and reflections (e.g. Barnea & Dori, 1999; Harle & Towns, 2011). Understanding physics requires students to solve problems that involve moving frames of reference, including everyday situations of objects moving with respect to each other as well as complex relativistic situations. Engaging in these problems is improved when students can visualize the relative motion of objects in these problems (Monaghan & Clement, 1999).

To motivate the importance of attending to spatial thinking as a cross-cutting theme in astronomy education, I will use a *learning progression* (LP) framework to make the case for spatial reasoning as a key element of what is *progressing* as students engage in more sophisticated ways of reasoning about astronomy. LPs are hypotheses describing how learners may grow in sophistication towards a core idea in science (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo-Silver, 2009; NRC, 2007). First, I will review the literature on student learning of celestial motion to highlight the important elements of spatial thinking in the domain. Second, I will develop a framework for organizing the use of spatial thinking in an astronomy learning progression. Third, I will apply the framework to analyse children's explanations for the daily apparent motion of the Sun, Moon, and stars and the lunar phases. Using spatial reasoning as the dimension of progress in this LP may be instructive for researchers in other science domains that draw heavily on spatial thinking (NRC, 2006). And, as spatial ability has been shown to be a key predictor of future success in science careers (Wai et al., 2009), and can be improved through training (Casey, Andrews, Schindler, Kersh, et al., 2008; Sorby, 2009; Uttal, Meadow, Tipton, & Hand, et al., 2012), examining how instruction promotes spatial thinking is an important area to explore for improving students' access to science careers.

Spatial thinking in celestial motion

A learner's engagement with the world and development of celestial motion concepts relies on their use of spatial thinking; spatial thinking includes several elements, including a range of internal cognitive processes (such as visualizing relations, imagining changes in scale or orientation, mentally rotating an object) and the ability to externalize these processes by creating spatial representations (such as producing maps, graphs, three-dimensional models, gestures, etc.; NRC, 2006). There are three functions of spatial thinking (NRC, 2006):

1. A descriptive function that captures and conveys the appearance and relationship among objects,
2. An analytic function that allows us to understand the structure of objects, and
3. An inferential function that allows us to generate new answers to problems based on the manipulation and function of spatial objects.

Developing a useful understanding of celestial motion requires all three components of spatial thinking. Increasingly sophisticated understanding of celestial motion requires a learning to understand how the relationship between the Earth and celestial objects' motions in space can be used to answer a variety of observable phenomena. Thus, learning to think spatially in astronomy requires understanding how the system of motions and orientations can be used to generate explanations for new phenomena. As I review literature on cognition and instruction in celestial motion, I will focus on the types of spatial knowledge, such as the properties of objects, the relationships between static objects and the relationship between dynamic objects that characterize ways of knowing celestial motion. I will also examine transformations of these relationships between objects, such as changing between Earth-based and space-based frames of reference, changing orientation, zooming in and out, and enacting these transformations in the physical world (NRC, 2006).

It is important to note that spatial thinking includes more than a simple measure of a learner's *spatial ability*. Spatial ability 'is conceptualized as a trait that a person has and 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).' Linn and Petersen (1986) identified three categories of spatial ability: spatial perception, mental rotation, and spatial visualization. These abilities have been shown to predict performance on measures of students' astronomical knowledge (Black, 2005; Heyer, 2012; Wilhelm, 2009). Engagement in spatial thinking may be dependent on spatial ability, but it also builds on prior knowledge and experiences.

I have interpreted the literature presented here from a primarily cognitive perspective while also recognizing that a purely cognitive approach to interpreting student knowledge and learning is limited. Literature on learning examines the importance of the cognitive versus situative aspects of learning (Anderson, Reder, & Simon, 1996, 1997; Greeno, 1997; Vosniadou, 1997). Situated learning (e.g. Lave & Wenger, 1991) places an emphasis on the context in which learning takes place, and can be interpreted to suggest that learning cannot be interpreted outside of the social situations in which knowledge arose. At the other end of the spectrum is the cognitive perspective, which 'treats knowing as having structures of information and processes that recognize and construct patterns of symbols to understand concepts and exhibit general abilities such as reasoning, solving problems, and using and understanding language' (Greeno, Collins, & Resnick, p. 18). I draw on the perspective that learning, though often facilitated and shaped through social interactions, can also be examined from a cognitive perspective in which learning can be studied from an individual perspective (Anderson et al., 1997). Neither the situative nor the cognitive approach is fully capable of explaining all empirical findings related to knowledge transfer (Vosniadou, 2007). Thus, learning does not need to be viewed as purely situated or purely cognitive; however, the goals of one's research can be used to determine the principal direction of the theoretical focus (Anderson et al. 1997; Greeno, 1996). Spatial thinking includes both internal cognitive processes, such as visualizing relationships, imagining new perspectives, and imaging changes in scale, and also allows us to externally represent those cognitive processes by creating spatial representations using a variety of modalities, including maps, physical models, and gestures (NRC, 2006). This allows the cognitive elements of spatial thinking to be part of a social dialogue in which learning is situated. I chose to forefront the cognitive perspective because of the importance of understanding the cognitive processes involved in learning to think spatially, such as the role of spatial ability and the mental visualization processes needed to learn celestial motion, and the role this type of analysis has played in the literature on spatial thinking (NRC, 2006). In doing so, I draw on a theoretical framework to guide interpretation of student learning using the framework theory approach to conceptual change.

According to framework theory, children's early views of science form *naïve*, domain-specific theories that have both explanatory and predictive power about the world (Carey & Spelke, 1996; Blown & Bryce, 2010; Vosniadou & Brewer, 1994; Vosniadou, 2007; Vosniadou, Vamvakoussi, & Skopeliti, 2008). Children's early explanations for the day/night cycle are primarily based on general presuppositions of naïve physics: the Sun is blocked resulting in night time darkness and the Sun moves straight up and straight down (Vosniadou & Brewer, 1994). Experience with the cultural artefacts and knowledgeable peers, adults, and teachers may lead children to enrich their existing knowledge structures or engender more radical restructuring of their naïve theories. Vosniadou suggests, 'the process of learning science appears to require children to understand a complex and counter-intuitive scientific theory that represents a completely different explanatory framework from their naïve theories' (2007, p. 59). The result of engaging in this process of conceptual change is the formation of *synthetic models,* which include aspects of the scientific view with the intuitive or naive theory (Vosniadou & Brewer, 1994). Studies of children's drawings and use of physical models have found a progression of children's explanations for the day/night cycle which includes several levels of synthetic mental models, such as day and night are caused by the Earth revolving about the Sun (Vosniadou & Brewer, 1994).

This analysis of student thinking about astronomy is also informed by cognitive science literature that helps us understand how experiences with the world shape the development of mental models. Sensory experiences with the world shape development of mental imagery (Paivio, 1986; Clark & Paivio, 1991; Gibbs, 2006; Wilson, 2002). Significant research has shown a link between visual perception and mental imagery (Gibbs, 2006; Kosslyn, 2005).

> Image schemas can generally be defined as dynamic analog representations of spatial relations and movement in space…. Image schemas are imaginative, nonpropositional structures that organize experience at the level of bodily perception and movement. Image schemas exist across all perceptual modalities, something that must hold for there to be any sensorimotor coordination in our experience. As such, image schemas are at once visual, auditory, kinesthetic, and tactile. At the same time, image schemas are more abstract than ordinary visual mental images and consist of dynamic spatial patterns that underlie the spatial relations and movement found in actual concrete images (Gibbs, 2006, p. 90-91).

The development and use of mental models are the result of our physical experience in a 3D environment (Gibbs, 2006; Wilson, 2002; Parsons et al., 1995). Cognition is embodied because it evolved to support our engagement with a 3D sensory world (Glensberg, 1997). Motor processing shapes our use of and understanding of language (Lakoff & Johnson, 1980; Gibbs, 2006). Our ability to make sense of celestial motion begins with our understanding of how observations of celestial objects in the sky relates to our own physical location, the nature of the Earth, and our ability to place ourselves in relationship to celestial bodies.

Celestial motion phenomena, such as the day/night cycle and lunar phases, are children's first access to *observational astronomy*, a description used by the astronomical community to refer to research conducted through collection of data, now often with digital cameras, advanced telescopes, and other astronomical tools and is separate from theoretical, experimental, or historical methods. However, the term *observational* has specific meaning in science education, as scientific observation is more than a direct physical perception. A scientific use of observation is shaped by the viewer's knowledge and understanding of domain specific practices (Eberbach & Crowley, 2009; Fodor, 1984; Shapere, 1982). Though celestial motion phenomena may be *observable* and studied by *direct observation* (Shapere, 1982), I do not suggest that children have actually observed these phenomena; most are unlikely have opportunity or background knowledge needed to make the type of *systematic* observations needed to infer a description of the phenomena, even in formal schooling. Even if children make observations of the location and appearance of celestial objects, they must infer the path of the Sun, Moon, and stars or the changing lunar phases; the change in position and appearance is too slow to track in real time. Thus, children's initial perception of astronomical objects is unlikely to be sufficient, and may be contradictory to the scientific descriptions of these phenomena.

Albanese, Danhoni Neves, and Vicentini (1997) raise a critical issue in understanding children's ideas about astronomy: how do researchers and educators take into consideration the role of children's observations and experiences? Unfortunately, previous research studies often have not clarified, in either their data collection methods or their analysis, how their assessment addresses *both* the Earth-based descriptive model *and* the explanation for the descriptive model (Albanese et al., 1997; Plummer et al., in press). Therefore, I will primarily confine my review of the literature to those studies that clarify the role of reference systems in their work, thus allowing for clear interpretation of students' cognition and the role spatial thinking may play in their reasoning. This review will focus on two phenomena, daily celestial motion and lunar phases, to illustrate elements of spatial thinking; these findings have implications for spatial thinking across celestial motion phenomena.

Daily celestial motion

Literature on children's ideas about the Earth-based perspective of daily celestial motion (DCM) suggests that children may initially learn that the Sun and Moon move up and down but not they move across the sky, thus leaving out the horizontal direction (Plummer, 2009a, 2009b; Plummer, Wasko, & Slagle, 2011). This may be a function of experience with making the necessary observations and their developing spatial ability regarding directions (e.g. Rigal, 1996). Children often do not believe that the stars appear to move at night; alternatively, some believe they are all physically moving about the Earth (Plummer, 2009a). Children's limited ability to describe the stars' apparent motion may be due to their limited *experience* viewing the stars as well as challenges associated with recognizing *patterns* in the stars and then following those patterns across time. This may suggest a spatial challenge with associated with disembedding individual stars or groups of stars in the sky (necessary to track change over time) and with the same type of dynamical pattern of motion and relative direction as is used in describing the Sun and Moon's apparent motion. These challenges with both experience and spatial thinking appear to follow children into adulthood, as adults often do not believe the stars appear to move from their Earth-based perspective (e.g. Plummer et al., 2010).

Children's initial explanations for the Earth-based perspective of DCM include believing that objects appear to move in certain ways because they are *actually* moving that way in space (Plummer et al., 2011). Thus, while they may imagine a space-based perspective, it is matched to their own observation and thus does not require any complex spatial perspective-taking in switching between reference frames. School-based and cultural experiences can introduce new ways of viewing what is moving and the consequences of those motions. This can result in synthetic explanations, combining elements of the scientific views taught in school and the child's original conceptions (Vosniadou & Brewer, 1994). For example, many children continue to believe that the Sun, Moon, and stars appear move due to their actual motions even after learning that the Earth rotates (Plummer et al., 2011, in press). In a study with third grade students' beliefs before instruction, half explained the Sun's apparent motion with its actual motion (Plummer et al., 2011). Most of the other students attempted to use the Earth's motion to explain the Sun's apparent motion – thus attempting to use a space-based perspective of the Earth's rotation to explain the Sun's observed motion from the Earth; however, many of these students were not able to match their description of how the Sun appears to move to their description of how the Earth moves, either through lack of symmetry between the reference frames or mismatched time frames. Similar patterns were observed with how students' explained the Moon's daily apparent motion, but most believed that the stars do not appear to move because they are not actually moving (Plummer et al., 2011).

Learning to explain the stars' daily apparent motion involves both visualizing the stars' appearing to smoothly rise and set above us, across the sky, from an Earth-based perspective and then also imagining that this motion is caused by our perspective changing as we rotate about as the Earth spins on its axis (the space-based perspective). Understanding this explanation may depend on certain spatial abilities, such as mental rotation and spatial visualization (Black, 2005; Mathewson, 1999). Mental rotation is the process of rapidly and accurately rotating objects mentally (Linn & Petersen, 1985). Spatial visualization is the ability to mentally visualize three-dimensional objects from different perspectives and is associated with spatial problem solving involving multiple steps (Barnea & Dori, 1999; Hegarty, 2010). Adults also reveal non-scientific views concerning relationships between the Earth-based reference frame and the space-based reference frame (Mant & Summers, 1993; Plummer et al., 2010). The knowledge that we live on a rotating Earth does not necessarily translate to making a connection between how our actual motion may cause everything celestial to appear to spin about us.

This is not altogether surprising. Our perceptions of the world around us contradict the connection between the Sun, Moon, and stars' apparent daily motion and the explanation using the Earth's rotation (Albanese et al., 1997). The time frame of these celestial objects' motion is much slower than we can perceive. For example, when observing the Moon in the sky, we cannot perceive its motion as its path across the sky takes on the order of a dozen hours. Thus, our understanding of this connection relies on an understanding of the correspondence in time frames (e.g. the timing of the Moon's apparent path across the sky compared to the time for the Earth to rotate once) without the benefit of observing those relative motions in a timeframe we can understand from direct experience. Further, our everyday perception of the Earth is at odds with the concept that we are constantly rotating facing a new direction in space. Telling a child that the Earth's rotation causes the Sun to move, or showing this by rotating a globe, may not be sufficient to help transform their mental model to move between each perspective and *generate* an accurate mental image of the relevant Earth-based and space-based relative orientations and patterns of motion. Research on children and adults use of maps provides clues as to the difficult spatial challenge this presents. The difficulty lies in the spatial perspective-taking ability, more so than understanding how representations we use during instruction may correspond to problems in the real world (DeLoache, 1989; Liben & Downs, 1993, 1997). Studies of children's perspective-taking ability in map reading tasks shows that lower elementary students have much greater difficulty with these types of tasks compared to upper elementary students (Liben & Downs, 1993). Such tasks may tap into similar spatial abilities as would be required to imagine how the Sun could appear to be moving East to West when their own orientation is actually what is shifting as the Earth rotates.

Phases of the Moon

The Earth-based understanding of lunar phases is the notion that over about 28 days, we observe the Moon increasing in illumination from completely invisible to completely illuminated, then it decreases in illumination back to the invisible or new Moon phase. Children are often unaware of the full range of lunar phases (Hobson, Trundle, & Sackes, 2010; Trundle, Atwood, & Christopher, 2007) and may continue to depict non-normative representations of lunar phases through middle school (e.g. ages 11-14; Trundle et al., 2010). While many children describe the Moon as appearing to move through a predictable sequence (Hobson et al., 2010), they also struggle with representing the lunar phases as waxing and waning (Trundle et al., 2007; 2010) and often believe change in lunar phases can happen quickly (during a single day) rather than slowly across many days or weeks (Plummer, 2009a). Reproducing the range of shapes that the Moon moves through and visualizing the relative position and orientation of the Sun-Moon-Earth system in space are spatially challenging actions. Using the temporal framework in which the phase change is also a challenge for learners. These spatial and temporal challenges are further enhanced by students' limited experience with observing the Moon.

Without instruction, children's early explanations of the lunar phases rarely reflect the complex use of reference frames characteristic of the scientific explanation. Young children often use simple occultation to explain the changing phases, such as the clouds moving in front of the Moon (Baxter, 1989). Thus their explanation is still grounded in an Earth-based perspective. As students learn more of how objects move in space, they may incorporate the Moon's orbit into their explanation by suggesting that the Moon's phases occur as the Moon passes through the Earth's shadow (Baxter, 1989). Children may only consider specific orientations and positions in constructing their explanations, such as specific when the Earth is positioned between the Sun and Moon (Parnafes, 2012). Though many older children know that the Moon can be observed during the day (Plummer, 2009a), they may not attempt to account for this in their explanations. Children who know that the Earth rotates may not account for this in the explanations they construct for lunar phases (Parnafes, 2012). These explanations begin to use elements of how the Moon and Earth actually move in space, but do not require a complicated shift in how perspectives change from Earth-based to space-based.

Parnafes' (2012) close examination of how primary students constructed explanations for the lunar phases illustrate two of difficult elements of spatial thinking in constructing the scientific explanation for lunar phases: our perception of how the Moon is illuminated by the Sun and our understanding of how people in different locations may view the Moon at the same time. In one example of two girls explaining lunar phases to each other, one partner focused on the importance of accounting for where you are on the Earth, as well as the view from other countries, and how this changes whether or not you would see the Moon in the sky. The spatial thinking exhibited in this explanation suggests the student is able to consider how her viewpoint on Earth, and other people's view points, are affected by the relative positions of the Earth and Moon. However, she does not fully consider how the illumination of the Moon from the Sun would appear from the Earth.

Her partner focused on how the Sun's illumination would impact observations made from the Earth. However, she was not able to make the normative transformation between the Earth-based and space-based reference frames, as she indicated a non-normative view that when the Moon is closest to the Sun we would see a full Moon and as it moves farther away, we would see less and less of the illuminated side. Similar reasoning has been observed in other studies of children and adults who know that the Moon's position affects the amount of the reflected side we can see but cannot visualize the correct positions (Barnett & Morran, 2002; Trundle et al., 2007; Subramaniam & Padalkar, 2009). This may indicate that she is not able to visualize how the light path would strike the Moon as a sphere. Thus, this highlights one of the central elements of progress in learning to explain the lunar phases – the ability to construct a mental model for a light source illuminates a spherical object when shifting between an Earth-based and space-based perspective on how we observe the Moon (Parker & Haywood, 1998).

The role of instruction in improving spatial thinking in celestial motion

Studies of adults' conceptions of celestial motion suggest that traditional instruction does not support the spatial thinking challenges in this domain (e.g. Mant & Summers, 1993; Plummer et al., 2010; Trundle et al., 2002). This may relate to the difficulty students have in

> making sense of two-dimensional representation and in translating three-dimensional position in space into two-dimensional diagrams. Culturally received science from textbooks illustrates the point, since in Western art, most representation is oriented from left to right side elevation which is a particularly distorting view of the frame, freezing the movement of spin and orbit. (Parker & Haywood, 1998, p. 516)

Performing mental rotation tasks, such as imagining turning to face a new way, is more difficult than physically performing the action of turning to face a new way (Klatzky, Loomis, Beall, Chance, & Golledge, 1998). This suggests that having students attempt to generate the connection between frames of reference in celestial motion, such as a rotating Earth and the apparent motion of the Sun, Moon, and stars, will be difficult without some form of physical, or embodied, support for developing this mental action.

The use of physical and kinaesthetic modelling may be a key element in supporting students' spatial thinking in astronomy (Parker & Haywood, 1998; Rivet & Kastens, 2012). We can 'reduce the cognitive workload by making use of the environment itself in strategic ways—leaving information out there in the world to be accessed as needed, rather than taking time to fully encode it' (Wilson, 2002, p. 628). Physical models allow learners to manipulate situations by trying different spatial or temporal configurations, aiding in their ability to view phenomena from different angles (Shen & Confrey, 2007). Working with physical models and representations can help students develop more sophisticated ways of mentally representing and applying spatial information (Uttal, 2000). Over time, manipulating physical models to solve problems can allow student to develop internal mental models to be called upon at later times.

Teaching sequences that use modelling can support learning through students' kinaesthetic and embodied experiences, as well. Sensory-motor engagement with the world is central to how we learn about our environment (e.g. Gallese & Lakoff, 2005; Glenberg, 1997; Wilson, 2002), facilitating our ability to engage in spatial thinking. For example, we are more likely to accurately understand changes in our orientation with our surroundings when we physically engaging in orientation-changes than just receiving a visual simulation of change in orientation (Klatzky et al., 1998). Students use gestures when attempting to solve novel problems, suggesting that the physical movement may help facilitate cognition (e.g. Liben, Christensen, & Kastens, 2010). The use of gestures has been found to improve performance on mental rotation and spatial visualization problem solving tasks either 'by helping spatial working memory or by facilitating the internal computation of spatial transformations' (Chu & Kita, 2011, p. 114). Gesturing can allow a person to interact with spatial information about an object, such as its relative location to other objects or its orientation while moving (Schwartz & Black, 1999).

One key way that gestures and body movement can help students learn celestial motion is by supporting students in shifting between frames of reference (Padalkar & Ramadas, 2011). Gestures can help students make connections between the Earth-based observation of astronomical phenomena and the explanation using actual motions and orientations in the solar system. These gestures could be used spontaneously during problem solving (e.g. Parnafes, 2012) or as part of guided instruction (e.g. Padalkar & Ramadas, 2011; Plummer, 2009b; Plummer et al., in press). Guided gestures during instruction can help students develop more sophisticated descriptions of the Sun, Moon, and stars' apparent motion. I have studied a planetarium program that uses guided gestures to focus children's attention on the patterns and change of direction of movement; primary students participating in this program demonstrated significant improvement in their ability to describe these patterns (Plummer, 2009b; Plummer et al., in press). My collaborators and I have also measured improvement in students using similar guided gestures during classroom instruction about apparent DCM, such as having students follow their teacher as she gestured with a flashlight across a wall to show the path of the Sun (Plummer et al., 2011, in press). These experiences provide both visual and embodied support for students learning to describe celestial motion phenomena.

My previous research has also examined how teaching sequences can be designed to support students in making the connections between their descriptions of apparent celestial motion and the explanations using the Earth's rotation (Plummer et al., 2011, in press). These studies combined students' kinaesthetic experiences (such as gestures and physical whole-body movement), model manipulation, and use of their physical environment. For example, after engaging in experiences that combine visual and embodied support for how the Sun appears to move across the sky, children used their own bodies as the Earth to experience how the Sun would appear to move (as represented by a lamp) as they rotated on their own axis. This method of supporting students' cognition was successful in improving children's mental models of the DCM phenomena by showing how the space-based reference frame explains their Earth-based observations (Plummer et al., 2011, in press).

Teaching sequences resulting in significant improvement in how students explain the phases of the Moon often include an opportunity for students themselves representing the Earth while holding a small ball (held in the hand or on a stick) to represent the Moon and a light-source represents the Sun. Several studies have found positive results when this type of instruction is used, often combining it with students' own observations of the Moon and opportunities for metacognitive processing, such as discussion and reflection (e.g. Trundle et al., 2002, 2007, 2010; Wilhelm, 2009). Wilhelm (2009) analysed 12-year-old students' development of spatial thinking in this domain using similar instruction. After instruction, students showed significant improvement in spatial relationships of dynamic objects, patterns of periodicity, spatial transformations between the Earth-based phase observation, and the relative position of the Sun, Moon, and Earth.

One of the critical areas of spatial thinking to support during instruction is how a light source illuminates a sphere. Introducing a light source and physical model to students can transform the type of explanations they generate for the lunar phases (Parnafes, 2012). Even in the absence of physical balls and light sources, calling students attention to these types of concrete models can improve reasoning. Subramaniam and Padalkar (2009) introduced college students to anchor situations, where they were asked to imaging a moving ball illuminated by a distant light source, to support students' ability to generate visual scheme of the relevant elements of the problem. The students found it easier to visualize these situations than the corresponding Sun, Moon, and Earth. The anchor situations, like the physical modelling exercises, allowed students to visualize changes in orientation from their own Earth-based frame of reference to how the Moon would appear in space.

Subramaniam and Padalkar (2009) found that helping students understand the different time scales in which lunar eclipses and lunar phases occurred (hours versus weeks) helped students shift towards a more scientific explanation. The participants in their study – a guided one-on-one interview situation – shifted towards the scientific explanation relatively easily. Meaning, they found it easy to accept and recount that the lunar phases are caused by a change in our observing angle on the Moon as it orbits. However, they continued to struggle with using this model to explain *all* the phases and to account for the *accurate* shape of the phase at each orientation. This suggests that the difficulty arises in their ability to engage in necessary spatial visualizations required to move between the space-based perspective of the Moon orbiting the Earth to the Earth-based perspective of how the Moon would appear in the sky.

One final, and yet critical, element important to address is the role of teachers' knowledge and beliefs. There is some indication that teachers may have low spatial abilities relative to other professions (Wei, Lubinski, & Benbow, 2009), which may make teaching in this domain challenging. A complete understanding of any celestial motion phenomena requires both understanding the Earth-based observational description of the phenomena and the model we construct to explain the observational pattern. However, some teachers feel that it is wrong to teach students descriptions of apparent motion and instead focus only on how objects *actually* move in the solar system (Shen & Confrey, 2010).

Learning progressions

LP research brings together cognition, assessment, and instruction to describe general trends in student learning across time. A LP is defined at one end, the 'upper anchor,' by a core idea or practice of science (Duschl et al., 2007), such as energy (Neumann, Viering, Boon, &

Fischer (2013) or scientific modelling (Schwarz, Reiser, Davis, Kenyon, Acher, Fortus, Shwartz, Hug, & Krajcik, 2009). Core ideas of science help make sense of a broad array of phenomena, offering explanatory power within and across disciplines (Krajcik et al., 2012; Smith et al., 2006). 'For the learning progression to be meaningful, the idea that develops needs to specify using cognitive terms that describe what is expected of students to accomplish with the content. The ideas expressed in a construct map need to use language that specifies the type of reasoning students should engage in when using core ideas beyond just statements of declarative knowledge' (Krajcik, 2011, p. 156). This sets the goal for where society hopes students will reach in their understanding of that idea or practice by the end of schooling. The learning progression is anchored at the lower end by descriptions of students' early ideas about that core idea as they enter school.

The full LP is a description of likely pathways students may take from the lower anchor to the upper anchor and are dependent on the instructional context students' experience (NRC, 2007; Corcoran, Mosher, & Rogat, 2009). Thus with different instruction, we may expect there to be a large number of potential learning progressions. However, though multiple pathways may exist, this number is likely to be relatively small as these potential pathways are defined by the logic of the discipline and student cognition, as well as the nature of instruction (Krajcik, 2011). Researchers describing these pathways attempt to identify potential intermediate levels of sophistication that, with the right instructional support, can be used as stepping-stones towards more sophisticated explanations or practices. These descriptions of potential pathways and stepping-stones 'are grounded in research regarding how students actually come to understand core ideas in science rather than relying solely on normative knowledge in the domain' and 'focus on deepening understandings and developing increased complexity, applicability, and epistemological rigor' (Duncan & Rivet, 2013, p. 396). Though LPs are informed by research on individual students, they do not purport to describe how all students will progress from their initial ideas about science towards the scientific goal. Instead, they provide information for educators on likely ways students will understand core ideas of science and what instruction is likely to support progress towards more sophisticated ideas, as they move up the levels of the learning progression. LPs often describe how understanding is developed across grade levels, though breadth of the progression and the grain-size of analysis vary between research groups and topics (Heritage, 2008; Gotwals, 2012).

Learning progression structure using construct maps

The core idea of celestial motion combines knowledge of how objects move in the solar system with knowledge of how objects appear to move and change their appearance based as based on observations made from the Earth's surface (Plummer, 2012). However, because different motions and orientations in the solar system cause different observable phenomena, learning the general principle of using frames of reference to explain astronomical phenomena may not transfer to an ability to explain all astronomical phenomena. For example, the daily apparent motion of the Sun, Moon and stars is caused by the Earth's rotation. The lunar phases are caused by the relative position of the Earth, Moon, and Sun as the Moon orbits the Earth, thus using a different space-based motion. But like all celestial motion phenomena, explanations require taking different perspectives across moving frames of reference to fully understand the phenomena. Thus, while some LPs have a somewhat linear display of levels that increase in sophistication towards the core idea, this structure is not useful for describing how students learn in this domain.

Therefore, this LP was designed using Wilson's (2009) proposal to build LPs from sets of construct maps. A *construct map* is similar to a LP in that it describes how students become increasingly sophisticated in their understanding of a given construct but do not necessarily span extended sets of grade bands typical of LPs. For the purpose of designing a LP for celestial motion, each construct map has the scientific explanation for separate astronomical phenomenon as the top anchor, which allows the development process to focus on a single set of Earth-based observational astronomy phenomena and their associated explanatory motions at a time (Plummer, 2012). Construct maps can be stacked or aligned to create a full LP leading towards a single core idea (Wilson, 2009). The exact placement of construct maps with respect to each other is a function of the difficulty of the concepts and nature of instruction. Building the LP involves uncovering these inter-construct map contingencies (Shea & Duncan, 2012).

Framework for the celestial motion learning progression

In describing the framework for this celestial motion LP, I will focus on three integrated elements of the LP: the *model of cognition, instructional design,* and *assessment.* The *model of cognition* 'should be based on the best available understanding of how students represent knowledge and develop competence in the domain' (NRC, 2001, p. 3). In the LP framework, this is then our hypothesis of how students may move from their initial ideas about the science concepts towards more sophisticated explanations, represented by the levels of the LP. In the framework for the celestial motion LP, I will draw on both the logic of the discipline and the literature on student cognition around daily celestial motion and lunar phases, reviewed above (Krajcik, Sutherland, Drago, & Merritt, 2012). Progress is primarily built around an ability to make connections between observable patterns that change over varying time scales and spatial dimensions and unobservable explanations involving spatial geometry, orientations, and motion. Most importantly, the central element of progress is developing the scientific connections between these perspectives (Albanese et al., 1997; Plummer, 2012; Plummer et al., in press). Interpretation of students' cognition in celestial motion should focus on how children begin by developing normative descriptions of target phenomenon from an Earth-based perspective (Plummer & Krajcik, 2010) and then how sophistication increases as students recognize that the explanation for their observations requires differentiating between two frames of reference. Early explanations may not be scientifically accurate but may begin to describe how celestial objects move in space, as part of their explanation, and then to use elements of the Earth and Moon's motion to explain why celestial objects appear to move (Parnafes, 2012; Plummer et al., in press; Vosniadou & Brewer, 1994;). Increasingly sophisticated explanations may require additional understanding of relative spatial and temporal scales, in addition to factual knowledge about how the Earth and Moon move.

As LPs are not developmentally inevitable, a full understanding of a LP is dependent on understanding the *instructional design* that can support progress up the LP (Krajcik, 2011). Further, 'research-based instructional components are necessary to validate a LP. When testing a learning progression, researchers need to examine how students progress when opportunities to learn exist' rather than relying on instruction that does not consider prior research on student cognition in the domain (Krajcik et al., 2012, p. 266). Though each construct map will need to be tied to instruction that focuses on specifics of that celestial motion phenomenon, the literature on instruction reviewed above provides some general guidelines towards understanding instruction likely to support increasingly sophisticated explanations in this domain. Instruction should be designed to support the cognitive challenges in constructing spatial descriptions and explanations for celestial motion but also consider which aspects to support when, through consideration of students' current understanding relative to the LP levels. Supporting students in the lowest levels of the construct maps begins with helping them visualize patterns of motion and change from an Earth-based perspective. Movement up the intermediate levels towards the scientific explanation then requires support for making the connections between the Earth-based observations and the space-based perspective of motions and orientations. These steps require significant support for the cognitive challenges in spatial thinking.

A focus on appropriate use of *assessment* is also essential to LP development. If the assessment is not well-aligned to the model of cognition, it will not provide useful evidence for support or revision of levels of progress in the LP. Thus, a systemic process towards developing LPs is warranted, to ensure the alignment of science concepts, instructional strategies, and assessments (Stevens, Delgado, & Krajcik, 2009). By carefully articulating the design and use of assessment in developing the LP, we can provide helpful information to future application of the LP to integrated systems of curriculum and assessment design for classrooms (Black, Wilson, & Yao, 2011). Assessments used to measure student's level on the construct maps must be designed in ways that considers cognition and be interpreted in ways that provide evidence for revising the initial model of cognition (i.e. construct map levels). Given the focus on the LP, assessment should consider how students describe the Earth-based perspective and the space-based perspective as well as the connections necessary to make sense of the phenomena (Albanese et al., 1997). Assessing only the students' explanation may not reveal the full extent of their reasoning in the domain when it is not clear they understand the phenomena they are attempting to explain (Plummer et al., in press). Assessment should consider how students are using elements of both the spatial and temporal frameworks, such as different temporal periods, size and distance. The way in which students have the opportunity to express their understanding, such as through drawings, gestures, or models, may influence the nature of their explanations and their ability to communicate different perspectives, thus yielding different results in the LP than if other assessment measures had been used.

Finally, development of the model of cognition in the LP requires clarification of what is progressing, moving up the levels of the LP, and how to design assessment to measure it. LP developers identify *progress variables* 'that identify the critical dimensions of understanding and skill that are being developed over time' (Corcoran et al., 2009, p. 15). For example, Jin and Anderson (2012) have developed LPs for energy in carbon-transforming around progress variables of association (students ideas about how forms of energy are alike/different) and tracing (students' ideas about what changes and what endures during an event). Through empirical studies of student ideas, they have traced patterns in how student ideas shift from informal practices that account for how energy is involved in everyday events towards the scientific account of energy as an analytical tool. This celestial motion LP will define spatial thinking as a progress variable. I will describe how it is spatial thinking that can be used to define what is changing in students' understanding of celestial motion as they develop increasingly sophisticated explanations for phenomena in this domain and how instruction aligned to this progress variable best supports improvement.

Development of construct maps: An example of applying the framework

My process of defining and validating the celestial motion LP has been built iteratively over several studies with each study building on previous work to add new information to the larger LP (Plummer, 2012). Some studies have only examined portions of construct maps, such as tracing learning trajectories for the apparent motion of the Sun, Moon and stars (Plummer & Krajcik, 2010) while others have examined how interventions can inform the development of a construct map, such as describing how children begin to explain daily apparent motions (Plummer et al., 2011) or the reason for the seasons (Plummer & Maynard, 2013). To illustrate how the framework for spatial thinking in celestial motion can be used to develop and define the LP, I report here how different instructional conditions supported children's development of explanations for two construct maps: daily celestial motion of the Sun, Moon, and stars and the lunar phases. Data used to develop the DCM construct map was previously published in Plummer, Kocareli, and Slagle (in press).

Participants

All participants were third grade students (ages 8-9 years) drawn from a suburban school district in the northeastern US. Students had not received extended astronomy instruction prior to the study. Based on the school district's website, the student body demographics includes: 81.5% White, 2.1% Hispanic, 8.5% Black, 4.8% Asian/Pacific Islander, and 3% Multi-racial American students.

Instructional conditions

All students participated in their traditional 6-week astronomy unit, with lessons occurring 2-3 days a week. Classes were assigned to one of four different conditions in which the teaching sequences addressing DCM topics were varied; for lunar phases, three of these conditions used the same teaching sequence while the one additional condition only addressed the apparent change in the lunar phases. These instructional conditions are summarized in Table 1.

[Table 1 about here. *Four instructional conditions used to develop the construct maps.*]

Students (N=24) in Condition 1 participated in a teaching sequence that primarily addressed how objects actually move in space and their relative size and scale, and how the lunar phases are caused by the Moon's orbit about the Earth (as well as other topics about the Moon unrelated to this LP). In *relative size,* the lesson explored the relative size of the Sun and Moon using models. In *defining celestial motion*, students use dictionary definitions to find the correct description of vocabulary words: axis, rotate, revolve, orbit, ellipse, and satellite. Students then work in groups to demonstrate the definitions. Students read a two-page document defining the concepts of rotation and revolution and discuss possible revisions to their original ideas. During *lunar phases*, students were asked to make a prediction of the cycle of the phases of the Moon. The explanation for the phases of the Moon was modelled using a lamp and a Styrofoam ball. Students stood about a lamp, representing the Sun; they were given a Styrofoam ball and asked to observe it as they moved it about themselves to represent the Moon's orbit. This type of modelling activity is commonly used in constructivist approaches to teaching the phases of the

Moon (e.g. Kavanagh, Agan, & Sneider, 2005) though the District's astronomy unit did not emphasize the connection between students' observations of the lunar phase cycle and the modelling. Later, students were asked to observe the Moon in the sky over the course of its cycle.

Students (N=22) in Condition 2 attended a 45-minute program in the district planetarium that addressed an Earth-based perspective on the patterns of change in celestial objects over time (see also Plummer, 2009b; Plummer et al., in press). During the program, students were asked to use their arms to trace the apparent motions of the Sun, Moon, and stars as they rose and set on the planetarium dome. The program also addressed the concept that we see different phases of the Moon on different nights by showing them the slow change of the lunar phases over the course of a month. Students in this condition participated in the district 6-week astronomy unit after data collection.

Students (N=21) in Condition 3 participated in the same District astronomy unit as students in Condition 1. However, their teachers participated in professional development around a new teaching sequence addressing *daily celestial motion* in ways designed to emphasize *how* the motion of objects in space cause the patterns of change observed from the Earth's surface through kinaesthetic and hands-on modelling activities. Teachers helped students explain the Sun's daily motion by first tracing the Sun's path on the wall with the flashlight, as the students also traced this motion with their arms, followed by having the students pretend to be the Earth and rotate to see how a model of the Sun would appear and disappear. A similar activity was designed for the Moon's apparent motion. Finally, students learned to explain the stars' apparent motion by taping star cut-outs on the walls then rotating to observe how they appear to move. Students participated in the same teaching sequence for *lunar phases* as in Condition 1.

Students (N=32) in Condition 4 attended the same planetarium program as in Condition 2 and received the same revised teaching sequence as in Condition 3. Teachers engaged students in the same teaching sequence on *lunar phases* as in Condition 1.

Instructional Conditions 1 and 2 were anticipated to provide limited support for students in moving up the levels of the *Daily Celestial Motion* construct map because they each only focused on one reference frame: space-based or Earth-based, respectively. Instructional Conditions 3 and 4 focused on supporting students in making the connection between their Earth-based observation and the space-based motions in construction explanations for DCM. Therefore, these conditions were hypothesized to provide the support students need to progress to the upper levels of the construct map because they were well-matched to the construct. Further, Condition 4 was designed to provide additional support for students' in progressing up the DCM construct map given that this condition included the planetarium visualizations of the Earth-based perspective prior to classroom instruction.

Instructional Conditions 1, 3 and 4 were hypothesized to provide support for students in moving from their initial explanations for the lunar phases towards the scientific explanation for the phenomena. However, the limited emphasis on connecting students' Earth-based understanding of the patterns of lunar phases with the space-based explanation constructed using the models did not fully match the hypothetical construct map for lunar phases.

Assessment

Interviews took place in an unused classroom at the students' school. Students were asked to first provide their ideas about what they think the Sun, Moon, and stars appear to do when viewed from the surface of the Earth. Only after these initial questions were the students asked to explain why they think those patterns of motion/change (or lack of motion/change) would occur. This allowed the student and the researcher an opportunity distinguish between frames of reference and consider the connection between apparent and actual motions. The interview protocol was designed from an embodied cognition framework, emphasizing the significance of embodied action in understanding students' mental models (Gibbs, 2006). This was done by first providing a small dome, representing the sky that they could sit under and demonstrate their understanding of the way the Sun, Moon, and stars appear to move in a 3D space. The dome was about 4' in diameter and sat on top of a 4'X4' open cube where the student and interviewer sat. The student was given a small flashlight to use to point out the locations and motions of the Sun, Moon, and stars on the interior of the dome. Later the students were given a piece of paper on which to draw their representations of the lunar phases. Students were provided with models to facilitate their ability to construct their explanations, including small Earth globe, a yellow ball for the Sun, and a small grey ball for the Moon. Thus, students did not have to try to communicate a 3D concept in only words or 2D representations. Generative questions were used to tap into students' mental models rather than only prompting factual recall (Vosniadou & Brewer, 1994).

A distributed cognition perspective - such that both internal and external representations play a role in how understanding is expressed and developed - influenced interpretation of the interview data (Vosniadou, Skopeliti, & Ikospentaki, 2005; Vosniadou, 2007). 'Memory, mental imagery, and problem solving do not arise from internal, computational, and disembodied processes but are closely linked to sensorimotor simulations' (Gibbs, 2006, p. 12). Coding of the interviews relied on interpretation of both students' words and their use of models and gestures. Each aspect of celestial motion was broken down into multiple categories describing aspects of the students' descriptions (e.g. the Sun's path, the Sun's rising and setting directions, etc.) resulting in the primary categories (Plummer et al., 2011). Within these categories, codes were defined over several previous studies (Plummer, 2009a, 2009b; Plummer et al., 2010, 2011, in press) and drawing on other literature (e.g. Trundle et al., 2007). The author and a graduate assistant individually coded a sample of 20 interviews to reach an inter-rater agreement of Cohen's kappa=0.84.

Melding Cognition, Instruction, and Assessment: Development of the Construct Maps

The initial step in developing the construct maps was to create a series of codes within each of the explanation categories. Each new category includes a series of codes defined by combining the codes for *apparent* celestial motion described from an Earth-based perspective with the explanation that the students provided (which could be from an Earth-based or a space-based perspective). These secondary codes were ordered according to accuracy and by looking for trends in reasoning, helping to define the structure of the construct map levels. For the celestial motion categories, this involved first sorting by accuracy of explanation, moving from naïve explanations, to explanations involving the Earth's motion, then to explanations that used the Earth's rotation. These explanations were further ordered by considering the accuracy of the description of the Earth-based perspective of apparent motion. For the lunar phases category, explanations were ordered first by using their descriptions of the phases as see from the Earth, length of time the phases change, description of the Moon's orbit, and then according to how the student uses motions and perspectives in space to explain why the Moon's appearance changes.

The next step in the process was to use the empirical data to further refine the order of the levels in these construct maps and the contingencies between the initial construct maps (Shea & Duncan, 2012). First, the three preliminary construct maps for the Sun, Moon, and stars were combined into one construct map describing DCM. This process involved looking at the frequencies of student responses, before and after instruction, to determine which elements of the scientific explanation were common, an indication of the relative ease of the concept to learn, and which were used more infrequently, an indication of the difficulty of the explanation. For the lunar phases construct map, the frequencies of responses were examined to help determine which aspects of the scientific explanation may be easiest and which may be the most difficult to clarify the ordering of potential levels.

The next step in the development of the construct maps was to understand the relationship between the *type of spatial improvement, conceptual improvement,* and the nature of the *instructional support*. Each student's pre and post interview results were categorized according to construct map levels. A Kruskal-Wallis test was used to compare the four conditions before instruction to see if they had a comparable distribution on the construct maps; the post instruction results for all four conditions were compared after this analysis. A Wilcoxon signed-ranks test was used to examine improvement for each instructional condition.

Overview of the daily celestial motion and lunar phases construct maps

Below, I will first discuss the construct map describing how students' explanations for *Daily Celestial Motion* (DCM) increase in sophistication from naïve to scientific followed by the construct map for *Lunar Phases*. Figures 1 and 2 present a 'thumbnail sketch of the character of the explanation or explanatory model that students at the level would characteristically offer for the relevant phenomena' (Rogat, Anderson, Foster, Goldberg, et al., 2011, p. 9) for the DCM and Lunar Phases construct maps, followed by a *narrative* version below.

Daily celestial motion construct map

Developing scientific descriptions and explanations that connect the Earth-based perspective of the Sun's apparent motion to the Earth's rotation in space appeared to be less difficult for students, compared to the Moon and stars. Therefore, I used changes in how students understand the connection between the Sun's apparent path across the sky and the Earth's rotation to distinguish the lower construct map levels. The upper levels of the construct map were defined by adding student explanations for the more spatially complex aspects of the construct: explanations for the Moon and stars apparent motion. Figure 1 provides an overview of the DCM construct map, left, and an illustration of students' spatial thinking changes as students move up the construct map, right.

[Figure 1 should appear about here. The Daily Celestial Motion construct map (left) along side the corresponding elements of progress in spatial thinking (right).]

The lowest level (**Level 1**) of the DCM construct map describes students with intuitive beliefs, showing limited impact of scientific or school-based explanations: students explained the their Earth-based observations of the apparent motion of the Sun, Moon, and stars with those objects' actual motion. Children indicate little or no use of perspective taking and limited sophistication in their description of 3D patterns of motion from their own Earth-based perspective. Most students in this study began at Level 1 on the DCM construct map. Students may know that the Earth rotates but they do not *use* this motion to explain descriptions of the Sun, Moon, or stars' apparent motions and thus have not begun to use explanations that move between space-based and Earth-based perspectives. One challenge for students at this age is that their perspective-taking abilities may still be developing (Roberts & Amin, 1989; Newcombe & Huttenlocher, 1992), which may limit their ability to construct the scientific explanation.

Tommy was at Level 1 during his pre-interview. He described the Sun's apparent daily motion as rising and setting in the roughly the same place on the horizon, rather than the scientific description of the Sun moving in a smooth path across the sky; he explained this using the Sun's own motion. He provided the same description of the Moon's apparent motion and explained this by moving a model of the Moon moving up and down next to the Earth. When asked why they move that way, he said 'Cause every time the Sun goes up, it looks like the stars go up and down with the Moon.' This is similar to many children who tie the stars' motion to the Sun or Moon's motion. He believed that the stars are significantly smaller than the Moon and located in the same area as the Moon, a common pre-instructional belief among children. When asked if the Earth also moves, he said that it rotates once every few hours. He described the stars as rising and setting in a similar pattern to the Sun and Moon.

Many other students at this level, as well as the next levels, did not provide scientific Earth-based observational descriptions of the Moon and stars appearing to rise in the East and set in the West in a smooth motion, a common challenge among children (Plummer, 2009a, 2009b; Plummer et al., 2011) and adults (Plummer et al., 2010; Shen & Confrey, 2010). Children have limited experience making appropriate observations of the Moon's location over time but their understanding may also be limited by challenging spatial factors. For example, attending to the Moon's apparent motion requires an organized sense of one's surrounding from which to compare the Moon's location over time. Even more challenging is the ability to recognize and track the location of individual stars over time; such a task requires knowing what features of the observation should be encoded for later analysis (Hegarty, 2011) and may rely heavily on the spatial visualization ability of the individual, to recognize embedded figures (i.e. constellations) in more complex backgrounds (Tversky, 2005). Thus, part of progression along this construct map is developing increasing sophistication in ability to *describe* the spatial patterns of the phenomena as seen from the Earth, not just to explain the phenomena (Plummer & Krajcik, 2010; Plummer et al., in press).

Students in **Level 2** are moving towards more coherent explanations in which the patterns of change in the sky are matched to the actual motion of the Earth. Students at Level 2 only used the Earth's motion, and not the Sun's motion, to explain the Sun's apparent motion, but did not accurately use the Earth's rotation; however, they may still combine the Earth's motion with the Moon and stars' actual motion to explain those objects' patterns of apparent motion. What distinguishes this from the lowest level is that students have begun to take a *frame-of-reference perspective* by recognizing that their own motion can explain celestial phenomena. This shift towards using reference frames in their explanations is a critical transition in their astronomical reasoning. Some of their difficulty in obtaining more sophisticated levels on the construct map may be due to limits in the extent to which they are able to generate spatial imagery of how their own motion on the Earth could impact the direction of the Sun's motion or limited spatial knowledge of the nature of the Earth's rotation in space.

At **Level 3,** students accurately used the Earth's 24-hour rotation to explain the Sun's apparent motion across the sky but not the Moon or stars' apparent motion. The understanding expressed by students at this level is an important step towards a more sophisticated spatial understanding because they recognize that the timescale and nature of the Earth's motion matches the timescale and pattern of the Sun's motion observed from the Earth-based reference frame. But at the same time, the students do not extend this symmetry of explanation to the Moon and the stars so their understanding of how the Earth's rotation affects the change in their observations of celestial objects' location over time is limited.

One of the challenges in communicating the findings of a LP is determining the detail needed to communicate potential 'levels of sophistication' that would be helpful for other educators, researchers, and policy makers. There is quite a bit of variation in Level 3 given the broad range of potential explanations for the Moon and stars' daily apparent motion. One of the goals of LPs is to unpack what it means for students' ideas to increase in sophistication as they experience instruction. Communicating ideas within learning progress levels should include productive ideas that teachers might build on during instruction. But in the interest of space, I have not unpacked all those possible variations of the intermediate levels and will instead draw the reader's attention to a few key examples of spatial thinking.

Isabella was at Level 3 prior to instruction. She described the Sun appearing to move across the sky, from East to West.

> Interviewer: What makes it so the Sun appears to move across the sky?
>
> Isabella: Well, when they're asleep we turn like this [she slowly moves the globe in front of her until the part of the U.S. we live in is visible to the model of the Sun], so we're facing that way [she uses her finger to point between our location on Earth and the model of the Sun, showing the angle of sight].

She continues to show how the globe's rotation results in the Sun setting. Her gestures indicate she understands how the angle of our observation changes when we can see the Sun from Earth.

> Interviewer: You said it [the Moon] moves around the sky like this [gestures to show Moon circling around the sky, the motion Isabella indicated earlier in the interview]?
>
> Isabella: Well, the Earth moves around [she rotates the Earth globe with her left hand while holding the Moon ball still to the side] and I think the Moon doesn't move [unintelligible words].
>
> Interviewer: So, while the Earth is spinning we see it move around the sky?
>
> Isabella: Well sometimes people think it might move around the sky but it doesn't. It stays in one spot and then when at night it shines the Sun's reflection makes the Moon shine.

Here, Isabella's description and explanation reveal both elements of sophistication as well as limitations to her spatial thinking. She has an alternative description Moon's apparent motion, believing that it appears to circle about the sky. She explains this with the Earth's rotational motion – this is a promising step as she's using the same normative reasoning as she applied to the Sun's apparent motion, but not to the extent that she understands the accurate nature of how the Moon would *appear* to move. But she is able to distinguish between apparent and actual motion – thus clarifying two the Earth-based and space-based reference frames. She believes that the stars do not actually move and do not appear to move, thus not generalizing the concept of the Earth's rotation causing all objects in space to appear to move around us.

Improvement from Level 3 to **Level 4** involves a shift in how students explain either the Moon *or* the stars' apparent motion, building on the explanation for the Sun's apparent motion developed at Level 3. This level was split as students could adopt a more scientific explanation for the Moon or for the stars without needing to explain the other accurately. At **Level 4A**, students accurately describe the stars as appearing to rise and set and explains this with the Earth's 24-hour rotation. Students found accurately *describing* the stars' apparent motion to be more challenging than using the Earth's rotation to *explain* the stars apparent motion. Prior research demonstrates that people have an easier time imagining they are moving to face new locations than to imagine a room moving about them (Tversky, Kim, & Cohen, 1999). This may help explain the difference in difficulty. Students moving into this level of understanding may be starting to find the concept of the Earth's rotation causing other objects to appear to move to be plausible. But generating a scientific description of stars appearing to rise and set because of this may be beyond many students' spatial visualization ability. Studying constellations before learning to describe stars' apparent motion may be beneficial, as it would allow students to chunk of information such that they can describe individual constellations as appearing to rise and set versus trying to imagine individual stars rising and setting.

Students at **Level 4B** described the Moon as appearing to move across the sky and explain this with the Earth's 24-hour rotation. Many students at this level believe that the Moon does not actually move; they hold a mental model in which the Sun and Moon are on opposite sides of the Earth while the Earth rotates between them. Within this mental model, moving between the two frames of reference (the Earth's rotation and the Moon's apparent motion) is no more difficult than a similar explanation for the Sun's daily apparent motion. However, the data suggests that once students learn that the Moon orbits the Earth, it is more difficult for students to apply the Earth's rotation to the Moon's daily apparent motion. Because the Moon is actually moving, they often used this in their explanations, sometimes along with the Earth's rotation. Part of the difficulty lies in determining how the different timescales of motion (one day for the Earth's rotation versus 28 days the Moon's actual orbital motion) affect their observations of the Moon. How the Moon's actual motion impacts the Moon's apparent motion is a challenge beyond the levels explored in this construct map (i.e., the change in rise and set time for the Moon).

At **Level 5,** students can explain the apparent motion of the Sun, Moon, and stars using the Earth's rotation. The objects' apparent motions are described as smooth paths, rising and setting, across the sky and, for the most scientific version of this explanation, in the same direction. Students may or may not accurately describe the length of time it takes for the Moon to orbit the Earth. They do not necessarily understand more complex aspects of daily apparent motion such as the change in the Moon's daily rising and setting time over the course of the Moon's orbit or the pattern circumpolar motion of the stars – these are areas of further improvement in sophistication beyond the construct map here but do represent increasingly sophisticated uses of spatial thinking and reasoning in celestial motion. What distinguishes Level 5 from lower levels is that students now systematically use the Earth's rotation to describe a coherent set of descriptions of daily apparent motion. This suggests a potential transformation in how they view the use of frames of reference: they can generalize how our motion on a rotating Earth affects an array of possible phenomena.

Tommy improved from Level 1 to 5. After instruction, Tommy describes the Sun as appearing to move in a smooth path across the sky, though from West to East. He explains this by holding the Sun-ball in one hand and slowly rotates the Earth globe, which he says takes 24-

hours. He demonstrated the same path for the Moon as for the Sun. Unlike many students, his spatial reasoning includes more a sophisticated use of temporal reasoning to distinguish the motions occurring in this explanation. Tommy is able to distinguish between the Moon's slow orbit and the Earth's relatively quick rotation in his explanation: 'Because the Earth is moving and [the Moon] is kinda moving too, just very slow'. His demonstration using the models clarifies this explanation as he barely moves the Moon in its orbit as the Earth rotates once to cause the Moon's daily apparent motion. He understands that the stars are farther than the Moon and stars, and that some can be larger than the Earth and Sun, but others are still smaller than the Moon. His explanation for the stars' apparent motion also improves:

> Interviewer: So what will it look like the stars are doing?
>
> Tommy: Moving like the Moon does, kind of, because Earth is moving to the left and stars are moving to the left, so it's pretty much…
>
> Interviewer: Do the stars look like they are rising and setting too?
>
> Tommy: Yes

He does not quite have the correct explanation for how one's own motion in one direction causes something to appear to move in the opposite but he is moving towards a far more sophisticated explanation in this domain than many students.

Phases of the Moon construct map

In the first steps of defining the lunar phases construct map levels, I examined trends in the relative difficulty of how students described the phases, their knowledge of appropriate timescales, and their explanations. As shown in Figure 2, the lower levels describe a shift in students' knowledge the Earth-based perspective on patterns of lunar phases while the upper levels describe increasingly sophisticated uses of spatial reasoning, including the ability to move between the space-based and Earth-based perspectives, towards the normative explanation for lunar phases.

[Figure 2 should appear about here. The Lunar Phases construct map (left) along side the corresponding elements of progress in spatial thinking (right).]

Level 1 includes students with limited understanding of the apparent change in the lunar phases as well as naïve conceptions about how and why the Moon changes shape. Students at this level believe that the Moon can appear in multiple shapes in a given night, drew non-normative shapes of the Moon, or did not believe the Moon appears to change shape. Without appropriate instruction, children often depict both normative and non-normative representations of the lunar phases (Hobson et al., 2009) and often believe that the Moon's phase can change over short time periods, such as minutes or hours (Plummer, 2009a). This is consistent with their explanation for the phases; many children believe that clouds cause lunar phases (e.g. Baxter, 1989). Other common naïve explanations included the idea that the Moon is blocked by something or passes through the Earth's shadow (Baxter, 1989). Thus, similar to the intuitive models for DCM, students construct explanations that do not require more sophisticated shifts between frames of reference or involve changes in spatial orientation.

Students in **Level 2** had general knowledge of the Moon's changing phases, such as being able to draw multiple accurate depictions of lunar phases and knowing that changes between these phases takes longer than a single night. But their explanations for the lunar phases are similarly non-normative as in Level 1.

Students in **Level 3** generate explanations which integrate aspects of the naïve explanations (e.g. using the Earth's shadow) with aspects of the scientific explanation that were not seen in explanations of students in Level 1 or 2 (such as our observations of the Moon are caused by half of the Moon being illuminated by the Sun). Chelsea improved from Level 2, where she believed that clouds covered the Moon to cause phases, to Level 3 after instruction. She was able to draw multiple phases of the Moon and when asked why we see different phases of the Moon, she used changes in the Moon's location with respect to the Earth and Sun to explain its changing phases; thus she and others at this level are beginning to think about how to incorporate a space-based reference frame into their explanations for the change in our Earth-based observations of lunar phases.

> Interviewer: Why does the shape of the Moon appear to change?
> Chelsea: Because the Sun isn't reflecting like on the, like we're right here and the Moon's right here [positions Moon on the opposite side of Earth from the Sun] and the Sun's only shining on half of the Moon [gesture points to Sun, across the Earth, to the Moon on the other side] so you can't see it.
> Interviewer: What's keeping the other half from getting light?
> Chelsea: The Earth.
> Interviewer: How would you get a new Moon?
> Chelsea: When the Moon's directly behind the Earth [holds Moon on opposite side of Earth from the Sun].
> Interviewer: How would you get a full Moon?
> Chelsea: Like this [positions the Moon directly between the Earth and the Sun].
> Interviewer: And the half Moon, how would you get a half Moon?
> Chelsea: Just like that. [She positions the Moon so that it would be halfway into the Earth's shadow, opposite the Sun.]

Students at this level have learned some of the spatial content they need to move towards the scientific explanation, such as the nature of the Moon's orbit and that the Sun's light causes half of a surface to appear illuminated. But students, like Chelsea, include non-normative reasoning as to how that illumination will impact our observations of the Moon. She uses the Earth's shadow to produce phases such as new and half. And she places the Moon in between the Earth and Sun claiming this would be the full moon (when from a scientific perspective, this would be the new Moon).

At **Level 4,** students only used aspects of the accurate explanation to explain the lunar phases and not the naïve explanations from the lower levels; however, their explanations do not completely explain the Earth-based phenomena: the specific phases of the Moon they can observe from the Earth's surface. For example, while they may use the Moon's orbit and the angle of our observation to explain the lunar phases, they do not indicate the correct alignment of the Sun, Earth, and Moon for particular lunar phases, such as showing the position for a crescent Moon but saying we would see a full Moon. This level of explanation represents a more sophisticated use of perspective taking between reference frames, as they now believe that the pattern of phases can be caused by our angle of observation rather than something blocking the Moon. Prior to instruction, David was at Level 3:

> Interviewer: Why does the shape of the Moon appear to change?

David: Because the Sun's light on the Moon… so depends on where the Moon is in its orbit. Get the light from the Sun.
Interviewer: Where does the light come from when we see the Moon?
David: From the Sun.
Interviewer: Can you show me where the Moon would be to see a full Moon?
David: Right here. [He places the Moon directly between the Earth and Sun.] No, it couldn't be here. If the Moon was here, it would look like an eclipse.
Interviewer: Do you know where it would need to be to be a crescent?
David: Here [puts it at a 90 degree angle to the Earth and Sun] or here [same angle, on the other side].
Interviewer: Why does it look like it is a crescent?
David: Because it shines on a piece of it [gestures to describe part of the Moon facing the Sun].

In this vignette, we can see David use elements of the scientific explanation without using non-normative explanations. However, he does not choose the correct position of the full Moon and crescent, perhaps because he cannot visualize how the Moon will appear at various angles.

At **Level 5,** students are more adept at choosing the correct alignment of Sun, Earth, and Moon to demonstrate each lunar phase suggesting that they are now capable of more complex spatial visualization than at lower levels. They are able to visualize the half of the Moon that will be illuminated by the Sun at any given angle and how the Moon will then appear on the Earth's surface at various angles with the Earth and Moon. After instruction, David's explanation was classified into Level 5 of the construct map.

Interviewer: Do you want to explain why we have different phases?
David: So, right now it is a new Moon because Sun, cause the Sun is only shining on [he gestures to indicate the side facing the Sun) the part it is shining on.] Now… [Looks around, then quietly says] Better to have a flashlight. So, Sun's always shining on this part. So, now, [he moves the Moon about 1/8th of an orbit while keeping his hand gesturing to indicate the illuminated side] it looks like a little part is lit up because the Moon is reflecting on the same side but it is tilted differently from the Earth. Then it would go around [shows it orbit to the opposite side of the Earth from the Sun] to almost full, that would be up here [raises it so that it would not fall in the Earth's shadow] otherwise we would have an eclipse. Then it would just go back to new Moon again.
Interviewer: When would we see the first quarter?
David: Here. Wait, it goes clockwise… yes.

His explanation now expertly considers the way in which the Sun will illuminate the sphere and how that would cause us to see different phases. At the end he is able to visualize the problem with having the Moon in an exact line with the Earth and Sun and thus corrects his model to allow the imaginary light from the Sun-ball to illuminate his Moon ball. But he also notes that this would be easier to explain if he could scaffold his ability to visualize the proper alignment by using a light source for the Sun (the flashlight).

Relationship between instruction and improvement using construct maps

LPs can be seen as tools to describe students' current level of knowledge and how various teaching sequences helps move them along towards a more sophisticated explanation. In this section, I will focus on how the two construct maps can be used to describe progress in students' spatial reasoning about astronomy in different teaching sequences and what that reveals about the role of instruction in this domain.

Daily celestial motion

Figure 3 shows a graphical representation of students' improvement along the levels of the DCM construct map for two of the instruction conditions. This visually reveals differences between how each instruction condition moved students towards a more scientific explanation for daily apparent motion patterns. Prior to instruction, most children had a naïve perspective about DCM: they explained any apparent motion or lack of motion with the objects themselves actually moving (Figure 3). And while all four conditions showed a shift towards higher levels, there were still few students at Level 5.

Statistical comparisons show that all four conditions improved significantly (Condition 1: Wilcoxon Signed Ranks Test $Z=-2.818$, $p<0.01$; Condition 2: $Z=-1.986$, $p<0.05$; Condition 3, $Z=-3.309$, $p=0.001$; Condition 4, $p=-3.694$, $p<0.001$). All conditions had similar distributions of students at levels on the DCM construct map before instruction (Kruskal-Wallis $H = 2.508$, $p=0.474$). After instruction, there was significant difference between all four conditions ($H = 12.822$, $p <0.01$). This was the result of Condition 3 and Condition 4 being significantly higher ranked on the Construct Map than Condition 1, after instruction, (Mann-Whitney $Z=-2.43$, $p=0.025$; $Z=-3.834$, $p<0.001$, respectively). Significant differences were not found between Condition 2 and other conditions. Conditions 3 and 4 were not significantly different after instruction.

[Figure 3 should appear about here. Student transitions along the Daily Celestial Motion construct map, broken down by instructional condition (N=24, N=22, N=21, and N=32, respectively). The line strength indicates the number of students who transitioned from one level to another. One-point line thickness represents one student.]

Condition 1 teaching sequence focused on engaging students in describing the *actual* motions in the solar system (i.e. the Earth rotates and revolves) but did not focus on using the Earth's motion to construct explanations about changes that may be observed in the sky. Thus, it was up to the student to decide how the Earth's rotation may or may not result in patterns of motion from the Earth's surface and to intuit a need to change between reference frames. As in the other conditions, nearly all students in Condition 1 knew that the Earth rotates (92%), though only 38% knew that this took 24 hours (Plummer et al., in press). Figure 3 shows that this instructional approach resulted primarily in improvement towards explanations for the Sun's apparent motion that used non-normative Earth's motion (Level 2). Using the Construct Map as a lens on *Condition 1* points to the spatial difficulty of constructing the scientifically parsimonious explanation that the Sun appears to rise in the East and set in the West because the Earth rotates in the opposite direction. This suggests that support for students' progress along this aspect of the LP requires more than a focus on describing the Earth's rotation in space. It further illustrates that students are unlikely to spontaneously construct the accurate apparent motion of the Moon and stars even when they understand they live on a rotating Earth; 67% of the students accurately described the Earth's 24-hour rotation after instruction in this condition.

Condition 2 teaching sequence focused on helping students learn to describe the apparent motion of the Sun, Moon, and stars through their experience in a 45-minute planetarium program. While these students made significant progress in their ability to *describe* apparent celestial motion (Plummer et al., in press), Figure 3 shows the sporadic nature of their post-instruction *explanations* for DCM. Though the overall trend was improvement along the construct map, the changes almost appear random with some students moving up the construct map and others moving down. This may suggest that individual students made sense of apparent motion differently, with some connecting these motions accurately to the Earth's rotation (the planetarium director consistently explained that the motions students were observing were the result of the Earth's rotation) while others believing these descriptions as the actual way in which objects move. For the LP, this suggests that instruction that supports students Earth-based descriptions of patterns of motion through visual and kinaesthetic engagement may be insufficient to support significant progress in explanations that connect the Earth-based perspective to how the Earth is moving. Students were not supported in the spatial thinking processes needed to engage in perspective-taking or more complex multi-step visualization processes.

Condition 3 teaching sequence was designed to help students make the connection between the Earth's rotation and the apparent motion of the Sun, Moon, and stars through classroom modelling activities. The improvement shown in Figure 3 suggests that impact of this instruction on students was to shift students from lower levels into Level 3 where they could accurately explain the Sun's apparent motion using the Earth's rotation. However, while many students' explanations for the Moon and stars improved, it was not sufficiently accurate to move them into Level 4. The major struggle students had in moving beyond Level 3 was separating the Moon's actual orbital motion from its daily apparent motion and describing stars' apparent motion. Interviews with the teachers suggest that they provided limited support to help students differentiate the temporal frameworks for the Moon's apparent motion: recognizing the difference between the Moon's orbital timeframe and the Earth's rotational timeframe. Instruction will need to focus more attention on this spatiotemporal problem. To support student learning of the stars' apparent motion, the teachers engaged students kinaesthetically as they spun in place, like the Earth, and watching the *apparent* motion of cut-out stars on the wall. Students were more likely to use the Earth's rotation to explain the stars' motion after instruction but still struggled with describing the complex 3D apparent motion of stars across the sky at night.

Condition 4 teaching sequence focused on helping students connect the Earth's rotation to apparent motion, using the same instruction as *Condition 3,* but students also attended the same planetarium program as *Condition 2*. Many students improved from Level 1 into Level 3 and Level 4. The improvement into Level 3 can be explained in similar ways as was found in *Condition 3.* Improvement into Level 4 can be explained using a combination of instructional supports. The trip to the planetarium may have helped students improve their ability to accurately describe both the Moon and stars' apparent motion to a greater extent than was found in Condition 3 (Plummer et al., in press). As many students had difficulty describing the stars' apparent motion, the planetarium was most likely a significant factor in helping students develop explanations for the stars. The teachers each engaged the students in kinaesthetically modelling to explain the Moon's apparent motion however only two of the teachers also engaged students in kinaesthetic modelling to explain the stars' apparent motion. These kinaesthetic experiences would have helped some of the students construct the scientific explanation for the Moon and/or stars' motion.

Lunar Phases

Figure 4 illustrates the improvement measured, before and after instruction, for the lunar phases construct map. *Conditions 1, 3* and *4* were grouped together for this analysis because they used the same teaching sequence. Students in *Conditions 1, 3,* and *4* made significant improvement (Wilcoxon Signed Ranks test, $p<0.001$) while students in *Condition 2* did not improve along the construct map ($p=0.646$).

[Figure 4 should appear about here. A comparison of improvement along the lunar phases construct map: Students in the classroom instruction (Conditions 1, 3 and 4, N=69) and students from the planetarium instruction (Condition 2, N=19). Students whose responses were unclear were not included in this analysis. The line thickness was set to 1-point represents one student's progress.]

Condition 2 teaching sequence: It is not surprising that students who only attended the planetarium program did not improve significantly along the lunar phases construct map as instruction did not address the explanation. The program showed students that during a single day the phases do not change significantly but that over the course of many days we see different phases. However, this was already knowledge that most students had as most were at Level 2 and above (see Figure 4).

Conditions 1, 3, and 4 teaching sequence: The kinaesthetic and psychomotor modelling students' engaged in during classroom instruction helped those students improve significantly. In the model, the student pretended that their own head is the Earth while holding a Styrofoam out away from them at various angles. A lamp illuminated the Moon-ball so that the student sees the phases change as s/he orbits the Moon around her/his body. This instructional approach allowed students to manipulate spatial orientations in space and to see first-hand how changes to the system could result in patterns of change in the Moon's appearance. However, only a small percentage reached Level 5 (17%).

Three possible issues with the instruction may explain why more students did not reach the highest level. First, most students began at the lowest levels of the construct map. Other studies have found that students who did not have some initial conceptions of the Moon's orbit and use only alternative explanations did not reach the full scientific explanation after instruction (Barnett & Morran, 2002). Second, teachers may not have fully addressed the size and scale issues, such as the relationship between the Moon's size and distance relative to the Earth's shadow along with limitations to how this is portrayed in the model. The Moon easily falls into the Earth's shadow because, in the model, the Moon is very close to the Earth (the student's head) as the orbit is constrained to the length of the student's arm. Given that the Earth's shadow is one of the most common alternative explanations for the lunar phases (e.g. Baxter, 1989; Schoon, 1995; Trundle, Atwood, & Christopher, 2002), this is a problematic aspect of an otherwise helpful model. Third, even when students understood the explanation while using the model, they did not have an opportunity to mentally engage with understanding how the Sun's angle illuminates the Moon. Therefore, when they had to recreate their model without the lamp, they could not visualize the correct angle in the space-based reference frame to produce their observation in the Earth-based frame.

Conclusion

Spatial thinking as progress in the sample construct maps

The goal of this manuscript was to show that spatial thinking could be used as a progress variable in a LP for celestial motion. I have illustrated how spatial thinking helps define progress in two construct maps, daily celestial motion and lunar phases, within the larger LP. To conclude, I will demonstrate how the two construct maps illustrated the role of spatial thinking in the elements that define a LP: cognition, instruction, and assessment. Then, I will discuss the implications of this work for the broader celestial motion LP and implications for future research.

Cognition and spatial thinking in the construct maps

Students' progress was initially defined by a shift from constructing explanations based on a single, Earth-based perspective, towards using the relationship between frames of reference to explain patterns of observable change. As students move up the DCM construct map, they adopt more sophisticated connections between the Earth-based and space-based perspectives, beginning with explaining the Sun's apparent motion then moving on to the Moon or stars. Thus, the progress is towards increasing use of the Earth's rotation to account for the apparent rising and setting motion of the Sun, Moon and stars. For some students, this may not be a fully developed ability to visualize two different perspectives; rather, they may adopt both the Earth-based and space-based descriptions, learned in school, and accept these as plausible ways to make sense of the world around them (Plummer et al., 2011). If they are not fully aware of *how* the Earth's rotation *causes* the appearance of motion in celestial objects, they may be limited in their ability to *apply* spatial reasoning to other phenomena.

Constructing a more sophisticated explanation requires students integrate spatial and temporal knowledge about the Sun, Moon, Earth, and stars. Explaining the Moon's daily apparent motion is difficult because students must integrate the Moon's actual motion into their explanation; they are challenged by the *temporal* frameworks needed to understand how their own Earth-bound motion on one time-scale (24 hours) explains the Moon's daily apparent motion rather than the Moon's relatively slow (one month) orbital motion. Spatial elements also define improvement in explaining the stars' DCM. The students found explaining that the stars appear to move because the Earth is rotating to be less difficult than describing how stars appear to rise and set. Thus, the most complex spatial action for students in this aspect of the construct map was to construct a 3D visualization in which multiple stars rose and set in the same direction across the sky.

For the lunar phases construct map, there was a similar shift from explanations that involve more direct mechanisms towards the more spatially complex explanation. In this case, students' explanations shifted first to understanding the role of different frames of reference and then to a complex ability to visualize different perspectives. As part of progress in explaining this phenomenon, students learn spatial content, including the description of the Moon's orbit and the way in which sunlight illuminates half the Moon's surface. The most interesting evidence for the shift in spatial reasoning is that some students understand the elements of the scientific explanation but they are unable to do the mental visualization that would allow them to accurately generate the phase that corresponds with a given alignment. Students need to be able to mentally visualize multiple elements that are combined to explain lunar phases.

Instruction and progress in spatial thinking in the construct maps

Using the construct maps as an analysis tool, I found that only supporting the space-based perspective of understanding how objects move in the solar system, through instruction that defines motions such as rotate and orbit, has a smaller impact on student progress up the construct map than providing support for describing and connecting the two frames of reference through instruction. Instruction that only supports the Earth-based description, such as viewing how the Sun, Moon, and stars appear to move in the planetarium, is also problematic; analysis suggests resulted in a more chaotic change in understanding, rather than a trend towards progress. Though many students had more sophisticated descriptions of the Earth-based patterns, many had not shifted towards using a frame-of-reference explanation that would have moved them towards the scientific explanation.

Conditions 3 and 4 provide further evidence for the types of teaching sequences needed to support improvement along the DCM construct map. The instruction was designed to combine visual simulations and gestures to supported connected development of visual schema and an embodied knowledge of how these motions relate (Glenberg, 1997; Plummer et al., in press; Sweller, 2004; Wilson, 2002). Previous studies of students' learning about relative motion suggest that interacting with visual simulations can provide students a framework from which to visualize new frame-of-reference problems (Monaghan & Clement, 1999). Developing the scientific explanation began with supporting students' improvement in the Earth-based descriptions of the patterns of motion. In the classroom, teachers supported student learning the descriptions of the Sun and Moon's paths of apparent motion by engaging them in developing a visual and embodied sense of the apparent motion through kinaesthetic actions – the students traced the path of the Sun and Moon while the teacher demonstrated these paths using a flashlight along the wall. Students in *Condition 4* who also attended the planetarium received additional support in constructing these explanations through the kinaesthetic engagement with a visual simulation (Plummer, 2009b; Plummer et al., in press).

The instruction in *Conditions 3 and 4* also supported students in making the connections between the Earth- and space-based perspectives by developing their visual and embodied knowledge. This was promoted by students' use of their own bodies as the Earth as they modelled the Earth's rotation. Students observed how a model of the Sun or a mode of the Moon appeared to move as they themselves spun on their axis; by personally rotating the students were able to see the connection between different frames of reference and engage in developing that an embodied knowledge. Attaining the cognitive ability to mentally move between spatially complex frames of reference is difficult. Immersing a learner with system being studied has been found to be more beneficial than instruction in which the learner is studying the system from the outside and can thus facilitate moving between frames of reference (Kozhevnikov, Gurlitt, & Kozhevnikov, 2013). The instruction also supported students by providing 3D physical models of the Earth and Moon that allowed them to download some of the cognitive challenge into their use of the environmental supports (Wilson, 2002). Putting pictures of stars around the walls may have also supported their understanding by allowing them to observe the affect on the stars' apparent location as they personally rotated, rather than only attempting to imagine that apparent motion. The instruction was further designed to reduce the cognitive load by focusing on apparent and actual motions separately then in combination (Sweller, van

Merrienboer, & Paas, 1998). Combining these elements may help students move up the construct map.

Though there was significant improvement in students' explanations for the lunar phases, many students also needed additional instructional support in reaching the top anchor of the lunar construct map, beyond what the classroom instruction provided. During instruction, students embodied the Earth perspective as they moved a model of the Moon about them in an orbit, illuminated by the light of the model Sun. By *becoming* part of the simulation, they could see how the space-based orientations and motions would cause an Earth-based observer to see particular phases. Moving beyond the first two levels requires spatial content knowledge of the elements of the explanation and the ability visualize the portion of the illuminated side of the Moon that would be visible from one's location on the Earth for different orientations. It is this second piece of developing a coherent mental model that allows for fluid translation between the space-based and Earth-based perspective that is most challenging for students. However, this reveals a mismatch between instruction and assessment. During instruction, children were embedded inside the model; they represented the Earth in the model and thus observed how the Moon appeared to change from their own perspective. During the assessment, the children were outside of the model, manipulating orientations and perspectives of the Earth, Moon, and Sun. Thus an additional spatial thinking challenge occurred in order to translate between how they learned the reason for lunar phases and the tools they were given to explain lunar phases during assessment.

This suggests students did not have opportunity to practice visualizing how their observational angle results in a particular lunar phase. While participating in modelling how the Moon's orbit affects our observation of the lunar phases from the Earth, students could easily observe how the Moon's orbit resulted in changing lunar phases because they were observing this change directly from their position as the Earth in the model as the light source illuminated the model of the Moon. Students were not asked to push their spatial thinking farther, by predicting the lunar phase in the model without the light source, during instruction. After instruction, they no longer had the scaffold of a light source. This further illustrates the importance of considering the nature of measurement in the LP design; perhaps students at Level 4 would have been able to construct a Level 5 explanation if they had a light source instead of a yellow ball to demonstrate their explanation.

Assessment and spatial thinking in the construct maps

Assessment plays multiple possible roles in LP research. The development of a LP requires an iterative process of developing assessments to measure student cognition that can then be used to revise the LP framework and, in turn, revise future assessments (Duschl et al., 2011). LP assessments 'must be able to elicit response from students at multiple levels and provide evidence to locate students on this pathway' (Gotwals, Songer, & Bullard, 2012, p. 207). Some researchers have distinguished between the roles of LP *assessment for learning* and *assessments of learning* (Black & Wiliam, 1998; Duschl et al., 2011). An *assessment for learning* would offer support for teachers' formative assessment practices, promoting teacher decision-making to address the needs of his/her students (Alonzo, 2012; Furtak, Thompson, Braaten, & Windschitl, 2012). LP assessments might also be used as *assessments of learning* when addressing achievement goals, such as in evaluating curriculum or in relation to developing standards and associated student achievement measurement systems (Corcoran et al., 2009;

Foster & Wiser, 2012; NRC, 2012). The assessment system I used for the celestial motion construct maps focused the analysis at an *assessment of learning* because the purpose of this work was to understand how instruction supports progress in spatial thinking. With this information in hand, future work can delve into methods of supporting teachers in using these construct maps to facilitate their own *assessment for learning* in ways that promote attention to the critical spatial features of student thinking.

Prior work has raised several issues around the challenges associated with the design, implementation, and interpretation of assessments for LPs (Alonzo, 2012). For example, Duncan and Rivet (2013) discuss the challenges of developing assessments capable of diagnosing students' level on a LP. Students near the upper anchor apply consistent and robust reasoning across assessment items and students near the lower end of the LP also often perform consistently, displaying low level or intuitive reasoning. However, 'at intermediate levels of a LP, students' levels of understanding may vary from item to item because their developing knowledge is not robust enough to be consistently applied to diverse situations and phenomena' (p. 397). Similarly, students at intermediate levels of the celestial motion LP may apply spatial thinking inconsistently, such as using a frames-of-reference-based explanation for the Sun's apparent daily motion but not other objects.

Developing robust mental models of celestial motion and the spatial habit of mind to solve new astronomical problems is difficult, requiring extensive time and practice to develop a mental model capable of running the necessary mental simulations. Thus, we should consider how our goals for student learning, understanding of student cognitive challenges, and realities of assessment might intersect. Is spatial problem solving in astronomy without environmental aids, such as may be typical in standardized testing situations, a worthwhile or even a valid goal for astronomy education? Alternatively, should assessment design focus on supporting students' ability to draw on appropriate environmental resources, including physical models and their own body, from which to use in constructing spatially sophisticated answers to novel problems in astronomy? Rivet and Kastens (2012) argue that 'assessing students' reasoning has required the development and validation of new kinds of assessments, supported by deep thinking about what constitutes scientific reasoning, which types of reasoning to assess, and what performances would indicate proficiency in a given type of reasoning' (p. 714). They analysed assessment of students' analogical reasoning with physical models; to do so, they developed a whole-class assessment based on students' reasoning about physical models demonstrated to the class. Gotwals and colleagues (2012) discuss the role of scaffolding in their assessment of a LP for scientific explanations in biodiversity. They found that providing scaffolds for students' allowed for a range of opportunities for students to express their understanding and thus their placement within the LP; however, the scaffolds also created additional challenges such as not differentiating students who could perform without the scaffolds and those that required supports.

The assessment used in DCM and lunar phases study provided individual students with environmental supports to facilitate their ability to communicate their ideas. The use of physical models was initially chosen to help improve my ability to assess students' ideas about concepts not easily communicated through words or drawings. The use of physical models supported the interaction between researcher and subject to communicate effectively about spatial knowledge and reasoning. The children may not have had the ability to communicate the connection between the Earth-based perspective and space-based motions and orientations without the use of the models and one-on-one conversation. However, the models themselves may have facilitated the children's understanding of concepts that they had not previously had an opportunity to explain.

Implications for the celestial motion learning progression and future instruction

The goal of this paper was not to describe a full LP for celestial motion; rather, it was to illustrate the use of spatial thinking as the central element of progress in students' thinking in this domain. The further development of this LP will require investigation of the challenges students have in learning to explain a variety of celestial motion phenomena, successful methods of supporting students' explanation building across these phenomena, and analysis of how learning to the scientific explanation for one celestial motion phenomena may be necessary for progress across the progression. Additional work is needed to facilitate teachers' use of construct maps towards making connections between curriculum and support for student learning (Black, Wilson, & Yao, 2011; Krajcik, 2011).

In addition to DCM and lunar phases, spatial knowledge and reasoning can define progress across construct maps for other celestial phenomena. For example, the construct map for explaining the seasons requires multiple layers of spatial knowledge and reasoning, building on the DCM construct map described in this manuscript (Plummer & Maynard, 2013). At the lower levels of the seasons construct map, students may begin by relating changes in the Earth-based patterns of change, such as length of day or the Sun's altitude, with change in seasons. Increasing sophistication involves making connections between different perspectives, such as making connections between the observable patterns of change in the Sun's path with change in temperature. This brings in non-spatial elements – the importance of understanding energy and temperature relationships. Finally, additional spatial reasoning is necessary to make the jump to the upper levels of the construct map; students must make sense of how the Earth's rotation, orbit, and tilt cause the Sun's altitude and length of day to change and also explain how those changes in the Sun's apparent motion cause change in temperature.

Supporting students' development of spatially complex explanations in these celestial motion phenomena may also help their progress as they move towards more advanced explanations in astronomy. For example, my colleagues and I are conducting learning progression research on the solar system: the relationships between planetary motion and properties with how the solar system formed (Plummer, Flarend, Palma, Rubin, & Botzer, 2013). Understanding the relative motions and positions of solar system objects involves visualizing the relative size and scale of objects and accounting for how objects move due to the balance of gravity and an objects' momentum. Explaining the formation of the solar system requires visualizing how a cloud of gas and dust can collapse, while rotating and flattening, to eventually result in a central Sun and planets. A complex chain of knowledge-building is required to go between how our Earth-based observations led scientists to understand how the planets currently orbit the Sun and then to use the formation model to account for that model of a dynamic planetary system. However, students are faced with challenges of learning spatial knowledge and conceptual knowledge (e.g. gravitational forces and momentum) through instruction that does not support their spatial thinking; students often learn these concepts from static, two-dimensional representations (Barnett & Morran, 2002; Barnett, Yamagata-Lynch, Keating, Barab, & Hay, 2005) which may not help them move between these different perspectives on the solar system, our observations of it, and its formation.

One of the implications of using spatial thinking as a progress variable – coupled with analysing specific phenomena separately – is that there may be several routes of progress up the LP. Children may progress up any number of construct maps for different phenomena (e.g. phases of the Moon, seasons, planetary motion, etc.). However, increased sophistication is also attained as students see celestial motion phenomena as part of the same explanatory *system*. This is where the potential benefits of learning to explain one phenomenon may help students to progress along other construct maps; they may begin to see how applying spatial thinking, such as perspective taking between frames of reference, can be useful in explaining multiple observations.

This suggests potential directions for organizing teaching sequences around celestial motion. This LP framework emphasizes the importance of supporting students' ability to describe the apparent patterns of motion and change in celestial objects. Therefore, in early primary school, children may be best served by instruction that supports their ability to describe and make predictions around these patterns, as well as early work on the relative size and scale and physical nature of celestial objects. Subsequent teaching sequences could introduce initial explanations that involve more complex spatial reasoning, such as the type of perspective taking needed to explain why and how the Sun appears to move across the sky. With this foundation of spatial thinking and reasoning in place, instruction could begin to make connections across phenomena, such as extending to other DCM phenomena or branching out to the lunar phases. Once students have had sufficient practice with the types of multistep visualizations, perspective taking, and temporal reasoning is required to explain, students could engage in more sophisticated explanations such as explaining the seasons. Assessment should be used as a tool to determine whether children have built an appropriate foundation of describing and explaining observational phenomena before moving on to more complex phenomena that build on these types of knowledge and reasoning skills.

Spatial thinking as an element of progress in an astronomy learning progression: An agenda for future research

More research is also needed to understand the role of teachers' knowledge about the 'conceptual territory' may influence their design and implementation of appropriate teaching sequences (Leach & Scott, 2002). The discussion of the relationship between instruction and progress in the construct maps in the examples presented in this manuscript focused primarily on the general pedagogical approach to the teaching sequences rather than a more nuanced look at how teachers chose to implement that instruction and their reasoning. Leach and Scott (2002) define a teaching sequence as including a) a particular way in which the scientific point of view is made public for the students, b) opportunities for students to internalize the scientific storyline, and c) opportunities for students to apply new ideas as scaffolding is removed, allowing for students to take responsibility for their use of the scientific explanations. Additional research is needed to examine the internalization and application factors around spatial thinking in this LP to uncover methods of supporting greater progress than was measured in the examples presented here.

Current research has been limited to examining progress across a few phenomena and at disconnected grade levels (Plummer, 2012; Plummer & Krajcik, 2010; Plummer et al., in press). Describing the contingencies between construct maps and how instruction can help students move both up construct maps and between construct maps will be critical in moving towards the goal of developing curriculum frameworks guide teachers in supporting deepening understanding of key science goals over time. However, the nature of these contingencies between construct maps remains an open question. Additional research will need to assess how engagement in astronomy teaching sequences may support progress along the LP across multiple grade bands leading to 'construct map-level descriptions that articulate plausible incremental learning pathways that are linked to instructional-assisted practices/interventions' (Duschl et al., 2011, p. 174). To understand progress across time will require close attention to how teachers choose to work with students existing spatial reasoning ideas (such as perspective taking, size and scale, and temporal frameworks) towards making sense of new phenomena.

Another next step in this type of research is to understand how measures of spatial ability can explain why some students made progress while others did not. We may then be able to consider which types of instruction provide the most support for students with low spatial abilities as well as exploring new research on methods to improve students' spatial abilities. While previous studies suggest spatial perception, mental rotation, and spatial visualization may be related to student learning in astronomy (Black, 2005; Heyer, 2012; Wilhelm, 2009), these studies used paper-pencil assessments covering multiple aspects of astronomy. Additional work is needed to consider whether different aspects of astronomical problem solving taps into different spatial abilities as well as looking closely at how students engage in spatial thinking in this domain. Research is also needed to explore differences in how learners visualize astronomical problems as this may lead to improved instructional approaches. Kozhevnikov and colleagues provide evidence that individuals can be grouped according to how they acquire and process information (Kozhevnikov, Hegarty, & Mayer, 2002; Kozhevnikov, Kosslyn, & Shephard, 2005). *Verbalizers* depend primarily on verbal-analytical strategies. Two groups of *visualizers* are distinguished by how they generate mental images and process-visual-spatial information: *object visualizers* 'use imagery to construct high-quality images of the shapes of individual objects' while 'spatial visualizers use imagery to represent and transform spatial relations' (Kozhevnikov et al., 2005, p. 723). Kozhevnikov and colleagues suggest that object visualizers tend to encode and process images globally as a single perceptual unit while spatial visualizers use spatial relations to analyse images piece by piece. This may suggest that spatial visualizers may find the type of spatial visualization needed for DCM or lunar phases to be easier to process than object visualizers.

The framework for spatial thinking in celestial motion has not fully explored how students' knowledge of spatial scale influences their explanations. Others have argued the importance of considering students' knowledge of scale issues in constructing explanations in astronomy as well as their understanding of representations and models used during instruction (e.g. Padalkar & Ramadas, 2010). Studies have found large differences between individuals' large-scale spatial abilities (i.e. reasoning about distance and location in new environments; Hegarty, Montello, Richardson, Ishikaa, & Lovelace, 2006) and suggest ways in which knowledge of spatial scales, from microscopic to astronomical sizes and distances, may depend on the nature of individuals' experiences with different categories of scale (Tretter, Jones, Andre, Negishi, & Minogue, 2006). Future research on spatial thinking in LPs should consider whether understanding of spatial scale is useful as a progress variable. Further, additional work may be needed to understand how spatial scale in our assessments may impact student reasoning; research suggests individuals differ in their spatial abilities when measured small- and large-scales and comparing virtual simulations to spatial reasoning 'in the wild' (Hegarty & Waller, 2005; Liben, Myers, & Kastens, 2008).

Spatial ability is known to influence how students learn across different domains of science (NRC, 2006). Thus, other researchers may find spatial thinking to be an essential element in understanding how students develop more sophisticated explanations across multiple science domains. For example, the type of spatial thinking required in geology is different than the elements of progress described for celestial motion. Geological explanations require spatial visualization that manipulates *internal features* of the Earth while celestial motion spatial visualization requires manipulation of external interactions within the larger system. Development of expertise in geology requires geoscientific spatial abilities and an understanding of geological time (King, 2008). Developing an understanding of geological processes requires understanding ‘how three-dimensional rock structures interact with three-dimensional topographic surfaces’ and ‘how these complex three-dimensional interactions change over time’ (King, 2008, p. 198). Kali and Orion (1996) suggest that two complementary factors are needed to engage in geology problem solving: mental penetration of geological structures and perception of spatial configuration of structures. Future LP work in geology may need to explore how instruction can support student progress in using penetrative thinking as well as engaging in spatial visualization to understanding the configuration of layers in structures. However, more work needs to be done to understand how to support low-spatial ability students in this domain (Ishikawa & Kastens, 2005).

Finally, further work should examine whether there is a transfer effect in spatial thinking to other domains or contexts after students improve their spatial thinking along the celestial motion LP. For example, we might hypothesis that little transfer would happen between celestial motion and geology but that understanding the role of reference frames in astronomy may aid students in future visualization of physics problems. However, this raises the question of *what might transfer*? Because spatial abilities can be improved through training, the improved spatial abilities a student achieves in work in one domain may then help students solve problems in other domains (Uttal et al., 2012). Instruction supporting improvement of spatial abilities early on in science education may help students may help promote future success in STEM learning and retention of students in STEM careers (Newcombe & Frick, 2010; Uttal et al., 2012; Uttal & Cohen, 2012). Another way of considering transfer might be to ask whether certain instruction, such as teaching sequences that support progress in celestial motion, may attune students to a spatial habit of mind (NRC, 2006), where they are aware of ways that spatial thinking can help them approach new problems. Much research is needed to answer these questions, but investigating concepts of transfer within a LP framework could yield an improved understanding of how to plan coherent curriculum across primary and secondary school science.

References

Albanese, A., Danhoni Neves, M.C., & Vicentini, M. (1997). Models in science and in education: A critical review of research on students' ideas about the Earth and its place in the universe. *Science & Education*, *6*, 573-590.

Alonzo, A. (2012). Eliciting student responses relative to a learning progression: Assessment challenges. In A. Alonzo & A.W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and future Directions* (pp. 241-256). Rotterdam: Sense Publishers.

Barnea, N. & Dori, Y.J. (1999). High-school chemistry students' performance and gender differences in a computerized molecular modeling learning environment. *Journal of Science Education and Technology*, *8*, 257-271.

Barnett, M., & Morran, J (2002). Addressing children's alternative frameworks of the Moon's phases and eclipses. *International Journal of Science Education*, *24,* 859-879.

Barnett, M., Yamagata-Lynch, L., Keating, T., Barab, S., & Hay, K. (2005). Using virtual reality computer models to support student understanding of astronomical concepts. *Journal of Computers in Mathematics and Science Teaching*, *24*, 333-356.

Baxter, J. (1989). Children's understanding of familiar astronomical events. *International Journal of Science Education, 11*, 502–513.

Black, P., Wilson, M., Yao, S.Y. (2011). Road maps for learning: A guide to the navigation of learning progressions, *Measurement: Interdisciplinary Research & Perspective, 9,* 71-123. http://dx.doi.org/10.1080/15366367.2011.591654

Black, A.A. (2005). Spatial ability and Earth science conceptual understanding. *Journal of Geoscience Education, 53*, 402-414.

Black, P. & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education: Principles, Policy & Practice*, *5*, 7-74.

Blown, E. & Bryce, T. (2010). Conceptual coherence revealed in multi-modal representations of astronomy knowledge, *International Journal of Science Education, 32*, 31-67.

Brown, N. & Wilson, M. (2011). A model of cognition: The missing cornerstone of assessment. *Educational Psychology Review, 23*, 221-234.

Carey, S., & Spelke, E. (1996). Science and core knowledge. *Journal of Philosophy of Science, 63*, 515–533.

Casey, B. M., Andrews, N., Schindler, H., Kersh, J.E., Samper, A., & Copley, J. (2008). The development of spatial skills in an interventions involving block building activities. *Cognition and Instruction, 26*, 269-309.

Chu, M. & Kita, S. (2011). The nature of gestures' beneficial role in spatial problem solving. *Journal of Experimental Psychology: General, 140*, 102-116

Clark, J.M. & Paivio, A. (1991). Dual coding theory and education. *Educational Psychology Review, 3*, 149-210.

Corcoran, T.B., Mosher, F.A., & Rogat, A.D. (2009). *Learning progressions in science: An evidence-based approach to reform* (CPRE Report). Philadelphia, PA: Consortium for Policy Research in Education.

DeLoache, J.S. (1989). Young children's understanding of the correspondence between a scale model and a larger space. *Cognitive Development, 4*, 121-139.

Duncan, R.G. & Rivet, A.E. (2013). Science learning progressions, *Science, 339,* 396-397.

Duncan, R. G. & Hmelo-Silver, C. E. (2009). Learning progressions. *Journal of Research in Science Teaching, 46*, 606-609.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis, *Studies in Science Education, 47,* 123-182. http://dx.doi.org/10.1080/03057267.2011.604476

Eberbach, C., & Crowley, K. (2009). From everyday to scientific observation: how children learn to observe the biologist's world. *Review of Educational Research, 79*, 39–68.

Fodor, J. (1984). Observation reconsidered. *Philosophy of Science*, *51*, 23–43.

Foster, J. & Wiser, M. (2012). The potential of learning progression research to inform the design of state science standards. In A. Alonzo & A.W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (435-460). Rotterdam: Sense Publishers.

Furtak, E., Thompson, J., Braaten, M. & Windschitl, M. (2012). Learning progressions to support ambitious teaching practices, In A. Alonzo & A.W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (405-434). Rotterdam: Sense Publishers.

Gallese, V., & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology, 21,* 1-25.

Gibbs, R.W., Jr. (2006). *Embodiment and cognitive science*. Cambridge: Cambridge University Press.

Glensberg, A. (1997). What memory is for. *Behavioral and Brain Sciences, 20*, 1-55.

Gotwals, A. (2012). Introduction: Leaping into learning progressions in science. In A. Alonzo & A. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (pp. 3-12), Sense Publishers: Rotterdam.

Gotwals, A.W., Songer, N.B., & Bullard, L. (2012). Assessing students' progressing abilities to construct scientific explanations, In A. Alonzo & A.W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (pp. 183-210). Rotterdam: Sense Publishers.

Harle, M. & Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. *Chemical Education Review, 88*, 351-360.

Heritage, M. (2008). Learning progressions: Supporting instruction and formative assessment. Paper prepared for the Council of Chief State School Officers (CCSSO), Washington, DC. Retrieved May 27, 2008, from http://www.nciea.org/

Hegarty, M. (2010). Components of Spatial Intelligence. *Psychology of Learning and Motivation, 52*, 265-296.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design, Topics in Cognitive Science, 3, 446-474. DOI: 10.1111/j.1756-8765.2011.01150.x

Hegarty, M., Montello, D., Richardson, A., Ishikaa, T. & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning, *Intelligence, 34*, 151-176.

Hegarty, M., & Waller, D. (2005). Individual differences in spatial abilities. In P. Shah, & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 121– 169). Cambridge University Press.

Heyer, I. (2012). *Establishing the empirical relationship between non-science majoring undergraduate learners' spatial thinking skills and their conceptual astronomy knowledge* (Unpublished doctoral dissertation). University of Wyoming.

Hobson, S. M., Trundle, K.C., & Sackes, M. (2010). Using a planetarium software program to promote conceptual change with young children. *Journal of Science Education and Technology*, *19*, 165-176.

Ishikawa, T. & Kastens, K. (2005). Why some students have trouble with maps and other spatial representations, *Journal of Geoscience Education, 53*, 184-197.

Jin, H. & Anderson, C. W. (2012). A learning progression for energy in socio-ecological systems. *Journal of Research in Science Teaching*, *49*, 1149-1180. DOI: 10.1002/tea.21051

Kali, Y. & Orion, N. (1996). Spatial abilities of high-school students in the perception of geological structures, *Journal of Research in Science Teaching, 33*, 369-391.

Kavanagh, C., Agan, L., & Sneider, C. (2005). Learning about phases of the Moon and eclipses: A guide for teachers and curriculum developers. *Astronomy Education Review*, 4, 19-52.

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*, 522 – 549.

Kikas, E. (2000). The influence of teaching on students' explanations and illustrations of the day/night cycle and seasonal changes. *European Journal of Psychology of Education, 15*, 281-295.

Kikas, E. (2003). University students' conceptions of different physical phenomena. *Journal of Adult Development, 10*, 139-150.

King, C. (2008). Geoscience education: An overview. Studies in Science Education, 44, 187-22.

Klatzky, R., Loomis, J., Beall, A., Chance, S., & Golledge, R. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion, *Psychological Science, 9*, 293-298.

Kosslyn, S.M. (2005). Mental images and the Brain. *Cognitive Neuropsychology*, *22*, 333-347.

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

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

Kozhevnikov, M., Gurlitt, J., & Kozhevnikov, M. (2013). Learning relative motion concepts in immersive and non-immersive virtual environments. *Journal of Science Education and Technology*. Doi:10.1007/s10956-013-9441-0

Krajcik, J. (2011). Learning progressions provide road maps for the development and validity of assessments and curriculum materials. *Measurement: Interdisciplinary Research Perspective, 9*, 155-158. Doi:10.1080/15366367.2011.603617

Krajcik, J. S., Sutherland, L. M., Drago, K., & Merritt, J. (2012). The promise and value of learning progression research. In S. Bernholt, K. Neumann, & P. Nentwig, (Eds.),*Making it tangible: Learning outcomes in science education* (pp. 261-284, Munster: Waxmann.

Lakoff, G. & Johnson, M. (1980). The metaphorical structure of the human conceptual system. *Cognitive Science, 4*, 195-208.

Leach, J. & Scott, P. (2002). Designing and evaluating science teaching sequences: An approach drawing upon the concept of learning demand and a social constructivist perspective on learning. *Studies in Science Education, 38*, 115-142. Doi: 10.1080/03057260208560189

Liben, L. & Downs, R. (1993). Understanding Person-Space-Map Relations: Cartographic and Developmental Perspectives. *Developmental Psychology, 29*, 739-52.

Liben, L. & Downs, R. (1997). Can-ism and Can'tianism: A straw child. *Annals of the Association of American Geographers, 87*, 159-167.

Liben, L. S., Myers, L. J., & Kastens, K. A. (2008). Locating oneself on a map in relation to person qualities and map characteristics. In C. Freksa, N. S. Newcombe, P. Gardenfors, & S. Wolfl (Eds.), *Proceedings of the International Conference on Spatial Cognition VI: Learning, Reasoning, and Talking About Space* (pp. 171–187). Heidelberg, Germany: Springer-Verlag.

Liben, L., Christensen, A., & Kastens, K. (2010). Gestures in geology: The roles of spatial skills, expertise, and communicative context. In C. Holscher et al., (Eds.), *Spatial Cognition VII* (pp. 95-111), Berlin: Springer-Verlag.

Linn, M.C. & Petersen, A.C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development, 56,* 1470-1498.

Mant, J. & Summers, M. (1993). Some primary-school teachers' understanding of Earth's place in the universe. *Research papers in education*, *8*, 101-129.

Mathewson, J. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education, 83*, 33-54.

Monaghan, J.M. & Clement, J. (1999). Use of a computer simulation to develop mental simulations for understanding relative motion concepts. *International Journal of Science Education, 21*, 921-944. Doi: 10.1080/095006999290237

National Research Council (2001). In Pellegrino, J.W., Chudowsky, N., and Glaser, R. (Eds.), *Knowing What Students Know: The Science and Design of Educational Assessment*, Washington, D.C.: National Academies Press.

National Research Council (2006). *Learning To Think Spatially,* Washington, D.C.: National Academies Press.

National Research Council (2007). *Taking science to school: Learning and teaching science in grades K-8*. Duschl, R. A., Schweingruber, H. A., & Shouse, A, (Editors). Washington, D.C.: National Academies Press.

National Research Council (2012). *Framework for K-12 Science Education.* Washington, D.C.: National Academies Press.

Newcombe, N.S. & Huttenlocher, J. (1992). Children's early ability to solve perspective-taking problems. *Developmental Psychology, 28*, 635-643.

Newcombe, N.S. & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education, 4*, 102-111. Doi: 10.1111/j.1751-228X.2010.01089.x

Padalkar, S. & Ramadas, J. (2011). Designed and spontaneous gestures in elementary astronomy education. *International Journal of Science Education*, *33*, 1703-1739.

Paivio, A. (1986). *Mental Representations*. New York, Oxford University Press.

Palen, S. & Proctor, A. (2006). Astronomy in the K-8 core curriculum: A survey of state requirements nationwide. *Astronomy Education Review, 5*, 23-35.

Parker, J., & Heywood, D. (1998). The Earth and beyond: developing primary teachers' understanding of basic astronomical events. *International Journal of Science Education*, *20*, 503-520.

Parnafes, O. (2012). Developing explanations and developing understanding: Students explain the phases of the Moon using visual representations. *Cognition and Instruction, 30,* 359-403.

Parsons, L.M., Fox, P.T., Downs, J.H., Glass, T. et al., (1995). Use of implicit motor imagery for visual shape discrimination as revealed by PET. *Letters to Nature*, 375, 54-58.

Plummer, J. D. (2009a). A cross-age study of children's knowledge of apparent celestial motion. *International Journal of Science Education*, *31*(12), 1571-1605.

Plummer, J. D. (2009b). Early elementary students' development of astronomy concepts in the planetarium. *Journal of Research in Science Teaching*, *46*(2), 192-209.

Plummer, J. D. (2012). Challenges in defining and validating an astronomy learning progression. In A.C. Alonzo & A.W. Gotwals (Eds.), *Learning Progressions in Science: Current Challenges and Future Directions* (pp. 77-100). Rotterdam: Sense Publishers.

Plummer, J., Flarend, A., Palma, C., Rubin, K., & Botzer, B. (2013). Development of a learning progression for the formation of the Solar System. *Annual Meeting of the National Association for Research in Science Teaching, Rio Grande, PR*.

Plummer, J. D., Kocareli, A., & Slagle, C. (in press). Learning to Explain Astronomy Across Moving Frames of Reference: Exploring the role of classroom and planetarium-based instructional contexts. *International Journal of Science Education*, (ahead-of-print), 1-24.

Plummer, J.D., & Krjacik, J. (2010). Building a learning progression for celestial motion: Elementary levels from an Earth-based perspective. *Journal of Research in Science Teaching, 47(7),* 768-787.

Plummer, J.D., & Maynard, L. (2013). Building a learning progression for celestial motion: An exploration of students' reasoning about the seasons. *Manuscript submitted for publication.*

Plummer, J. D., Wasko, K. D., & Slagle, C. (2011). Children learning to explain daily celestial motion: Understanding astronomy across moving frames of reference. *International Journal of Science Education*, *33*(14), 1963-1992.

Plummer, J. D., & Zahm, V. M. (2010). Covering the standards: Astronomy teachers' preparation and beliefs. *Astronomy Education Review*, *9*, 010110.

Plummer, J. D., Zahm, V. M., & Rice, R. (2010). Inquiry and astronomy: Preservice teachers' investigations of celestial motion. *Journal of Science Teacher Education*, *21*(4), 471-493.

Rigal, R. (1996). Right-left orientation, mental rotation, and perspective-taking: When can children imagine what people see from their own viewpoint? *Perceptual and motor skills, 83,* 831-842.

Rivet, A.E. & Kastens, K.A. (2012). Developing a construct-based assessment to examine students' analogical reasoning around physical models in Earth science, *Journal of Research in Science Teaching, 49*, 713-743. DOI 10.1002/tea.21029

Roberts, R. J. & Amin, C.J. (1993). Developmental differences in giving directions: Spatial frames of references and mental rotation. *Child Development, 64*, 1258- 1270.

Rogat, A., Anderson, C., Foster, J., Goldberg, G., Hicks, J., et al., (2011). Developing learning progressions in support of the new science standards: A RAPID workshop series (CPRE Report). Philadelphia, PA: Consortium for Policy Research in Education.

Schneider, R. & Plasman, K. (2011). Science teacher learning progressions: A review of science teacher's pedagogical content knowledge development. Paper presented at the Association of Science Teacher Educators, January 2011, Minneapolis, MN.

Schoon, K.J. (1995). The origin and extent of alternative conceptions in the Earth and space sciences: A survey of pre-service elementary teachers. *Journal of Elementary Science Education*, *7*, 27-46.

Schwartz, D. & Black, J.B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science, 20*, 457-497.

Shapere, D. (1982). The concept of observation of science and philosophy. *Philosophy of Science, 49*, 485-525.
Sharp, J. & Grace, M. (2004). Anecdote, opinion and whim: lessons in curriculum development from primary science education in England and Wales. Research Papers in Education, 19, 293-321. DOI: 10.1080/0267152042000247981
Shea, N. A., & Duncan, R. G. (2012). From Theory to Data: The Process of Refining Learning Progressions. *Journal of the Learning Sciences*, (ahead-of-print), 1-26. DOI:10.1080/10508406.2012.691924
Shen, J. & Confrey, J. (2007). From conceptual change to transformative modelling: A case study of an elementary teacher in learning astronomy, *Science Education, 91*, 948-966. DOI 10.1002/sce.20224
Shen, J. & Confrey, J. (2010). Justifying alternative models in learning astronomy: A study of K-8 teachers' understanding of frames of reference. *International Journal of Science Education, 32,* 1-29. DOI: 10.1080/09500690802412449
Smith, C. L., Wiser, M., Anderson, C.W., & Krajcik, J. (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic molecular theory. *Measurement: Interdisciplinary Research and Perspectives,* 4, 1-98. DOI: 10.1080/15366367.2006.9678570
Sorby, S. (2009). Educational research in developing 3-D spatial skills for engineering students, *International Journal of Science Education, 31*, 459-480.
Subramaniam, K., & Padalkar, S. (2009). Visualisation and reasoning in explaining the phases of the Moon. *International Journal of Science Education, 31*, 395-417.
Sweller, J. (2004). Instructional design consequences of an analogy between evolution by natural selection and human cognitive architecture. *Instructional Science, 32*, 9-31.
Sweller, J., van Merrienboer, J., & Paas, F. (1998). Cognitive Architecture and Instructional Design. *Educational Psychology Review, 10*, 251-296.
Tretter, T.R., Jones, M.G., Andre, T., Negishi, A. & Minogue, J. (2006). Conceptual boundaries and distance: Students' and experts' concepts of the scale of scientific phenomena. *Journal of Research in Science Teaching, 43*, 282-319. DOI 10.1002/tea.20123
Trundle, K. C., Atwood, R.K., and Christopher, J.E. (2002). Preservice Elementary Teachers' Conceptions of Moon Phases before and after Instruction. *Journal of Research in Science Teaching*, *39*, 633-658.
Trundle, K.C., Atwood, R.K., & Christopher, J.E. (2006). Preservice elementary teachers' knowledge of observable Moon phases and pattern of change in phases. *Journal of Science Teacher Education, 17*, 87-101. DOI: 10.1007/s10972-006-9006-7
Trundle, K. C., Atwood, R. K., & Christopher, J. E. (2007). Fourth-grade elementary students' conceptions of standards-based lunar concepts. *International Journal of Science Education, 29*, 595-616.
Trundle, K.C., Atwood, R.K, Christopher, J.E., & Sackes, M. (2010). The effect of guided inquiry-based instruction on middle school students' understanding of lunar concepts. *Research in Science Education*, 40, 451-47.
Tversky, B. (2005). Visuospatial reasoning. In K.J Holyoak & R.G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp.209-240). Cambridge: Cambridge University Press.

Tversky, B., Kim, J. & Cohen, A. (1999). Mental models of spatial relations and transformations from language. In G. Rickheir & C. Habel (Eds.), *Mental models in discourse processing and reasoning* (pp. 239-258). Amsterdam: Elsevier Science.

Uttal, D.H. (2000). Seeing the big picture: Map use and the development of spatial cognition. *Developmental Science, 3,* 247-286.

Uttal, D.H. & Cohen, C.A. (2012). Spatial thinking and STEM education: When, why, and how? *Psychology of Learning and Motivation, 57*, 148-181. DOI: 10.1016/B978-0-12-394293-7.00004-2

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N.S. (2012). The malleability of spatial skills: A meta-Analysis of Training Studies. *Psychological Bulletin, 139*, 352-402. doi: 10.1037/a0028446

Vosniadou, S., & Brewer, W. F. (1994). Mental Models of the day/night cycle. *Cognitive Science, 18*, 123-183.

Vosniadou, S., Skopeliti, I., & Ikospentaki, K. (2005). Reconsidering the role of artifacts in reasoning: Children's understanding of the globe as a model of the Earth. *Learning and Instruction, 15,* 333-351.

Vosniadou, S., (2007). The cognitive-situative divide and the problem of conceptual change, *Educational Psychologist*, *42*, 55-66.

Vosniadou, S., Vamvakoussi, X. & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change.* New York, NY: Routledge Press.

Wai, J., Lubinski, & Benbow, C.P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*, 817-835.

Wilhelm, J. (2009). Gender differences in lunar-related scientific and mathematical understandings, *International Journal of Science Education*, *31*, 2105-2122.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*, 625-636.

Wilson, M. (2009). Measuring progressions: Assessment structures underlying a learning progression. *Journal of Research in Science Teaching, 46,* 716-730.

Table 1. Four instructional conditions used to develop the construct maps.

Timeline	Condition 1: Space-based instructional focus[a]	Condition 2: Earth-based instructional focus	Condition 3: Instruction supporting connections between reference frames[a]	Condition 4: Instruction supporting connections between reference frames
October & November	Pre-interview	Pre-interview	Pre-interview	Pre-interview
December		Kinaesthetic planetarium programme		Kinaesthetic planetarium programme
December		Post-interview		
January	Classroom lessons: 1. Relative size of Sun, Earth, and Moon 2. Defining celestial motion vocabulary, such as rotation and revolution 3. Reflection of sunlight off the Moon 4. Predict lunar phase cycle and then explain using physical models 5–8: Additional lessons on lunar craters, space exploration, and eclipses	Classroom lessons: 1. Relative size of Sun, Earth, and Moon 2. Defining celestial motion vocabulary, such as rotation and revolution 3. Reflection of sunlight off the Moon 4. Predict lunar phase cycle and then explain using physical models 5–8: Additional lessons on lunar craters, space exploration, and eclipses	Classroom lessons: 1. Develop a scale to compare the Sun, Earth, and Moon 2. Connect the Earth-based observations of daily celestial motion to Earth's rotation 3. Reflection of sunlight off the Moon 4. Predict lunar phase cycle and then explain using physical models 5–8: Additional lessons on lunar craters, space exploration, and eclipses	Classroom lessons: 1. Develop a scale to compare the Sun, Earth, and Moon 2. Connect the Earth-based observations of daily celestial motion to Earth's rotation 3. Reflection of sunlight off the Moon 4. Predict lunar phase cycle and then explain using physical models 5–8: Additional lessons on lunar craters, space exploration, and eclipses
February	Post-interview		Post-interview	Post-interview

[a]Students in Conditions 1 and 3 attended the planetarium after the post-interviews.

Daily Celestial Motion Construct Map

Level 5
Accurately explains apparent motion of Sun, Moon, and stars with Earth's rotation; Apparent motion is described as a smooth path across the sky, in same direction.

Level 4A
Accurately describes and explains apparent motion of *Sun and stars* using Earth's rotation.

Level 4B
Accurately describes and explains apparent motion of *Sun and Moon* using Earth's rotation.

Level 3
Accurately describes and explains apparent motion of Sun with Earth's rotation, but not Moon or stars.

Level 2
Accurately describes Sun's apparent motion and only uses the Earth's motion to explain, but this is not the scientific description of rotation.

Level 1
Objects appear to move because of their actual motion. Description of apparent motion likely to be non-normative.

Spatial Thinking Associated with DCM Progress

Increasingly engaged in **visualization as a multi-step process** of manipulating spatial information -- tracking motions and positions of objects in in ways that move between Earth-based and space-based reference frames.

Considers how different time scales affects relationship between observation and motions of objects in space.

Earth-based frame of reference: Increasing sophistication in **visualize patterns of motion in 3D** on the sky, over time.

Constructing explanations that connect movement across frames of reference: Increasingly sophisticated use of **perspective-taking** allows students to visualize how objects will appear from different view points and how an object's apparent motion could be caused by one's own motion.

Figure 1.

Lunar Phases Construct Map

Level 5
Moon is always half-lit by the Sun. Explains normative descriptions of lunar phases by describing how the angle at which we observe the Moon changes as the Moon orbits the Earth. Able to indicate the correct alignment of the Sun-Earth-Moon for various phases.

Level 4
Describes the Moon's orbit and our angle of observation as the explanation for why we observe the pattern of change in lunar phases. However, alignment for specific phases is non-normative.

Level 3
Moon goes through a cycle of change in apparent lunar phases. Explanation combines aspects of scientific and alternative conceptions.

Level 2
The change of the lunar phases is a long process (more than one night). Normative phases are described and a pattern is indicated. Explanations are non-normative and do not involve moving between reference frames.

Level 1
The Moon's phases can change quickly. Non-normative shapes are indicated for the lunar phases. Explanations include only non-normative features.

Spatial Thinking Associated with Lunar Phases Progress

Increasingly engaged in **visualization as a multi-step process** of manipulating spatial information -- tracking motions and positions of objects in ways that connect Earth-based observations with space-based reference frames.

Able to visualize how a light source will illuminate a 3D object (a sphere) and how this changes from different angles of observation.

Increasing sophistication in **visualizing patterns of change** in objects' appearance, over time, from an Earth-based reference frame.

Constructing explanations that connect frames of reference: Use **perspective-taking** to visualize how an object will appear from different reference frames and how an object's appearance could be caused by one's reference frame and angle of observation.

Figure 2.

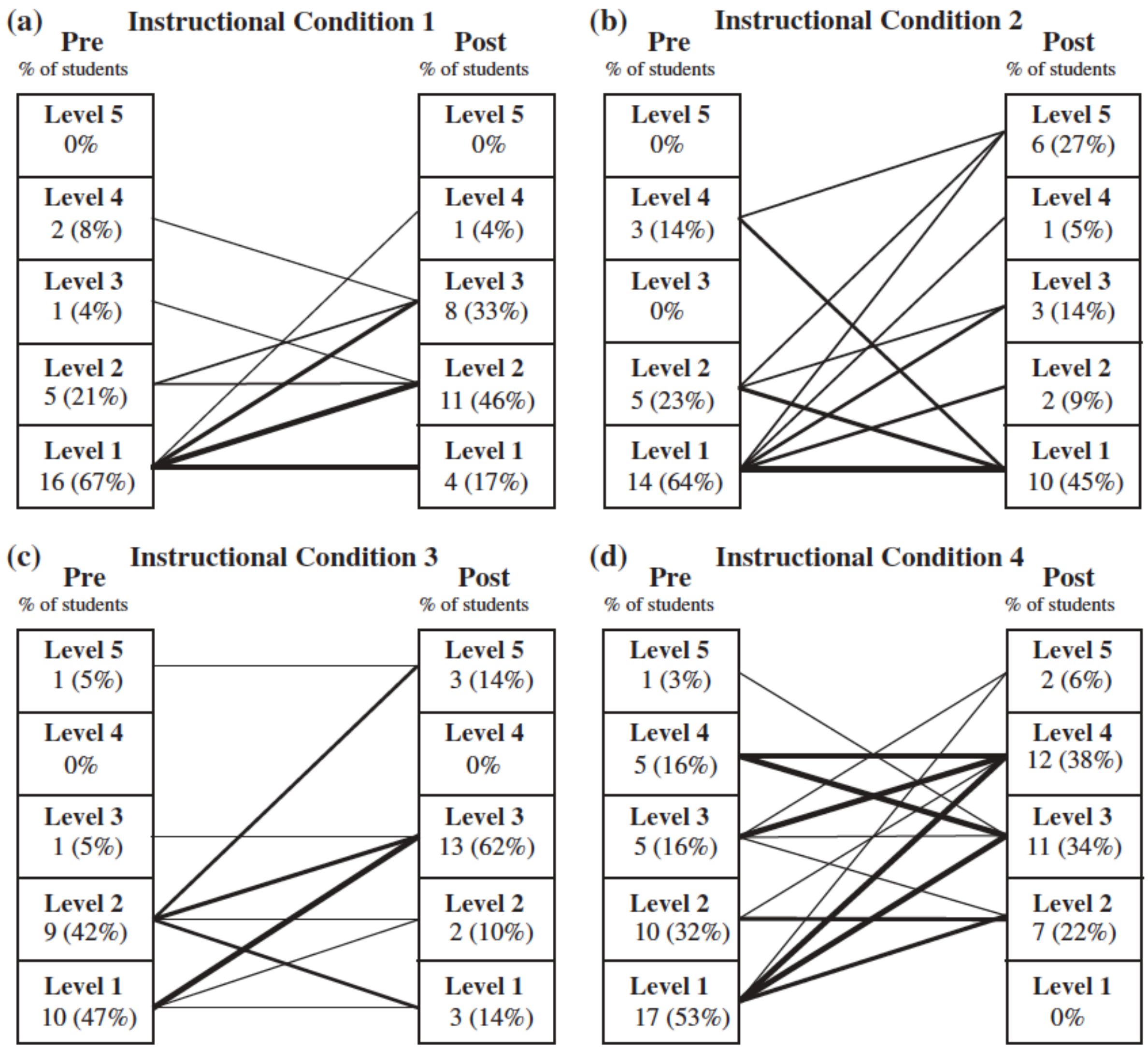

Figure 3. Student transitions along the Daily Celestial Motion construct map, broken down by instructional condition ($N = 24$, $N = 22$, $N = 21$, and $N = 32$, respectively). The line strength indicates the number of students who transitioned from one level to another. One-point line thickness represents one student.

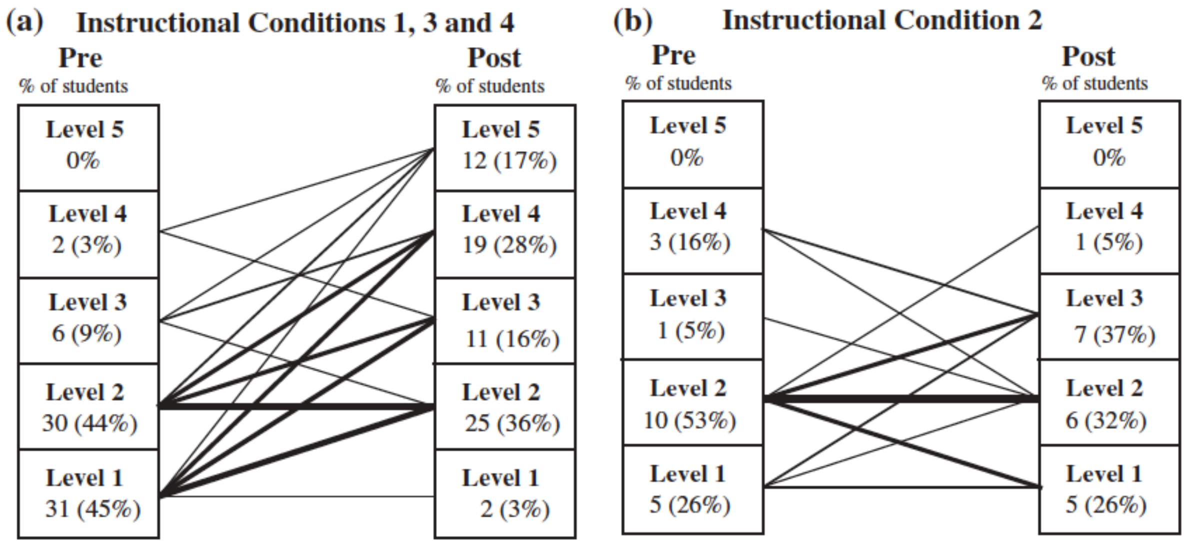

Figure 4. A comparison of improvement along the lunar phases construct map: Students in the classroom instruction (Conditions 1, 3 and 4, $N = 69$) and students from the planetarium instruction (Condition 2, $N = 19$). Students whose responses were unclear were not included in this analysis. The line thickness was set to one-point represents one student's progress.