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RESEARCH REPORT

Children Learning to Explain Daily Celestial Motion: Understanding astronomy across moving frames of reference

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This study investigated elementary students' explanations for the daily patterns of apparent motion of the Sun, Moon, and stars. Third-grade students were chosen for this study because this age level is at the lower end of when many US standards documents suggest students should learn to use the Earth's rotation to explain daily celestial motion. Interviews with third-grade students (n = 24), prior to formal astronomy education, revealed that about half are working from naive mental models. The other half of the students used more scientific explanations for the Sun's apparent motion but used scientific descriptions or explanations of the Moon's and stars' daily apparent motion far less frequently. We also describe an instructional approach designed to support students as they move between the Earth-based and heliocentric frames of reference using computer simulations and modelling with hands-on and kinaesthetic strategies. This instruction was tested with another group of third-grade students as part of their gifted programme (n = 16). Pre/post-interview analysis supports the instructional approach as the students showed a more sophisticated ability to move between the Earth-based and heliocentric frames of reference. The students' high initial knowledge level, entering instruction at the more advanced end of the general third-grade student population, limits our ability to generalize the instructional findings; however, these findings provide an important step in improving our understanding of how to support students in this complex area of astronomical reasoning.

Keywords: *Astronomy; Alternative conception; Elementary school*

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Introduction

The basis for understanding many aspects of astronomy is the ability to use the actual motions and relative positions of celestial objects (e.g. the Sun and the Moon) to describe observed phenomenon and make predictions about future observations. The Atlas of Science Literacy (*Atlas*; AAAS, 2001) recommends that, between the third and fifth grade, students learn that the,

> rotation of the Earth on its axis every 24 hours produces the night-and-day cycle. To people on Earth, this turning of the planet makes it seem as though the Sun, Moon, planets and stars are orbiting the Earth once a day (p. 45).

This is purposefully linked to the recommendation that children learn about the apparent daily rising and setting motion of the Sun, Moon, and stars by second grade. Thus, *Atlas* makes a critical distinction that learning astronomy begins with describing daily patterns of motion of celestial objects and then using the actual motions of the relevant objects (at this level, the Earth and the Moon) to explain those motions. This is a complex area of reasoning that requires children understand and imagine two complex sequences of motion through an understanding of different *frames of reference*. First, they must visualize the apparent motions of these objects, from their own perspective. Second, they must also imagine a new space-based perspective from which to explain why celestial objects appear the way that they do as seen from the Earth. These shifts rely on children imagining concepts that change over time and at different timescales (days, months, and years). This type of reasoning between moving frames of reference is necessary for other topics of K-12 astronomy such as the phases of the Moon, eclipses, tides, and the seasons.

In this manuscript, we focus on children's first steps towards a more sophisticated understanding of motion and perspective in the solar system by targeting how children learn to shift from their own Earth-based perspectives to explaining apparent motion through an outside observer or heliocentric frame of reference. Third-grade students' pre-instructional knowledge of daily celestial motion was assessed to uncover how children may describe and explain these concepts prior to formal school instruction. Next, we analysed the improvement in understanding these concepts with a second group of third-grade students following a short instructional intervention as part of their gifted and talented programme. Based on these analyses, we present an initial look at how children develop an understanding of this complex scientific concept and suggest that instruction should be designed to explicitly teach these perspectives to allow students to build the scientific mental model for daily celestial motion.

Celestial Motion

Children's Ideas about Astronomy before Instruction

Without targeted instruction, research suggests that most children will not reach a scientific level of accuracy in their ability to describe both the Earth-based and heliocentric reference frames in daily celestial motion. Previous research on first-, third-, and eighth-grade students in the USA suggests that most children's understanding of the apparent motion of the Sun, Moon, and stars will not improve significantly after mid-elementary school (Plummer, 2009a). In early elementary school, children may describe the rising and setting of the Sun and the Moon as straight up and down, rather than across the sky. And while many students develop this sense of motion across the sky by mid-elementary grades, they are unlikely to believe that the stars also appear to move by middle school (Plummer, 2009a) or even into adulthood (Plummer, Zahm, & Rice, 2010). Studies with children in middle grades suggest that students' description of the Sun's apparent motion is unlikely to include the scientific understanding that the Sun does not pass directly overhead every day or that the Sun's path changes across the seasons (Plummer, 2009a; Trumper, 2001).

Limited research has addressed the combination of children's ability to describe apparent daily celestial motion and their explanations from a heliocentric perspective. However, research on children's mental models regarding the day–night cycle may begin to shed light on the nature of their understanding of daily celestial motion from a frames-of-reference perspective. Children's early explanations for the day/night cycle are primarily based on two general presuppositions: the Sun (and sometimes the Moon) is blocked resulting in night time darkness and that the Sun moves straight up and straight down (Samarapungavan, Vosniadou, & Brewer, 1996; Vosniadou & Brewer, 1994). Studies using elementary-aged children's drawings and physical models have found a progression moving towards more heliocentric explanations for the day/night cycle; understanding the scientific explanation first requires students understand the spherical shape of the Earth (Samarapungavan et al., 1996; Vosniadou & Brewer, 1994). The progression of children's explanations towards the scientific includes several levels of synthetic mental models which combine aspects of the naive with aspects of the scientific, such as day and night are caused by the Earth revolving about the Sun (Vosniadou & Brewer, 1994).

Research reveals that many students have alternative conceptions about the Moon's apparent and actual motions. Some children in elementary school believe that the Moon and Sun are fixed on opposite sides of the Earth, with the Earth spinning between them for day and night; other children believe that the Moon orbits about the Earth daily but that the Moon is what causes night to occur (e.g. Sharp, 1996; Vosniadou & Brewer, 1994). Based on studies in the US and UK, most children in upper elementary school do not know how to use the Moon's orbital motion to explain the apparent changes to the Moon's phases (e.g. Barnett & Moran, 2002; Sharp, 1996; Trundle, Atwood, Christopher, & Sackes, 2010). And a study of a small group of Greek fourth- and fifth-grade students (n = 8) suggests that many children believe the Moon rises around sunset and sets around sunrise (Starakis & Halkia, 2010). The Moon actually rises and sets about 50 minutes later each night because of 29-day orbit.

Few studies have investigated children's beliefs about the nature of stars and their actual or apparent motion. Vosniadou and Brewer's investigation of first-, third-, and fifth-grade US children included questions about why we cannot see the stars during the day time (1994). Students at all age groups gave a range of ideas that included both models in which the stars actually move and models in which the stars do not move. However, their study does not address whether students believe the stars could *appear* to move because of the Earth's motion. Sharp (1996) found that 14% of the 10- and 11-year-old students (n = 31) in his study believed that the stars appear to move though, again, it is unclear as to the nature of the explanation for that motion.

Instructional Interventions in Celestial Motion

The central concept in daily celestial motion, from a heliocentric frame of reference, is the Earth's rotation. Most studies of children learning about the Earth's rotation have focused on upper elementary though a recent study in the UK suggests that children as young as four to six years old may be capable of learning to use the Earth's rotation to explain the day/night cycle (Kallery, 2010). Instruction with 9–11-year-olds in Cyprus and the UK that offers individual students experience psychomotor modelling of the Earth's actual motion and considers children's prior knowledge has been found to improve students' ability to explain the day/night cycle (e.g. Diakidoy & Kendeou, 2001; Sharp & Kuerbis, 2005). Manipulation of 3D models in a virtual computer environment has also been shown to improve 11–13-year-old Greek students' understanding of the Earth's rotation (Bakas & Mikropoulos, 2003). However, these studies did not specifically take a frame-of-reference approach and lacked a description of how students described apparent celestial motion and their understanding of the *connection* between the Sun's apparent pattern of motion and the Earth's actual motion.

Teaching students the concept 'the Earth rotates' is unlikely to be sufficient for students to make the full connection between the Earth's rotation and the apparent daily motion of the Sun, Moon, and stars. For example, even with extensive instruction on mental model building in astronomy including the Earth's rotation, few students were able to make the connection that we can see the Moon during the day and the night (Taylor, Barker, & Jones, 2003). Transferring knowledge of the Earth's rotation to the apparent motion of stars also appears to be difficult for students. Diakidoy and Kendeou (2001) found that despite learning to explain the day/night cycle, 31% of the fifth-grade students (n = 63) did not infer that the stars remain in the sky during the day.

While much is known about aspects of children's naive concepts and select areas of instruction, gaps remain in the following areas. The first author's previous research uncovered the range of ways elementary-aged children describe the pattern of apparent celestial motion as well as successful methods of instruction (Plummer, 2009a, 2009b). However, these studies did not examine how they *explain* these patterns in a way that clearly examines each perspective (the Earth-based and heliocentric frames of reference). The literature on instruction primarily focuses on children learning to explain the day/night cycle, understanding rotation and revolution, or learning more advanced concepts in this domain. Therefore, the goal of this study is to describe the relationship between students' understanding of the Earth-based and heliocentric patterns in elementary grades prior to instruction and to investigate an instructional sequence in order to describe potential pathways and intermediate steps towards the scientific conception of daily celestial motion across both frames of reference. We asked the following research questions:

(1) What is the nature of third-grade students' mental models of daily celestial motion, prior to instruction, considering both the Earth-based and heliocentric frames of reference?
(2) To what extent do third-grade students develop an ability to move between frames of reference in daily celestial motion when instruction is designed to explicitly engage students in making these connections?

To respond to the first question, children in third-grade classrooms were interviewed before they participated in school-based astronomy curricula. To answer the second research question, third-grade students in the same school district (but during a different school year) took part in targeted instruction as part of their gifted and talented programme. This particular group of students was chosen because, while the school district was interested in improving their astronomy curriculum, the leadership wished to see a demonstration of the need for these particular changes and the specific instructional techniques that we hoped to initiate within the whole third-grade astronomy curriculum. Therefore, the district gave us access to the students who were already pulled out for their gifted curriculum to implement our experimental curriculum. We hypothesize that instruction that provides opportunities for students to make connections between the Earth-based and heliocentric frames of reference will help students to develop more sophisticated mental models for daily celestial motion. We chose to present both the general third-grade pre-instructional data and the results of the instructional intervention because, as we will illustrate below, the gifted students' pre-instructional beliefs were slightly more sophisticated than was generally seen in the general third-grade population. We will discuss the implications of the instruction with the gifted students on its possibilities with the general elementary population.

Theoretical Framework

Interpretations of students' pre-instructional understanding and the design of the specific learning environment were based on the *framework theory* approach to conceptual change. In this theoretical framework, conceptual change can occur both through a radical restructuring which involves ontological category shifts as well as through gradual assimilation of new concepts within the existing mental framework (Vosniadou, 2007). At the heart of this theoretical approach 'is the idea that initial explanations of the physical world in naive physics are not fragmented observations but form a coherent whole, a framework theory' (Vosniadou, Vamvakoussi, &

Skopeliti, 2008, p. 4). A learner's experience in the classroom and other cultural experiences may result in the assimilation of ideas that, rather than replacing the naive theory, form *synthetic models* which include aspects of the scientific view with the personal, naive theory (Vosniadou & Brewer, 1992). Several empirical studies support the usefulness of the framework theory towards describing how children learn about the natural world (e.g. Blown & Bryce, 2010; Ioannides & Vosniadou, 2002; Vosniadou & Brewer, 1992, 1994).

Recent research reflects a theoretical divide between the cognitive and sociocultural perspectives; Vosniadou (2007) suggests that framework theory accounts for the essence of both theories while providing a more complete description of the empirical evidence. Vosniadou points to definitions of the cognitive and sociocultural perspectives articulated by Greeno, Collins, and Resnick (1996). The cognitive perspective takes the view of learning as an internal process of constructing structures to organize information in the mind of an individual. The sociocultural perspective defines knowledge as existing in the external actions of individuals with their environment and the communities in which they exist. Framework theory recognizes the importance of understanding learning from both perspectives; knowledge can be acquired and integrated into an internal mental framework through participation in social (external) activities.

Framework theory considers human cognition as a system that allows an individual to create 'analog mental representations of physical objects that embody the internal structure of the concept and can be run in the mind's eye to generate predictions and explanations of phenomena' (Vosniadou et al., 2008, p. 17). This view of cognition accounts for how individuals incorporate both everyday interactions with the physical world as well as how they integrate cultural artefacts, such as globes and models of the Sun and Moon, into their internal knowledge structure (Vosniadou et al., 2008). The resulting mental representations are likely to be a synthesis of the learners' prior knowledge and the properties of the cultural artefact unless instruction provides guidance in how to use the physical model to constructing a new, scientific mental model (Vosniadou, Skopeliti, & Ikospentaki, 2005).

Based on the framework theory, instruction on celestial motion should consider the motion of celestial objects from both an Earth-based and a heliocentric frame of reference as part of the student's mental model. Learning is more than replacing non-normative with normative concepts; rather, learning involves 'the ability on the part of the learner to take different points of view and understand when different conceptions are appropriate depending on the context of use' (Vosniadou, 2007, p. 58). We argue that conceptual change towards the normative is more likely to occur when both frames of reference are addressed by instruction. The alternative, focusing on one frame of reference over the other, may result in unintentional synthetic models rather than the coherent and culturally accepted scientific view.

Framework theory describes one aspect of the theoretical framework in which this study is based, specifically the coherence of mental structures associated with understanding of astronomy. Further consideration of other cognitive theories is needed to provide information on how instructional strategies can be designed to support efficient and productive learning in celestial motion. First, improving students' non-normative ideas about astronomy requires changes to long-term, stored memories. Cognitive load theory (CLT) describes how changes to long-term memory start with accessing working memory Humans have a limited capacity to bring in new information and hold it in working memory; as a result, instruction must be designed to allow learners to process a few new concepts at a time (Sweller, 2004). The load on working memory increases due to challenges associated with understanding elements of information together rather than separately (Sweller, van Merrienboer, & Paas, 1998). This can potentially create a problem in learning celestial motion as the goal is to understand the relationship between various moving objects and our own observational viewpoint.

To reduce the load on working memory, we designed instruction to begin by engaging in descriptions of apparent celestial motion from their perspective before attempting to model the explanation. Developing children's understanding of apparent celestial motion requires that students acquire a repertoire of mental images that they can run through in their mind to represent the daily motion of these objects. Simulations have been shown to help elementary-aged children develop a visualization of apparent celestial motion, such as in the planetarium (Plummer, 2009b) and using desktop computer-based programmes (Hobson, Trundle, & Sackes, 2010). These simulations support students in building mental images of these patterns of motion that are not easy to construct from first-hand observations of the sky due to the slow time frames and complexities of tracking position. Once stored in long-term memory, as part of the child's mental model of celestial motion, these descriptions can be used as elements in working memory and therefore free up additional space for new information.

Cognitive theories also explain the reason why multiple-modality instruction has the potential to improve learning in this domain. The working memory can be subdivided into visual and verbal subcomponents, allowing for additional input and reducing the chance for cognitive overload (Cook, 2006; Kirschner, 2002; Mayer, 2001). Thus, combining verbal descriptions with visual, kinaesthetic, and/or haptic interactions may support learning to a greater extent (Clark & Paivio, 1991; Druyan, 1997; Jones, Minogue, Tretter, Negishi, & Taylor, 2006; Plummer, 2009b). Using a multiple-modality approach may be important in supporting learners in areas relating to celestial motion; attempting to make connections between two moving frames of reference that occur on timescales of hours or days creates a cognitive load that is not easily juggled by the learner. The use of either kinaesthetic modelling (children using their bodies to model celestial motion) or physical models may be necessary to support the high cognitive load of comparing mental images of apparent celestial motion with the actual motions in a heliocentric frame of reference.

Instructional Setting

In this section, we describe the instructional setting used to answer the second research question with a group of students in a gifted and talented programme.

The first and third authors of this paper designed the instruction and taught the students. One month before instruction, students were asked to observe and record the location of the Sun and Moon, during the morning and evening, and the Moon's appearance for two to three days (10 of the 16 students completed and returned their observing sheets). Instruction was approximately 100 minutes across two consecutive days. We began with the apparent motion of the Sun using both kinaesthetic descriptions in the classroom (using direction markers, observations of the actual Sun out the window, and the students physically mimicking the path of the Sun with their arms) and observations of the Sun's motion over time using Stellarium (http://www.stellarium.org), a computer-based planetarium programme. Students kinaesthetically modelled the Earth's rotation by spinning on their own axis and worked with Earth globes to explain the Sun's apparent motion. The class then discussed the students' prior observations of the Moon and observed the Moon's apparent motion on the computer. The lesson ended with students drawing a picture to illustrate their idea of why the Moon appears to rise and set.

Lesson two began with a review of the Sun and Moon's apparent motion on the computer followed by students sharing their drawings with the whole class. The students' ideas were discussed and physical models were used to test possible reasons, including the scientific model. The students modelled the Moon and Earth's motion to understand the Moon's slow orbit relative the Earth's rotation. The size and distance to the stars was discussed using a *PowerPoint* showing the relative size of stars to the Sun and planets. Students kinaesthetically modelling why the stars appear to rise and set by rotating while observing stars they had taped to the walls of the classroom. Finally, students drew new pictures illustrating why the Moon and stars appear to rise and set to allow students to engage in the concepts in an alternative medium.

Methodology

Subjects Characteristics and Setting

The students were drawn from elementary schools across a suburban school district in the Eastern USA. Each elementary school serves between about 350 and 450 students in grade K-3. Almost all students in this study had visited the district planetarium during the previous school year but had otherwise not received extensive classroom instruction in astronomy 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.

To investigate students' knowledge of daily celestial motion, 24 third-grade students, split evenly by gender, were randomly selected from four classrooms from students who had returned permission letters. The students' average age was eight years and nine months. To answer the second research question, 18 third-grade students from the district's gifted programme participated in the two-day instructional sequence from three elementary schools within the district. These were a different group of students because the instructional study took place during a different school year. Sixteen of the students completed both the pre and post-interviews (nine male; seven female). Average age during instruction was eight years and eight months.

Data Collection

The interview, conducted by the first author, began with semi-structured questions covering concepts of *apparent celestial motion* and took place in a 4′ diameter dome (see the Appendix). The student was given a flashlight to use in demonstrating the apparent motion of the Sun, Moon, or stars on the interior of the dome. This portion of the interview was audio recorded, and the students' demonstrations were drawn by the interviewer. Students then *explained* what they had demonstrated using physical models of the Sun, Earth, and Moon. For students in the gifted programme, pre-instruction interviews were held approximately one month before instruction, because of winter vacation, and post-interviews were completed approximately one week after instruction. Interviews were used in this study, as opposed to other assessment methods such as written tests, both because of the age of the students and because of the difficulty in obtaining meaningful information on children's ideas of three-dimensional, moving, concepts. The interview structure allowed us to first assess children's beliefs about their own Earth-based perspective and then ask the students to use props to help them explain their ideas about why objects appear to move the way that they do. We are still limited in our ability to assess each child's mental model as our interpretation is based on their use of the cultural artefacts presented. However, most students appeared comfortable in using the objects as stand-ins for the actual celestial objects and dome to represent the imaginary sky.

Coding

Primary categories. 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). A coding scheme for these categories was developed based on previously reported research on children's ideas and was modified to accommodate new ideas uncovered within these samples. The first and second authors individually coded a random sample of 20% of the interviews reaching an inter-rater agreement of 90.0%. A detailed coding document is available upon request.

Secondary categories. A set of three categories was created to classify students' use of explanations for Earth-based observational descriptions of the Sun, Moon, and stars. These three categories classify how each student describes the Sun's, Moon's, and stars' pattern of apparent motion and explanation for that motion, respectively. Each secondary category is populated by a series of codes (see Tables 1–3). These secondary codes were defined by combining the primary codes for apparent and actual celestial motion to describe individual aspects of the student's mental model. The secondary codes were iteratively refined to account for possible student responses.

Tertiary coding. Each subject was assigned a single tertiary code that describes our generalization of the students' overall mental model for daily celestial motion. In the final stage of coding, we created a ranked organization of possible combinations of secondary codes. Ranking was based on the underlying sophistication of their explanatory model and begins with ordering the accuracy of possible relationships between the explanation for the Sun's apparent motion and the description of that apparent motion. First, an initial pass to describe these tertiary codes was completed using the scientific description at the highest level, a completely naive understanding at the lowest level, and possible intermediate, or synthetic, codes in the mid-levels. Previous research on the apparent celestial motion trajectories (Plummer & Krajcik, 2010), children's mental models in astronomy (Vosniadou & Brewer, 1994), and an understanding of the discipline guided this initial outline of the codes. Further codes were added and refined by examining the students' actual combinations of secondary codes (Table 4).

Four major levels of mental models were defined, taking into account how children understand both the Earth-based and heliocentric frames of reference: naive, lower synthetic, upper synthetic, and scientific. Including both the children's knowledge of the Earth-based perspective and the heliocentric explanations in a meaningful and logical way was a challenge; we chose to allow both accurate and non-normative apparent motions at the lower levels of the scale while highlighting the importance of being accurate across both frames of reference in the upper levels. The levels, as well as the coding of the students, appear in Table 4. The overall levels are defined as follows:

- *Naive*: Students begin with a naive level of understanding where they believe that the Earth-based patterns of motion (or lack of motion) is because these objects are actually moving or not moving in that way.
- *Lower synthetic*: Students adopt the idea that the Sun is stationary and that the Earth is moving. Less sophisticated expressions of this include the Earth orbiting the Sun once a day. There may be limited coherence with the actual Earth motion and the apparent patterns of motion.
- *Upper synthetic*: Increased sophistication appears as students adopt the Earth's rotation to explain that the Sun appears to rise and set across the sky. However, students do not extend this explanation to *all* celestial objects. Some students may determine that the Moon rises and sets because of the Earth's rotation. Others may learn that the stars rise and set because of the Earth's rotation.

- *Scientific daily celestial motion*: Students reach the scientific level as they are able to use the Earth's rotation to explain all patterns of celestial motion from an Earth-based perspective as motions moving across the sky.

Two additional layers of improvement in sophistication within the scientific level are noted. Students' ability to demonstrate all motions in the same direction shows a greater level of understanding than students showing accurate paths but with differences in direction. The second distinction was in the students' understanding of the orbit of the Moon. Here, we begin to depart from the simple concept of daily celestial motion and suggest the next level of complexity in which students can also use the Moon's slow orbit to explain the phases of the Moon.

Findings

Research Question 1: Third-grade students' knowledge of daily celestial motion

This section discusses the results of pre-instructional interviews with students from the general third-grade population (n = 24) for the purpose of describing children's initial ideas as they enter school-based instruction on the topic of daily celestial motion. We present a descriptive analysis based on the frequencies within the secondary categories followed by a qualitative analysis of these dimensions of the students' mental models. A similar approach was used in the second section to analyse the nature of students' overall mental models of daily celestial motion using the tertiary codes.

Explanations for the Sun's, Moon's, and Stars' apparent motion. In this section, we present the ways in which the third-grade students connected the apparent motion and explanation of the Sun, Moon, and stars as three separate dimensions of the students' celestial motion mental model. First, if we consider only the Earth-based perspective, the distribution of students' knowledge of apparent celestial motion is consistent with the first author's previous work describing US third-grade students' knowledge of apparent celestial motion (Plummer, 2009a). About half knew that the Sun and Moon appear to rise and set across the sky, but most believed that the stars do not appear to move. Prior research has found a relationship between a child's understanding that the Earth is spherical and their ability to learn to use the Earth's rotation to explain the day/night cycle (Samarapungavan et al., 1996). Eighty-eight per cent of students in this study believed that the Earth is spherical. Although 92% of the students indicated that the Earth rotates, only 38% knew that this action takes 24 hours. As we will demonstrate below, this did not translate to accurate connections between the Earth-based and heliocentric frames of reference for most students. Tables 1–3 provide students' categorization for each of the secondary categories organized by the sophistication of the explanation. For each explanation, the codes are split to indicate an accurate apparent motion (a smooth curved path that rises and sets on opposite sides of the sky, not necessarily from east to west) or a non-normative description of apparent motion.

The Sun. Very few students were able to make an accurate connection between the apparent motion of the Sun and the explanation using the Earth's rotation. Half of the students explained the Sun's apparent motion with its actual motion (50%; Table 1). On the other hand, 11 students (46%) had responses that attempted explain the apparent motion of the Sun with something other than just the Sun's actual motion, thus showing that they are beginning to think about using different frames of reference to explain what they observe. We also examined the consistency of students' responses between their description of the apparent motion and the explanation for those motions. Students who gave naive explanations were consistent in their description of the actual and apparent motion—these were the same motions for those students. A few other students gave responses that were also consistent across both frames of reference; five students (21%) explained the Sun's apparent motion across the sky in terms of the Earth's rotation, though some of these students did not know the accurate length of time for the Earth's rotation making their response less coherent. The remaining students (25%) gave responses in which the apparent motion did not logically match the explanation of the heliocentric frame of reference. This included a few students (13%) who suggested that the Sun's straight up and down apparent motion was caused by a combination of the Earth's rotation and the Sun's actual motion.

The Moon. Most students (71%) gave naive explanations for the Moon's apparent motion: the Moon's motion (or lack of motion) is due to its actual motion (Table 1). A few students used a description of the Moon's orbit to explain an accurate description of the Moon's apparent motion. Other students used the Earth's rotation to explain the Moon's daily apparent motion, but these students did not believe that the Moon actually moves (no orbit) often believing that the Moon stays on the opposite side of the Earth from the Sun. Most students gave descriptions of the Moon's movement that were logically consistent between the apparent motion and the explanation. The most common of these descriptions was the naive response (54%). Seven students (29%) attempted to reason across different frames of reference between their description of what we would see in the sky and the explanation for that apparent motion. Five of these students (21%) made a logical connection between their description of the Moon's apparent motion and the Earth's rotation (the Moon appears to move across the sky and this is explained by the Earth rotating in the other direction).

The stars. The majority of the students believe that the stars do not move (58%; Table 3). Others gave non-normative descriptions that they explained with the stars' actual motion about the solar system (21%). These students' descriptions and explanations were logically consistent. Five students (21%) attempted to explain the stars' appearance in the sky with the Earth's rotation, suggesting they are beginning to reason across frames of reference, though none did so accurately. Three of these

Table 1. Children's explanations for the apparent motion of the Sun

Code/explanation	Apparent motion	General third grade ($n = 24$)	Gifted students ($n = 16$) Pre	Gifted students ($n = 16$) Post
Explanations using the Earth's rotation				
Sun-A1: Earth's 24-hour rotation.	Accurate	3 (13%)	10 (63%)	13 (81%)
	Non-normative	2 (8%)	1 (6%)	0
Non-normative explanations that include use of the Earth's rotation				
Sun-B1: Earth's rotation and revolution around the Sun.	Accurate	0	1 (6%)	1 (6%)
	Non-normative	1 (4%)	0	0
Sun-B2: Inaccurate description of the Earth's rotation.	Accurate	0	0	0
	Non-normative	0	0	0
Sun-B3: Accurate use of the Earth's rotation and other inaccurate explanations.	Accurate	0	1 (6%)	0
	Non-normative	0	0	0
Sun-B4: Inaccurate use of the Earth's rotation; may include other inaccurate explanations.	Accurate	3 (13%)	0	1 (6%)
	Non-normative	0	0	0
Non-normative explanations that include the Sun revolving around the Earth				
Sun-C1: Earth's rotation and the Sun orbiting the Earth.	Accurate	0	1 (6%)	0
	Non-normative	3 (13%)	0	0
Sun-C2: The Sun revolving around the Earth.	Accurate	2 (8%)	1 (6%)	1 (6%)
	Non-normative	0	0	0
Explanations that do not differentiate between Sun's apparent and actual motion				
Sun-D1: Sun is actually moving.	Accurate	5 (21%)	0	0
	Non-normative	5 (21%)	1 (6%)	0

Note. Accurate description of apparent motion is any path that is a smooth curve in which the Sun rises on one side of the sky and sets on the other side of the sky. The Sun may or may not pass through the zenith.

Table 2. Children's explanations for the apparent motion of the Moon

Code/explanation	Apparent motion	General third grade (n = 24)	Gifted students (n = 16)	
			Pre	Post
Explanations using the Earth's rotation				
Moon-A1: Uses the Earth's rotation to explain. Moon orbits once a month.	Accurate	0	0	5 (31%)
	Non-normative	0	0	0
Moon-A2: Uses the Earth's rotation to explain. Moon's orbit is not a month.	Accurate	0	0	1 (6%)
	Non-normative	0	0	0
Explanation using the Earth's rotation and the Moon's 28-day orbit				
Moon-A3: Uses the Earth's rotation and the Moon's monthly orbit to explain.	Accurate	0	0	2 (13%)
	Non-normative	0	0	0
Explanation using the Earth's rotation; the Moon does not orbit				
Moon-B1: Uses the Earth's rotation. Moon does not orbit.	Accurate	4 (17%)	0	7 (44%)
	Non-normative	2 (8%)	0	0
Explanation using the Earth's rotation and other inaccurate explanations				
Moon-C1: The Earth's rotation and inaccurate description of the Moon's orbit.	Accurate	0	4 (25%)	1 (6%)
	Non-normative	0	0	0
Moon-C2: The Earth's rotation and the Moon's up/down motion.	Accurate	0	0	0
	Non-normative	1 (4%)	0	0
Explanation is based on the Moon's orbit				
Moon-D1: The Moon's monthly orbit.	Accurate	1 (4%)	1 (6%)	0
	Non-normative	0	0	0
Moon-D2: The Moon's orbit. Orbit is not close to a month.	Accurate	2 (8%)	5 (31%)	0
	Non-normative	0	3 (19%)	0

Table 2. (*Continued*)

Code/explanation	Apparent motion	General third grade ($n = 24$)	Gifted students ($n = 16$) Pre	Gifted students ($n = 16$) Post
Explanations that do not differentiate between the Moon's apparent and actual motion				
Moon-E1: The Moon moves up and down.	Accurate	5 (21%)	0	0
	Non-normative	6 (25%)	0	0
Moon-F1: The Moon does not move.	The Moon does not appear to move.	3 (17%)	2 (13%)	0
Moon-F2: Student unable to give an explanation.	Non-normative	0	1 (6%)	0

Note. Accurate description is any path that is a smooth curve in which the Moon rises on one side of the sky and sets on the other side of the sky.

Table 3. Children's explanations for the apparent motion of the stars

Code/explanation	Apparent motion	General third grade ($n = 23$)[a]	Gifted students ($n = 16$) Pre	Gifted students ($n = 16$) Post
Explanations using the Earth's rotation				
Stars-A1: Earth's rotation.	Accurate	0	1 (6%)	10 (63%)
	Non-normative	1 (4%)	3 (19%)	4 (25%)
Stars-A2: Inaccurate description of the Earth's rotation.	Accurate	1 (4%)	0	0
	Non-normative	0	0	0
Explains with the Earth's rotation and other inaccurate motions				
Stars-B1: Earth's rotation as well as other inaccurate motions.	Accurate	0	1 (6%)	0
	Non-normative	0	0	0
Explanation uses the Earth's rotation but the stars do not appear to move				
Stars-C1: Earth's rotation.	Stars only move at end of night	1 (4%)	1 (6%)	0
Stars-C2: Earth's rotation.	Stars do not appear to move	1 (4%)	2 (13%)	0
Explanation using the Earth's orbit				
Stars-D1: Earth's orbit around the Sun.	Accurate	0	0	0
	Non-normative	0	1 (6%)	0
Explanations that do not differentiate between stars' apparent and actual motion				
Stars-E1: Stars move around the Earth.	Accurate	0	2 (13%)	0
	Non-normative	0	0	0
Stars-E2: Stars move around the solar system.	Accurate	0	0	0
	Non-normative	5 (21%)	3 (19%)	0
Stars-E3: Stars do not move or only move slowly.	Non-normative.	14 (58%)	2 (13%)	2 (13%)

Note. Accurate description is any path that is a smooth curve across the sky, rising and setting.
[a]One student could not be classified.

responses were logically consistent, connecting the apparent motion with the explanation though there were still inaccuracies in their descriptions of the stars' motion. The remaining two students gave logically inconsistent descriptions with respect to the Earth's constant rotation: the stars only set at the end of night or that the stars do not appear to move.

Students' mental models of daily celestial motion. Half of the student had a naive level for their overall mental model, while many others (38%) had lower-level synthetic mental models (Table 4). This suggests the level of understanding held by students in early- to mid-elementary school before astronomy instruction. Many believe that whatever pattern of apparent motion an object has (which includes both accurate and non-normative patterns for this age group) is caused by the objects' actual motion. Two of the students classified as 'naive' actually had a more sophisticated explanation for the Moon's or stars' apparent motion suggesting that these students may be at least a step closer towards the scientific concept and may be better equipped to recognize the importance of the Earth's rotation for the Sun's apparent motion. In general, children at this level are not attempting to reason between moving frames of reference, and, when they do (mostly for the Sun or the Moon), they may not be doing so with a scientific level of accuracy.

Research Question 2: Instruction with third-grade students in a gifted programme

This section discusses the results of pre/post-interviews with third-grade students in a gifted and talented programme (n = 16) for the purpose of describing the impact of instruction on children's ability to accurately reason between frames of reference in astronomy and to uncover areas of difficulty for children. In the first section, a descriptive approach was used to compare the frequencies within the secondary categories, before and after instruction. In the second section, improvement in students' daily celestial motion mental models was measured using the Wilcoxon match-pairs signed-ranks test by classifying each student, pre and post, according to their tertiary level mental model, numbered one through four.

Explanations for the Sun's, Moon's, and Stars' apparent motion. Students in the gifted programme started with a higher level of prior knowledge of the Sun's, Moon's, and stars' apparent motion compared with the general third-grade population. All students in the gifted programme, both pre and post-instruction, indicated that the Earth is spherical. Most students in the gifted programme (63%) were already using the Earth's rotation to explain the Sun's apparent motion before instruction, suggesting that these students entered instruction at the upper end of the distribution of understanding expressed by the general third-grade population. After instruction, the students showed significant improvement in their

Table 4. Children's mental models for daily celestial motion

	General third grade ($n = 24$)	Gifted students ($n = 16$) Pre	Gifted students ($n = 16$) Post
Level 4—Scientific mental models	0	0	7 (44%)
Code 4A: Student describes the Sun, Moon, and stars as rising and setting across the sky and explains with Earth's rotation. The Moon orbits the Earth once a month, but this is not the cause of the Moon's apparent motion. Sun-A1-A[a], Moon-A1-A, Stars-A1-A. a: All apparent motions in the same direction. b: The Sun, Moon, and stars do not move across sky in the same direction.	0	0	a: 3 (19%) b: 1 (6%)
Code 4B: Student describes the Sun, Moon, and stars as rising and setting across the sky and explains with the Earth's rotation. Inaccuracies in description of the Moon's orbit. Sun-A1-A (Moon-A2-A, Moon-A3-A, or Moon-B1-A), Stars-A1-A a: All apparent motions in the same direction. b: The Sun, Moon, and stars do not move across sky in the same direction.	0	0	a: 2 (13%) b: 1 (6%)
Level 3—Upper synthetic mental models (accurately use the Earth's rotation to explain at least the Sun's apparent motion)	3 (13%)	10 (63%)	6 (38%)
Code 3A: Student uses the Earth's rotation to explain a generally accurate description of the Sun's apparent motion and *either* the Moon or stars, but not both. Sun-A1-A and [(Moon-A1-A, Moon-A2-A, Moon-B1-A) OR (Stars A1-A)]	0	1 (6%)	1 (6%)
Code 3B: Student uses the Earth's rotation to explain a generally accurate description of the Sun's apparent motion but *neither* the Moon *nor* the stars. Sun-A1-A and NOT [(Moon-A1-A, Moon-A2-A, Moon-B1-A) AND Stars A1-A]	3 (13%)	9 (56%)	5 (21%)
Level 2—Lower synthetic mental models (does not accurately use the Earth's rotation)	9 (38%)	4 (25%)	2 (13%)
Code 2A: Student uses the Earth's rotation and other inaccurate explanations for a generally accurate description of the Sun's apparent motion. Explains the generally accurate description of the Moon *or* stars' apparent motion using the Earth's rotation. (Sun-B1-A or Sun-B3-A or Sun-C1-A) and [(Moon-A1-A, Moon-A2-A, Moon-B1-A) OR Stars A1-A]	0	0	1 (6%)

Table 4. (*Continued*)

	General third grade (n = 24)	Gifted students (n = 16)	
		Pre	Post
Code 2B: Student accurately uses the Earth's rotation and other inaccurate explanations to explain a generally accurate description of the Sun's apparent motion. Descriptions/explanations of the Moon and stars contain inaccuracies. (Sun-B1-A or Sun B3-A or Sun-C1-A) and NOT [(Moon-1-A, Moon-A2-A) AND Stars A1-A]	0	3 (19%)	0
Code 2C: Student explains inaccurate description of the Sun's apparent motion with accurate description of the Earth's rotation. May also include other inaccurate explanations. Descriptions/explanations of the Moon and stars also contain inaccuracies. (Sun-A1-NN, Sun B1-NN, or Sun C1-NN) NOT [(Moon-A1-A, Moon-A2-A, Moon-B1-A) AND Stars A1-A]	6 (25%)	1 (6%)	0
Code 2D: Student gives an inaccurate description of the Earth's rotation and may include other inaccurate explanations (such as the Sun's own motion or revolution); description of the Sun's apparent motion is accurate or inaccurate. a: Student gives an accurate description/explanation for Moon and/or stars: (Sun-B2-A, Sun B2-NN, Sun-B4-A, Sun-B4-NN), AND [(Moon-A1-A, Moon-A2-A, Moon-B1-A) AND/OR Stars A1-A] b: Descriptions/explanations of the Moon and stars' apparent motion contain inaccuracies. (Sun-B2-A, Sun B2-NN, Sun-B4-A, Sun-B4-NN), NOT [(Moon-A1-A, A2-A, Moon-B1-A) AND Stars A1-A]	a: 2 (8%) b: 1 (4%)	a: 0 b: 0	a: 1 (6%) b: 0
Level 1—Naive mental models	12 (50%)	2 (13%)	1 (6%)
Code 1A: Student believes that the Sun's apparent motion is caused by its actual motion. Explains the Moon's and/or the stars' apparent motion using the Earth's rotation. [Sun-D1, Sun-D3, or Sun-C2] and NOT [(Moon-D1-A, D2-A, E1-A, E2-NN, F1, or F2) and/or (Stars-E1, E2, or E3)]	2 (8%)	1 (6%)	1 (6%)
Code 1B: Student believes that the Sun and Moon rise and set across the sky but use the object's own motion to explain. Stars move/do not move due to their own motion/lack of motion. Sun-C2-A, (Moon-D1-A or D2-A), (Stars-E1, E2, or E3).	1 (4%)	0	0

Table 4. (*Continued*)

	General third grade (n = 24)	Gifted students (n = 16)	
		Pre	Post
Code 1C: Student believes the Sun and Moon appear to rise and set (or go up/down) because of their own up/down motion. Stars move/do not move due to their own motion/lack of motion. (Sun-D1-A or D1-NN), Moon-E1-A (Stars-E1, E2, or E3)	9 (38%)	1 (6%)	0

[a]A and NN refer to an accurate (A) and non-normative (NN) description of the apparent motion for each code (see Tables 1–3).

descriptions of the Sun, Moon, and stars appearing to rise and set from east to west ($p < 0.05$ for each of the three descriptions). The majority of students learned to describe a smooth, continuous path for all celestial objects, and nearly half indicated the rising and setting of the Sun, Moon and stars in the same direction—an important step in making the connection between the Earth's rotation (one frame of reference) and the appearance of motion of celestial objects (another frame of reference).

The Sun. The shift to a scientific understanding of the Sun category after instruction was small (63–81%) as most students began with accurate descriptions and explanations for the Sun's apparent motion (Table 1). Prior to instruction, all but two of the students attempted to reason between moving frames of reference by explaining the apparent motion of the Sun with the Earth's actual motion (with both accurate and non-normative results). All but one of the students gave descriptions of apparent motion that was logically consistent with their explanation, including the two students who gave naive descriptions. After instruction, all but one of the students were reasoning between moving frames of reference and all but one student made relatively logical connections.

The Moon. Prior to instruction, about half of the students (56%) used the Moon's orbit or the Earth's rotation combined with the Moon's orbit to explain the Moon's apparent motion (Table 2). Most students were working from the naive perspective (75%) rather than attempting to reason between moving frames of reference. Those students who did not make logical connections between the apparent motion and the explanation for that motion were all working from the naive perspective (31%). After instruction, all of the students in the gifted programme attempted to use the Earth's rotation to explain accurate descriptions of the Moon's pattern of motion. But in addition to accurate explanations (37%), this included students whose explanations combined the Moon's orbit with the Earth's rotation (19%) and others that believed that the Moon does not move (no orbit; 44%). All of these responses were logically consistent between their description of the Moon's apparent motion and the explanation of that motion.

The stars. Nearly half (44%) of the students in the gifted programme had a naive understanding of stars in their pre-interview (Table 3). Half of the students worked between frames of reference in their responses by using the Earth's rotation as their explanation (50%), but the majority of those students gave non-normative descriptions, including that the stars do not appear to move or only move a the end of the night. This resulted in four students (25%) who gave descriptions that did not logically match their explanation. Their non-normative ideas of the stars' size and distance may have contributed to their pre-instructional beliefs; 81% believed that at least some stars are as close as or closer than the Sun and Moon.

After instruction, nearly all of the students explained with the Earth's rotation (88%), with 63% accurately connecting the Earth's rotation with the stars' rising and setting apparent motion. This may be related to the students' significant improvement in understanding of the stars' relative distance; 63% of the students knew that all stars are farther than the Sun-Earth-Moon system. (Wilcoxon $Z = 2.656$, $p < 0.01$). Only two of the students gave responses that did not make logical connections between their description of the Earth-based and heliocentric frames of reference.

Students' mental models of daily celestial motion. Few students in the gifted programme began at a naive level of the tertiary codes, with the majority beginning at an upper synthetic level (63%) based on their application of the Earth's rotation to explain the Sun's apparent motion before instruction. It may be that additional learning opportunities contributed to that difference or, alternatively, that the gifted students possessed a greater ability to apply their knowledge of the Earth's rotation. Nearly all students in both studies were initially aware of the Earth's rotation, but most of the general population of third-grade students had not made the normative connection between the Earth-based frame of reference and the Earth's actual-motion frame of reference.

Students showed significant improvement as measured by their change in tertiary codes, an ordinal ranked scale (Wilcoxon $Z = -2.887$, $p < 0.01$). The majority of students improved in tertiary code (63%), while the remainder stayed at the same code (38%). All four of the students who began at a lower synthetic level improved. Five of the six students who did not change levels were in the upper synthetic group. This may be suggestive of the difficulty of accurately applying the Earth's rotation to the Moon and stars and may indicate that two days of instruction was not sufficient for this change. Most of the students who did not change level still showed improvement, as measured by positive changes in their primary codes.

Discussion

The research presented here is consistent with prior research demonstrating that children in early- to mid-elementary school are often working from naive or synthetic mental models for observational astronomy topics (e.g. Vosniadou & Brewer, 1994). We have continued this line of research by explicitly addressing how children both describe the Earth-based perspective and how they attempt to explain those observations. Learning to reason scientifically between moving frames of reference is a key aspect of understanding astronomy concepts at the elementary and secondary level. Our results suggest that as students enter mid-elementary school, many believe that the patterns of apparent motion they observe are because of the actual motions of the celestial objects themselves. Another large portion of the students are closer to the scientific perspective by recognizing that motions of celestial objects could be *apparent motions* caused by the actual motions of the Earth. Only a few children are likely to use the Earth's rotation accurately to explain the Sun's apparent motion and are less likely to apply this concept of apparent motion to the Moon or stars.

Vosniadou and Brewer (1994) reported that children with a scientific or synthetic understanding of the Earth's spherical shape would only occasionally explain the day/night cycle in terms of the Sun and Moon's actual up/down motions or as something blocking the Sun. However, this is not consistent with the results of our interviews with third-grade students. All but one of the students had spherical or synthetic spherical Earth models; yet these students were split between describing the Sun's apparent motion as naive versus using the Earth's rotation. Most students also gave naive explanations for the Moon's apparent motion. The difference in our findings compared to Vosniadou and Brewer's findings may be explained by the differences in how the students were asked these questions. Note that all but two of the students in our sample said that the Earth rotates at some point in the interview (either in response to asking about the Sun's apparent motion or when asked if the Earth moves). Students in Vosniadou and Brewer's study were not explicitly asked to differentiate between what we observe from the Earth's surface and what is the *cause* of those motions. The findings presented here support our assertion that students need to be guided in understanding how to make connections between the actual motions of heliocentric objects and the observable consequences from their Earth-based perspective.

An instructional intervention with gifted students was assessed to test the impact of instruction that explicitly taught students the apparent patterns of celestial motion while also supporting their ability to explain their observational knowledge. The gifted students in the instructional condition were not directly comparable to students in the general population of third-grade students; they were more sophisticated in their use of the Earth's rotation to explain the Sun's apparent motion though not in their understanding of the Moon or the stars. After instruction, many students shifted from synthetic towards the scientific level of accuracy. To reduce the cognitive load, students were supported in first visualizing the patterns of apparent motions (using a computer-based simulation and kinaesthetic mimicking of patterns) and then explicitly taught to make the connection between the apparent and actual motions through the use of their own bodies and hand-held globes. Their improvement suggests that explicitly teaching these two frames of reference using strategies that both mentally engage students and offer students appropriate support in constructing their own mental constructs of these patterns may be successful for students beyond this study.

We also attribute improvement in students' overall models of celestial motion to the iterative nature of the instruction, a focus on metacognitive strategies, and the focus on multiple-modality engagement strategies. Students were asked to engage in strategies that would increase their metacognitive awareness and their intentionality of learning through opportunities to make predictions and then observe simulations of the apparent motion of celestial objects (Vosniadou, 2003, 2007). Students then offered their own personal explanations for these observations followed by guided, multiple-modality modelling. The outcomes measured from this instruction reveal that children were modifying their existing explanations to incorporate the scientific perspective in ways that were consistent with their improved knowledge of apparent celestial motion.

While most students improved, and many reached the scientific level on our scale, a few challenges appear to hinder the remaining students from moving to more sophisticated levels of understanding. Students exhibited difficulties in the interplay between the relatively quick rotation of the Earth and the much slower orbit of the Moon with respect to explaining the Moon's apparent motion even after instruction. This concept is more complex as it requires integrating the implications of *two* moving objects (the Earth and Moon) with a single resulting motion in the Earth-based frame of reference. The resulting cognitive load in combination with the short duration of the instructional intervention contributes to the difficulty students had in assimilating this aspect of the scientific notion. A second challenge appeared in the resistance towards using the Earth's rotation to explain the stars' apparent motion. Students were explicitly taught these frames of reference through visual observation and kinaesthetic modelling; however, not all students adopted the scientific concept of the stars' rising and setting motion. Some of this may be due to their limited knowledge of the distance to the stars as well as the overall complexity of imagining thousands of stars appearing to rise and set (compared to the relatively simple ability to imagine a single Sun and Moon rising and setting). These are areas where improvement to the scientific level may require a more radical change in the students' conceptual framework rather than a more general additive growth (Vosniadou, 2007). A final challenge to learning to reason between frames of reference relates to students' spatial ability. Daily celestial motion requires the use of spatial abilities: mental rotation, spatial perception, and spatial visualization (Black, 2005; Linn & Petersen, 1985; Wilhelm, 2009). A mismatch between students' description of apparent motion and their explanation may be due to limited ability to use the necessary spatial abilities to make the logical connection. Instruction may have differentially supported high spatial ability students over low spatial ability students; Mayer and Sims (1994) found that subjects with higher spatial ability perform relatively better than low spatial ability subjects in multiple-modality instruction. Dual coding theory suggests that low spatial ability students must apply a greater cognitive effort and are thus limited by their working memory (Clark & Paivio, 1991).

The results presented here do not allow us to differentiate between students' spatial abilities. Nor do they differentiate between students who are actively moving between frames of reference by generating predictions internally or if they are linking two cognitive schemas that they hold separately within long-term memory, developed through instruction (Sweller et al., 1998). Holding the accurate schema of both perspectives may be the initial necessary step for students to begin to understand these concepts in a deeper way that would allow them to generate a mental model that can be used to predict Earth-based descriptions and mentally run through three-dimensional spatial interactions. Students in this study were explicitly asked to first describe what they might see from the surface of the Earth and were then asked to explain that description in terms of what was actually moving. As a result, the interview acted to scaffold the students' ability to make the frames of reference connection—a connection they may or may not have thought about before.

Our assessment of the third-grade students' pre-instructional knowledge as well as the results of the instructional intervention with third-grade students in the gifted programme allows us the opportunity to examine implications for instruction for a broader population of elementary students. First, given the prevalence of inconsistencies among the general third-grade students, instruction on moving between frames of reference in astronomy will need to help students see the logical consistency between the apparent and actual motions. We recommend that this begin with multimodality instruction supporting their understanding of the Earth-based frame of reference; computer simulations combined with kinaesthetic modelling was found to be successful with the gifted students and has been found to be successful with other general populations (Plummer, 2009b). Far fewer general third-grade students began with the more advanced notion that the Earth's rotation causes the Sun to appear to move. Thus, additional time should be spent helping students use their existing knowledge of the Earth's rotation to model the apparent motion concept than was used with the shorter instruction of the gifted students. Students demonstrated limited tendency towards moving frames of reference with respect to their understanding of the stars' concept. This suggests that many students in third-grade need assistance in putting together the pieces: the stars are extremely distant and appear to move like the Sun and Moon because of our actual motion on the spinning Earth. Instruction with the gifted students approached this by including a discussion of the size of the stars with respect to the Sun. For students in the general elementary population, additional time engaging with the nature of the stars, as well as guidance in focusing on the apparent path of a single star, rather than a collection of stars, may help students reach the scientific relationship between the frames of reference.

Conclusion

The present study extends the literature by presenting a clear focus on the Earth-based and the heliocentric frames of reference as well as examining the impact of instruction on children's understanding of daily celestial motion. We address a missing piece of astronomy education literature: children's ability to move between frames of reference in the solar system. First, our study goes beyond Vosniadou and Brewer's seminal work discussing children's mental models in astronomy, as well as subsequent research (e.g. Kallery, 2010; Samarapungavan et al., 1996; Sharp, 1996; Vosniadou & Kyriakopoulou, 2006), by explicitly asking students to describe their Earth-based perspective and then asking them to shift to a new perspective and offer an explanation. Previous studies have not explicitly examined the distinction between actual and apparent motions leaving questions about the students' abilities to explain and interpret observational astronomy. Our results suggest that many students will not move between these frames of reference at a scientific level even if they know that the Earth rotates without instructional intervention.

Second, we present our findings on how specific instructional strategies support children's development in this domain. Previous research has focused on aspects of daily celestial motion (e.g. Diakidoy & Kendeou, 2001; Sharp & Sharp, 2007) without specifically articulating the entire daily celestial motion concept. Instruction that supported students in using 3D physical models and their own kinaesthetic experiences helped students in the gifted programme move towards the scientific concept. Similar results have been found with college students using 3D computer modelling programmes in more advanced areas of celestial motion (Barnett, Yamagata-Lynch, Keating, Barab, & Hay, 2005; Hansen, Barnett, MaKinster, & Keating, 2004a, 2004b).

We presented here the initial development of an instructional approach which supports students moving between moving frames of reference in order to develop more sophisticated mental models of celestial motion by focusing on the Earth's rotation and patterns of daily motion. This builds on our previous work which demonstrated how instruction in the planetarium can move students towards more sophisticated descriptions of apparent celestial motion (Plummer, 2009b) by extending some of the visual and kinaesthetic techniques to the classroom to support students' explanations. With our goal of children moving fluently between frames of reference to explain apparent patterns across daily, monthly, and yearly time frames, understanding of the concepts explored here is certainly foundational. These concepts may be built on towards an understanding of the reason for the seasons, phases of the Moon, and more sophisticated descriptions of our observations of the stars. Additional research is needed to understand at a deeper level the interplay between instruction and students' cognitive growth in these different levels of observational astronomy.

Because the students in the gifted programme entered instruction with a different distribution of prior knowledge compared with the general population, we do not argue here that the targeted two-day instruction would have had the same effect if used with all third-grade students. Rather, the results lead us to suggest that the next phase of this research is to examine the impact of these strategies if infused into the third-grade astronomy curriculum and across longer duration. Further research is also needed on children's development of relative spatial size and distance relationships within this domain and the extent to which this understanding is required for moving to more sophisticated explanations; development in this area may also best be accomplished using kinaesthetic experiences (Tretter, Jones, Andre, Negishi, & Minogue, 2006). Many elementary teachers also hold on to synthetic rather than fully scientific models of celestial motion (Plummer et al., 2010) and may believe that teaching the Earth-based perspective is wrong (Shen & Confrey, 2010). Thus, future research would benefit from investigating ways to challenge these alternative conceptions among teachers and how this may change student outcomes.

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Appendix. Interview Questions

Versions of this protocol have been used in previous studies (Plummer, 2009a, 2009b; Plummer et al., 2010). Students were given a flashlight to demonstrate their answers by shining the flashlight on the roof of a small planetarium-like dome:

1. Sun's apparent motion today:
    a. Can you show me where the Sun is first thing in the morning?
    b. Can you show me the Sun's apparent motion throughout the day?
    c. What happens at the end of the day?
    d. Where is the Sun at noon?
    e. Would that be directly over your head?
2. Motion of the Moon:
    a. Does the Moon appear to move across the sky?
    b. (If the Moon appears to move) Can you show me what that looks like?
    c. (If the Moon appears to rise and set) When does the Moon rise? When does the Moon set?
    d. Are there times when we cannot see the Moon? Why cannot we see it? Can you think of any other reasons?
3. Motion of the stars:
    a. You showed me the motion of the Sun and the Moon. Do the stars appear to move at night too?
    b. (If yes) Pretend the flashlight is showing one bright star. Can you show me the motion of that star?
    c. Do we see the same stars all night long? Why or why not?
    d. What happens to the stars when the Sun comes up in the morning?

Interviewer and the student sit at a table.

4. Can you tell me what the shape of the Earth is?
   (If answer is round or a sphere):
    a. What other objects could you find that are the same shape as the Earth?
       Ask the subjects to use a model of the Sun (a ball), the Earth (a small globe), and Moon (a small ball) to describe why they showed the Sun's, Moon's, and stars' apparent motion.
5. Can you use these objects to explain why the Sun appears to move across the sky as you showed in the dome?
    a. (If they do not show rotation) Does the Earth move? Can you show me?
6. Can you use these objects to explain why the Moon appears to move (or not move) like you showed in the dome?
7. Where would the stars be in this model?
8. How big are the stars? Are they bigger or smaller than the Moon? Than the Sun?
9. Can you use these objects to explain why stars (do not) appear to move?