*International Journal of Science Education*, 2014
Vol. 36, No. 7, 1083–1106, http://dx.doi.org/10.1080/09500693.2013.843211

# Learning to Explain Astronomy Across Moving Frames of Reference: Exploring the role of classroom and planetarium-based instructional contexts

Julia Diane Plummer[a*], Alicia Kocareli[b] and Cynthia Slagle[c]
[a]*Curriculum and Instruction, Pennsylvania State University, State College University Park, PA, USA;* [b]*School of Education, Arcadia University, Glenside, PA, USA;* [c]*Colonial Middle School, Colonial School District, Plymouth Meeting, PA, USA*



Learning astronomy involves significant spatial reasoning, such as learning to describe Earth-based phenomena and understanding space-based explanations for those phenomena as well as using the relevant size and scale information to interpret these frames of reference. This study examines daily celestial motion (DCM) as one case of how children learn to move between frames of reference in astronomy wherein one explains Earth-based descriptions of the Sun's, Moon's, and stars' apparent motion using the Earth's daily rotation. We analysed interviews with 8–9-year-old students ($N = 99$) who participated in one of four instructional conditions emphasizing: the space-based perspective; the Earth-based perspective in the planetarium; constructing explanations for the Earth-based observations; and a combination of the planetarium plus constructing explanations in the classroom. We used an embodied cognition framework to analyse outcomes while also considering challenges learners face due to the high cognitive demands of spatial reasoning. Results support the hypothesis that instruction should engage students in learning both the Earth-based observations and space-based explanations, as focusing on a single frame of reference resulted in less sophisticated explanations; however, few students were able to construct a fully scientific explanation after instruction.

Keywords: *Astronomy; Elementary; Multimodal Instruction; Embodied Cognition; Spatial Reasoning*

*Corresponding author. Curriculum and Instruction, Pennsylvania State University, University Park, PA, USA. Email: jdp17@psu.edu

This study examined changes in children's understanding of astronomy after participating in one of four instructional conditions designed to test different facets of learning to explain daily celestial motion (DCM): the apparent rising and setting of the Sun, Moon, and stars due to the Earth's rotation. All celestial objects appear to move from east to west due to the Earth's rotation. Thus our Earth-based perspective suggests that the Sun, Moon, and stars all appear to be circling around us. This complex area of reasoning requires a person to imagine motion in two different frames of reference, 'the most important factor in the astronomy of position' (Albanese, Danhoni Neves, & Vicentini, 1997). A person considers the observational reference frame by visualizing the motions of the celestial object(s) from one's own Earth-bound perspective. To explain these apparent changes, one must also imagine how a space-based perspective can cause us to observe specific patterns of change from the Earth's surface. These shifts rely on an ability to visualize change over different timescales. Reasoning between moving frames of reference is necessary for other topics of K-12 astronomy and may therefore serve as a foundation for the types of reasoning expected in more advanced study of astronomy and other sciences that involve frames of reference.

We draw on an epistemological framework in which understanding a scientific model includes making an explicit connection between the model and the empirical observations that the model is supposed to explain (Albanese et al., 1997). However, the existing literature on children learning about astronomy is often limited in the extent to which it explores these connections, which may result in differences between how the researcher and the subject perceive assessment questions (Albanese et al., 1997; Siegal, Butterworth, & Newcombe, 2004). Researchers' exploration of children's ideas in astronomy is limited by not disentangling students' perspectives on the two frames of reference or by not investigating students' knowledge of the Earth-based perspective as part of an analysis of their explanations.

Other research has carefully examined both how students describe astronomical phenomena and how they explain this perspective (e.g. Blown & Bryce, 2010; Plummer, Wasko, & Slagle, 2011; Trundle, Atwood, Christopher, & Sackes, 2010). Learning to explain celestial motion phenomena requires more than understanding how objects move in space. For example, children may understand that the Earth rotates without using this to explain the day/night cycle (Plummer et al., 2011) and they may be able to describe how the Moon orbits the Earth without being able to explain the lunar phases (Subramaniam & Padalkar, 2009).

We hypothesize that the cognitive challenges involved in understanding the role of the Earth's rotation in our observations are sufficient to require specific instructional strategies that help students understand both the Earth-based and space-based perspectives. We investigated instructional conditions that focused on (1) learning the space-based motions of celestial objects, (2) learning the Earth-based perspective of apparent motion, (3) supporting students using space-based motions to explain Earth-based observations, and (4) engaging students in both the Earth-based and space-based perspectives as they construct explanations. This allowed us to compare the extent to which children's understanding changed within each of these different emphasis areas. The study was guided by the following research question: To what extent can each instructional condition help us understand how to support students in constructing explanations that move across frames of reference?

## Cognitive Challenges in Learning Astronomy

### *Spatial Thinking and Demands on Working Memory*

Central to constructing scientific explanations around celestial motion phenomena is the ability to track and remember positions and motions of objects in three dimensions. For example, understanding the stars' apparent motion involves visualizing how the Earth-based observation of stars rising and setting, a motion that occurs on the 3D 'surface' of the sky. Our changing perspective explains this as we rotate about the Earth's axis. This level of explanation involves challenging aspects of spatial thinking, such as mental rotation and spatial visualization (Mathewson, 1999). Mental rotation involves rapidly and accurately rotating objects in one's mind (Linn & Petersen, 1985). Spatial visualization includes the ability to interpret 3D information from 2D representations, imagine objects from different perspectives, and to visualize how rotation can change the appearance of objects (Barnea & Dori, 1999). Spatial ability has been identified as a factor explaining differences in students' understanding of astronomy (e.g. Black, 2005; Heyer, 2012; Wilhelm, 2009).

The reliance on spatial thinking in celestial motion points to the importance of designing instruction that supports students in learning to visualize patterns and constructing mental models that allow them to move between frames of reference in their explanations. Instruction in astronomy often requires students to reason between 2D representations and their own 3D imagination of the astronomical system. However, relating 2D to 3D is difficult for students with low spatial ability (Hegarty, 2010). Further, early elementary-aged children find perspective taking to be challenging (e.g. Rigal, 1996; Roberts & Amin, 1993).

Instructional design must also consider the limits of working memory due to the nature of human cognitive architecture (Sweller, van Merrienboer, & Paas, 1998). The load on working memory increases as a learner attempts to understand elements of information together, rather than separately (Sweller et al., 1998). Instruction should be designed to support learners in processing a few new concepts at a time, within their existing schemas (Sweller, 2004). A student may not be able to fully imagine the complex motions and perspectives involved with celestial motion all at once. Rather, people tend to solve complex problems by decomposing the task into a set of relatively simple steps (Hegarty, 2010). For example, students may reduce the challenge of incorporating complex spatial information for explaining the lunar phases by creating a 'snap shot' of a dynamic situation through a diagram or using familiar situations as analogy for the Sun-Earth-Moon system (Subramaniam & Padalkar, 2009).

Students' abilities to solve problems in astronomy may potentially depend on gender. Two types of spatial ability appear to favour men: *spatial perception* (a person's sense of horizontal or vertical) and *mental rotation* (a person's ability to mentally rotate two- or three-dimensional representations) (Voyer, Voyer, & Bryden, 1995). Mental rotation ability may account for some of the gender variance in college students' astronomy knowledge (Heyer, 2012).

### *Implications of Cognitive Challenges for Instructional Design*

We used a multiple modality framework to consider how instruction can support students in developing *visual* and *embodied* schemas of astronomy. Dual coding theory (DCT) suggests that engaging in both verbal and non-verbal modalities will support learning beyond a single modality (Paivio, 1986). The verbal and non-verbal cognitive systems are linked such that mentioning the word 'sunrise' can invoke images associated with that verbal cue. Visual simulations can support students in developing mental schemas of celestial motion, such as observational patterns, that can be called upon to help them construct explanations. Maintained in long-term memory, these can be used to reduce cognitive load in later problem solving (Merrienboer & Sweller, 2005).

Engaging in kinaesthetic experiences can support students in developing embodied schemas of celestial motion. Embodied cognition theory suggests that cognitive structures are embodied, arising from our interactions with the world (Lakoff & Johnson, 1980). Human cognition is embodied because it evolved to support our perception and to facilitate interaction with in a 3D world (Glenberg, 1997). Research using brain scans support the conclusion that mental imagery includes motor imagery (Parsons et al., 1995). Thus, learning astronomy through the use of kinaesthetic action may help students understand the spatial relationships between Earth-based and space-based perspectives and allow students to use motor imagery to run mental simulations of celestial motion concepts. 'Mental structures that originally evolved for perception or action appear to be co-opted and run "off-line," decoupled from the physical inputs and outputs that were their original purpose, to assist in thinking and knowing' (Wilson, 2002, p. 633). Physical engagement with models may support learning and spatial cognition by reducing cognitive load. Wilson (2002) argues that 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' (p. 628).

The embodied cognition framework can also explain the importance of students' gesture use in spatial problem solving. Training children to gesture may improve their ability to solve problems that involve mental transformations, such as mental rotation (Ehrlich, Levine, & Goldin-Meadow, 2006), help them integrate the spatial and temporal aspects of astronomical problem solving (Padalkar & Ramadas, 2010), and improve their ability to imagine change in reference frames (Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

*Children's Learning Astronomy*

Without targeted instruction, research suggests that most children will not develop scientific explanations that account for both the Earth- and space-based reference frames in DCM (e.g. Plummer et al., 2011). Children in early elementary school often describe the apparent motion of the Sun, Moon, and stars in non-normative ways. For example, early elementary students' descriptions of the Sun and Moon's motion often included rising and setting on the same side of the sky and few are aware of the stars' daily rising and setting motion (Plummer, 2009a). In a study of third grade students, nearly all knew that the Earth rotates but few used this concept to explain their descriptions of apparent celestial motion. Instead, many students use intuitive models to explain these observational patterns—an object's apparent motion explained by the object's actual motion (Plummer et al., 2011).

Research on instruction that supports students' movement between reference frames often indicates the importance of using physical models, such with the day/night cycle (Kallery, 2011) and lunar phases (Parker & Heywood, 1998; Trundle et al., 2010). Computer-based simulations may help students make observations of the Earth-based perspective, which can be followed by explanation-building opportunities using psychomotor modelling with balls and a light-source (Hobson, Trundle, & Sackes, 2009; Plummer et al., 2011). Plummer (2009b) found that guided gesturing during a planetarium programme supports learning about the Earth-based perspective. In another study, Plummer and colleagues (2011) examined an instructional approach in which students learned to describe apparent motion using observations of a computer-based simulation and then explained those motions through kinaesthetic and psychomotor modelling. While most improved, students exhibited difficulties in explaining the Moon's and stars' apparent motion.

## Instructional Conditions Used in This Study

Four instructional conditions were chosen to test how emphasis on different features of DCM would influence children's explanations. All students were in third grade and participated in their district's six-week astronomy curriculum (see Figure 1 for an overview). Each participant took part in only one instructional condition.

*Condition 1—District Curriculum*

No changes were made to the teachers' enactment of the district six-week curriculum (30–45 minute lessons, approximately three days a week). In *Relative Size* (two days), students used a large ball and a small ball to find out why the Sun and Moon appear to be the same size in the sky. In *Defining* (two lessons), students wrote and demonstrated definitions for vocabulary words: axis, rotate, revolve, orbit, ellipse, and satellite. Teachers discussed why we have day and night but without supporting students' understanding of the Sun's apparent motion.

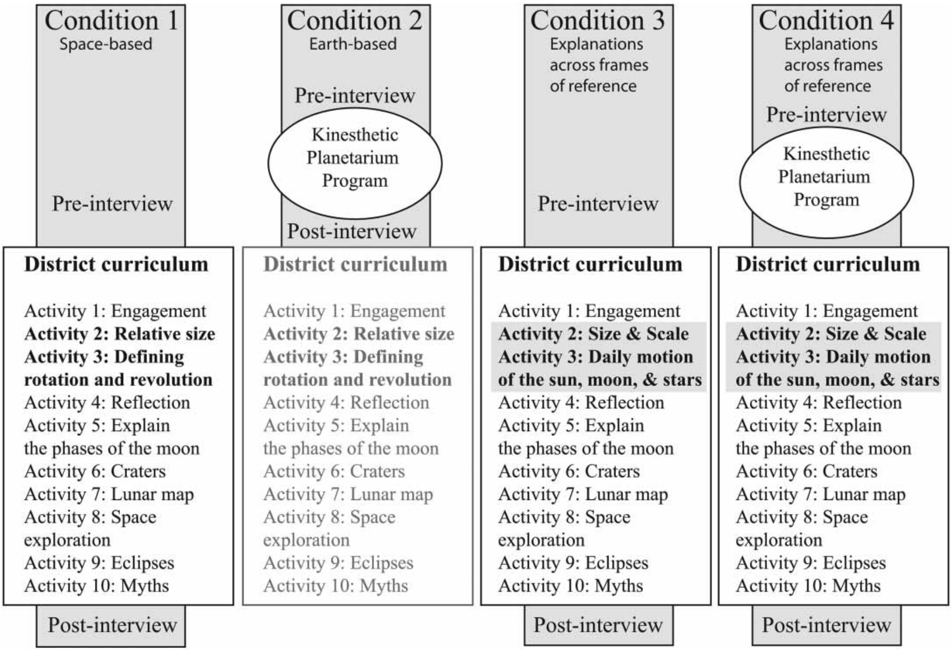


Figure 1. Each of the four instructional conditions is shown, with time running from top to bottom. All students participated in the district's astronomy curriculum, but post-instruction interviews were completed for Condition 2 before the start of this curriculum

*Condition 2—Planetarium Lesson*

This 45-minute live planetarium programme engaged students kinaesthetically with the patterns of apparent DCM by asking the students to use their arms to trace out the motions of the Sun, Moon, and stars as they appear to rise and set. Although the primary focus of the instruction was on apparent celestial motion, the planetarium director used language that supported the idea that this was an apparent (not actual) motion (see Plummer, 2009b for more detail on the programme).

*Condition 3—Revised Curriculum*

We engaged teachers (Conditions 3 and 4) in four hours of professional development, focusing on helping teachers understand the importance of addressing both perspectives as some elementary teachers believe that teaching the Earth-based perspective is wrong (Shen & Confrey, 2010). The teachers participated in two new lessons and discussed examples from pilot testing the lessons with other third grade students (Plummer et al., 2011).

In the new lesson *Size and Scale* (one day), students engaged with accurate scale comparisons for size and distance between the Sun, Earth, and Moon using physical models. The lesson *Daily Celestial Motion* replaced the lesson *Defining*. On the *first day*, the teacher discussed and labelled the cardinal directions with the students and guided them in observing and mimicking the path of the Sun by tracing this pattern across the classroom walls. Students were guided to construct an explanation for this motion by kinaesthetically modelling the Earth's rotation while they watch the Sun (a lamp) as it appears to 'rise' and 'set' from their perspective; this was repeated with small Earth globes. On the *second day*, the class modelled the Moon's apparent motion kinaesthetically. Students added the Moon to their earlier space-based model and observed how the Moon also appears to rise and set like the Sun when they rotate like the Earth. The teacher introduced the idea of the slow motion of the Moon's orbit to the model and students repeated their observations of the relatively quick rotation of the Earth compared to the slow orbit of the Moon. On the *third day*, the teacher guided students in a discussion of the relative size of the planets, Sun, and stars using visual representations. Students taped cut-out stars around the room to represent the background of stars. Students were guided to observe that the stars appear to move across their field of view as they kinaesthetically rotated, like the Earth (lesson plans available upon request).



### *Condition 4—Planetarium Plus Revised Curriculum*

The purpose of including this condition was to investigate the value added by combining the Earth-based planetarium perspective with kinaesthetic and psychomotor modelling experiences to the classroom. Three classrooms first attended the planetarium programme and then participated in the same lessons as Condition 3.

## Methodology

### Context

The study took place in a suburban school district in the North-Eastern USA. The district website describes the student demographics as: 81.5% White, 2.1% Hispanic, 8.5% African-American, 4.8% Asian/Pacific Islander, and 3% Multi-racial students. District test scores in Grade 4 science in 2011 was 92% proficiency, compared to the state average of 83%.

In the 2008–2009 school year, third grade students from four classrooms were interviewed before and after instruction (Condition 1, $N = 24$; evenly split by gender).[1] In the 2009–2010 school year, third grade students from two classrooms were interviewed before and after the planetarium visit (Condition 2, $N = 22$; evenly split by gender). Five additional classrooms were split between Condition 3 ($N = 21$; 10 boys and 11 girls) and Condition 4 ($N = 32$; 17 boys and 15 girls). The students' average pre-interview age was 8 years 8 months.

This study used a design-based research (DBR) methodology, which can

> generate plausible causal accounts because of its focus on linking processes to outcomes in particular settings, and can [assist] in the identification of relevant contextual factors, aiding in identification of mechanisms (not just relationships), and enriching our

understanding of the nature of the intervention itself. (Design-Based Research Collective, 2003, p. 6).

Our goal was to gather evidence that can help improve understanding of instructional practices in naturalistic settings and investigate children's cognition in celestial motion. Conducting this study in naturalistic conditions can also lead to limitations in the extent to which findings can be generalized—due to challenges with controlling variables (Collins, Joseph, & Bielaczyc, 2004). We argue that from a *naturalistic generalization* perspective, there is value in 'providing vicarious experience to the readers who may then intuitively combine this with their previous experiences' (Stake & Trumbull, 1982), allowing the reader to decide whether case-to-case generalization may be appropriate (Firestone, 1993).

*Interviews*

The first author conducted pre-/post-interviews lasting about 15 minutes. The interview protocol was designed to avoid problems with ambiguity of whether questions refer to Earth- or space-based perspectives by asking questions about each reference frame separately. First, students described their understanding of apparent celestial motion using a flashlight while sitting under a small planetarium-like dome (see Plummer, 2009a). Second, students explained their demonstrations of apparent motion using physical models of the Sun, Earth, and Moon. The interview protocol can be found in a previous paper (Plummer et al., 2011).

*Analysis*

Eighteen primary categories described students' ideas about apparent motion, their explanations for observable motions, and knowledge of size and scale of these celestial objects. Codes within each category were initially defined by examining existing literature and then by adding additional codes, as new ideas were uncovered in the interviews (Plummer et al., 2011). Table 1 shows examples of codes developed for this analysis; a full coding protocol is available upon request. The first and second authors individually coded a sample of 20 interviews reaching an acceptable level of inter-rater reliability (Cohen's kappa = 0.84). Four secondary categories resulted from combining multiple primary codes. First, a secondary category called *direction* was defined, using codes for how students described the Sun's, Moon's, and stars' apparent motion, to categorize children's overall understanding of the apparent motion. Three additional secondary categories were created to combine how students described an object's apparent motion with how they explained that motion. For example, at the scientific level for *SecondarySun*, students describe the Sun's apparent motion as a smooth path across the sky and explain this with the Earth's daily rotation.

Codes were assigned ordinal values based on level of accuracy. This allowed us to use non-parametric tests to look for differences between conditions as well as improvement. We used the Kruskal-Wallis H test to look for difference by gender

Table 1. Examples of primary and secondary categories and codes

| Category | Codes | Rank |
|---|---|---|
| **Primary** | A smooth arc across the sky (does not have to be from E to W) | 2 |
| *Sun's Path*: Describe the Sun's path. | A path across the sky that includes a sharp turn in the middle, or rising and setting position within ~45 degrees of each other | 1 |
| | No resemblance to actual path | 0 |
| **Primary** | The rotation of the Earth | 3 |
| *SunExp*: Examines explanation for the Sun's apparent motion; does not evaluate apparent motion | Inaccurate use of the Earth's rotation (e.g. direction of the Earth's rotation changing); or, the Earth revolving around the Sun; or, the Earth both rotates and revolves on a daily basis | 2 |
| | Rotation of the Earth in combination with the Sun's own motion | 1 |
| | The Sun revolving around the Earth; or, the Sun's own motion, such as moving up and down | 0 |
| **Secondary** | Sun's apparent motion is a smooth path across the sky. The Earth's 24-hour rotation is used to explain this observation | 3 |
| *SecondarySun*: Overall connection between the description of the Sun's apparent motion and the explanation for that perspective | Sun's apparent motion is a smooth path across the sky. Non-normative explanation that includes some form of the Earth rotating (and may include the Earth orbiting the Sun) | 2 |
| | Sun's motion is entirely explained by Earth's motion but does not include the Earth's rotation or the path of the Sun's apparent motion is non-normative. Includes the Sun's actual motion as part of the explanation | 1<br>0 |

and the Wilcoxon signed ranks test to measure improvement. The Kruskal-Wallis H test was used to determine if the students across conditions held comparable knowledge of astronomy, prior to instruction, to minimize threats to internal validity due to differential selection. This allowed us to compare post-instruction results to determine which condition made more progress in each category. For those categories in which a significant difference was found, the Mann-Whitney test was used on the post-instructional results to identify which specific condition showed more improvement.

We considered other potential threats to internal validity. Students' experience with the initial interview may have impacted their learning as it could have sensitized students to certain features of the astronomy content. The physical models may have aided students in making new explanations. Threats to instrument validity were minimized by using a detailed coding document to code the videos of the interviews.

Table 2. Summary of major findings from the analysis of improvement for each condition as well as the statistical comparison between conditions

| | Condition 1 | Condition 2 | Condition 3 | Condition 4 | Comparison between conditions |
|---|---|---|---|---|---|
| Apparent motion | Did not show improvement | Improved in all apparent motion categories | Improved in sun and stars apparent motion | Improved in all apparent motion categories | Conditions 2 and 4 showed significant improvement over Conditions 1 and 3 in most apparent motion categories |
| Explanations | Only improved in explaining Sun's apparent motion | Improved in use of Earth's rotation to explain Sun's apparent motion and in the connection between the Earth's rotation and stars' apparent motion | Improved in all explanation categories save one of the Moon explanation categories | Improved in all explanation categories except both Moon explanation categories | Conditions 3 and 4 showed significant improvement over Condition 1 in most explanation categories Condition 4 showed significantly greater improvement over Condition 2 in some categories relating to explaining the Sun's and stars' motion |
| Other topics | Improved in knowledge of Moon's orbit | Improved in knowledge of Earth's rotation, Moon's orbit, and the size of Sun, Moon, Earth, and stars | Improved in all categories except knowledge of Earth's rotation | Improved in all categories | Condition 4 showed significantly greater improvement in understanding of rotation compared to all other conditions No other differences found |

## Findings

Table 2 summarizes the major findings from the analysis of improvement for each condition as well as the statistical comparisons between conditions.

### *Improvement Within Each Condition*

*Apparent celestial motion.* Figure 2 shows change in student responses for the four apparent motion categories. Two sets of categories, *Sun's Path* and *Moon's Path*, distinguish between three levels: the normative path, a partially accurate path (either not smooth or rising/setting in the same place), and paths that do not resemble the scientific description of rising/setting. Another category distinguishes three levels of accuracy of the stars' apparent motion (*Stars' Path*): stars rise/set in a smooth path across the sky, stars appear to move in a continuous pattern (not rising/setting), or other non-normative motions/not-moving. The final category (*Direction*) describes four levels of increasing sophistication towards understanding that the Sun, Moon, and stars all appear to move in the same direction across the sky.

Students in Condition 1 did not improve in their descriptions of apparent celestial motion. In Condition 3, students showed limited improvement in how they described the Sun's and stars' apparent motion. Conditions 2 and 4 showed significant improvement in all categories; most reached the scientific description of the Sun's and Moon's apparent motion, relatively few were at the scientific level for the stars' apparent motion. Students in Conditions 2, 3, and 4 improved in their overall description of

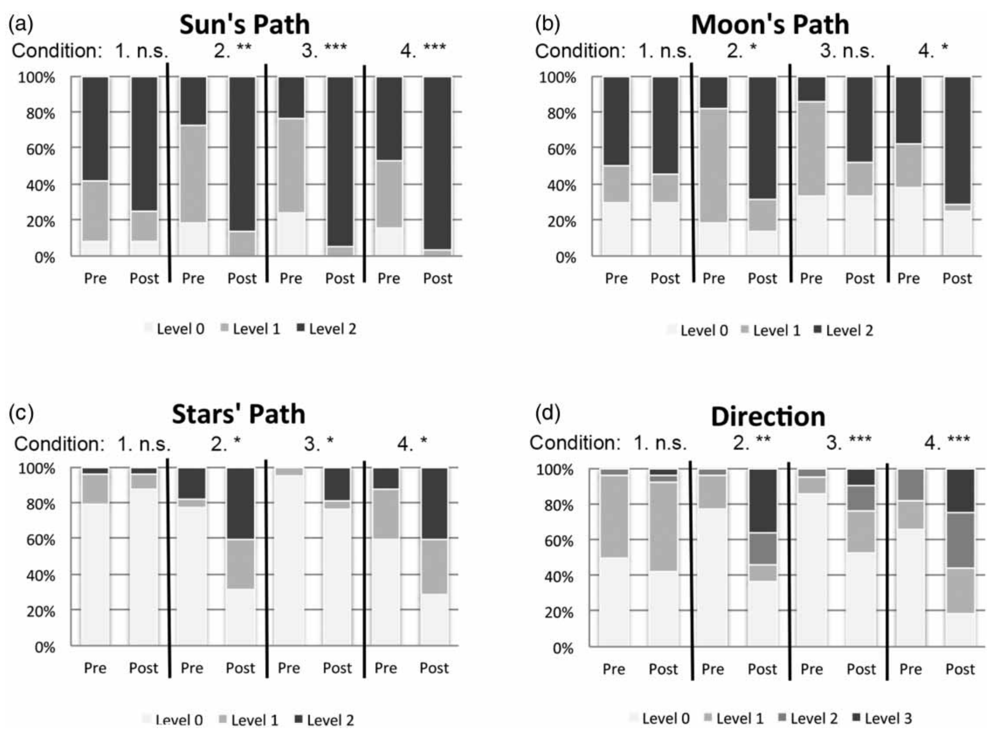


Figure 2. Improvement in descriptions of apparent motion from each of four instructional conditions. Each condition is numbered at the top of the bar graph with pre-data followed by post-data. Asterisks indicate significance of improvement ($p < .05$: *; $p < .01$: **; $p < .001$: ***; $p > .05$: not significant [n.s.])

the *direction* of the Sun's, Moon's, and stars' motion. Most students in Conditions 2 and 4 either reached Level 3, where the Sun, Moon, and stars rise and set, or Level 4 where all objects rise and set from east to west.

*Explanations for the apparent motion.* Figure 3 shows changes in responses for how students explain apparent celestial motion. We categorized how students explained the apparent motion of the Sun, Moon, and stars (Figure 3(a, c, e): *SunExp*, *MoonExp*, *StarsExp*, respectively). These categories examined the accuracy of the explanations, not how they described the apparent motion. Next, we created a set of categories that ranked the accuracy of the *combination* of the description of apparent motion and their explanation (Figures 3(b, d, f): *SunSecondary*, *MoonSecondary*, *StarsSecondary*, respectively). For example, a student that combined a scientific description of the Sun's daily apparent motion with an explanation using the Earth's rotation would be coded with the highest score (Level 3); a student that described the Sun as rising and setting in the same place on the horizon but said that this is because the Earth rotates would be coded at Level 1. The final category (Figure 3(g): *tertiary*) combines codes from *SunSecondary*, *MoonSecondary*, and *StarsSecondary* to rank the student's overall explanation for DCM.

Students in each condition improved in their explanation of the Sun's apparent motion. The planetarium programme included an opportunity for students to stand and rotate after watching the Sun appear to rise and set; for students who already knew the Earth rotates, this brief experience combined with observing the Sun rise and set may have helped them make the connection. Condition 1 also showed significant improvement; this was due to the students learning the space-based description of the Earth's rotation, as there was no improvement in their description of the Sun's path. After instruction, most children in Conditions 3 and 4 could both describe the Sun's apparent motion accurately and explain this using the Earth's rotation (*SecondarySun);* less than half reached this level in Conditions 1 and 2.

Students in Conditions 3 and 4 improved in their use of the Earth's rotation to explain the stars' apparent motion. Significant improvement was also observed in Condition 2; the improvement was largely due to students developing more sophisticated descriptions of the stars' apparent motion rather than an increase in use of the Earth's rotation to explain.

Improvement was not observed in any condition for *MoonExp* and only for one condition for *MoonSecondary*. The category *MoonSecondary* has four levels that range from the Moon's apparent motion is caused by its actual motion (lowest level) through increasingly scientific use of the connection between the Earth's rotation and the Moon's apparent path across the sky. Only Condition 3 showed significant improvement in their explanation of why the Moon appears to rise and set. However, in Conditions 3 and 4 the percentage of students explaining the Moon's apparent motion with *both* the Earth's rotation and the Moon's orbit (Level 2 in *MoonExp*) more than doubled.

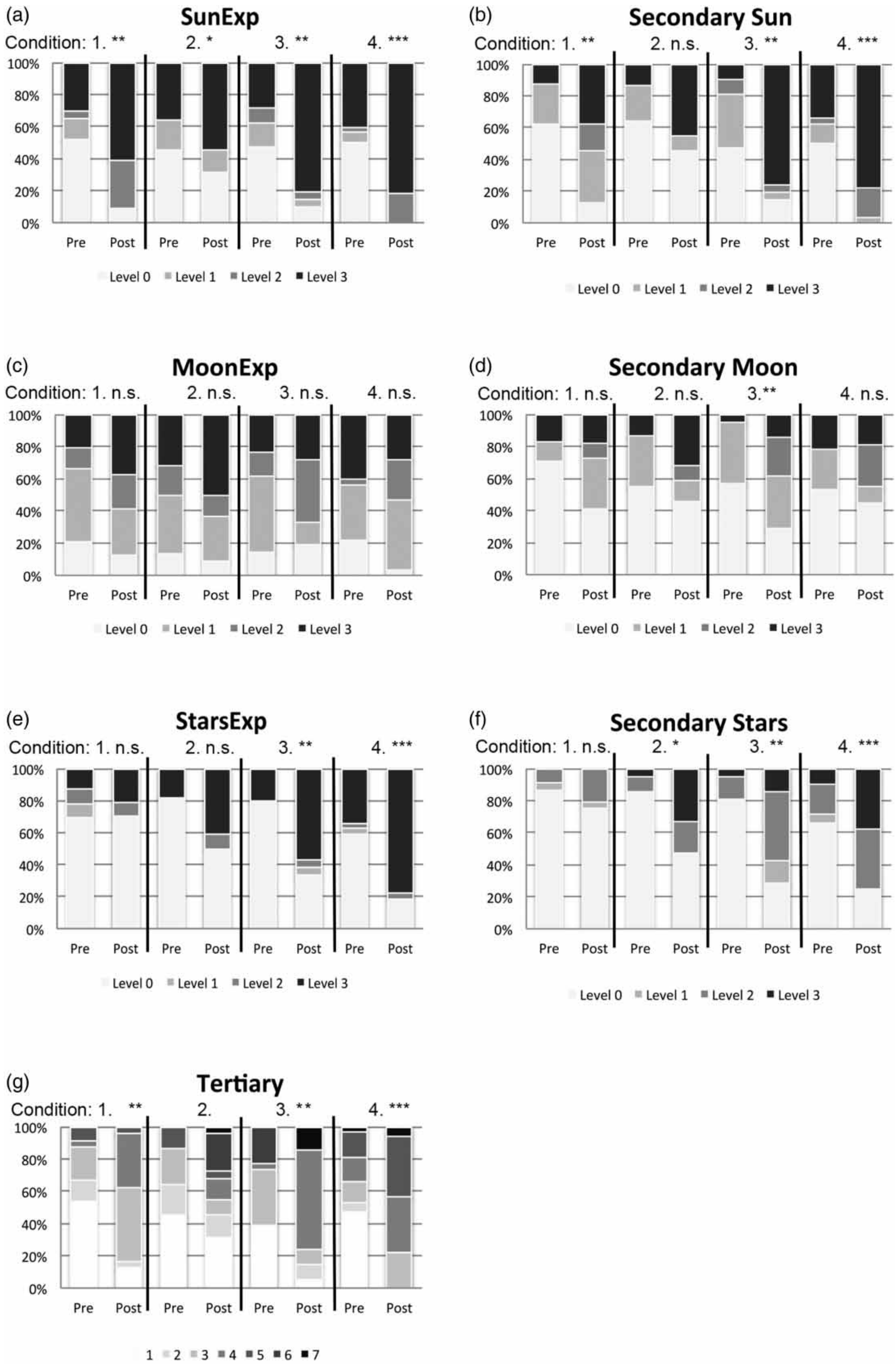


Figure 3. Improvement in descriptions of explanations for DCM. Asterisks indicate significance of improvement ($p < .05$: *; $p < .01$: **; $p < .001$: ***; $p > .05$: not significant [n.s.])

Figure 3 shows that Conditions 1, 3, and 4 improved significantly in their overall explanation for DCM (*tertiary*). Some students in Conditions 3 and 4 reached the scientific level explanation for DCM while none of the students in Condition 1 reached above Level 5 (students who explain the Sun's apparent motion with the Earth's rotation and either the Moon's *or* stars' apparent motion with the Earth's rotation, but not both).

*Other aspects of astronomy.* Figure 4(a) shows *rotation* in something other than 24-hours as Level 1 and the scientific description of rotation in 24-hours as Level 2. Before instruction, most of the students knew the Earth rotates and many described this as happening in 24-hours. The number of students who could demonstrate the Earth's rotation increased significantly in Conditions 2 and 4. Knowledge of the Moon's *orbit* showed significant improvement in all conditions (Figure 4(b)); this improvement was somewhat surprising for the planetarium condition given that it was a minimal portion of the planetarium instruction, perhaps indicating how simple this concept is for students to learn.

We also examined four categories relating to the size and distance to celestial objects. Conditions 3 and 4 showed significant improvement in understanding the relative distance to the stars (*Stars' Distance*). An accurate response for this category was to say that the stars are farther than the Sun and Moon; partially accurate responses indicated that the stars are both closer and farther than the Sun and Moon. Conditions 2, 3, and 4 showed improvement in the size of the stars (*Stars' Size*), indicating that stars are as big or bigger than the Sun.

Questions relating to the relative distance to the Moon and Sun (*SEMdistance*) and relative size of the Sun, Earth and Moon (*SEMsize*) were added in Year 2. Prior to instruction, many students believed that the Sun and Moon were at the same distance from the Earth or that the Sun was closer than the Moon to the Earth. Students in Conditions 3 and 4 improved their understanding of the relative distance to the Moon and Sun. All three conditions showed significant improvement in their understanding of the relative sizes of the Sun, Earth, and Moon.

### *Comparison of Improvement Between Groups*

A Kruskal-Wallis test revealed a significant difference between conditions for the size and distance categories; therefore, these categories were dropped from the analysis. Table 3 shows the results of the Kruskal-Wallis test comparing the post-instructional outcomes, showing only instances in which a significant difference was found between conditions.

Trends in Table 3 broadly match our initial predictions. First, the two conditions that attended the planetarium often showed significantly more improvement in apparent motion. We also predicted that the revised curriculum would result in more students learning to use the Earth's rotation accurately in their explanations of the apparent motion of the Sun, Moon, and stars. In general, the findings support this

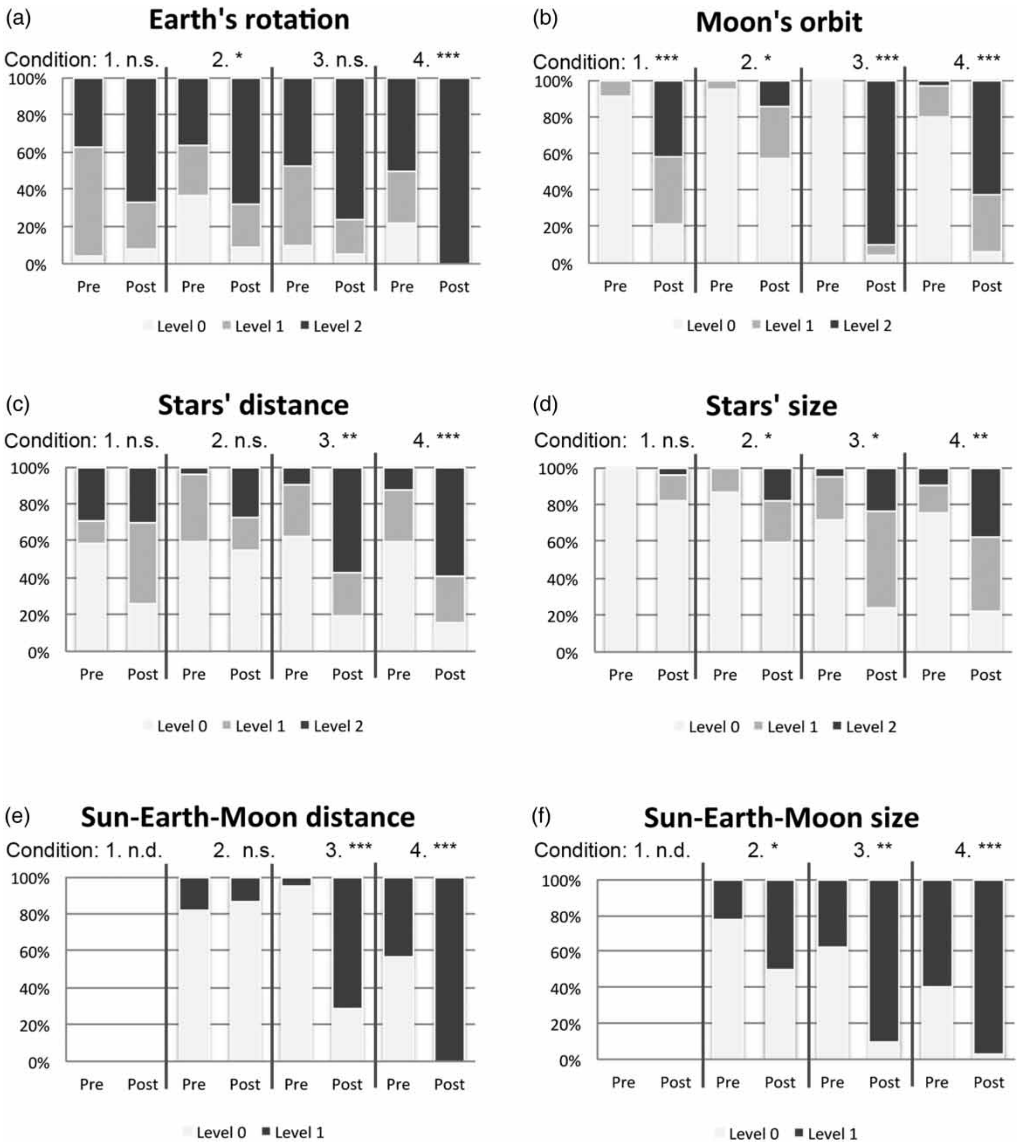


Figure 4. Improvement in descriptions of other categories related to DCM. No data (n.d.) collected from Condition 1 for *SEMdistance* and *SEMsize*. Asterisks indicate significance of improvement ($p < .05$: *; $p < .01$: **; $p < .001$: ***; $p > .05$: not significant [n.s.])



claim. Looking across the categories of students' explanations, Conditions 3 and 4 often significantly outperformed Conditions 1 and 2. However, the improvement in the revised curriculum over the standard curriculum did not include the explanation for the Moon's apparent motion. We originally anticipated that the revised curriculum experiences would have yielded significantly greater improvement in the overall explanation compared to the other conditions. Although Conditions 3 and 4 were

Table 3. Results of non-parametric tests for significance between conditions

| | Categories | Kruskal-Wallace H score (3 df) | $p$-value and significance | Which condition ranked higher than the other? | Mann-Whitney test $p$-value |
|---|---|---|---|---|---|
| Apparent motion | *SunPath* | 7.973 | .047* | Cond 3 > Cond 1 | .035* |
| | | | | Cond 4 > Cond 1 | .014* |
| | *StarsPath* | 27.571 | <.001*** | Cond 2 > Cond 1 | <.001*** |
| | | | | Cond 3 > Cond 1 | .039* |
| | | | | Cond 4 > Cond 1 | <.001*** |
| | | | | Cond 2 > Cond 3 | .024* |
| | | | | Cond 4 > Cond 3 | .006** |
| | *Direction* | 13.454 | .004** | Cond 4 > Cond 1 | .001** |
| | | | | Cond 2 > Cond 1 | .039* |
| | | | | Cond 4 > Cond 3 | .008** |
| Explanations | *SunExp* | 9.000 | .029* | Cond 4 > Cond 2 | .007** |
| | *StarsExp* | 19.055 | <.000*** | Cond 4 > Cond 2 | .007** |
| | | | | Cond 3 > Cond 1 | .010* |
| | | | | Cond 4 > Cond 1 | <.001*** |
| | *SunSecondary* | 17.042 | .001** | Cond 3 > Cond 1 | .033* |
| | | | | Cond 4 > Cond 1 | <.001*** |
| | | | | Cond 3 > Cond 2 | .027* |
| | | | | Cond 4 > Cond 2 | .01** |
| | *StarsSecondary* | 18.168 | <.000*** | Cond 2 > Cond 1 | .015* |
| | | | | Cond 3 > Cond 1 | .002** |
| | | | | Cond 4 > Cond 1 | <.001*** |
| | *Tertiary* | 13.451 | .004** | Cond 3 > Cond 1 | .021* |
| | | | | Cond 4 > Cond 1 | <.001*** |
| Other topics | *Rotation* | 12.483 | .006** | Cond 4 > Cond 1 | <.001*** |
| | | | | Cond 4 > Cond 2 | .001** |
| | | | | Cond 4 > Cond 3 | .004** |

*$p < .05$.

**$p < .01$.

***$p < .001$.



significantly improved in their tertiary level category compared to Condition 1, the planetarium condition was not significantly different than any of the classroom instructional groups.

### *Differences by Gender*

A Kruskal-Wallis test was performed for the pre-instructional data. Boys significantly outperformed girls in 4 of 18 categories: the path of the Sun (*SunPath*, $\chi^2 = 3.920$, $p < .05$), the path of the Moon (*MoonPath*, $\chi^2 = 4.224$, $p < .05$), Moon's orbit (*MoonOrbit*, $\chi^2 = 5.830$, $p < .05$), and the direction of the Sun's, Moon's, and stars' apparent motion (*Direction*, $\chi^2 = 4.572$, $p < .05$), a secondary category dependent on students' categorization in *SunPath* and *MoonPath*. After instruction, no gender difference was observed for Conditions 1–3. Significant differences, favouring boys, were observed in two categories for Condition 4: boys outperformed girls in their knowledge of the distance to the stars (*Stars' Distance*, $\chi^2 = 0.733$, $p < .01$) and in their explanation for the Sun's apparent motion (*SunSecondary*, $\chi^2 = 5.340$, $p < .05$).

## Discussion

### *Explanations for Daily Celestial Motion*

We begin our discussion by returning to our main research goal: to investigate the importance of providing instructional support to the connections between the Earth-based observations and space-based explanations in learning to explain DCM. Findings suggest that the conditions that supported this connection showed significant improvement in most descriptive and explanatory categories. Improvement was observed in the other conditions as well: participation in the planetarium condition improved their ability to describe apparent motion while the district's standard curriculum improved their explanations for the Sun's motion. We suggest that the engagement in kinaesthetic activities played an important role in why all four conditions showed improvement by developing students' embodied cognition (Lakoff & Johnson, 1980). If cognition is embodied, and thus mediated by kinaesthetic experiences, then connecting descriptions and explanations in the abstract realm of celestial motion to physical experiences may help support learning through the development of embodied cognitive structures. Tversky argues that 'both internalized perceptual transformations and internalized motor transformations can serve as bases for transformations in mental imagery,' (2008, p. 215) and thus facilitate moving between frames of reference in astronomy.

The planetarium programme supported student learning by helping children to focus on the relevant features of the motions observed by helping them to overcome distracting perceptual information (Plummer, 2009b). Children's engagement in the programme included gestures to predict and imitate observed motions. Gesture embodies thought, may facilitate working memory, and is important for conveying spatial information in both children and adults (Newcombe & Flick, 2010; Sauter, Uttal, Alman, Goldin-Meadow, & Levine, 2012; Tversky, 2008). Children who gesture about movement while explaining mental rotation tasks perform better than children who do not (Ehrlich et al., 2006). Students who only participated in the planetarium also improved their explanations of the Sun's and stars' daily apparent motion.

We had not initially anticipated the level of improvement in knowledge of apparent celestial motion exhibited by the students in Condition 3. The revised curriculum included strategies to help the students visualize the apparent motions of the Sun, Moon, and stars. The experience in the classroom, through a combination of the visual simulation and the students' own kinaesthetic experience using their arms to gesture this motion, helped students generate a connection between the image schema and an embodied sense of this apparent motion (Vosniadou, 2009). The data suggest that this experience was helpful, though not quite as much as attending the kinaesthetic planetarium programme.

The students in Condition 3 did not improve knowledge of the stars' apparent motion as much as students that went to the planetarium. Rather than observing a realistic simulation of the stars' apparent motion, the students created their own physical simulation by placing stars on the walls then kinaesthetically rotating and observing how the stars appear to move about them. We predicted that it could be easier to learn that the stars appear to rise and set if you are focusing on how the Earth's rotation causes the stars to appear to move. We anticipated that this would reduce the cognitive load, compared to trying to visualize thousands of stars moving about a stationary location. However, this method did not appear to be sufficient to help most students reach the scientific level explanation. One of the challenges in using the kinaesthetic-modelling of the stars' apparent motion in the classroom may be the challenge students have in imagining objects moving around them. It is easier for people to imagine themselves moving to face different directions in a room than to imagine themselves as stationary with the room moving around them (Tversky, Kim, & Cohen, 1999). This may explain why Condition 3 showed a similar level of improvement as Condition 4 in using the Earth's rotation to *explain* the stars' apparent motion (based on an embodied sense that they, on the Earth, are spinning) but less improvement in generating a mental image of the stars appearing to move around them.

Students did not show significant improvement in their explanation for why the Moon appears to rise and set. There was an increase in students' use of the Moon's orbit to *explain* the Moon's apparent daily motion after instruction. Prior to instruction, nearly half of the students used the Moon's actual motion to explain its daily apparent motion. Thus, rather than altering their mental model to only use the Earth's rotation to explain the Moon's daily motion, many combined the Earth's rotation with the scientific concept of the Moon's orbit to explain their observational knowledge. The instruction did not fully support their ability to distinguish the differing effects of the two timescales of motion: the Earth's rotation and the Moon's orbit.

### *Spatial Reasoning in Elementary Astronomy Education*

Our findings suggest that many children in this study showed increased sophistication in their perspective-taking ability, going beyond just taking someone else's perspective, by moving their own perspective out into the solar system. After instruction, few students continued to believe that the Sun appears to move because it is actually moving. However, many children did not fully appreciate the implications of how their own motion on a rotating object would influence the appearance of motion of *all* celestial objects in the sky. It may be that the children were not fully engaging in a mental simulation of the moving frames of reference; instead, they may have accepted that their own motion could cause something (the Sun) to appear to move because of the simplicity of this system (two objects—one object moving) compared to the Moon (two objects moving) or the stars (many stationary objects to visualize and one object moving). Given the age of the students, some developmental issues may have influenced learning, such as working through the different frames of reference (Roberts & Amin, 1993), differentiating along the left–right dimensions (Rigal, 1996), and the propensity to make egocentric errors (Newcombe & Huttenlocher, 1992). The students' limited familiarity with the Moon's and stars' changing position may have increased the cognitive load in constructing the scientific explanation.

Understanding of the relative size of and distance to celestial objects is another important aspect of spatial knowledge in astronomy. Previous research suggests that students' ability to visualize, manipulate, and construct 3D representations is related to their understanding of size and scale (Jones, Gardner, Taylor, Wiebe, & Forrester, 2011). Prior to instruction, most children believed that stars are smaller than the Moon and that at least some stars are as close or closer than the Sun and Moon. Children's knowledge was significantly improved after participating in the revised curriculum conditions. Given the short length of the intervention, we suggest that the *relative* comparisons of size and distance in astronomy may not be a challenging concept for students of similar background and age.

While prior research has found gender differences in students' spatial abilities (e.g. Voyer et al., 1995) and understanding of astronomy (e.g. Heyer, 2012), we found only a few significant differences by gender. Some research suggests that significant gender differences do not arise until around age 13 (Voyer et al., 1995). However, others have found gender differences on spatial tasks with children as young as second grade, though only among high socioeconomic status (SES) children (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). Some researchers suggest that significant gender difference in astronomy knowledge does not appear until after middle school (Bisard, Aaron, Francek, & Nelson, 1994), while others have found middle school males to have significantly greater knowledge after instruction (Wilhelm, 2009). Even if gender differences in spatial ability existed among our participants, this did not result in differences in astronomy knowledge, except for post-instruction Condition 4 (size and distance). It may be that the instruction provided enough support to help students with lower spatial reasoning abilities or the spatial strategies students used may have been those in which we do not see significant gender differences (i.e. spatial visualization, Voyer et al., 1995).

## Conclusion

The findings support our hypothesis that students' understanding of DCM improved when they engaged in instruction that supported their ability to visualize Earth-based observations and develop explanations by engaging in multiple modalities: observe visual simulations, engage in guided gesturing, and participate in kinaesthetic and psychomotor modelling. Instruction that primarily focused on either the Earth- or space-based perspectives did not result in the same level of sophistication as a combined focus on explaining the Sun's, Moon's and stars' apparent motion. Explaining DCM continued to present a challenge for many of the students as few reached the scientific level.

Some may argue that children at this age are not capable of the type of sophisticated spatial thinking associated with celestial motion; and yet, despite few students completely mastering the full application of the Earth's rotation to their observations, students made significant progress in constructing explanations that connected the two frames of reference. This is an important age group in which to explore children's capabilities with spatial thinking, as concepts of celestial motion are often included in elementary standards. Engaging in these types of astronomy activities is important for development of spatial literacy (National Research Council [NRC], 2006). Spatial abilities emerge in early childhood and show significant development during preschool years (Newcombe & Flick, 2010). These types of spatial abilities are malleable; school science instruction could be designed to support and improve children's perspective taking ability (e.g. Casey et al., 2008; Sorby, 2009; Uttal et al., 2013). Early spatial training is important because limited spatial ability is a barrier to continued success in STEM courses (Uttal & Cohen, 2012).

### *Instructional Implications*

Successful instruction may require both visual simulations of the Earth-based perspective (such as computer simulations or planetarium experiences) in combination with children's own psychomotor and kinaesthetic modelling. While other astronomy education studies have found success in children using kinaesthetic modelling (Slater, Morrow, & Slater, 2008), psychomotor modelling (Trundle, Atwood, & Christopher, 2007), and computer-based simulations (Barnett & Morran, 2002), limited research has examined these strategies in concert. Our findings suggest that children's ability to connect the Earth-based and space-based explanations of the Sun's daily motion can successfully be supported through instruction that engages in describing the Sun's apparent daily path, using gestures and visual observations, with kinaesthetically explaining the Sun's apparent motion using their own rotation. Students had less success in developing the scientific explanation for the Moon's and stars' apparent motions. Students likely needed more opportunities to *apply* the Earth's rotation to explain the apparent motion patterns. For the Moon, additional time spent distinguishing between the Moon's daily apparent motion due to the Earth's rotation and the very small change that occurs due to its slow orbital motion is needed. This discussion could occur during lessons explaining the lunar phases. This monthly cycle is caused by the orbit of the Moon around the Earth, changing the angle at which we observe the illuminated side of the Moon. Children need experiences that help them see that the Moon's phase does not change as the Moon appears to rise and set, due to the Earth's rotation.

Much of the challenge in explaining the stars' nightly motion is in visualizing the stars' apparent motion. Attending the planetarium programme was clearly useful as it helped many children improve their ability to describe the apparent motion of the stars. However, others still struggled with communicating this description. This suggests that while our instruction will help many students, it may not be enough for others. Additional scaffolding might make the difference in improving explanations. For example, children could learn specific constellations and watch as they appear to rise and set using computer simulations. Children could then place pictures of these constellations on the walls and use their own kinaesthetic rotational motion to model the explanation for how the constellations rise and set. The advantage here would be to focus on the larger constellation patterns rather than the vast array of stars, possibly simplifying the visualization for students.

We also recommend that curriculum be designed to help teachers support students to improve spatial thinking. Few elementary teachers are trained in ways to support children's spatial abilities (NRC, 2006) and teachers may have poor spatial abilities compared to other professions (Wai et al., 2009). Teaching elementary astronomy would allow the teacher to infuse classroom conversation with spatial language, such as discussing directions, helping them to learn to describe actions they observe through simulations, and participate through gestured modelling (Newcombe, 2010; Padalkar & Ramadas, 2010). Sketching can also be helpful in developing children's spatial thinking (Brooks, 2009), such as encouraging them to draw their explanations of why objects appear to move in the sky.

### *Research Limitations and Future Directions*

Although the results of this study provide insight on how children learn, there are also limitations to be addressed. First, the instructional conditions were not directly comparable in terms of the amount of time spent on the DCM concepts. A second limitation was that each condition had few teachers, thus limiting our ability to generalize the curricular changes over nuances in particular teachers' implementation of the curriculum. Third, the instructional interventions were tested within a relatively high SES population; more work is needed to understand the generalizability to other populations.

Our next step in this research will be to continue a DBR agenda where we take a closer look at *how* children move between frames of reference and whether they are able to apply this concept to novel situations. We did not specifically ask them to make sense of *how* their model explained the apparent motion. Thus it is possible that, like on mental rotation tasks (e.g. Hegarty, 2010), children may have used multiple strategies without actively running the model to check for consistency. Future work should also consider how students use gesture to support their ability to work through the explanation connecting frames of reference in astronomy (Crowder, 1996).

## Note

1. The results of the pre-instructional student interviews were previously reported (Plummer et al., 2011).

## 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.

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.

Bisard, W., Aaron, R., Francek, M., & Nelson, B. (1994). Assessing selected physical science and earth science misconceptions of middle school students through university preservice teachers. *Journal College Science Teacher*, *24*, 38–42.

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

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

Brooks, M. (2009). Drawing, visualization and young children's exploration of "big ideas". *International Journal of Science Education*, *31*, 319–341.

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

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *Journal of the Learning Sciences*, *13*, 15–42.

Crowder, E. M. (1996). Gestures at work in sense-making science talk. *The Journal of the Learning Sciences*, *5*, 173–208.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*, 5–8.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental psychology*, *42*, 1259–1268.

Firestone, W. A. (1993). Alternative arguments for generalizing from data as applied to qualitative research. *Educational Researcher*, *22*, 16–23.

Glenberg, A.M. (1997). What memory is for. *Behavioral and Brain Sciences*, *20*, 1–55.

Hegarty, M. (2010). Components of spatial intelligence. *Psychology of Learning and Motivation*, *52*, 265–296.

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. (2009). Using a planetarium software program to promote conceptual change with young children. *Journal of Science Education and Technology*, *19*, 165–176.

Jones, M. G., Gardner, G., Taylor, A. R., Wiebe, E., & Forrester, J. (2011). Conceptualizing magnification and scale: The roles of spatial visualization and logical thinking. *Research in Science Education*, *41*, 357–368.

Kallery, M. (2011). Astronomical concepts and events awareness for young children. *International Journal of Science Education*, *33*, 341–369.

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.

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

Levine, S., Vasilyeva, M., Lourenco, S., Newcombe, N., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science*, *16* (11), 841–845.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*(6), 1479–1498.

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

Merrienboer, J., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review*, *17*, 147–177.

National Research Council. (2006). *Learning to think spatially*. Washington, DC: National Academies Press.

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *Summer* (43), 29–35.

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

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

Padalkar, S., & Ramadas, J. (2010). 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.

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.

Parsons, L. M., Fox, P. T., Downs, J. H., Glass, T., Hirsch, T. B., Martin, C. C., Jerabek, P. A., & Lancaster, J. L. (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*, 1571–1606.

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., Wasko, K., & 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.

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.

Roberts, R. J., & Amin, C. J. (1993). Developmental differences in giving directions: Spatial frames of references and mental rotation. *Child Development*, *64*(4), 1258–1270.

Sauter, M., Uttal, D. H., Alman, A. S., Goldin-Meadow, S., & Levine, S. (2012). Learning what children know about space from looking at their hands: The added value of gesture in communication. *Journal of Experimental Child Psychology*, *111*, 587–606.

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.

Siegal, M., Butterworth, G., & Newcombe, P. A. (2004). Culture and children's cosmology. *Developmental Science*, *7*, 308–324.

Slater, S. J., Morrow, C. A., & Slater, T. F. (2008). The impact of a kinesthetic astronomy curriculum on the content knowledge of at-risk students. Paper presented at the meeting of the *National Association for Research in Science Teaching*, Baltimore, MD.

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, *31*, 459–480.

Stake, R. E., & Trumbull, D. J. (1982). Naturalistic generalizations. *Review Journal of Philosophy and Social Science*, *7*(1), 1–12.

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.
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*, 451–478.
Tversky, B. (2008). Spatial cognition: Embodied and situated (Chapter 12). In P. Robbins & M. Aydede (Eds.), *The Cambridge handbook of situated cognition* (pp. 201–216). 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., & Cohen, C. (2012). Spatial thinking and STEM education: When, why and how? In B. Ross (Ed.), *Psychology of learning and motivation* (pp. 57, 147–181). Oxford: Academies Press.
Uttal, D., Meadow, N., Tipton, E., Hand, L., Alden, A., Warren, C., & Newcombe, N. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402.
Vosniadou, S. (2009). 'Conceptual metaphor meets conceptual change': Yes to embodiment, No to fragmentation. *Human Development*, *52*, 198–204.
Voyer, D., Voyer, S., & Bryden, M. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*, 250–270.
Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*, 817–835.
Wilhelm, J. (2009). Gender differences in lunar-related scientific and mathematical understandings. *International Journal of Science Education*, *31*(5), 2105–2122.
Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625–636.