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The role of perspective taking in how children connect reference frames when explaining astronomical phenomena

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ABSTRACT

This study investigates the role of perspective-taking skills in how children explain spatially complex astronomical phenomena. Explaining many astronomical phenomena, especially those studied in elementary and middle school, requires shifting between an Earth-based description of the phenomena and a space-based reference frame. We studied 7- to 9-year-old children ($N = 15$) to (a) develop a method for capturing how children make connections between reference frames and to (b) explore connections between perspective-taking skill and the nature of children's explanations. Children's explanations for the apparent motion of the Sun and stars and for seasonal changes in constellations were coded for accuracy of explanation, connection between frames of reference, and use of gesture. Children with higher spatial perspective-taking skills made more explicit connections between reference frames and used certain gesture-types more frequently, although this pattern was evident for only some phenomena. Findings suggest that children – particularly those with lower perspective-taking skills – may need additional support in learning to explicitly connect reference frames in astronomy. Understanding spatial thinking among children who successfully made explicit connections between reference frames in their explanations could be a starting point for future instruction in this domain.

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Spatial thinking in astronomy

Spatial thinking is increasingly recognized as a foundation for participation and success in STEM disciplines (Janelle, Hegarty, & Newcombe, 2014). As described in the report on *Learning to Think Spatially* prepared by the National Research Council (NRC, 2006), spatial thinking includes skill in understanding and using *concepts of space*, tools of *spatial representation*, and processes of *spatial reasoning*. Empirical evidence points to differences in the types of spatial thinking necessary for success in learning specific science content areas such as organic chemistry (Stieff, Ryu, Dixon, & Hegarty, 2012), geology (Liben, Kastens, & Christensen, 2011), engineering (Sorby & Baartmans, 2000),

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and physics (Kozhevnikov, Motes, & Hegarty, 2007). Thus, taking a domain-specific approach is important to understanding the role of spatial reasoning in science learning. Astronomy is particularly spatially demanding because many phenomena are explained by shifting between Earth-based and space-based frames of reference (Albanese, Danhoni Neves, & Vicentini, 1997). However, despite the importance of connecting these two reference frames in constructing explanations for astronomical phenomena, Plummer, Wasko, and Slagle (2011) found little research on children's ability to make these connections. In this manuscript, we investigated how children use spatial thinking to explain three astronomical phenomena: apparent motion of the Sun, apparent motion of the stars, and seasonal change in constellations. These phenomena were selected because connecting reference frames is central to their explanations and they appear in standards documents for K-12 students (NRC, 2012).

The first of these phenomena, Sun's apparent motion, refers to the fact that to an observer on Earth, the Sun appears to move from East to West across a three-dimensional sky. Explaining this apparent motion requires imagining a new, space-based frame of reference wherein the Sun is fixed and the observer's location on the Earth rotates completely every 24 hours. To fully appreciate how the space-based perspective explains the Earth-based observation includes understanding that it is our own motion in one direction that makes the Sun appear to move in the opposite direction. A similar pattern of visualizing and reasoning occurs when explaining the second phenomenon, the apparent motion (rising and setting) of the stars. The third phenomenon concerns the seasonal change in the constellations seen over the course of a year. Within a short time frame of night to night, we see the same constellations. But over a longer time frame of weeks and months, when seen from the Northern Hemisphere, constellations in the Southern sky slowly shift westward, with new constellations appearing and old ones disappearing. A parallel pattern of shifting constellations occurs across the Northern sky for observers in the Southern Hemisphere. These changes occur as the Earth orbits the Sun such that the angle at which we observe constellations is shifting throughout the year.

Researchers have generally used one of two methods to explore students' engagement in spatial thinking in astronomy: the first involves analysing how students develop and communicate astronomical explanations, and the second employs correlational studies that examine the relation between spatial skills and astronomical knowledge. We review earlier studies of both kinds, and consider what their results mean for understanding how children think spatially when explaining astronomical phenomena.

Communicating spatial explanations in astronomy

Researchers have considered how children construct explanations by connecting complex sequences of motion across reference frames. Plummer and colleagues (Plummer, Kocareli, & Slagle, 2014; Plummer et al., 2011) asked 8- to 9-year-old US children to explain the daily apparent motion of the Sun, Moon, and stars. Many children explained the Sun's apparent motion by saying that the Sun actually moves. And with children who used the Earth's motion to explain the Sun's apparent motion, many gave inconsistent explanations. For example, some suggested that the Earth rotating continuously in one direction (accurate) can explain the Sun appearing to rise and set, straight up-and-down, in the same spot (a non-normative description). Even when they knew that the Earth's rotation causes the

Sun's apparent motion, children often did not apply the Earth's rotation to explain the stars' apparent motion. Knowing the scientific description of both an Earth-based phenomenon and how objects move in space does not necessarily lead to understanding *why* motion in one frame of reference causes the appearance of motion in the other.

Studies of children's explanations for additional astronomical phenomena shed further light on how children reason across reference frames. Parnafes (2012) examined how 10–14-year-old Israeli children generated representations to explain the lunar phases. Children used drawings of the Sun–Earth–Moon system to support their spatial reasoning as they communicated their ideas. As children attempted to reconcile differences in their explanations for lunar phases, they used gestures to communicate pertinent spatial information. Crowder (1996) considered how 11- to 12-year-old US children used gestures and whole-body movements to indicate different perspectives while communicating their explanation for the seasons. Children took on the 'inside observer perspective': they were not part of the model themselves, such as when they held a physical model of the Earth as part of their explanation, but they still physically gestured within the space around the model. This helped children visualize challenging elements, such as the Sun's position, by placing their eye gaze inline with positions in the model. This occurred more often when children were trying to understand relationships, such as predicting how motion in one reference frame would influence observations in another.

Collectively, these studies suggest learners may find it challenging to connect Earth-based observations and space-based motions (Plummer et al., 2011, 2014). When learners do attempt to make these connections, they go beyond just verbal explanations by calling on physical resources and their own body movements to support their reasoning and communication (Crowder, 1996; Parnafes, 2012).

Spatial skill and astronomical knowledge

Considering children's spatial skill may provide insight into why some children are more likely to construct astronomical explanations that connect reference frames than others. Spatial skill 'is conceptualized as a trait that a person has and as a way of characterizing a person's ability to perform mentally such operations as rotation, perspective change, and so forth' (NRC, 2006, p. 26). Thus, spatial skills are a sub-component of spatial thinking (NRC, 2006). Considering learners' spatial skill is often used as a starting point in understanding differing success in domain-specific spatial thinking and reasoning (Liben, 2006).[1] Individuals can vary in how well they perform different spatial tasks. Determining which spatial skills correlate with performance in different science domains may suggest ways that learners engage in spatial reasoning and indicate where additional training should be focused.

Spatial skills such as mental rotation, spatial perception, and spatial visualization have been found to predict astronomical knowledge among US college-age students (Black, 2005; Heyer, Slater, & Slater, 2013). However, only a few studies have examined whether similar relationships hold in childhood. Kikas (2006) investigated the link between visuo-spatial skills in Estonian students (7- to 8-year-olds) and their explanations of astronomical phenomena. Results indicated that children's spatial skills, including mental rotation, were predictive of their learning of factual astronomy knowledge. Wilhelm (2009) analysed 12-year-old US students' development of spatial thinking about lunar phases after an inquiry-based astronomy curriculum. Not only did students significantly improve their understanding of lunar phases through improved spatial thinking, they also showed improvement across a range of spatial skills, including geometric spatial visualization.

One kind of spatial skill that appears to be relevant to understanding astronomical phenomena is perspective taking – skill in imagining how a scene or an array would look from viewpoints different from one's own current position (Liben & Downs, 1993). Making sense of why the Sun appears to move across the sky relies on visualizing and connecting the view of the Sun from the Earth and the view of the Earth and Sun from a space-based perspective, leading to the hypothesis studied here that individual differences in perspective-taking skills would predict differences in the sophistication and accuracy of astronomical explanations.

An embodied-cognition framework

In studying the link between perspective taking and astronomical explanation, we used an embodied-cognition framework. Embodied cognition suggests the motor and perceptual processes, important for our physical interaction with the world, are also important for developing mental representations of the world (Gibbs, 2006; Hostetter & Alibali, 2007). The continuous interaction between embodied cognition and action is relatively straightforward: 'while a cognitive process is being carried out, perceptual information continues to come in that affects processing, and motor activity is executed that affects the environment in task-relevant ways' (Wilson, 2002, p. 626). Cognitive processing can also be aided by offloading mental tasks onto some environmental support, especially for the purpose of manipulating spatial information (Wilson, 2002). Kastens, Liben, and Agrawal (2008) described *epistemic actions* in science as those actions in the physical environment that facilitate cognition by simplifying the necessary mental computations during problem solving. For example, geology students use epistemic actions that offloaded a portion of the mental task onto the environment when they rotate a physical model to align with geological outcrop to facilitate comparison of the structures.

The use of gestures in communicating and problem solving is one line of evidence that knowledge is embodied (Alibali & Nathan, 2012; Gibbs, 2006; Hostetter & Alibali, 2007). Hostetter and Alibali (2007) developed the gesture-as-simulated action framework, asserting that 'gestures emerge from the perceptual and motor simulations that underlie embodied language and mental imagery' (p. 502). Previous researchers have analysed the gestures children use while explaining astronomical phenomena as a window on their astronomical understanding or reasoning (e.g. Crowder, 1996; Plummer et al., 2011, 2014). Children seem to use gestures to help them predict, revise, and coordinate certain pieces of a conceptual model when constructing new explanations, in-the-moment; in contrast, children use gestures redundantly to emphasize verbal elements of previously thought-out explanations (Crowder, 1996). Children may also use gestures to reduce the cognitive load when problem solving (e.g. Ping & Goldin-Meadow, 2010). Thus, gestures can serve both as an opportunity for the individual to make sense of spatial information while problem solving and also to communicate information to others (Paas & Sweller, 2011).

Using an embodied-cognition framework may help us understand how children engage in perspective taking when explaining astronomical phenomena, both in terms of how they communicate and how they reason through the problem. When children construct a new explanation that requires coordinating reference frames, they may rely on their own body and environmental supports, in concert with their existing mental imagery, to make sense of different perspectives (Crowder, 1996; Subramaniam & Padalkar, 2009). Gesturing may allow children to access spatial information about an object, thereby facilitating shifts in perspective (Schwartz, 1999). For example, Padalkar and Ramadas (2011) found that students gestured to determine orientation of a person on a globe, suggesting that gestures might help children visualize different perspectives during astronomy lessons.

Thus, our first goal was to use an embodied-cognition framework to investigate how children understand and express connections between Earth-based experiences of astronomical phenomena and space-based descriptions of those phenomena (i.e. referring to the motions of celestial objects to account for astronomical phenomena as experienced by someone on Earth). In particular, we designed the study to elicit explanations that could reveal children's understanding of how the two frames of reference are connected, and to observe the use of embodied representations of those connections (i.e. the use of gestures and physical models in addition to the use of words). We build on Plummer's prior research (e.g. Plummer et al., 2011, 2014) to illustrate the ways in which children embody these connections when explaining astronomical phenomena. Our second goal was to investigate our hypothesis that perspective-taking skills would predict the scientific accuracy of children's explanations for astronomical phenomena and, more specifically, their success in connecting the Earth-based and space-based reference frames. The study was guided by the following research questions:

(1) How do children use gestures and models, in relation to their verbal explanations, to communicate their understanding of the connections between reference frames when explaining astronomical phenomena?
(2) How does perspective-taking skill relate to children's understanding of astronomy, connections made between reference frames, and gesture use?

Methods

Participants and setting

The study took place during a weeklong summer astronomy camp held in a suburban planetarium in the northeastern US. The camp included instruction on the day/night cycle and the seasonal change in constellations, as well as other astronomy topics. The goal of our research was not to investigate student learning in the context of this astronomy camp. Rather, we used this venue as an opportunity to gather data over two interview sessions that would allow us first, to develop a methodological framework for studying how children use gestures and models to communicate about reference frames, and second, to begin to explore our hypothesis about the relevance of perspective-taking skill. We gathered data both prior to and following camp experiences because we were interested in addressing these issues across varying levels of knowledge about astronomical phenomena.

Prior research has shown that even short periods of instruction can improve the accuracy of students' explanations of the Sun's and stars' apparent motion (Plummer et al., 2011, 2014), and thus by collecting data over these two sessions we could sample across a greater range of understanding than would otherwise have been possible.

All children (7- to 9-years; seven girls; eight boys) attending the camp were participants in the study. All but two children were from European American families; all but one attended the same high-SES suburban school district.

Data collection

Assessments were given on both the first and last days of the five-day camp (hereafter labelled pre- and post-camp assessments). In both interview sessions, children were interviewed (~15 min) about the Sun's apparent motion, the stars' apparent motion, and the seasonal change in constellations. Using a clinical interview protocol (Ginsburg, 1997), children were asked to describe what we observe from Earth and then explain what accounts for observed motion or position changes. Physical models of the Earth (a small globe with a red dot indicating our location) and the Sun (a yellow ball) were provided; all children were prompted to use the models to help them explain. The interview protocol is available as a supplemental file. Interviews were video recorded for later analysis.

Following the pre-camp interview, a perspective-taking task (Liben, 2012) was administered. As illustrated in Figure 1, the task requires respondents to select how two different-coloured circles (placed in left-right; up-down; or diagonal positions) look to a doll viewing the display from a depicted vantage point. All positions were a fixed distance from the

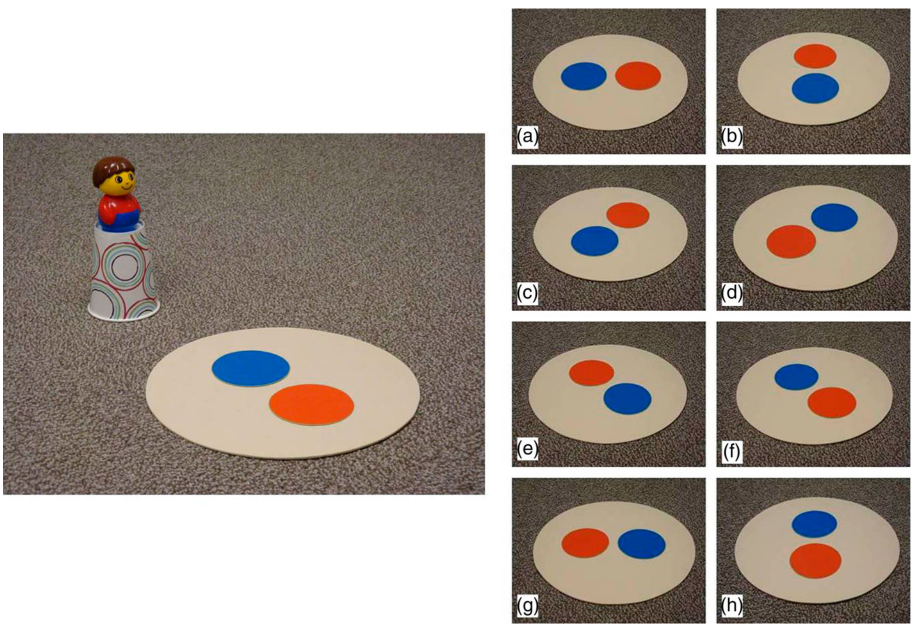

Figure 1. Sample item from the photographic perspective-taking task (Liben, 2012) modified from Liben and Downs (1993). In this item, the circles are placed diagonally; the doll is at 315°; the correct response is b.

display's centre; viewing azimuths varied by 45° increments. For all 16 items, the response choices were photographs of the circles as viewed from the eight 45° directions.

Coding systems

Coding systems addressed understanding of each of the three astronomical phenomena, use of reference frames, and use of gesture. The first two authors independently coded one-third of the data then calculated Cohen's kappa coefficient for inter-rater reliability for each category. Based on the guidelines from Landis and Koch (1977), the kappa for conceptual understanding is almost perfect ($\kappa = .85$), and substantial for frames of reference ($\kappa = .74$), and gesture ($\kappa = .63$). Codebooks are available as a supplemental file.

The system for coding accuracy of children's explanations was adapted from our prior research (Plummer et al., 2014). Children's explanations for the Sun's apparent motion were coded as *scientific* if they both (a) described the Earth-based perspective of the Sun's apparent motion as a rising and setting motion across the sky and (b) explained this apparent motion by referring to the Earth's rotation only (i.e. without invoking movement of the Sun). Explanations for the stars' apparent motion were coded as scientific if they both (a) described the stars appearing to move across the sky during the night and (b) explained this apparent motion referencing the Earth's rotation but without invoking movement of the stars themselves. For seasonal constellations, two possible explanations were coded as scientific. One was that the Sun blocks some constellations from sight as Earth orbits the Sun. The second was that for any given position on Earth, the particular constellations an individual can see changes throughout the year because someone at a given location faces towards new constellations as the Earth orbits the Sun. Explanations for any of the three astronomical phenomena that did not include the required scientific features were labelled as *alternative* explanations, in reference to the children's alternative frameworks for astronomy (Driver, 1983).

Second, we developed a coding system describing how children used reference frames in their explanations. *Earth-based* reference frames were coded when the child indicated a perspective that entailed viewing space from Earth. *Space-based* reference frames were coded when the child indicated a perspective that entailed viewing from a vantage point in space. A *connection between reference frames* was coded when a child either *explicitly* or *implicitly* integrated both perspectives. An *explicit connection* was coded when a child explained (verbally and/or with gesture) the connection between perspectives, such as rotating an Earth globe (a gestural space-based reference frame) while saying that this makes the Sun look like it is moving (verbally using an Earth-based reference frame). An *implicit connection* was coded when a child responded to an Earth-based question with a space-based answer, such as stating that the Earth rotates, without clarifying how that space-based perspective explains the Earth-based reference frame observation. Additional examples are provided in the online supplemental file codebook.

Third, to analyse gestures that conveyed spatial information, we developed a gesture-coding system adapted from previous classification schemes (Alibali & Nathan, 2012; McNeill, 2005; Padalkar & Ramadas, 2011; Roth, 2000). Gestures were divided into *spatial pointing* and *iconic*. *Spatial pointing* gestures are those that convey spatial properties such as location and direction, such as pointing to the imaginary location and direction of the stars with respect to a model of the Earth. We did not include in this category, as pointing gestures were used only to identify which object was being discussed. *Iconic* gestures are those that show spatial relations with concrete entities or actions, such as a hand used to indicate the viewing angle from Earth or to trace the shape of an orbit. Thus, *spatial pointing* gestures indicate static spatial information while *iconic* gestures communicate dynamic spatial information. We coded the two gesture types separately because we expected that they might serve different communicative needs, with pointing used to situate the location or direction of celestial objects and iconic gestures used to show how motion in one reference frame looks in a different one. Each gesture type had two sub-codes, depending on whether the gesture involved their hands/arms[2] or if they also involved physical models (model adjustment). While hand/arm movement gestures are often discussed in the literature, we separated the two iconic gesture sub-codes to allow us to see whether their use differed. Gesturing near or pointing to a model would have been coded as hand/arm movement, not model adjustment.

Two additional gestures were coded but not used in our qualitative analyses or compared to the subjects' perspective-taking skill. *Metaphoric* gestures – representing abstract rather than literal interpretations of concepts – were rarely observed, and thus were not included. *Simple deictic* gestures – used for emphasis, often in time with speech – were not analysed because the students did not use them to communicate information, spatial or otherwise, or to help solve a problem.

Analysis

Raw frequencies were converted into proportion scores to adjust for the total number of gestures and reference frames used by individual children. Specifically, proportion scores were calculated by dividing an individual's total number of each behaviour type (gesture type or frame of reference type) by the total number of codable behaviours used in the explanation. For example, the proportion of spatial pointing gestures was calculated out of the total number of gestures, which included all iconic, spatial pointing, metaphoric, simple deictic, and unclear gestures. The relationships between children's scores on the perspective-taking task and the variables (accuracy, reference frames, and gesture types) were analysed using both logistic and linear regression analyses. The purpose of the regression analysis was to quantify the association between independent and dependent variables. Even though this study has a small sample size and may cause the regression analyses to overestimate the magnitude of the associations, these analyses can help shed light on possible associations while investigating other potential influential predictor variables. Furthermore, to assess effect size and to account for this overestimation, the adjusted R^2 is reported (Howell, 2013). Adjusted R^2 adjusts the original R^2 value based on the number of predictor variables in the regression model. Specifically, adjusted R^2 decreases when there is any variable without a strong correlation and increases when there is a strong/significant correlation in the model.

Findings

The findings are organized by research question. First, we discuss ways that our gesture and reference-frame coding documents how children communicate when explaining astronomical phenomena. Second, we present findings that suggest how perspective-taking skill is associated with accuracy of explanation, use of reference frames, and use of gestures.

Research question 1: communicating connections between reference frames

Throughout the interviews, children used both *Earth-based* and *space-based* frames of reference. An *Earth-based* perspective was often prompted by the interviewer's initial question, such as 'Does it look like the Sun stays in the same place in the sky all day long?' Most children suggested answers similar to Richard[3] (nine years): 'It looks like the Sun goes across the sky' while using an iconic gesture of a curved arc with his arm. Other questions resulted in children describing a *space-based* perspective. For example, children were asked whether or not the Earth stays in one place in space, allowing them to indicate their knowledge of the Earth orbiting Sun. This was solely a *space-based* description because the child's response focused on how objects move in the Solar System without also explaining an Earth-based observation.

However, we were more interested in how children communicated their understanding of the *connection* between an Earth-based reference frame and what is happening from a space-based reference frame. During the interview, we asked children to explain why we would see the phenomena they described from an Earth-based perspective. Their attempts to construct these explanations often used *implicit* and/or *explicit connections*.

Explanations were coded as *implicit connection* when the child indicated they were using space-based reference frames in their explanation for an Earth-based description of a phenomenon, but did not clarify how one reference frame explains the phenomenon as seen from the other. For example, when asked: 'Would we see the same constellations that we see tonight (in July) as we would in January?' Ashley (seven years) responded, 'No. We would be all the way over here', while moving the globe to a position around the orbit 6-months later from its position in July and added: 'We would see new constellations'. She connects the *space-based* perspective using Earth's change in location while performing an *iconic model adjustment* to explain that 'we would see new constellations' – the Earth-based perspective. However, she does not communicate how the change in the Earth's position would result in seeing new constellations.

In contrast, explanations coded as making an *explicit connection* were those that expressed and linked the two reference frames. For example, Mary (nine years) was asked whether the constellation Orion would be visible six months after being observed in July:

Mary: [*Moves Earth-globe to opposite side of Sun-ball*] He's probably right here or here or here [*holds index finger and thumb apart like she's holding the constellation Orion then moves her fingers to spaces beyond the Earth-globe opposite the Sun*]. Depending on the day.

Interviewer: Why can't we see the Scorpion?

Mary: Because we're not facing this way [*rotates red dot indicating our position on Earth to face Sun*] and the Sun's blocking out all the other stars here [*picks up Sun and waves it back and forth towards the location where she indicated the Scorpion earlier in her interview, opposite from where she placed Orion*]. So until we go around [*moves Earth to opposite side of Sun from Orion*] we won't see those constellations until you go to summer again.

This response explicitly connects an *Earth-based* perspective to a *space-based* perspective: Mary uses *iconic model adjustment* gestures to show how the Earth and stars are situated in such a way that a specific line of sight (via an *iconic hand/arm* gesture) can allow us to see these stars. Mary used verbal descriptions to indicate when she is talking about an *Earth-based* perspective and clarifies how the Earth's motion and orientation influence this view by positioning the models and using a *spatial pointing* gesture with the Sun model to indicate the direction of observation.

Each of these two types of connection explanations was further divided into *perspective-taking* versus *no-perspective* categories. To be coded as a *perspective-taking* explanation required the child to shift to a space-based reference frame such that it was explicit that the space-based perspective of motion or orientation was different from the Earth-based observation of motion or orientation. For example, Ashley (seven years) was shown a drawing of the stars as they would be seen that night when facing South at 9:30 pm. She was asked if she would see those same stars if she went out later in the night. Ashley said she would not and explained:

> See, this was 9:30 [*rotates Earth-globe so the red dot faces her*] and we could see them [*holds paper up with her other hand so the red dot on the globe faces the paper*]. And now this is midnight, [*rotates the globe away from her*] now we can't.

She uses the paper to help her communicate the *Earth-based* perspective and manipulated the globe to show how our viewing angle would change throughout the night. In doing so, her explanation involved both *perspective taking* and *explicit connections*.

Other children gave explanations that did not include a shift in perspective. For example, a common alternative explanation for seasonal constellations was to indicate the distance between Earth and the constellations was too far apart to be able to see them. For example, when asked why we do not see the same constellations in January as July, Peter (nine years) responded:

> Because we are too far away to see the stars … Because the Earth is circling around the Sun. So we would be here [*places Earth-globe*] and then we move to here [*moves Earth to opposite side of Sun*]. Either we would have to see really, really, really far to there [*uses hand to gesture distance between Earth and constellations on the other side of the Sun*] or we would have to wait until we get back to there [*points to Earth's original location*].

In this example, Peter explicitly connects the two frames of reference. Peter indicates an *Earth-based* perspective while also indicating the viewing angle from Earth to the constellations in space (*space-based* perspective) with his hand by following the observation angle from Earth to the constellations. However, the connection is a direct one that does not involve the ability to imagine how the change in location would shift the viewer's observation angle.

Children's methods of communicating explicit connections

Next, we took a closer look at explanations coded as both *explicit connections* and *perspective taking*. These explanations indicate a deeper understanding of the astronomical phenomena insofar as these children were able to communicate how shifting one's perspective can be used to explain observable phenomena. All but two explanations coded as *explicit connections* and *perspective taking* were scientifically accurate.

Sun's apparent motion

Students who made *explicit connections* when explaining the Sun's apparent motion were those who not only verbally expressed the idea that the Sun appears to move because the observer is actually moving, but also communicated Earth's movement by rotating the Earth globe or making a circular gesture. Many students also added explicit gestures to help them explain the connection between reference frames. Tara (nine years) gestured the Sun's apparent motion as a curved path across the sky. When she was then asked why the Sun appears to move, she responded: 'When it moves [*rotating the Earth-globe with left hand and points to the Sun with right hand*], it looks like the Sun is moving [*points between the Earth and Sun*] but we are'. She verbally expresses the idea that people on Earth perceive the Sun to be moving when in fact it is the Earth moving; simultaneously she uses a gesture to connect the two objects.

Peter (nine years) was even more explicit in connecting the reference frames. As he begins, he holds the Sun-ball in his right hand while rotating the Earth-globe with his left hand:

> The Sun looks like it goes across the sky [*uses thumb to gesture across the direction of the Sun while fingers spin globe*] because we're moving so we see the Sun in a different spot because then in the morning it starts this [*rotates globe so the red dot is positioned tangential to the Sun*] and you can barely see it [*draws a line from red dot to the Sun with left index finger*] and then at 12 [*rotates globe so the red dot faces the Sun-ball*] you can really see it [*traces line between red dot and Sun*] then you can barely see it again [*rotates globe so that red dot is tangential to the Sun ball and uses finger to trace a line between dot and the Sun*].

His gestures in combination with his verbal description clarify how he is considering how relative position on the rotating Earth influences how the Sun is seen in the sky throughout the day. The children used *iconic* gestures that connected the line-of-sight from one's vantage point on Earth to the location of the Sun to communicate relative changes in orientation.

Stars' apparent motion. After viewing a drawing of the constellations at 9:30 pm, children were asked what they would see at midnight. Some children focused on how, over that time period, the Earth would rotate partway around, changing our angle of observation. Mary (nine years) described how our changing viewing angle affects our observations:

> Mary: They'll all probably have to be shifted over a little bit [*at midnight*].
> Interviewer: Why?
> Mary: 'Cause this is 9:30 [*gestures to point at the Earth globe*] and 9:30 is when this happens [*gestures to the drawing of the stars*] but when the Earth moves [*moves both hands as if spinning a ball*] every hour so that's like 3 hours later and the Earth has moved [*gestures with right hand in a circle*] 3 hours.
> Interviewer: Can you use the model to show me?
> Mary: Let's just say this is like 9:30 [*rotates globe so that red dot on the globe faces towards her and points the red dot*]. You move it one, two, three [*on each number, she rotates globe turning the red dot away from her*]. Now it's right here [*red dot is now facing away from her*] and you saw what was over here [*points to the point on the globe that is now closest to her*]. So see something like young woman or Virgo [*taps on the drawing of the constellation*], you might see everything else but Virgo.

She initially uses *spatial pointing* gestures to ground both the location on the Earth and view of an Earth-based observer, as well as using *iconic* gestures and verbal descriptions to move between Earth-based observations and how these orientations are changing in space.

Children made other choices to explain the connection between reference frames. Some children used objects or gestures to physically represent the location of the stars in space about the model Earth, such as using the Sun-ball to represent the location of the constellations. They used physical objects to anchor important locations in the space they created while also using gestures to connect our view to these points beyond the Earth.

Seasonal constellations. Children whose *explicit connections* explained the seasonal change in constellations often used their hands to virtually create the constellations, thus creating a shared understanding of the location. They further used gestures to connect the point on the Earth, from which their observations originated, to the direction from which they would view the constellations. Katrina (nine years) illustrates these behaviours:

> Because the Earth is moving, and if constellations are over here [*holds Earth globe in left hand and gestures to a spot up and towards the Sun for constellations*] uhm, no maybe over here [*switches hands and repositions constellations by gesturing to spot opposite side of globe from Sun*] and if we go over here [*moves globe in an orbit around the Sun ball*] … So if you're right here [*puts Earth globe in starting spot, rotates so red dot faces the hand representing a constellation*], and you go over there its constantly rotating [*orbits globe to point opposite the Sun from the constellation*] and that's one reason. But the other reason is [*rotates globe so red dot faces away from Sun, other hand is in same place as the constellation*] there might be constellations over here [*points to red dot then traces a line out into space, opposite from Sun and original constellation, and extends her fingers*] you could see.

Throughout her explanation, Katrina uses one hand to indicate the position of a constellation; at the end, she gestures (*iconic hand/arm*) the line-of-sight viewing angle for observing a second constellation whose location she defines through this tracing gesture and an extension of her fingers to place this in the virtual space she has created. Children added the constellations to the shared space between themselves and the interviewer through gesture alone; during their explanations they consistently referred back to the location of these virtual constellations.

In summary, children created a shared space in which to communicate their ideas to the interviewer that took advantage of the physical model elements available to them along with invisible elements created with gestures. Children used gestures to add the location of the constellations visible at night or at different times of the year. They used gestures and manipulated the models to indicate how the Earth moves to change our perspective on space. Finally, they used gestures to help communicate how our position on Earth or change in position would impact our viewing angle on the Sun and stars, thus connecting our Earth-based views to the space-based perspective generated by the shared space between child and interviewer.

Research question 2: linking perspective-taking skills to explanations of astronomical phenomena

We begin by presenting descriptive statistics to clarify the nature of children's astronomy understanding, use of reference frames, and use of gestures. For the Sun's apparent motion, 11 children before camp and 11 children after camp provided a scientific explanation. For the stars' apparent motion, 12 children before camp and 12 children after

Table 1. Definitions and descriptive statistics (mean proportion) of frames of reference and gesture codes.

Frames of Reference	Code Definition	Sun Apparent Motion Pre	Sun Apparent Motion Post	Star Apparent Motion Pre	Star Apparent Motion Post	Seasonal Constellations Pre	Seasonal Constellations Post
Earth	Viewing astronomical phenomena from Earth's surface	.46 (.16)	.37 (.15)	.59 (.19)	.54 (.27)	.25 (.28)	.18 (.25)
Space	Viewing space from random location in space (not Earth)	.19 (.16)	.15 (.18)	.11 (.17)	.10 (.13)	.50 (.31)	.64 (.26)
Implicit Connection	Indirect connection: Participant responds to Earth-based question with space-based answer.	.22 (.14)	.30 (.23)	.19 (.16)	.20 (.20)	.13 (.26)	.06 (.21)
Explicit Connection	Direct connection: Directly explains (verbally or with gesture) the connection between perspectives.	.13 (.13)	.17 (.16)	.10 (.12)	.16 (.26)	.09 (.16)	.10 (.13)
Unclear	Participant does not gesture or verbalize clear perspective in explanation	.00 (.00)	.01 (.02)	.01 (.03)	.00 (.00)	.03 (.09)	.02 (.05)
Gesture and Movements							
Spatial Pointing	Uses body or physical model (including model Sun and/or Earth) to convey spatial properties such as location and direction	.17 (.11)	.22 (.13)	.32 (.29)	.44 (.28)	.45 (.39)	.60 (.29)
Iconic – Hand/Arm	Uses body to show perceptual relations with concrete entities/events	.34 (.19)	.28 (.15)	.22 (.32)	.10 (.26)	.05 (.10)	.06 (.10)
Iconic – Model Adjust	Uses physical model to show perceptual relations with concrete entities/events	.47 (.21)	.48 (.16)	.32 (.35)	.39 (.28)	.22 (.36)	.25 (.23)
Unclear	Gesture is not clear	.02 (.04)	.01 (.02)	.00 (.00)	.00 (.00)	.00 (.00)	.00 (.00)

Note: Number in parentheses is standard deviation. Proportions for Gesture and Movements for each session of each phenomena do not sum perfectly to 1.0 because 'simple deictic' and 'metaphoric' codes were not included.

camp provided a scientific explanation. For seasonal constellations, three children before camp and five children after camp provided a scientific explanation. See Table 1 for the mean proportions of each type of gesture and frame of reference used in explanations for each of the testing sessions and phenomena.

We explored the relationship between children's perspective-taking skill and explanations. Specifically, regressions were run for explanations of each of the three astronomical phenomena at each of the interview sessions (pre-camp and post-camp). In all analyses, perspective-taking score was the predictor variable. Regression analyses were conducted to estimate the relationship between certain variables and to control for other possible influential predictors, such as chronological age. Chronological age did not significantly correlate with perspective-taking scores so it was not included in the regression models. Separate regressions were run for each outcome variable: astronomy understanding; frames of reference; iconic hand/arm gestures; iconic model adjustment gestures; spatial pointing hand/arm gestures; and spatial pointing model adjustment gestures.

Astronomy understanding

Logistic regressions were conducted to examine the relation between children's perspective-taking skill and the scientific accuracy of their explanations for each of the three astronomical phenomena. Proportion correct on the perspective-taking score (which showed high reliability, $\alpha = .81$) was entered as a continuous predictor variable and the explanation code (0 = alternative understanding versus 1 = scientific understanding) was the outcome variable. None of the analyses showed statistically significant associations (all *p*'s > .05).

Frames of reference

A regression analysis was performed to test the relation between perspective-taking scores with the proportion of *explicit* connections the child made while explaining each of the astronomical phenomena. Perspective-taking score predicted the proportion of explicit connections made for the Sun's apparent motion during pre-camp explanations. Perspective-taking skill predicted the proportion of explicit connections made for star apparent motion and for seasonal constellations, both during post-interviews. See Table 2 for all regression statistics.

Gesture

Regression analyses showed no association between perspective-taking scores and children's iconic gestures in explaining the Sun's apparent motion, in either pre- or post-camp session. However, perspective-taking skill did predict the proportion of model adjustment iconic gestures made during post-camp explanations for the stars' apparent motion. Perspective-taking skill also predicted the proportion of hand/arm iconic gestures made during post-camp explanations for seasonal constellations. Regression analyses showed no associations between perspective-taking scores and children's spatial pointing gestures, for any phenomena, in either testing session.

Scientific explanations that use explicit connections

As indicated above, scores on the perspective-taking task did not predict children's understanding of the three astronomical phenomena. However, this was based on coding children's explanations as scientifically accurate if both Earth- and space-based explanations were factually correct, but not necessarily if they explicitly demonstrated how one

Table 2. Regression analyses: perspective-taking scores as predictors of proportions of explicit connections, iconic hand/arm gestures, and iconic model adjustment gestures in pre- and post-camp explanations.

	Sun Apparent Motion				Stars Apparent Motion				Seasonal Constellations			
Explicit Connections	Pre		Post		Pre		Post		Pre		Post	
Variable	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE
PT	.36	.15	.32	.20	−.13	.16	.70	.30	.25	.21	.33	.15
Adjusted R^2	.25		.11		.00		.25		.03		.22	
F	5.94*		2.65		0.59		5.61*		1.38		5.00*	
Iconic Hand/Arm Gestures	Pre		Post		Pre		Post		Pre		Post	
Variable	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE
PT	.15	.26	.07	.20	−.15	.43	.16	.36	.12	.14	.33	.11
Adjusted R^2	.00		.00		.00		.00		.00		.37	
F	0.34		0.12		0.12		0.20		0.69		9.27**	
Iconic Model Adjust Gestures	Pre		Post		Pre		Post		Pre		Post	
Variable	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE	*B*	SE
PT	.05	.29	.14	.22	.30	.48	.70	.32	−.50	.48	−.15	.32
Adjusted R^2	.00		.00		.00		.21		.01		.00	
F	0.03		0.41		0.39		4.76*		1.11		0.22	

Note: SE = Standard Error.
*$p < .05$.
**$p < .01$.

Table 3. Correlations of perspective-taking scores to accurate explanations that use explicit connections between frames of reference.

	Pre	Post
Sun Apparent Motion	.38 (.076)	.07 (.402)
Star Apparent Motion	.46 (.038)*	.57 (.014)*
Seasonal Constellations	.48 (.032)*	.47 (.039)*

Note: Numbers in parentheses indicate *p*-value.
*$p < .05$, one-tailed.

reference frame could explain the other. Requiring both scientific understanding and the ability to explain the connection between frames would tap a deeper understanding of the phenomena; this more demanding threshold for crediting understanding might be predicted by perspective-taking skill. We explored this possibility by calculating correlations between perspective-taking scores and whether a child gave a scientific explanation that used explicit connections between frames of references (Table 3). These correlations reveal that perspective taking significantly correlates with explanations of stars' apparent motion and seasonal constellations at both testing sessions. A similar pattern is not, however, evident with respect to explanations of the Sun's apparent motion. For this phenomenon, even when using the stricter criterion for a scientific explanation (i.e. one that requires an explicit frame-of-reference connection), there was no significant association between perspective-taking skill and explanation at either testing session.

Discussion

Our qualitative analysis of children's discourse and gestures revealed different levels of sophistication in children's application of spatial thinking to communicate explanations for astronomical phenomena. While some children used *no-perspective* explanations, others used *perspective-taking* methods to demonstrate how shifting perspectives can be used to explain astronomical phenomena. Children who provided alternative explanations that did not involve perspective taking used reasoning similar to naive notions described in the literature, such as stating that the Sun appears to move because the Sun actually moves about us (Vosniadou & Brewer, 1994). Our findings are consistent with the observation that children usually begin school with attending primarily to their immediate or egocentric visual experiences and that it is only gradually during elementary school years that children come to appreciate that appearances differ depending upon one's vantage point (Piaget & Inhelder, 1956). As a result, the 7- to 9-year-old children interviewed in the current research could be expected to be transitional with respect to their understanding of perspective taking and thus not likely to apply such understanding consistently to explain astronomical phenomena. Indeed, we found that even when children knew the elements of the scientific explanation for an astronomical phenomenon, they did not necessarily explicitly communicate how motion in one reference frame can account for changes in what is observed. Children who made implicit connections were able to accurately describe the Earth-based perspective and describe space-based motions that account for why the phenomenon occurs; but they did not show how those two sets of motions connect.

We also found that some children made use of more sophisticated *explicit* connections between reference frames. Children who made explicit connections demonstrated a deeper understanding of these astronomical phenomena by showing how their explanations were more than a set of related statements; rather, they were able to justify cause and effect through gestures and physical manipulation of models in coordination with verbal cues. We drew on Alibali and Nathan's (2012) gesture framework to explain how children's use of two gesture types during these perspective taking-based explanations suggests that their understanding of astronomy is embodied.

First, spatial pointing gestures are evidence that cognition is situated in the environment because of the ways people make connections between physical objects or spaces and non-present objects; further, spatial pointing gestures anchor speech to the environment in ways that enhance the information communicated (Alibali & Nathan, 2012). This connection between physical world and mental imagery was apparent as children made explicit connections when spatial pointing to a place represented on a physical object, such as a location on the Earth globe, to indicate our observing location. These objects or locations became anchored to imagined objects in space through spatial pointing gestures. Children extended their imagined environment during their explanations to include non-present objects, such as gesturing to an imagined location of a constellation or in reference to a location the Earth could be at another time of year. Later in their explanations, these invisible locations were seamlessly integrated into their explanation to help support the complex, three-dimensional explanation in ways that went beyond what was conveyed verbally.

Second, iconic gestures provide evidence that cognition is embodied because they arise from mental processes stimulated through imagined experiences of action and perception (Alibali & Nathan, 2012; Hostetter & Alibali, 2007). In our analysis of explicit connections, we found that children used specific iconic gestures to physically connect the reference frames in a way that communicated otherwise invisible aspects of their mental imagery. These iconic gestures show how children were mentally simulating the connections between reference frames in their explanations as in gesturing to show the angle or change in orientation of their observation on Earth.

Our second research question addressed the relationship between spatial perspective-taking skill and characteristics of children's explanations, specifically their astronomy accuracy, reference-frame connections, and gestures. Our findings are consistent with the hypothesis that perspective-taking skills are associated with the proportion of explicit spatial connections made during explanations for all three astronomical phenomena. In particular, perspective-taking scores were associated with explicit connections made when explaining the Sun's apparent motion (during pre-camp interviews) and when explaining stars' apparent motion and seasonal constellations (during post-camp interviews). The use of explicit connections in explaining the Sun's apparent motion may have been associated with perspective-taking skill at the pre-camp session because children are more likely to have previously been exposed to opportunities to learn about this phenomenon (e.g. Palen & Proctor, 2006). Having been exposed to this information prior to attending the summer camp may have allowed children with higher perspective-taking skill to have already developed a deeper understanding of the spatial connections. The role of perspective-taking skills may have dissipated by the post-camp interviews in part because at least some students with lower perspective-taking skills may have profited from camp instruction, which may have reinforced nascent understanding about this particular astronomical phenomenon stemming from earlier experiences. In contrast, children are less likely to have studied the other two phenomena prior to the astronomy camp; perhaps children with higher perspective-taking skills were better positioned to benefit from the camp and learn how to construct explanations with explicit connections.

And while scores on the perspective-taking task did not predict the children's scientific understanding of any of the three astronomical phenomena, when scientific understandings were combined with their use of explicit connections, we found significant correlations with perspective-taking scores for stars' apparent motion and for seasonal constellations at both testing sessions. Simultaneously demonstrating scientific understanding and the ability to explain the connection between reference frames indicates a deeper understanding of the scientific phenomena. These findings are consistent with the hypothesis that perspective-taking skill predicts students' ability in this domain; however, we note the small size of our data set and suggest the current work should be understood as only a first step towards testing this hypothesis. We also found no correlation between perspective taking and children's use of explicit connections in accurate explanations for the Sun's apparent motion; perhaps, children's familiarity with this phenomena, given that this topic is one that is commonly taught in school and media, influenced children's decisions on whether to make explicit connections. Their familiarity may have skewed the distribution of children who chose to make explicit connections in their accurate explanations. It will be necessary to examine this hypothesis in future research involving far larger samples of children and in the context of instructional experiences.

Finally, the data also showed perspective-taking skill predicted the proportion of hand/arm iconic gestures made during post-camp explanations of seasonal constellations and model adjustment iconic gestures made during post-camp explanations for stars' apparent motion. Again, the camp experience appears to be associated with increased use of these gesture types for children with high perspective-taking skill. As iconic gestures are an expression of spatial images, speakers are more likely to make gestures when the ideas underlying the speakers' verbal explanation contain spatial components (Hostetter & Alibali, 2007). Using gestures, particularly iconic gestures, may help the child communicate a spatially complex idea. Children with higher perspective-taking skill may find it easier to make connections and therefore communicate these connections with gestures more frequently. We found no correlation between spatial pointing gestures and perspective-taking skill. Students used spatial pointing gestures to ground objects in the physical environment, aiding in communication (Alibali & Nathan, 2012). Children in this study used spatial pointing gestures to indicate their ideas of where the Sun, Earth, and constellations are located in space. This did not require the more complex spatial transformations or shifts in perspective associated with iconic gestures and thus, perhaps, did not relate to perspective-taking skill.

Conclusions

This study provides new insights into children's spatial reasoning in astronomy and points to potential directions for additional research on student thinking. Our results extend prior research by showing that children are capable of explaining how an Earth-based perspective can be explained by a space-based reference frame. While prior studies indicate children can learn to accurately describe the Earth-based and space-based components of explanations for astronomical phenomena (e.g. Plummer et al., 2011, 2014), few studies have taken a close look at how children understand and communicate the more spatially challenging aspect of these phenomena by showing *how* one reference frame is explained by motion in another reference frame. Our use of an embodied-cognition framework led to findings that extend the prior literature examining the use of gestures in astronomy explanations (Crowder, 1996; Padalkar & Ramadas, 2011). As the use of gestures in communicating and problem-solving suggests that knowledge is embodied (e.g. Alibali & Nathan, 2012), children's use of gestures to communicate their understanding of how reference frames are connected suggests that their understanding of astronomical perspective-taking is embodied. According to embodiment theory, cognition is aided by offloading mental tasks onto the environment (Wilson, 2002). We observed this type of mental offloading through children's epistemic actions (Kastens et al., 2008) in which they gestured and manipulated the physical models to enrich their verbal descriptions of the relationship between perspectives.

Further, children who were able to make these types of explicit connections were children who had higher perspective-taking skills. Although previous research has examined the use of gesture when solving problems associated with a specific spatial skill, such as mental rotation (e.g. Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013), few have analysed problems that include perspective taking.

A few limitations of this study point to directions for future research. Our small sample limits the conclusions we can draw about the relationship between perspective-taking skill and astronomical explanations, explicit connections, and gesture use. The sample size may account for a failure to find a significant association between children's understanding and perspective-taking skill. In particular, the high initial content knowledge for the Sun's and stars' apparent motion explanation may have constrained our opportunity to uncover associations due to ceiling effects. The small sample size also limits the extent we can generalize from correlations found when combining use of explicit connections and accurate explanations with perspective taking. Finally, it may be useful to examine the developing understanding of this phenomenon with younger children who have not yet been engaged in formal instruction with this domain (Kallery, 2011).

The findings are consistent with our hypothesis that perspective-taking skill is useful in students' spatial thinking in astronomy. Thus, we recommend that science educators foster this type of reasoning and provide children who have low perspective-taking skills with additional spatial aids, such as simulations showing the Earth-based perspective and physical models to support explanations. In addition, encouraging children to gesture can improve their ability to reason about spatial transformations (Ehrlich, Levine, & Goldin-Meadow, 2006) and may improve the nature of the spatial information they convey through speech (Sauter, Uttal, Alman, Goldin-Meadow, & Levine, 2012). Padalkar and Ramadas (2011) recommend training children to gesture and use their entire bodies when learning to move between reference frames in astronomy as this 'may help them to form mental representations which would be useful in the visualization, even in the absence of actual situations or (later) the gestures' (p. 1724). However, more research is needed to determine whether such training will improve students' skill in explicitly connecting reference frames and whether this will also improve their ability to learn how to construct similar types of explanations for other astronomical phenomena.

Notes

1. The term spatial ability is often interpreted as referring to an inborn intellectual trait or talent that is resistant to instruction, practice, or age-related development. Given that there is ample evidence that performance on spatial tasks can be improved by all of these factors (e.g. see Liben, 2006; NRC, 2006; Uttal et al., 2013), we hereafter use the term spatial skill rather than spatial ability.
2. Children were also coded for this category if they used eye-gaze shifts (three times during the study) or moved their entire body (once during the study) to indicate a location.
3. All names used are pseudonyms.

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