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Research Article

Building a Learning Progression for Celestial Motion: An Exploration of Students' Reasoning About the Seasons

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Abstract: We present the development of a construct map addressing the reason for the seasons, as a subset of a larger learning progression on celestial motion. Five classes of 8th grade students ($N = 38$) participated in a 10-day curriculum on the seasons. We revised a hypothetical seasons construct map using a Rasch model analysis of students' pre/post-assessments followed by a closer examination of individual student explanations. Our proposed construct map is consistent with the *Framework for K-12 Science Education* [National Research Council (2012). Framework for K-12 Science Education. Washington, DC: National Academy Press] but includes a more nuanced discussion of critical conceptual and spatial connections. Movement up the construct map begins with learning foundational concepts about the Earth's motion in space and how observational patterns of the Sun relate to temperature changes. Movement into the upper levels of the seasons construct map occurs as instruction supports students in making sense of how the space-based perspective of their location on a spherical Earth can be used to account for observable patterns of change. However, our findings suggest that making this connection between Earth-based observations of the Sun and the motions and perspectives of the Earth in space is one of the major challenges that limit student progress in this domain. Findings have implications for instruction designed to support astronomy education as described by the *Next Generation Science Standards* [NGSS Lead States (2013) *Next Generation Science Standards: For the States, By the States. Achieve, Inc. on behalf of the twenty-six states and partners that collaborated on the NGSS*. Retrieved from: http://www.nextgenscience.org/next-generation-science-standards]. Instruction that supports progress along this construct map, and the larger celestial motion learning progression, must purposefully support the spatially complex connection between the Earth's motion in space and phenomena observed from the Earth's surface. © 2014 Wiley Periodicals, Inc. J Res Sci Teach 51:902–929, 2014.
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The *Next Generation Science Standards* (*NGSS*), now adopted by many U.S. states, organize standards for astronomy using a systems-based approach (NGSS Lead States, 2013; National Research Council [NRC], 2012) that includes placing a focus on the big idea of *celestial motion*: astronomical phenomena observed from an Earth-based perspective can be explained using the actual motions and orientations of objects in the Solar System. Understanding this big idea requires transferring between moving frames of reference: the Earth-based perspective (observations from the Earth's surface) and a space-based perspective (the solar system from a vantage point in space). Students must learn to coordinate these two perspectives to interpret

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observational phenomena and construct explanations based on the actual motions and orientations of objects in space. The *NGSS* uses this big idea to organize standards towards facilitating student learning of astronomy across K-12 education.

We have selected one of the central concepts of celestial motion, the reason for the seasons, to examine how students' understanding of celestial motion may progress with instruction that supports students' ability to move between moving reference frames as they construct increasingly sophisticated explanations. The changing seasonal temperature patterns are explained by the changes in the Sun's daily apparent motion, which results in changes in the intensity of sunlight and changes in the length of day. These changes in the Sun's path are the result of the tilt of the Earth on its rotational axis with respect to the plane of its orbit. Because the Earth remains tilted in a relatively constant direction, observable changes in the Sun's path and the accompanying seasonal temperature changes alternate with the northern and southern hemisphere. This is a complex explanation to learn; extensive research has demonstrated the prevalence of alternative conceptions about the reason for the seasons (e.g., Atwood & Atwood, 1996; Baxter, 1989; Sharp, 1996) and the difficulty learners have in developing full understanding (e.g., Kikas, 1998).

The seasons phenomenon is an astronomical topic relevant to students' lives, thus allowing us to delve into an important but challenging aspect of supporting astronomy education with the *NGSS*. Learning to explain the seasons provides an opportunity for students to extend their understanding of several key areas of science. First, climate change is a critical socio-scientific issue. For students to understand evidence-based arguments for human-induced climate change, they will need a foundation in the reason for the seasons, such as understanding typical patterns of temperature and weather, and how these relate to seasonal and locational variations in the amount of energy received from the Sun (Sneider, Bar, & Kavanagh, 2011). Second, learning about the seasons is an important opportunity to explore crosscutting concepts of science including energy and patterns, which can help students organize their knowledge across disciplines into more coherent structures (NRC, 2012). Explaining the seasons involves the application of the relationship between energy and temperature—at a local and global scale. Students engage in the crosscutting concept of patterns by studying the relationship between changes in global temperatures and the Sun's altitude and length of day. This relates to the third benefit: studying the reason for the seasons provides an excellent opportunity to engage students in relating evidence to model-based reasoning: students learn to make sense of patterns in the observational evidence for the seasons, both locally and globally, and explain this with scientific models of the Earth's movement in space. Finally, learning to explain the reason for the seasons engages students in spatial thinking, a key predictor of future success in science (Wai, Lubinski, & Benbow, 2009). Generating explanations for seasons-related observations requires understanding different frames of reference in order to coordinate patterns of change of Earth-based observations of temperature and the Sun's path with patterns of motion of the Earth in space, and interpreting how the Earth's spherical shape influences observations.

However, children and adults often explain the seasons using non-normative ideas. Sneider et al. (2011) conducted a thorough review of the literature on students' ideas about the seasons; therefore, we will focus on some pertinent elements relevant to our own investigation of the topic as an example of celestial motion, beginning with how children understand the changing seasons from an Earth-based perspective. Prior research with elementary and middle school students (Plummer, 2009), as well as adults (Heywood, Parker, & Rolands, 2013; Mant & Summers, 1993; Plummer & Krajcik, 2010), suggests that learners are often unaware of changes to the Sun's apparent path between summer and winter, including the change in the Sun's altitude. This limitation is also reflected in the design of instruction and assessment; some previous studies have focused only on the space-based perspective in assessing students' explanations (e.g., Tsai & Chang, 2005) and designing instruction (e.g., Taylor, Barker, & Jones, 2003) or have not sufficiently demonstrated how explanations accounted for both the Earth- and space-based perspectives (Hansen, Barnett, MaKinster, & Keating, 2004; Hsu, 2008; Trumper, 2006). Students' explanations often focus on changes happening in the space-based perspective while ignoring elements of the Earth-based perspective, such as change in the Sun's altitude and length of day (e.g., Baxter, 1989; Kikas, 1998).

Many students hold alternative explanations for the reasons for the seasons using non-normative views of how the Earth moves in the Solar System, including: a change in distance between the Earth and Sun between summer and winter (Schoon, 1995), the Earth's orbit is highly elliptical (Kikas, 1998), the Earth's tilt flip/flops between seasons (Trumper, 2006), and the Earth faces more towards the Sun in summer (Sharp, 1996). More complex scientific reasoning about the seasons may also be hindered by students' limited understanding of how the Earth's rotation relates to the change in the Sun's path. Plummer and colleagues found that elementary students are likely to use the Sun's own motion to explain our observations of its rising and setting, even when they are aware of the Earth's rotation (Plummer, Kocareli, & Slagle, 2014; Plummer, Wasko, & Slagle, 2011).

Our investigation of student reasoning about the seasons is part of on-going research program developing a celestial motion learning progression (LP). LPs explore how students' understanding of big ideas in science becomes more sophisticated, across time, through targeted instruction (Duschl, Schweingruber, & Shouse, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Big ideas hold broad explanatory power in the domain, make connections across isolated concepts, and are developed over time as learners understand them in increasingly sophisticated ways (Smith et al., 2006). Celestial motion phenomena, including diurnal motion and lunar phases, share a common use of motion and perspective in the solar system to construct their explanations. However, because different combinations of motions and orientations of celestial objects explain each phenomenon, they do not fit neatly into linear levels in an LP and thus need to be studied separately in order to start understanding methods of supporting student learning across phenomena (Plummer, 2012). Therefore, this study represents an *in depth exploration of one piece of a larger LP* as we build towards understanding how students construct and apply scientific explanations for the seasons and investigate the role of instruction plays in supporting this change.

LP-based research offers an opportunity to examine ways of improving scientific literacy by emphasizing the importance of developing conceptual goals that build over time towards big ideas of science in ways that help students form important connections, linking key ideas together an a web-like manner (Corcoran, Mosher, & Rogat, 2009; Krajcik, Sutherland, Drago, & Merritt, 2012). LPs also offer the potential for designing instruction based on the notion that different students may progress at different rates along a hypothesized learning pathway (Corcoran et al., 2009). They emphasize the importance of understanding where children are currently and then selecting instruction that best supports their progress to the next level. LP development has the potential to support the creation of standards that are based on empirical evidence and to uncover the types of pedagogical support needed to move students towards appropriate learning goals (Anderson & Cobb, 2012).

Research is needed that explores student learning from an LP perspective in order to support the implementation of the *NGSS*. The *Framework for K-12 Science Education* (NRC, 2012), a document that guided the development of the *NGSS*, suggests "many aspects of the core ideas and their progressions over time with instruction... remain unexplored territory. The work needed would probably start with design experiments situated in classrooms that explore (a) how to specify the knowledge to be acquired by students at particular grade bands and (b) what instructional approaches might best support the proposed progressions" (p. 315–316). Previous studies on children learning about the seasons have often focused only on the space-based perspective in how students' explanations were assessed (e.g., Kucukozer, 2008; Tsai & Chang, 2005) or not sufficiently demonstrated how students' explanations accounted for both the Earth-based and space-based perspectives (e.g., Hansen et al., 2004; Hsu, 2008; Trumper, 2006). These limitations do not allow us to fully build on the previous literature towards understanding how students develop sophisticated explanations that use motions in space to account for patterns observed on Earth, as recommended by the *NGSS*. Thus, this study purposefully explores how student learning of the seasons is supported by classroom instruction in ways that help us shape the types of LPs that could be useful to implementing the *NGSS*. It was guided by the following research question: How can a learning progression framework be used to design an intervention that effectively supports student progress in explaining the reason for the seasons, as describe in the *NGSS*?

Learning Progression Framework

LPs are hypothetical descriptions of how students' understanding of big ideas may increase in sophistication across time. These descriptions of student thinking are typically organized in *levels*, representing key points along the way from students' initial understanding of the concepts towards the scientific level of understanding. Typically, the structure of a learning progression includes a lower anchor (what students know entering school), several intermediate levels, and an upper anchor (an appropriate level of understanding of a big idea in science, as determined by societal goals and central concepts of the discipline). Intermediate levels describe increasingly productive ways students make sense of the world that can position students to move towards the upper anchor with appropriate instruction (Corcoran et al., 2009). "Each level of the progression describes comprehensible and developmentally appropriate steps towards more sophisticated understanding of the big idea" (Stevens, Delgado, & Krajcik, 2010, p. 688).

The purpose of describing an LP is not to suggest that this is the single, linear, pathway that a student may take towards learning the big idea (Corcoran et al., 2009; Rogat et al., 2011). As students' understanding of science may increase and decrease with respect to the target construct over time, "the levels of an LP do not necessarily describe a unidirectional route to more sophisticated understanding... the ideas included in the LP must be productive in that they describe knowledge that helps students develop more sophisticated understanding" (Stevens et al., 2010, p. 688). LP-levels are descriptions of potentially productive ways of understanding a scientific concepts, based on observations of students' understanding of the target concept, at different points along a potential trajectory moving towards understanding the scientific explanation; this is a potential or hypothetical trajectory because improvement relies on the nature of students' educational experiences (Stevens et al., 2010). While there may be multiple pathways and multiple descriptions of potential levels, this number is likely to be relatively small set as these pathways are defined by the logic of the discipline, student cognition, and instructional design (Krajcik, 2011).

LPs differ from previous works that developed standards and instruction, listing scientific ideas as scope, and sequence; instead, they are a combination of unpacking the scientific concepts and using empirical evidence of student thinking in the domain (Duncan & Rivet, 2013). However, a range of approaches has been used to develop and validate LPs. The development of the LP often begins through a combination of reviewing existing literature on student thinking and unpacking the big idea (Rogat et al., 2011). This forms a hypothetical LP that requires "additional empirical work... to develop detailed descriptions of how students' understanding might develop over time with adequate instruction" (Rogat et al., 2011, p. 4). After an initial process of defining and hypothesizing, researchers typically work towards iteratively refining and validating the LP. This process "relates to obtaining evidence about students' progression with respect to the learning progression and to using this information to iteratively align curriculum, instruction and assessment to foster students' progression in mastering the particular domain in the best possible way" (Neumann, Viering, Boone, & Fischer, 2013, p. 165). However, researchers approach the process of validating LPs using different methodologies (Anderson & Cobb, 2012; Duncan & Hmelo-Silver, 2009; Neumann et al., 2013); the differences include contextual issues (such as the relationship to instruction) and the methods of using evidence to validate the LP.

Some researchers have designed LPs using a cross-grade level analysis as a measure of the "status quo instructional practices and curricula" (Gunckel, Covitt, Salinas, & Anderson, 2012, p. 852). For example, Gunckel and colleagues investigated elementary, middle, and high school student accounts of water in environmental systems. They began by developing their LP hypothesis using a review of literature on students' alternative ideas about water systems and exploring what it means to be scientifically literate in the domain. This initial LP was used to design open-ended assessment items, which they used to better articulate the lower and intermediate levels of the LP. Their LP was not tied to a particular instructional approach, but instead represents the students' range of experiences across grade levels to suggest potential LP levels. However, some argue that "data gathered from large-scale assessments are insufficient as explanations of whether a learning progression is useful for standards development or any other application" because LPs are reliant on appropriate instruction (Gotwals, 2012, p. 470).

This study used a different approach by developing a "new or novel trajectory" to uncover new ways of describing an LP (Anderson & Cobb, 2012). Such research investigates the role of instruction in how students may make progress along the LP as "[v]irtually all researchers in learning progressions recognize a key role for instruction in students' progress along a learning trajectory" (Anderson & Cobb, 2012, p. 13). As traditional instruction often does not result in students reaching a sophisticated understanding of scientific phenomena, we suggest that an important goal of LP-research is to identify instruction that will move students towards more sophisticated levels of understanding (Duschl et al., 2007). This type of LP development often involves close work between the researcher and curriculum implementation in order for the LP hypothesis to be realized in the instructional practices of the teacher. For example, Shea and Duncan (2013) developed an LP for genetics using this method. The data used to test and revise their LP came from interviews and written artifacts with middle school students during a 2-year longitudinal study; the students participated in two instructional units, collaboratively designed with teachers, using the researcher's LP hypothesis. They then used a qualitative approach to analyze student thinking towards revising their initial LP levels. This use of empirical data can then be used to validate LP construction within a particular instructional context (Duschl, Maeng, & Sezen, 2011); "LPs validated in ideal learning conditions represent what we hope students could do given better instruction" (Mohan & Plummer, 2012, p. 145). This suggests a further purpose of the LP, to test potentially beneficial curricula designed using our best understanding of the hypothetical LP (Krajcik, 2012). Through iterative testing of optimal teaching and learning situations we can begin to develop evidence for the type of instruction that moves children from the lower levels of an LP towards the scientific level.

Aside from the different situations in which data is collected (e.g., cross-age vs. specific instructional conditions), researchers vary in how they use data to validate their LPs. LP levels can be revised and validated using analysis of interviews with students, written artifacts, and observations of student in-class discourse (e.g., Lehrer & Schauble, 2012; Mohan, Chen, & Anderson, 2009; Plummer, 2014; Plummer & Krajcik, 2010; Schwarz et al., 2009). Some researchers develop assessments that can be used with large numbers of students across multiple settings, ranging from multiple-choice items (e.g., Neumann et al., 2013) to open-ended assessment items (e.g., Gunckel et al., 2012). Student responses to these large-scale assessments can be qualitatively analyzed towards revising levels (e.g., Gunckel et al., 2012; Jin & Anderson, 2012). Other researchers use these assessments to conduct psychometric modeling to understand student progress, such as Rasch modeling (e.g., Rivet & Kastens, 2012). Krajcik (2012) argues that learning progressions should include psychometrically validated assessments in order to align students to levels along an LP. Regardless of the method used to design and validate the LP, many researchers argue that the LP development process is an iterative one, requiring multiple rounds of testing with students and different curricula and not to expect every student to move through the LP as has been hypothesized (e.g., Duncan & Hmelo-Silver, 2009; Neumann et al., 2013).

We see the LP as becoming a *tool* by which a teacher may measure a student's level of understanding and use this to make informed instructional choices (Black, Wilson, & Yao, 2011; Corcoran et al., 2009). Large-scale LPs can be both "a vision tool and a large-scale map" of student progress across grade levels (Gotwals, 2012, p. 463). Small-scale LPs that "zoom in" on particular features of the progression can become useful tools for designing curriculum and classroom activities. LPs that describe levels of sophistication at very broad grain-size may have limited value in providing information for a teacher to use in improving science instruction (Gotwals, 2012; Mohan & Plummer, 2012). With this in mind, we approach the development of an LP for celestial motion from a fine grain-approach that closely examines the role of instruction in students' progress.

Methodology

Research Design

Our work adopts Wilson's framework (2009) for building LPs from a set of inter-linked *construct maps* (Plummer, 2012). Construct maps "are representations of models of cognition by which the results of the assessment can be interpreted" (Brown & Wilson, 2011, p. 226). Construct maps have upper and lower anchors and include descriptions of levels of increasing sophistication in a similar way as we may map out an LP. But while LPs are primarily viewed as mechanisms for showing progress towards a big idea in science, construct maps can be used to focus on a smaller grain-size in the analysis of learning science (Alonzo & Steedle, 2009). Once multiple construct maps describing different sub-ideas have been developed, then these maps can be linked together such as stacking them one on top of the other, linking them horizontally, or any arrangement that describes the process of reaching the big idea (Wilson, 2009). This approach works well for developing a celestial motion LP because of the variety of different phenomena that need to be explained by different sets of space-based motions and orientation-changes (Plummer, 2012). Plummer (2012) has previous described the outline of how potential construct maps may fit together to create the celestial motion LP. Here, we describe the methodology used to develop, test, and revise the seasons construct map, including the instruction used to move students along the construct map.

Construct Modeling Methodology. We developed and revised the seasons construct map using the *construct modeling approach* for LP development (Brown & Wilson, 2011; Wilson, 2005, 2009). *Construct modeling* is a four-step cycle of measurement. The cycle begins as the researcher makes *observations* to determine the subjects' understanding of the construct. After assessing the target population, the researcher begins the process of inferring the respondents' level of the construct by categorizing, and *scoring* the responses to rank student responses according to their scientific accuracy. Individual student performances are *summarized* to yield a measure of the target construct. Finally, an *interpretational model* is applied to the outcome space; this is a process by which the researcher compares results from the assessment to the hypothetical construct map.

The interpretation relies on the researcher's assumptions about the model of *cognition* (Brown & Wilson, 2011; Wilson, 2005). The process of interpreting and validating a construct map includes recognition that a process of conceptual change is occurring (Duschl et al., 2011). Our interpretation of student learning is influenced by the work of cognitive and developmental psychologists. Explanations for natural phenomena are embedded in a framework-theory that holds some coherence in how the learner interprets the world and give rise to mental models that represent a person's understanding of real, hypothetical, or imagined situations (Carey & Spelke, 1996; Ioannides & Vosniadou, 2002; Vosniadou & Brewer, 1994). Conceptual change or growth occurs as learners compare new information with existing mental models and then determine whether their mental model should be added to or revised, or if a more fundamental restructuring of the underlying theories that guide the generation of their mental models needs to take place (Vosniadou, Vamvakoussi, & Skopeliti, 2008). When children assimilate new scientific ideas, they may be combined with the existing naïve mental model to form new *synthetic models* that include aspects of both intuitive and scientific influences (Vosniadou & Brewer, 1994).

However, other theories for interpreting knowledge structure and conceptual change have been proposed, including the knowledge-in-pieces perspective. This theory suggests that elements of learners' knowledge system begin as an unstructured collection of simple elements known as phenomenological primitives (p-prims) that originate from experience with physical reality (DiSessa, 2008; Vosniadou et al., 2008). Both the knowledge-in-pieces and framework theory perspectives reflect similar important traits in how they describe the learning process, such as the focus on how a learners' current beliefs shape the ways they refine their current knowledge structure and the new connections they make. We chose to use framework theory because of its focus on how children construct specific theories, embedded in framework theories, that can be used to explain specific phenomena, such as the day/night cycle, and that these specific theories give rise to mental models when needed for problem solving situations (Vosniadou & Ioannides, 1998). In our work, the important unit of analysis is students' generation of mental models, which are tied to the specific attributes of celestial objects. Understanding how children develop mental models that account for the relationship between objects as they move in space, and in relation to points of observation on Earth, is central to understanding celestial motion (Heywood et al., 2013; Taylor et al., 2003). Several empirical studies support the usefulness of using framework theory to interpret students' knowledge in physics and astronomy (e.g., Blown & Bryce, 2010; Ioannides & Vosniadou, 2002; Vosniadou & Brewer, 1994).

Our assumptions about student cognition are made explicit through the description of our *construct map hypothesis*, which includes the construct to be measured (explanation for global seasonal change) and a description of the potential levels of sophistication or "amount" of understanding of the target construct (Alonzo & Steedle, 2009). Our hypothesis for the construct map was influenced by literature on students learning about the seasons (discussed above) and other researchers' descriptions of hypothetical construct maps[1] for the seasons (Sneider et al., 2011; Willard & Roseman, 2007). These hypothetical construct maps suggest that instruction should first support students in developing knowledge of observable patterns of change in the Sun's intensity and length of day and then help them to relate those changes to seasonal temperature changes. A concurrent step along the construct map is developing knowledge of the Earth's rotation, to explain the Sun's daily apparent movement, and the Earth's orbit, to account for the length of our year. As students progress up the construct map, they should be supported in building on these concepts by learning a frame-of-reference perspective as they use Earth's orbit and the tilt of the Earth's rotational axis to explain global seasonal climate patterns. We also hypothesized that at the intermediate levels students' explanations for the seasons would include both elements of the normative explanation and non-normative components as they progress towards the scientific explanation. This hypothetical construct map guided the development of instruction and how we assessed changes in student understanding.

Participants

Prior research suggests that students' experience in "status-quo" instruction has not lead to a scientific understanding of this construct (Sneider et al., 2011). Therefore, it is important to conduct LP-research in instructional settings designed to match the researcher's LP hypothesis (Krajcik et al., 2012). It is also important to study this construct map at the middle grade level because the reason for the seasons is often taught in middle school (Palen & Proctor, 2006) and the *NGSS* places this explanation in the middle grades (NGSS Lead States, 2013). Therefore, we selected to work with the second author's five 8th grade classes (students age 13–14 years old). The second author holds a Physical Science 7–12 certification, has a Masters in science education, and had been teaching for seven years at the time that data was collected. There were 19–24 students in each class. All students who returned consent forms were included in the study ($N = 38$). The middle school, grades 6–8, is located in a small city outside of a larger metropolitan area. The school's racial demographics is: White (non-Hispanic) 94.0%, Black (non-Hispanic) 3.4%, Hispanic 1.6%, and Asian 1.0%; 44.6% of students are eligible for free or reduce price lunch (National Center for Educational Statistics, 2010).

Instructional Context

All students in each of the second author's five classes received the same instructional activities across 10 class periods (50 minutes per period). The curriculum was based on lessons from The Real Reasons for Seasons (*Reason for Seasons*; Gould, Willard, & Pompea, 2000) with additional resources drawn from Project Star (Coyle, 1993) and teacher-created materials. More information on our adaptation of the curriculum can be provided, upon request. The description of instruction, below, and in Supporting Information Table 1, is based on the second author's curriculum plans and a written journal completed while teaching the lessons.

We designed instruction to support the students in building on and changing the specific theories that guided their mental model for phenomena in the solar system leading towards explaining the seasons. Students explored foundational concepts necessary for further exploration of the season. The students physically modeled the reason for day and night using a central light source and balls representing the Earth; this was followed by an activity in which students modeled elliptical orbits to discuss the Earth's orbital pattern. During these activities, individual students acted out the motions that cause change in day and night and our location around the Sun during the year. The teacher led students in a discussion of whether the Earth's orbit was a circle or not. The teacher demonstrated to the students how to draw an ellipse, and then guided students in drawing the Earth's elliptical orbit (using two focal points) and compared this to Pluto's more elliptical orbit. This experience was designed to lead students to recognize that the Earth's orbit, though elliptical, was close to a circle. In addition, the students considered the ramifications of the fact that the Earth is closest to the Sun when the Northern Hemisphere is experiencing winter, an approach similar to successful instruction using discrepant events (Tsai & Chang, 2005). Students used this information as they wrote reflections on how their understanding of the Earth's orbit changed during the lesson.

Students' exploration of the relationship between temperature and other variables began by plotting and examining graphs of yearly temperature changes for different locations on Earth. The teacher engaged students in discussing patterns in temperature change by completing the prompt: "Over the course of a year, temperatures in [our location]. . ." They continued to analyze these temperature graphs, to see that the temperature of any location tends to increase and decrease in a predictable cycle over the course of a year and how this cycle depends on proximity to the equator.

Students then explored the relationship between amount of sunlight and change in temperature. Students made their ideas about the Sun's path across the sky public by individually tracing the path on clear plastic hemispheres that represented the sky. They used their own observations of the Sun's path from pre-recorded video clips to revise their tracings of the Sun's path on their plastic hemispheres hemisphere. Recording this data was designed to help students to see that the Sun's apparent path across the sky shifts higher and then lower, over the course of the year. Students analyzed changes in light intensity as the Sun's angle changes using a flashlight and paper as a model. This model served as evidence that the intensity of sunlight striking a place on the surface of the Earth varies depending on the Sun's altitude in the sky. The teacher also defined key terminology for students (energy, strength, and brightness) and helped the students understand the concept through the use of analogies, such as orange juice concentrate. Students worked together to post data gathered from the flashlight model on the classroom chalkboard and then, working in small groups and as a whole class, discussed how intensity and angle of sunlight may relate to change in temperature. Students also plotted and examined graphs of daylight hour changes for different locations on Earth. This allowed students to see that the number of daylight hours a location receives varies in a predictable pattern over the course of the year, depending on distance north or south from the equator. Students were introduced to the scientific principle: increased solar intensity results in increased energy received from the Sun, raising the temperature. Students worked in groups to analyze the data to draw conclusions on how change in amount of daylight contributes to global patterns of temperature change.

As a culminating activity, students participated in a psychomotor modeling activity to tie together the observational patterns with the space-based perspective of the Earth orbiting the Sun on it is tilted rotational axis. This was a whole class exercise where the teacher and students stood in a circle around a central bulb representing the Sun. All students pointed their Styrofoam Earth-ball's "north pole" to the "Polaris" sign placed high on the northern wall. Knowing that the Earth rotates on a tilted axis while orbiting the Sun may not be enough for students to understand how these space-based changes affects the seasons; knowledge of space-based motions is not sufficient for students to construct explanations for Earth-based observations due to the complex spatial reasoning required (Plummer, 2014; Taylor et al., 2003). Students measured changing light intensity on the Earth as they moved the globe, to simulate an orbit around a light bulb representing the Sun. This helped to support students' understanding that the amount of sunlight striking a place on the Earth's surface depends on the Sun's altitude. Students measured changing amounts of light on the latitude lines of a globe as the globe orbited the light bulb. This model allowed students to calculate the number of hours of day or night at various locations on the Earth and how this related to distance from the equator. The teacher further prompted the students to reflect on the seasonal orientation as they continued to discuss their exploration of the model and apply what they learned in previous lessons to this whole-class discussion.

Data Collection and Instrument Design

To begin the process of revising our hypothesized construct map using a construct modeling approach, we developed an instrument to elicit student thinking about the seasons. Items were chosen to measure students' placement along the hypothetical construct map and to represent a range of potential ideas, both in terms of yielding information about potentially non-normative ideas and varying levels of complexity in depth of understanding (Liu, 2010). Therefore, we selected assessment items from *Reason for Seasons*, the SCALE-uP project (a previously developed in-depth assessment of the seasons; C. Pyke, private communication), and teacher-generated questions (where existing questions did not fully cover the range of the construct). As shown in Table 1, there were a total of 13 items: six multiple-choice and seven open-ended. The full assessment instrument can be found in a Supporting Information appendix. The written

Table 1
Descriptions and sources of assessment items

Item	Item Type	Concept Assessed and Alternative Conceptions Addressed	Construct Map Level[a]	Item Source
1a	Multiple choice	Which of the four drawings do you think best shows the shape of the Earth's orbit around the Sun? (The view is top down.) Distracters include both oval orbits and off-centered Sun position	KSEM	*Reasons for Seasons*
1b	Open-ended	Look at the position of Earth in the drawing you selected above. Mark on that drawing the location of the Earth in 1 year	KSEM	*Reasons for Seasons*
2	Multiple choice	Stem prompts: "When the northern hemisphere is tilted *away* from the Sun" followed by choices that vary the length of day and the altitude of the Sun	OKD	*Teacher developed*
3	Multiple choice	Stem prompts: "At noon, when the northern hemisphere is tilted *towards* the Sun" followed by choices that compare the Sun's altitude in Northern US to Australia	OKD	*Teacher developed*
4	Multiple choice	Which is the best drawing to show the sizes and distances between the Earth and the Sun? Three drawings compare the size and distance between the Sun, Earth and Moon	KSEM	*Reasons for Seasons*
5	Multiple choice	Stem prompts "Why do you think it is hotter in Maine in June than in December?" followed by a list of accurate responses and non-normative responses	OKD, Sci	*Reasons for Seasons*
6a	Open-ended	Carlos lives in Washington, DC. He is walking to school in September. In the morning he notices the shadow from the flagpole (see picture below). Carlos wonders what the shadow will look like at 3:00 in the afternoon. (Image shows a pole's shadow and the Sun's location at 9 AM.) In the picture above, draw where the shadow will be at 3:00 in the afternoon	DCM	*Scale-up Project*
6b	Open-ended	Why does the Sun appear to move across the sky and cause the flagpole's shadow to change?	DCM	*Scale-up Project*

(*Continued*)

Table 1. (*Continued*)

Item	Item Type	Concept Assessed and Alternative Conceptions Addressed	Construct Map Level[a]	Item Source
6c	Open-ended	In Washington, DC the Sun appears higher above the flagpole in the summer than it does in the winter at the same time of day. This causes the shadow to be shorter (see picture below). (Image shows a pole's shadow at noon in summer and in winter.) Why does the Sun appear to be higher above the flagpole in the summer than the winter?	Incomp, Sci	*Scale-up Project*
7a	Multiple choice	Below is a diagram of Earth in June. As Earth spins, Buenos Aires gets light from the Sun for 10 hours in a day. Earth moves around the Sun. Imagine Earth's position in December. In Buenos Aires, will the number of daylight hours in December be more, the same, or less than in June?	Incomp	*Scale-up Project*
7b	Open-ended	Use what you know about Earth to explain your answer (to question 7a)	Incomp, Sci	*Scale-up Project*
8a	Open-ended	Table 1 shows the average water temperature in winter at three different locations along the Atlantic coast of the United States. The average winter water temperature is cooler along the North Atlantic Coast than the South Atlantic Coast. Use what you know about light from the Sun to explain why the water temperatures are different	Incomp, Sci	*Scale-up Project*
8b	Open-ended	Table 2 shows the average water temperature along the South Atlantic Coast of the United States in winter and in summer. Use what you know about light from the Sun to explain why the water temperatures are different in winter and summer	Incomp, Sci	*Scale-up Project*

Note: The full instrument is available in the Supporting Information Methods file.
DCM, daily celestial motion.
[a]Indicates match between item and construct map level described in Table 2.

paper/pencil task was given to students 3 weeks prior to the start of instruction and 1 week following the end of instruction.

Data Analysis

The next step is the construct modeling approach involves scoring student responses, guided by the hypothesized construct map. We developed a coding scheme for open-ended items to account for the range of scientific and non-normative responses (Supporting Information Table 2). The first and second author coded pre- and post-instruction data for 15 students (39% of the data). Inter-rater reliability calculated using Cohen's Kappa ($\kappa = 0.938$, $p < 0.001$). For open-ended questions, codes were aligned to a four level scoring guide: (0) limited understanding demonstrate by incorrect response, (1) partial understanding demonstrated by a combination of scientific and non-normative response, (2) inclusion of some but not all aspects of the scientific response, and (3) inclusion of all aspects of the scientific response (Supporting Information Table 2). For example, question 8a asks students to explain the difference in temperature along the Atlantic coast at three locations in winter using understanding of light from the Sun. A score of 3 would include a description of increased number of daylight hours AND intensity of light ("gets more light") at southern latitudes compared to northern latitudes; a score of 2 would include a description of length of day or intensity but not make explicit connections to the temperatures and latitudes; a score of 1 would include a description of the increased number of daylight hours or intensity of light as well as an incorrect explanation for the phenomenon; and a score of 0 would include only an incorrect explanation. Dichotomous multiple-choice item responses were assigned a score of 3 for the accurate choice and 0 for the non-normative distracters. A related-samples *t*-test was used to compare pre to post scores based on the four-level scoring guide.

Internal reliability of the instrument was measured using Cronbach's alpha; though the pre-assessment result was 0.63, the post-instruction Cronbach's alpha 0.75, above the standard "rule of thumb" minimum (Brace, Kemp, & Snelgar, 2009). The point-biserial (PB) values for each item showed the expected pattern of increasing point-biserial with increasing score. Minimum PB values are typically expected to be >0.2 (Jackson, Draugh, Slack, Zachry, & D'Agostino, 2002; Liu, 2010). The PB values on our assessment ranged from 0.4 to 0.7, except for item 6a, with a value of 0.1. We performed a principal components analysis using *SPSS*. This revealed that all but one item strongly positively loaded onto one factor. After removing that item (6a) from our model, all the other items loaded onto the first component with eigenvalues from 0.4 to 0.7 suggesting that the items were coherently measuring one construct (explanation for global seasonal change).

We used a Rasch analysis as our interpretational model, allowing us to compare results from our assessment to the hypothetical construct map. A Rasch model is "a mathematical model that describes the relationship between the probability of correctly answering an item and the difference between the person's ability and the item's difficulty" (Jackson et al., 2002, p. 234). The model allows for persons to be ordered according to their ability as well as items according to their difficulty by computing expected response probabilities (Bond & Fox, 2007). The Rasch analysis was performed using a partial credit model in *ConstructMap* (Kennedy, Wilson, Draney, & Tutunciyan, 2007). We stacked the pre-test and post-test scores, treating each as individual persons in the model. This brought the total number of respondents in the model to 76. The item separation reliability, how well subjects are able to separate the items in the assessment, was 0.89, an acceptable value. The person separation reliability, the extent to which the person-abilities were distributed across the instrument, was 0.68, a moderate value due to the small number of items on the instrument.

Construct validity of the instrument was examined using the item infit and outfit statistics, which indicate variation between the observations and model-predicted response patterns (Bond & Fox, 2007). The infit statistic "gives relatively more weight to the performances of persons closer to the item value" while the outfit statistic is more sensitive to "the influence of outlying scores" (Bond & Fox, 2007, p. 57). The infit and outfit mean square values were between 0.8 and 1.3 suggesting an adequate fit the Rasch model and unidimensionality in our instrument; acceptable ranges are generally between 0.7 and 1.3 (Bond & Fox, 2007; Liu, 2010). We also examined whether participant responses were consistent with the expectations of the Rasch model. The mean infit mean square over all respondents was 0.99 ($SD = 0.4$), and the corresponding mean outfit was 1.00 ($SD = 0.47$). A low infit indicates less randomness to their responses; a high infit indicates more randomness. Only 14% of students had infit and outfit mean squares above 1.3 indicating few students had more randomness than expected. Some variation in responses is expected and is less important than having all items behaving properly.

Our use of Rasch modeling was limited by the sample size. Minimum sample size is an issue of the *SE* of measures for the person and item parameter estimates (Liu, 2010). Liu (2010) reports that, for a 5-logit difference in range of scores, the relationship between *SE* and sample size is $N = 6/SE^2$. The *SE* estimated for our sample, 0.28, suggests that our results may be informative as exploratory work (Liu, 2010). Linacre (1994) suggests that samples as small as $N = 30$ may be sufficient to obtain a reasonable level of measurement stability.

Revision of the Construct Map

One of the ways to interpret the Rasch model analysis is through the Wright Map output, which allows for a comparison between the original construct map and students' responses to the items. A Wright Map visually displays the relative difficulties of items, increasing as you go up the right-hand side of the graph (see Figure 1). The item's location on the map indicates the *item difficulty.* On the left-hand side of the map are the locations of respondents in relation to the item difficulty. A person with a location at the same level as an item has a 50% probability of responding correctly to that item (assuming a dichotomous item). That person will have a smaller probability of correctly answering questions higher up on the map and a greater probability of correctly answering items below their location on the map. The Wright Map was used to refine our hypothetical season construct map. The relative difficulties of items were used to create a potential order of concepts. We then looked for ways to create meaningful groupings of items, as items of similar difficulty would indicate a potential level on the construct map. This analysis resulted in an initial revision of the hypothetical construct map.

Rasch models indicate the students' probability of responding correctly or incorrectly for the items, not their overall understanding in relation to the target construct. Thus, we continued our process of revising the construct map by comparing the levels implied by the Rasch model to students' individual responses. We first treated the levels as a scale in which students at higher levels also met the criteria for lower levels. This analysis revealed that the initial construct map, based only on item grouping in the Wright Map, is not fully supported by how students actually responded to the items. Rather, there appear to be variations in the pathways towards the scientific understanding. For example, we reconsidered *daily celestial motion*'s role on the construct map as analysis of students' individual explanations did not suggest this to be a coherent level on the map.

As part of presenting and interpreting the construct map, we also analyzed the relationship between student progress and the instruction used in this study. This was done to begin the process of communicating potential instructional sequences that may support progress in this domain, as has been recommended for LP-research (NRC, 2012). We began by looking at patterns of where students began, before instruction, and their knowledge of the seasons, after instruction. We compared the nature of the improvement as well as the limitations in their improvement to the support they received during instruction. We considered the conceptual supports provided and the methods used to provide that instruction in interpreting patterns in student progress along the construct map. This led us to suggest some potential relationships between progress along the construct map, students' prior knowledge of astronomy, and the nature of instruction.

Findings

Construct Map Development Using the Wright Map and Student Responses

The Wright Map was analyzed to compare student proficiencies against item difficulty with the overall goal of establishing empirical support for levels in the seasons construct map. Each "X" represents one student (see Figure 1). Initially, our analysis of the item difficulty in the Wright

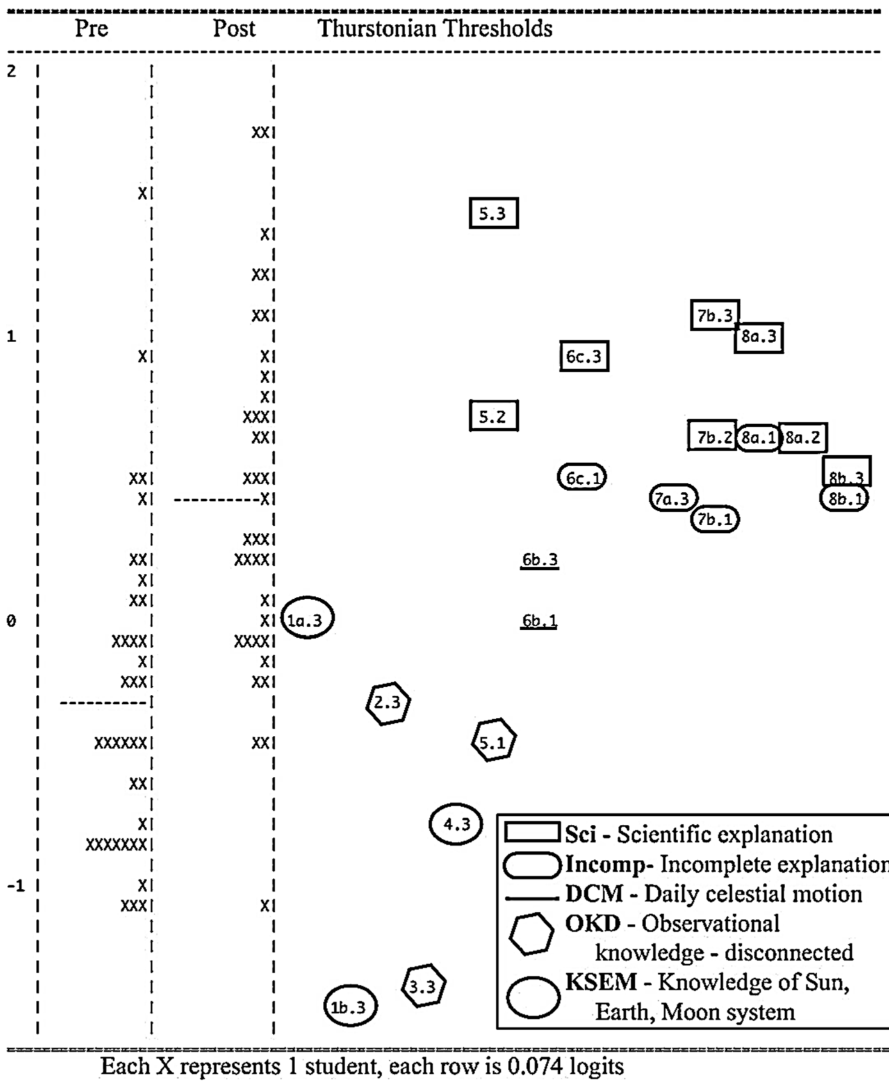

Figure 1. The Wright map shows both pre- and post-assessment results using *ConstructMap* in the left and center columns. The right-hand column shows the item levels from most difficult to least difficult, top to bottom.

Map suggested six potential levels of increasing sophistication for the construct map. Concepts within each level were based on items of similar difficulties, from most difficult to least difficult.

After applying individual students' responses to the initial six levels, we further revised the levels into the final version of the seasons construct map (Table 2). Using the construct map as a tool for measuring students' level of explanation, we determined that 29 students improved, six stayed at the same level, and three regressed. We also examined student improvement through an analysis of their overall score on the assessment by summing their scores on individual items, using the scoring guide (total possible score = 39). Prior to instruction, students had an average score of 13.3 ($SD = 6.3$). After instruction, students had an average score of 21.9 ($SD = 7.2$); this was a significant improvement ($t(37) = 8.103, p < 0.0001$) with an effect size of $r = 0.54$.

Table 2
Construct map for the seasons increasing in sophistication towards the top of the table

Levels	Assessment Items[a]	Pre Level[b] ($N = 38$)	Post Level[b] ($N = 38$)
Level 5—Scientific Explanation of the Seasons (Sci)—Seasonal change in the temperature is caused by both a change in the Sun's altitude and the length of day; these are explained by the Earth's tilt as the Earth orbits the Sun. On the same day, locations at different latitudes will receive different amounts of sunlight due to the spherical nature of the Earth and the tilt of the Earth's axis with respect to the Sun. No other inaccurate explanations or descriptions are included in responses. *Daily celestial motion*: Students at this level can also use the scientific description of the Earth's rotation to explain the Sun's daily apparent motion across the sky	Reaches score indicated for four out of five items: 5: 2 or 3 6c: 3 7b: 2 or 3 8a: 2 or 3 8b: 3	2 (1)	7 (6)
Level 4—Incomplete Explanation for the Seasons (Incomp)—The length of day or altitude of the Sun, and the tilt of the Earth, are involved in explaining seasonal temperature change on the Earth and students recognizes these items as explanatory factors relating to the changes in regional temperature but retain other inaccuracies and/or did not provide complete explanations	Reaches score indicated for four out of five items: 6c: 1 or higher 7a: 3 7b: 1 or higher 8a: 1 or higher 8b: 1 or higher	0 (0)	6 (1)
Level 3—OKD + KSEM—Knowledge of both observational features of the seasons and fundamental knowledge of the solar system related to learning about the seasons	Reaches scores indicated for OKD and KSEM below	3 (3)	9 (5)
Level 2A—Observational Knowledge—Disconnected from Scientific (OKD)—The length of day and altitude of the Sun are important to explaining the seasons but are not necessarily integrated with descriptions of the Sun's path and the tilt of the Earth. [At the same level as 2B]	Reaches score indicated for all items: 2: 3 3: 3 5: 1 or higher	4 (1)	4 (2)
Level 2B—Knowledge of the Sun–Earth–Moon system (KSEM)—Knowledge of the Earth's orbit and the scale of the Sun–Moon–Earth system. [At the same level as 2A]	Reaches score indicated for both items: 1a: 3 1b: 3 4: 3	7 (2)	8 (5)
Level 1—Naïve Knowledge of Astronomy (Naïve)—Limited knowledge of astronomical topics assessed in this instrument	Non-normative responses to all or most items	22 (6)	4 (1)

[a]Scores for all assessment items can be found in the coding guide (Supporting Information Table 2).
[b]Parenthetical number indicates number of students at that level who accurately used the Earth's rotation to explain the Sun's daily motion.

In the discussion below, we begin with a general description of students' knowledge of the seasons at each level and then discuss how students in this study moved within each level, before and after instruction (see Table 2).

Level 1: Naïve Knowledge of Astronomy. Students at the naive level held a non-normative understanding of foundational topics related to the seasons, such as not understanding the length of the Earth's orbit, the relative size of the Sun and Earth, or the use of the Earth's rotation to explain the Sun's daily apparent motion. Prior to instruction, the majority of students (58%) were categorized into the naïve level. After instruction, nearly all students (89%) had moved up to a level above this on the construct map. In addition to holding intuitive ideas about the nature of these foundational astronomy concepts, students at the naïve level were likely to hold alternative views of the reason for the seasons; we found that students who gave non-normative responses to the items at this level also gave non-normative responses to those items assessing higher levels of understanding of the seasons. For example, when asked to explain why the Sun appears higher in summer than winter (item 6c), one student wrote: "The Sun is farther away in the winter and closer in the summer."

Level 2A: Knowledge of the Sun–Earth–Moon System. Students at this level (KSEM) understood that the Earth orbits the Sun once a year in a relatively circular shape and had a sense of the relative size and distance between the Sun, Earth, and Moon. This is a step towards understanding more complex relationships in the seasons explanation. The number of students who achieved *at least* this level improved from 12 (32%), before instruction, to 30 (79%), after instruction. Our Wright Map analysis indicates that knowledge of the shape of the Earth's orbit was at the upper end of difficulty of these items. Prior to instruction, 13 students (34%) accurately indicated the shape of the Earth's orbit (as a circle centered on the Sun as opposed to a highly elliptical ellipse or off-centered circle) while 27 students (71%) were accurate after instruction. Students often believe that the seasons are caused by the Earth getting closer and farther from the Sun (e.g., Baxter, 1989; Sharp, 1996). Students who understand that the shape of the Earth's orbit is *nearly* circular may then be ready to accept the scientific perspective over the non-normative change-in-distance explanation.

Level 2B: Observational Knowledge-Disconnected From Seasons Explanation. Students at the observational knowledge-disconnected (OKD) level understood that the length of day and altitude of the Sun are part of the explanation for the seasons. What distinguishes this level from more sophisticated levels is that they do not accurately use this information to explain changes in temperature patterns across the seasons or across the globe. Students were aware that a relationship exists between the Earth's tilted rotational axis and the change in the Sun's altitude and day length but did not accurately connect these and used other non-normative explanations for the seasons. For example, a student at Level 2B could indicate that the days are shorter and the Sun is lower when the northern hemisphere is tilted away from the Sun. But they may have difficulty expressing how this explains differences in average temperature using changes to day length or solar intensity, such as: "In the summer, more sunlight is given off because the Earth is facing the Sun. The more sunlight, the hotter it gets so the water gets warmer" (ID #28, post). Students at this level accommodated new concepts that conform to the scientific norm, concepts emphasized through schooling, but without completely altering their naïve explanations for the seasons. Their recognition of the association of the word "tilt" with changes in the Sun's altitude and length of day may only indicate memorization of the relationship, and not an ability to apply the spatial geometry or the relationship to energy and temperature.

Prior to instruction, nine students (24%) responded accurately to the OKD items; this increased to 26 students (68%) at this or a higher level after instruction. These results suggest that students were aware of a difference in the seasons between the hemispheres and may be more aware of differences in altitude between the seasons than the length of day. But they may not necessarily connect those observational differences with changes in temperature, which would limit their responses to the more difficult items.

Level 3: Combined OKD and KSEM. Students at this level understood both KSEM and OKD level concepts. Based on the conceptual logic, students' responses to the items, and the similar difficulty of the items, we determined that both KSEM and OKD represent alternative paths rather than elements of the same level. Thus, students may understand either these fundamental astronomy concepts (KSEM) or have some observational knowledge of the seasons (OKD), without either being a prerequisite level of understanding for the other. At this level, students did not use these concepts to develop the scientific explanation but this may be an important step towards the more sophisticated explanations. Prior to instruction, only three (8%) students were at this level (two students were at a higher level); after instruction, this increased to nine students (24%) at this level and 13 (34%) at higher levels.

Level 4: Incomplete Explanations for the Seasons. Students who reached the *incomplete explanations for the seasons* (incomp) level were able to apply explanatory factors relating to the changes in regional temperature but often provided incomplete explanations and may have retained other inaccuracies. To reach this level of sophistication, students accurately related temperatures across latitudes in the same hemisphere with the length of day or intensity of sunlight. They were able to compare the amount of sunlight across the northern and southern hemisphere and how this will change across the seasons. They were likely to use intensity of light or the change in length of day to explain why temperature in a given location changes across the seasons. However, they often included incomplete answers to some questions, thus not indicating they understood the connections between the Earth's tilt and changes in the Sun's path in a given location or between locations. For example, students at this level often used the Earth's tilt to explain why the Sun is higher in summer, but were not specific in their reasoning (item 6c): "It's like this because of the way the Earth is tilted during the year" (ID#25, post). Similarly, their answers often did not fully connect changes in sunlight and temperature. For example, a student stated that the reason why the average winter temperatures are different than summer temperatures along the Atlantic coast is because (item 8b): "The temperatures are different because the Earth is tilted away from the Sun" (ID#11, post). Though correct, the student has not explained how the tilt is related to this difference in temperature. Similarly, when asked to explain why average water temperatures are cooler in the North Atlantic coast compared to the South Atlantic coast, another student at this level wrote: "Because it is closer to the equator and the equator has summer all year around because of the Earth's tilt" (ID#2, post).

These students gave complete and scientific responses to many items. Their responses indicated that they had assimilated aspects of the scientific model but could not fully articulate the connections between the Earth-based observations and the space-based perspective on what is causing seasonal temperature changes. Prior to instruction, no student was at this level. After instruction, six students (16%) had reached this level, which also includes correctly responding to items at Level 3.

Level 5: Scientific Explanation of the Seasons. Students who reach the upper level of the seasons construct map recognized that seasonal change in the temperature is caused by changes in the Sun's altitude and the length of day. For example, when asked to compare the differences in average temperatures in a location in North America, a student at this level wrote: "The Sun is higher in the sky in summer and it has more time to warm stuff and the light is more concentrated" (ID#17, post). Students were also able to explain how amount of sunlight relates to temperature along different latitudes on Earth; when asked to explain the difference in temperature along the Atlantic coast at three locations in winter (item 8a), a student wrote: "[The South Atlantic] Coast is warmer because it is closer to the equator and as you go up it gets colder because there is less daylight to warm the water because of the tilt of the Earth is away from the Sun" (ID#15, post). Students were able to explain these changes using the Earth's tilt as the Earth orbits the Sun. For example, a student explained why the length of day will be longer in December compared to June in the southern hemisphere by writing (item #7b): "There will be more hours of daylight because the Earth's axis always points at Polaris, and in December, the Earth is tilted so the southern hemisphere is getting more light" (ID#31, post). Prior to instruction, two students were categorized into this level though one did not use the Earth's rotation to explain the Sun's daily apparent motion, limiting the accuracy of their overall explanation. After instruction, this increased to seven students (18%) with all but one accurately using the Earth's rotation to explain the Sun's daily motion.

The Role of Daily Celestial Motion in the Seasons Construct Map

Our original hypothesis was that explaining the Sun's daily apparent motion would be a clear step towards achieving higher levels of the seasons construct map (Plummer, 2012). The Wright map analysis appeared to support this assumption: items measuring the Sun's daily celestial motion were less difficult than concepts which begin to integrate the tilt model with observable changes to the Sun's path. Successfully and accurately integrating these observational concepts within an explanatory model would seem to require a scientific-level understanding of the Earth's daily rotational motion combined with an ability to shift frames-of-reference to understand what we experience from the Earth's surface. This may be important to consider as prior research has shown that many children and adults do not use the Earth's rotation to explain the Sun's apparent rising and setting motion (Plummer, Zahm, & Rice, 2010, 2014). On the assessment, students were asked to first indicate how the Sun's location and the location of a shadow would change from morning to afternoon and then to write an explanation. A typical scientific response was: "Because the Earth is turning which causes the Sun to look like its moving from one side to another" (ID#7, pre). A typical non-normative response was: "Because the Earth is orbiting around the Sun causing the shadow to move" (ID#15, pre). Other non-normative responses focused on reiterating how the Sun appears to move or, after instruction, some students referred to the Earth's tilt as causing the change in the shadow's location over the course of 1 day.

While other studies also found that the scientific explanation for the seasons is more difficult than explaining the day/night cycle (Briggs, Alonzo, Schwab, & Wilson, 2006; Sadler, 1998), our findings do not suggest that this is definitive level in the construct map. Analysis of individual students' level categorization in the seasons construct map revealed that interpreting the students' understanding of the Sun's daily celestial motion is not as simple as anticipated. Both before and after instruction, use of the Earth's rotation appeared distributed across a portion of students at all levels (see Table 2). Notably, only one of the students (out of six) who reached the *incomplete* level and six of the students (out of seven) reaching the scientific level used the Earth's rotation to explain daily motion after instruction. While these numbers are small, they may point to the possibility that limited understanding of how the Earth's rotation causes the Sun to appear to move may have inhibited some of the Level 4 (*Incomplete*) students from reaching Level 5 (*Scientific*).

Discussion

This study takes the first steps in providing empirical evidence for a construct map describing levels of progress in students' explanations for the seasons. The lower levels of the construct map describe students with non-normative beliefs about seasons-related observations, the explanations for those patterns of observations, as well as prerequisite concepts for understanding the seasons. Progress up the construct map can be generally described as (1) developing a foundation of important prerequisite concepts of astronomy, then (2) making sense of how patterns of Earth-based observations relate to temperature change, and finally (3) towards constructing explanations for why the observable patterns of change occur. Our proposed construct map is consistent with the NGSS and *Framework for K-12 Science Education* (NGSS Lead States, 2013; NRC, 2012) but includes a more nuanced discussion of critical connections that students need to make in order to develop a sophisticated understanding of the seasons. The *Framework* suggests a progression of goals: seasonal patterns of the Sun rising and setting by the end of 2nd grade, explaining the changes in the Sun's apparent motion by the end of 5th grade, then explaining the seasons using the Earth's tilt relative to its orbit by the end of 8th grade. Our construct map makes the distinction that global patterns of change in the Sun's path must also be connected to patterns of temperature change prior to explaining this with the Earth's motion in space. Without these connections in place, students' explanations for the seasons will lack the depth of understanding needed to flexibly use the seasons' explanation in new situations. Below, we will discuss three major areas our findings contribute to the research literature: sequencing of instruction using the construct map, attending to issues with spatial reasoning in celestial motion, and methods of analyzing data towards revising construct map levels.

The Role of Instruction in Progress Along the Seasons Construct Map

Our development of a seasons construct map was (a) dependent on our interpretation, as the researchers, of what it means to construct a scientific explanation for the target phenomena and (b) influenced by the students' curricular experience. These elements should be analyzed together in LP development: as learning is dependent on students' opportunities to build their knowledge of the domain, instruction that guides the development of a construct map should be built around the LP hypothesis (Krajcik et al., 2012; Shea & Duncan, 2013; Songer, Kelsey, & Gotwals, 2009). This includes designing instruction to help students make connections between their observations of the world and the scientific model, as dictated by knowledge of the domain, but also using what is currently known about the challenges students have in learning in that domain. The instruction was designed to *review* elementary-level, prerequisite concepts, to *focus* on engaging students in the patterns of change that directly influence seasonal temperature changes, and to *make connections* with the space-based perspective that explains the Earth-based patterns of change across the seasons. Representations and phenomena were carefully chosen to engage students in making the connection between how daily and yearly patterns of the Sun's path across the sky relates to the change in temperature. Thus, the planned instructional focus was on moving students through intermediate to scientific levels of the progression.

Our instructional design presumed we would be building on a conceptual foundation of astronomy achieved by students in elementary school; similar assumptions have been made by previous researchers investigating the impact of instruction on the reason for the seasons (Tsai & Chang, 2005) and was consistent with the hypothetical seasons LPs proposed by Willard and Roseman (2007) and Sneider et al. (2011). However, prior to instruction, most students were at the lowest level of the construct map. Their limited understanding of the observational aspect of the seasons was consistent with previous studies. For example, both children and adults often believe that the Sun always passes directly overhead (e.g., Lightman & Sadler, 1993). Prior research with elementary and middle school students (Plummer, 2009), as well as adults (Mant & Summers, 1993; Plummer et al., 2010), suggests that learners are often unaware of changes to the Sun's apparent path between summer and winter.

Developing the Foundation. We considered how instruction may have supported students' attainment of key foundational concepts on the seasons construct map. First, we considered how students learned to use the Earth's rotation to explain the Sun's daily apparent motion. Relating the Sun's daily apparent motion to the Earth's rotation remained a challenge to many students in the study. Students initially modeled how day/night is caused by the Earth's rotation. However, this did not fully explore how the rotation *causes* the Sun's apparent path across the sky. Recent research suggests that children can successfully learn to explain the Sun's daily motion by first learning to mimic the Sun's apparent motion with gestures and then connect the Earth's rotation to the Sun's apparent motion kinesthetically and with physical models (Plummer et al., 2011, 2014). Our findings lead us to recommend that it may be important to engage students in more explicit instruction connecting the Sun's daily apparent motion to the Earth's rotation prior to using the tilt-model to explain seasonal changes in the Sun's path, as the students' limited ability with explaining the Sun's daily motion may have limited them from achieving the more sophisticated explanation for the seasons.

We reviewed prior research on how students learn to explain the seasons to see if other researchers had examined this connection; only two studies explicitly addressed the Sun's daily celestial motion. Slater, Morrow, and Slater (2008) report significant improvement in students' use of rotation to explain observations as part of a study of students learning about the seasons. They suggested that this is prerequisite knowledge for learning the seasons, but did not explain how this relates to students' improvement in explaining the seasons in their study. Parker and Heywood (1998) suggested that understanding the seasons "demands differentiation of the Earth's orbit and spin with respect to the sun's position as well as knowledge of the Earth's axis in relation to the sun" (p. 509). However, they did not explore how this might have impacted the students' understanding of the seasons after instruction.

Students also learned about the shape of the Earth's orbit in order to address the common alternative conception that the seasons are caused by large changes in our distance from the Sun. As seen in previous studies (e.g., Kikas, 1998), the students originally believed that the shape of the Earth's orbit is an elongated ellipse. Students improved their understanding of the shape of the Earth's orbit by selecting a more circular description of its orbit. While an important step, this is not sufficient to also adopt the scientific explanation, which requires far more sophisticated spatial reasoning to connect observed patterns with space-based explanations.

Relating Earth-Based Observational Patterns to Temperature Change. Explaining how observable changes in the Sun's local and global patterns impacts local and global seasonal temperature changes requires students to (a) learn to describe the nature of these patterns of change and (b) accurately apply the relationship between solar intensity and temperature change. Instruction was designed to support students in learning this aspect of the seasons through several days of analyzing data and working with physical models. Instruction was designed to support students in making connections by looking for correlations in global temperature and the amount of sunlight received. They used physical modeling activities to examine how the Sun's path changes over the course of the year, using evidence gathered through video of the Sun's changing path. To make the connection between the change in the Sun's path and the change in temperature required students to explore how the Sun's altitude changes the intensity of light and that this change in energy will impact local temperatures. Students engaged in a physical model demonstrating how angle of incident affects intensity to understand this scientific principle.

Many students demonstrated relatively sophisticated connections in these areas though other students did not accurately apply these concepts across all contexts in the post-instruction assessment, thus limiting the their progress along the construct map. This may suggest that some students need additional opportunities to apply the patterns they observed in the seasons' data towards explaining specific temperature patterns on the Earth's surface. Students' everyday, unguided experiences are unlikely to result in a scientific description of the seasonal pattern of the Sun's apparent motion (Plummer, 2009; Plummer et al., 2010). Perhaps personal observations could provide a framework on which to build an understanding of a broader range of seasonal and global patterns of the Sun's apparent motion and daily temperature change. Trumper (2006) engaged preservice teachers in explorations of the Sun's altitude, length of day, and temperature through 3-weeks of the students' own personal data collection. Instruction should include also experiences that support students' ability to visualize the change in the Sun's path over the seasons, such as analyzing video and making a physical representation of this path. This may help students move from lower levels on the construct map towards the intermediate level in which they are able to make connections between observational patterns of sunlight and temperature.

Next, students need opportunities to understand the connection between patterns of day length and solar altitude with seasonal temperature change in ways that help them understand the global patterns. As with our instruction, this should including engaging students with data on day length and altitude changes over the year to compare to similar data on temperature changes and opportunities to analyze and discuss correlations in these patterns. Then, to make sense of how this explains seasonal temperature change, we introduced students to the scientific principles that relate changes in solar intensity and amount of time sunlight is gathered to how this impacts temperature. To do so, we supported students in learning how the change in the Sun's path affects the amount of energy absorbed over time and relate this to temperature. These connections are a critical step in explaining the seasons that should not be overlooked in instruction or assessment design and should be addressed before attempting to explain the seasons using the Earth's tilt. Though some students, especially by middle school, may be already aware of the *idea* that the Earth's tilt is the cause of the seasons, their use of this as an explanation will be limited if they do not understand how the change in the Sun's path relates to temperature change.

Connecting Earth-Based and Space-Based Perspectives. The final step in achieving a scientific explanation for the seasons is explaining how and why the Earth's rotation, tilt, and orbit can be used to explain the *pattern of change* in these Earth-based experiences of the Sun's altitude and length of day. Instruction was designed to support students in the complex spatial reasoning required to make these connections using physical modeling of how the amount of sunlight changes as the tilted-Earth model orbited the Sun. Each student held their own model Earth during the lesson allowing them to use this simulation to explore changes observed on the Earth's surface. However, most students did not reach a consistent, scientific use of the tilt-model explanation for patterns of change in sunlight and temperature. In reviewing the instructional design, we note that the time allotted for students to examine the connection between the Earth-based observational patterns and the tilt-model may have been too limited, including few opportunities to *apply* the model to the observations. We suggest that instruction allow for additional opportunities for students to discuss and analyze the connections between the observational patterns and the space-based orbit and tilt model of the Earth's motion.

Importance of the Instructional Context in Our Construct Map Development. Had our analysis not focused on student learning in the context of this particular instructional sequence, we assume different outcomes would have been observed, potentially suggesting other descriptions of the levels or ordering of levels. For example, had the instruction not supported the intermediate explanation that connects the seasonal change in the Sun's path to the global temperatures, it is likely that the evidence would not have shown how students begin to take up those intermediate elements of the scientific explanation. On the other hand, had instruction placed a greater emphasis on supporting students in using the Earth's rotation to explain changes in the Sun's path, we may have observed more robust evidence for how this element is a stepping-stone towards progress up the construct map. Thus, analysis of the role of instruction in interpreting student outcomes was important to our consideration of validity evidence for our seasons construct map but also implies that research in other contexts may find variations on potential levels of progress in the construct map.

Explaining the seasons is a complex process where students build increasingly sophisticated explanations that begin with developing descriptive knowledge of seasonal changes in the Sun's path and global temperatures, then constructing explanations that make connections between these Earth-based observational patterns, and finally developing more complex explanations using the Earth's place in the Solar System. Our instruction was based on this hypothesized sequence of explanation building; it is this type of instructional sequencing towards supporting different levels of explanations that will be needed to help students make progress in celestial motion construct maps. Similar instructional sequencing may help other researchers developing LPs, especially in the earth sciences where students first need to construct descriptive explanations for patterns in their observations before developing more sophisticated model-based explanations for the observed phenomena.

Spatial Reasoning in Explaining the Seasons

Instruction that supports progress along this construct map must also support the spatially complex connection between the Earth's motion in space and the change in the Sun's apparent path across the sky. Our instruction began this process through psychomotor modeling experiences that challenged students to observe how their physical model of the Earth and Sun could account for changes in solar intensity from points on the Earth's surface. However, it is at this step that having prior knowledge of how the Earth's rotation explains the Sun's daily motion becomes critical. Without that knowledge, some students may not have been able to make sense of the full explanation for the seasons and thus limiting the number of students who reached the upper anchor of the construct map. Further, the challenges students had in integrating their emerging understanding of Earth-based observable patterns with space-based perspectives may be due to the challenges learners have with spatially complex concepts (NRC, 2006). Students with lower spatial abilities may have had a more difficult time learning these explanations (Black, 2005; Wilhelm, 2009). Moving between the Earth-based and space-based frames of reference involves the use of spatial visualization, the ability to imagine objects from different perspectives and visualize how motions change the appearance of objects (Mathewson, 1999; Plummer et al., 2014). Students need support in the type of complex spatial visualization used in constructing celestial motion explanations (Hegarty, 2010; Parker & Heywood, 1998; Plummer et al., 2014). During instruction, physical models of the Sun–Earth system may have helped to support the difficult cognitive load while students attempted to move between a visualization of the Sun's apparent motion and the motions of the Earth in relation to the Sun in space (Wilson, 2002). However, given the limited improvement, many students needed additional support in developing and using the tilt-based explanation for the seasons. More research is needed that looks at spatial reasoning here and across other science domains, as instruction will need to support this if students are to fluently use scientific explanations to account for their observations (NRC, 2006).

Revising Construct Map Levels

We also recommend that researchers pay close attention to how they use evidence from assessments to develop and revise construct maps. We were guided in our analysis by the use of the *construct modeling* approach, which led us to use a Rasch analysis to test our hypothetical construct map (Wilson, 2005; Brown & Wilson, 2011). However, because this gave us a broad overview of the relative difficulty of concepts for all students, we were hesitant to accept these results as the construct map levels at face value. Therefore, we took a closer look at pattern of responses for individual students. This led us to further revise our construct map to better fit the nature of student responses to the descriptions of the levels.

The seasons construct map has limited generalizability due to the small sample size and single context in which the instruction was implemented. The small sample size also limits our ability to examine differences in how students used change in daylight and the Sun's altitude in their explanations. Both changes contribute the reason for temperature change; however, due to the small number of subjects and items, we grouped these two aspects of their explanations together. Additional research is needed to ascertain whether different patterns of improvement would be observed if students engaged in a different instructional sequence, or if they began with more sophisticated understandings of foundational astronomy concepts. We hypothesize that understanding the relationship between the Sun's apparent path and the Earth's rotation may provide a cognitive advantage to students prior to learning concepts relating to the seasons. Students who have a mastery of the daily celestial motion concepts may result in different pathways—potentially ones that yield more students reaching the construct map's upper level.

The Hypothetical Celestial Motion Learning Progression

The move from a hypothetical LP to one that is empirically validated "occurs in multiple iterative cycles rather than during a one-time empirical validation study" (Shea & Duncan, 2013, p. 9). Thus, rather than claim that this is the definitive description of a construct map for the seasons, we have provided a stepping-off point for further in-depth analysis of the role of instruction in students learning to explain the seasons as well as contributing to our larger celestial motion LP. Like the seasons, progress up other construct maps, such as for diurnal motion and lunar phases, is also a process of moving from an Earth-based perspective towards more sophisticated *spatial reasoning* that uses frames-of-reference explanations and accounts for movement on different time scales (Plummer, 2012, 2014; Plummer et al., 2011, 2014). This approach is similar to Briggs and Alonzo's (2012) "Earth in the Solar System" LP. Levels in their LP describe movement from the observational patterns of celestial objects, to the motion of objects in space, to coordinating apparent and actual celestial motion across a range of celestial motion phenomena. Our work also adds to other literature on celestial motion that suggests instruction should explicitly support students in learning to describe the Earth-based perspective and space-based perspectives, and then directly support students in making the connection by showing how motion and orientations in space can be used to explain Earth-based observations (Heywood et al., 2013; Plummer, 2012, 2014; Plummer et al., 2011, 2014). These studies also demonstrate how challenging this type of spatial reasoning is for students as many still struggled to make appropriate connections between perspectives, even after instruction. Attending to these challenges in instruction will be important to achieve the goals of the *NGSS*.

This method of developing LPs by first investigating the component construct maps may be useful to other researchers (Plummer, 2012, 2014; Wilson, 2009). We have taken an incremental approach by investigating a subset of astronomical phenomena with students at a specific grade band. In previous studies, the first author and colleagues investigated how elementary students explain the apparent daily motion of the Sun, Moon, and stars as well as the monthly cycle of lunar phases, leading to descriptions of construct maps for these phenomena (Plummer, 2012, 2014; Plummer & Krajcik, 2010; Plummer et al., 2011, 2014). Together with these previous studies, we are putting together the pieces of a larger puzzle—the celestial motion LP. A next step in building the celestial motion LP may be to further investigate and categorize the relationships between the various learning progression constructs (Shea & Duncan, 2013). Additional research is also needed that explores the ways students' understanding of the Sun's energy and temperature change may allow us to link the seasons construct map to an LP for energy (e.g., Jin & Anderson, 2012; Lee & Liu, 2009; Neumann et al., 2013) or how students use analogical reasoning when using physical models to explain the seasons (Rivet & Kastens, 2012). Such research is important because it will contribute to our understanding of how to supports students in developing deep knowledge of the integration of content and practices in ways that allow them to access information effectively and solve complex problems (Krajcik et al., 2012; NRC, 2012).

Note

[1]Both Sneider et al. (2011) and Willard and Roseman (2007) refer to their work as describing *learning progressions* for the seasons. To improve clarity, we have chosen to use the term *construct map* for our work on the seasons and thus have used this same term to refer to their LPs in this manuscript.

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