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Designing Technology-Enhanced Science Inquiry Instruction to Scaffold
Student Choice Through Explanation and Reflection

by

Jennifer King Chen

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Education

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Marcia F. Linn, Chair
Professor Michelle H. Wilkerson
Professor Tania Lombrozo

Fall 2016

Designing Technology-Enhanced Science Inquiry Instruction to Scaffold
Student Choice Through Explanation and Reflection

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Abstract

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Student Choice Through Explanation and Reflection

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Jennifer King Chen

Doctor of Philosophy in Education

University of California, Berkeley

Professor Marcia F. Linn, Chair

Science education reform efforts stress the importance of engaging students in authentic inquiry practices to promote the development of self-sufficient and independent learning skills. Independent learners are able to accurately evaluate their own understanding and make informed decisions that can productively advance their learning. The ability to assess one's own thinking to identify and address weaknesses or gaps in understanding is especially critical for successful learning, during which new information must be integrated with existing prior ideas, experiences and knowledge. The design-based research discussed in this dissertation investigates the impact of an inquiry instructional model that utilizes explanation and reflection as metacognitive learning scaffolds to promote more reflective and self-directed independent learning through choice-making. A choice-based inquiry instructional model allows for more flexible instruction by offering customizable, student-determined inquiry paths that can adapt to and provide support for learners with different starting levels of prior knowledge and experiences.

The dissertation consists of two separate but intersecting components. The first section of the document details my research work on the iterative design, development, pilot testing and refinement of *Investigating Seasons*, a web-based online inquiry curriculum unit for high school students. *Seasons* incorporates multiple dynamic visualizations and extensive instructional scaffolding to support students in collecting, evaluating, making sense of and integrating their diverse ideas for explaining seasonal temperature changes. Dynamic visualizations embedded within the curriculum function as critical learning opportunities for students to encounter important normative ideas and test their pre-existing beliefs. Supporting instructional scaffolds promoting explanation and reflection encourage students to monitor, evaluate and refine their changing repertoire of ideas as they proceed through the unit. Carefully designed curricular materials can help to guide students in reconciling their ideas from multiple sources towards formulating a more coherent and normative explanation for seasons. In addition, the use of

instructional technologies such as dynamic visualizations (i.e., student-driven scientific models designed for learning) can provide students with interactive opportunities for conducting “hands-on” inquiry investigations that encourage the reflection upon and revision of conceptual understandings.

The second part of the dissertation presents the collective findings from two classroom comparison studies (choice versus no-choice) that I conducted to investigate the effect of a learner-directed, choice-guided model of inquiry on students’ conceptual learning and understanding about the seasons. Both studies were implemented using the iteratively refined *Investigating Seasons* curriculum unit and visualizations. Study results indicate that the two conditions benefited equally from instruction, regardless of condition. However, a consistent trend was seen of students in the choice group exhibiting possibly greater learning benefits across a number of different outcome measures (this trend was not observed for the no-choice students). These study findings, taken together with the known motivational and affective advantages of choice already documented in the literature, provide a promising indication of the instructional value of choice for supporting students in pursuing reflective, independent and unique inquiry learning trajectories.

Dedication

We don't accomplish anything in this world alone... and whatever happens is the result of the whole tapestry of one's life and all the weavings of individual threads from one to another that creates something.

– Sandra Day O'Connor

To all of the wonderful teachers who were kindly nurturing and valued positive influences on my life, and to three especially inspiring teachers in particular:

My dad, my first and most dedicated teacher, who impressed upon me very early on the importance of seeking out knowledge and continually striving to understand, learn and grow;

and

My husband and son, my favorite teachers, who have taught and continue to teach me every single day just how beautiful, precious and joyous life is with the two of them by my side.

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Thank you all.

Chapter 1: Introduction and Rationale

Introduction

State, national and international documents on science education reform have long emphasized the need for engaging students in authentic inquiry practices that foster the development of critical thinking skills as well as more self-sufficient and independent learning (Abd-El-Khalick et al., 2004; American Association for the Advancement of Science [AAAS], 1993; California Department of Education [CDE], 1998; National Research Council [NRC], 1996; Next Generation Science Standards [NGSS], 2013). Independent learners are able to accurately assess their own understanding and make decisions that productively advance their learning (Ertmer & Newby, 1996; White & Frederiksen, 1998). The ability to identify and address weaknesses or gaps in understanding is especially critical for learning, when new information must be successfully integrated with existing prior knowledge and experiences (e.g., Linn & Eylon, 2006; Lombrozo, 2006; Smith, diSessa & Roschelle, 1993).

This dissertation investigates the impact of an inquiry instructional model that utilizes choice as a metacognitive scaffold to engage students in more reflective, mindful and self-directed independent inquiry. A choice-based inquiry instructional model allows for more flexible instruction by offering customizable, student-selected inquiry paths that can adapt to and provide support for learners with different starting levels of prior knowledge and experiences (Murata, 2013).

Rationale

Where does choice fit into current efforts? Unstructured, student-led models of inquiry instruction such as project-based science (Blumenfeld et al., 1991; Marx, Blumenfeld, Krajcik, & Soloway, 1997) have emerged in response to reform recommendations for more independent learning experiences. However, many educators face multiple barriers (e.g., logistical, institutional or cultural challenges) to implementing models such as project-based science, thus limiting the widespread adoption of open-ended innovative inquiry instructional approaches (e.g., Anderson, 2002; Trautmann, MaKinster, & Avery, 2004). Consequently, many students in today's classrooms continue to experience scientific inquiry as a linear, step-by-step "cookbook" endeavor (Chinn & Hmelo-Silver, 2002). All students learn the same material through the same sequence and steps of instruction. This traditional, "one size fits all" approach misrepresents and does not capture the open-ended and exploratory nature of authentic scientific inquiry. Thus there is a clear need for research that explores instructional approaches that inhabit the middle ground between authentic and open-ended inquiry (highly challenging to implement but with potentially more powerful and transformative learning outcomes; e.g., Blumenfeld et al., 1991; Marx, Blumenfeld, Krajcik, & Soloway, 1997) and more

traditional, structured inquiry instruction (lacking in rich learning outcomes but far easier to implement; Chinn & Hmelo-Silver, 2002).

Choice as a middle-ground model that maximize opportunities and minimizes challenges. My dissertation research aims to contribute to science education reform efforts by investigating a semi-structured approach to inquiry. Choice-based inquiry can engage students in more self-directed, open-ended, nonlinear instruction, resulting in more adaptable and customizable inquiry experiences for learners. This work positions itself as a compromise that seeks to bridge the space between fully constrained and completely open-ended instruction. By doing so, a choice-based approach can support student enactment of critical independent inquiry practices (e.g., assessing understanding, reflecting on gaps in explanatory knowledge, making decisions about what to investigate next) while simultaneously minimizing some of the implementation challenges that arise with more authentic and complex models of inquiry instruction. My research explores the potential utility of choice as a form of instructional support that can help to shift teaching practices from the more familiar format of traditional linear inquiry towards richer, more open-ended and nonlinear learning investigations.

Choice promotes constructivism and supports diverse learners. Finally, choice supports a constructivist perspective towards instruction (Bransford, Brown, & Cocking, 2000) by capitalizing upon the diverse population of learners in classrooms and using students' pre-existing ideas as productive starting points for instruction (Smith, diSessa & Roschelle, 1993). By offering the opportunity for students to complete different investigation paths of their own choosing, choice-based inquiry can support unique learning trajectories for students with differing incoming levels of prior knowledge. As Murata (2013) argues, instruction should "be sufficiently open to allow for the flexibility that accommodates and values the diversity of the learners. By allowing for multiple entry points and multiple paths, all students ultimately come into proximity to core learning goals, with richer and deeper learning experiences" (p. 20).

Chapter 2: Theoretical and Empirical Foundations

Overview of Chapter

Guiding research question for the dissertation. This dissertation investigates the effect of a choice-based model of inquiry on student learning and how instruction can be designed to support more customized and independent inquiry investigation trajectories with diverse students. In particular, my research seeks to understand whether choice can engage students in reflecting upon and identifying weaknesses and gaps in their understanding, thus allowing learners to make more informed and mindful decisions about how best to support and promote their own learning.

About design-based research. Design-based research (DBR) strives to “investigate cognition in context” (Barab & Square, 2004, p. 1); that is, to understand how people learn in authentic (i.e., “messy”) contexts: “A fundamental assumption of many learning scientists is that cognition is not a thing located within the individual thinker but is a process that is distributed across the knower, the environment in which knowing occurs, and the activity in which the learner participates. In other words, learning, cognition, knowing, and context are irreducibly co-constituted and cannot be treated as isolated entities or processes” (Barab & Square, 2004, p. 1). Through repeated, iterative cycles of implementation and evidence-supported refinement, DBR seeks to inform and advance both theories of learning and the design of innovative learning environments (Barab & Squire, 2004; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Sandoval, 2014; Sandoval & Bell, 2004; Wang & Hannafin, 2005). Cobb and his colleagues describe design experiments as resulting in “greater understanding of a *learning ecology*—a complex, interacting system involving multiple elements of different types and levels—by designing its elements and by anticipating how these elements function together to support learning” (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003, p. 9). In his paper, Sandoval argues for the need to make explicit for testing and research the theoretical and design hypotheses embodied in the design of a learning environment: “Conjecture mapping is an effort to reify specific conjectures and how they are expected to function in interaction to promote learning. Such specification leads to empirical predictions that can be tested, and the results of such tests can lead to both refinements of a particular design as well as refinements of a theoretical perspective (Sandoval 2004, as quoted in Sandoval, 2014, p. 20-21). Figure 2.1 gives a general-level overview of the theoretical and design commitments underlying the design and development of the *Seasons* curriculum unit. I unpack the details of the conjecture map in considerably more detail in Chapter 3.

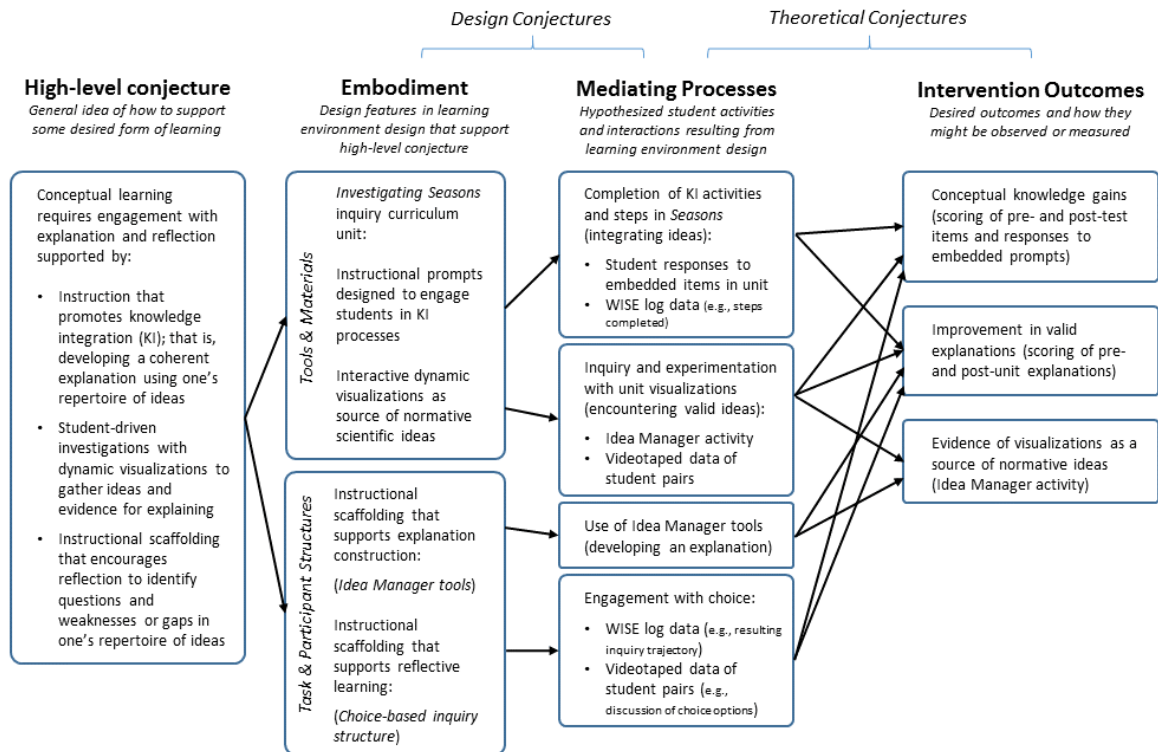


Figure 2.1. A conjecture map of the theoretical and design commitments for the design of the *Seasons* curriculum unit.

Overview of chapter. This chapter presents a synthesis of the relevant bodies of research that constitute the theoretical framework underlying my dissertation work. I review our understanding of the importance and role of explanation and reflection as instructional strategies for supporting learners in constructing and revising their knowledge.

The Instructional Value of Explanations

Why are explanations important for science education? We have a natural desire to understand and make sense of things—to seek out explanations to our questions. As young children, we exhibit wonder and curiosity about the world we live in, asking our parents questions prompted by our observations: “Why is the sky blue? What makes it rain? Why does the moon follow me wherever I go?” This desire to understand and make sense persists even as we leave our childhoods behind; as adults we continue to look for answers to the things that pique our curiosity, pondering questions ranging from the mysterious and grand (e.g., “What is the meaning of life?”) to the more commonplace and mundane (e.g., “I wonder why the bus is running late?”). While explanations figure prominently in how we make sense of our everyday observations of the world around us, they also play a critical role in supporting and driving forward the enterprise of scientific discovery and inquiry (Nagel, 1961). Consequently, developing students’ proficiency with generating and evaluating explanations are considered important instructional goals for science education (American Association for the Advancement

of Science [AAAS], 1993; California Department of Education [CDE], 1998; National Research Council [NRC], 1996, 2007) and viewed as vital for supporting scientific literacy (e.g., Driver, Newton, & Osborne, 2000). As Driver and her colleagues (1994) note: “Learning science involves young people entering into a different way of thinking about and explaining the natural world; becoming socialized to a greater or lesser extent into the practices of the scientific community with its particular purposes, ways of seeing, and ways of supporting its knowledge claims” (Driver, Asoko, Leach, Scott, & Mortimer, 1994, p. 8).

How is the term “explanation” defined? A review of the literature reveals that different and varying conceptualizations of the term “explanation” exist between groups of researchers (cf. Braaten & Windschitl, 2011; Brewer, Chinn, & Samarapungavan, 1998; Lombrozo, 2012). Furthermore, there exists some uncertainty and confusion about the similarities and differences between argumentation (Toulmin, 1958) and explanation and how these two forms of scientific discourse have been conceptualized and implemented in science classrooms (Bell & Linn, 2000; Driver, Newton, & Osborne, 2000; Duschl, 2003; Erduran, Simon, & Osborne, 2004; McNeill, Lizotte, Krajcik, & Marx, 2006; Sandoval, 2003). Consequently, educational researchers have debated the need for and nature of distinction between the two terms (cf. Berland & McNeill, 2012; Osborne & Patterson, 2011, 2012). For my work I utilize the following definition: An explanation attempts to make sense of a phenomenon by providing a causal account, supported by scientific facts and evidence, that addresses the question of “how” or “why” (e.g., Bell & Linn, 2000; Berland & Reiser, 2009; Brewer, Chinn, & Samarapungavan, 1998; Duschl, 2000; Lombrozo, 2006; McNeill, Lizotte, Krajcik, & Marx, 2006; Osborne, Erduran, & Simon, 2004; Osborne & Patterson, 2011; Sandoval & Reiser, 2004).

What are the benefits of explanation for learning? The benefits of explanation on student learning and conceptual understanding are well documented in the existing literature (see Fonseca & Chi, 2011; Lombrozo, 2012). Generating an explanation, in fact, may be more effective for learning than simply being provided with one (Aleven & Koedinger, 2002; Lombrozo, 2012). A number of studies demonstrating the positive learning effects of self-explanation have been carried out across different age groups, subject domains, and learning contexts (e.g., Bielaczyc, Pirolli, & Brown, 1995; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Fonseca & Chi, 2011). For example, Chi and her colleagues (1994) found that learners explicitly prompted to self-explain during their reading of a text about the circulatory system demonstrated higher pre-test to post-test knowledge gains than learners in the unprompted condition. Furthermore, high explainers (learners in the prompted condition who generated a large number of explanations) developed more accurate mental models of the human circulatory system than both low explainers (prompted students who generated only a small number of explanations) and students in the unprompted condition. This study confirmed and extended upon earlier research by Chi et al. (1989) which documented the self-explanation effect on students’ successful acquisition of problem-solving skills while studying worked-out example solutions to physics mechanics problems.

Why are explanations beneficial for learning? The research suggests a number of possible reasons for the positive outcomes observed when students engage in explanation during learning. Generating explanations can:

Direct attention and focus to elucidating the causal structure of a phenomenon. Explanations can focus attention on uncovering the underlying causal mechanism (Lombrozo, 2006, 2012). In addition, explanations can help to situate a phenomenon within one's larger conceptual framework, thus guiding generalization and application of the underlying causal mechanism to explain similar events in the future or to help with the integration of diverse phenomena (Brewer, Chinn, & Samarapungavan, 1998; Keil, 2006; Lombrozo, 2006, 2011, 2012).

Help to contextualize new information within existing knowledge. Explanation can support learning by promoting the integration of newly acquired ideas with prior beliefs (Chi, de Leeuw, Chiu, & LaVancher, 1994; Lombrozo, 2006). Some have proposed that explanations that are consistent with previously known facts and evidence can impart a satisfying sense of increased understanding (Brewer & Chinn, 1994; Brewer, Chinn, & Samarapungavan, 1998; Keil, 2006). One danger facing learners is the tendency to seek for confirming evidence (Chinn & Brewer, 1993; de Jong & van Joolingen, 1998) and to discount ideas that challenge existing beliefs (Chinn & Brewer, 1993, 2001; Keil, 2006).

Reveal weaknesses or gaps in understanding. We are often unaware of the incompleteness of our understandings (diSessa, 1983), believing that we understand with far greater accuracy and coherence than we actually do ("illusion of explanatory depth" or IOED; Rozenblit & Keil, 2002, p. 522). Generating explanations can help one to identify and address weaknesses in understanding, or to resolve inconsistencies between conflicting or competing ideas (Bell & Linn, 2000; Bielaczyc, Pirolli, & Brown, 1995; Chi, 2000; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Davis, 2003; Davis & Linn, 2000; Keil, 2006; Scardamalia & Bereiter, 1994).

Connect with and activate metacognitive monitoring skills. While observing students studying solution examples of physics mechanics problems, Chi and her colleagues (1989) noticed that not only did the more successful ("Good") students generate more self-explanations than their less successful ("Poor") peers, they were also more adept at detecting their own comprehension failures. The authors suggest a possible relationship between self-monitoring and self-explanation: "We surmise that it is important to be able to detect comprehension failures in order for students to know that they ought to do something to understand... Indeed, for both the Good and Poor students, detections of comprehension failures do initiate explanations, although more often for the Good than for the Poor students..." (p. 170). This conclusion is supported by the work of others (e.g., Alevan & Koedinger, 2002; Bielaczyc, Pirolli, & Brown, 1995), suggesting that explanation can function to support learning on two levels, as both a cognitive task as well as a metacognitive strategy.

What are some key issues for supporting students with developing explanations? There are a number of challenges for educators to consider from an instructional design standpoint. One

central issue concerns the unfamiliarity and lack of exposure students have had with the practice of constructing a scientific explanation and what exactly that entails (e.g., Driver, Asoko, Leach, Scott, & Mortimer, 1994; Driver, Newton, & Osborne, 2000; Duschl, 2000; Krajcik, Blumenfeld, Marx, Bass, & Fredericks, 1998; Osborne, Erduran, & Simon, 2004; Sandoval & Reiser, 2004). Another challenge is the difficulty many students encounter in identifying and using evidence appropriately in their explanations (e.g., McNeill & Krajcik, 2007; McNeill, Lizotte, Krajcik, & Marx, 2006; Sadler, 2004; Sandoval, 2003). Researchers have investigated how to design instructional support to help students overcome these challenges and become more proficient at developing explanations. A number of studies indicate that making the goals and process of explanation more transparent and explicit can be helpful (e.g., Bell & Linn, 2000; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999; Kuhn & Reiser, 2005; Lizotte, McNeill, & Krajcik, 2004; McNeill & Krajcik, 2007; McNeill, Lizotte, Krajcik, & Marx, 2006; Reiser et al., 2001; Sandoval, 2003). For example, scaffolding tools embedded in technology-enhanced learning environments that explicitly structure and guide students through the process of generating explanations from evidence have yielded promising results for domain topics such as physics (e.g., the SenseMaker argument editor; Bell & Linn, 2000) and evolutionary biology (e.g., ExplanationConstructor; Reiser et al., 2001; Sandoval, 2003; Sandoval & Reiser, 2004). These tools are effective possibly because they implement the “cognitive apprenticeship” principle (Collins, 1988) of “making thinking visible” (Bell & Linn, 2000; Collins, 1988; Collins, Brown, & Holum, 1991; Linn, Davis, & Eylon, 2004; Reiser et al., 2001); by explicating the components that comprise a scientific explanation, the process is deconstructed, demystified and made concrete (and consequently, more tractable) for students.

The Role of Reflection in Independent Learning

What is reflection and how does it support independent learning? Broadly defined, reflection is a self-regulative process under the larger overarching construct of metacognition. The term “metacognition” refers to both the awareness and control (or self-regulation) of one’s own cognitive processes (e.g., Brown, Bransford, Ferrara, & Campione, 1983; Flavell, 1979; Georghiades, 2004; Pintrich, Wolters, & Baxter, 2000; Schraw & Moshman, 1995). Metacognitive individuals are thus considered to be aware of, knowledgeable about, and capable of actively monitoring and managing their own thinking and learning (e.g., Bransford, Brown, & Cocking, 2000; Brown, 1987; Flavell, 1976, 1979; Georghiades, 2004; Greeno, Collins, & Resnick, 1996; Pintrich, Wolters, & Baxter, 2000; Schraw & Moshman, 1995). Within the literature on self-regulation, three principal categories of executive control activities have been identified (e.g., Brown, 1987; Flavell, 1979; Jacobs & Paris, 1987; Meijer, Veenman, & van Hout-Wolters, 2006; Schraw & Moshman, 1995):

1. *Planning.* The anticipation of the appropriate strategies and resources required to successfully embark on or complete a cognitive task.
2. *Monitoring.* The real-time observation and awareness of comprehension and performance during the undertaking of a cognitive task.

3. *Evaluation.* The self-assessment of resulting performance or learning on a cognitive task.

For my work, I argue for the inclusion of reflection as a distinct fourth form of self-regulative control. Reflection interacts with the processes of planning, monitoring and evaluation and is essential for supporting independent and autonomous learning. I define the term “reflection” as a self-regulative process directed towards assessing the success of one’s efforts on a learning task or experience after it has occurred, *in order to determine adjustments or changes that should be implemented next to achieve or move towards a desired goal or outcome.* As reflection is informed by one’s judgment about how a cognitive endeavor went, it necessarily requires evaluation and self-assessment. However, while reflection depends upon evaluation and can inform the planning for future cognitive tasks, I consider it wholly distinct from either of these two self-regulatory activities. Rather, I view reflection as a bridge between the processes of evaluation and planning that results in continuous, self-directed improvement upon one’s own performance as a learner (e.g., the distinction between reflection-in-action *during* an activity and reflection-on-action *following* an activity; Schön, 1987, as cited in Barab, Hay, Barnett, & Keating, 2000). This conceptualization of the importance of reflection for achieving ever higher levels of awareness and expertise about the “self-as-learner” (Lin, 2001, p. 27-28) aligns closely with the perspectives of other researchers who also consider reflection key for promoting more metacognitive and independent learning (Ertmer & Newby, 1996; Hatano & Inagaki, 1986, 1992; Lin, 2001; Scardamalia & Bereiter, 1991; Quintana, Zhang, & Krajcik, 2005; White & Frederiksen, 1998, 2005). As Quintana, Zhang and Krajcik (2005) note: “Reflection is deliberate thinking about a learning experience to improve it” (p. 238). Thus reflection serves as “the critical link between knowledge and control of the learning process” (Ertmer & Newby, 1996, p. 3) and is instrumental in enabling a novice learner to move towards more expert and self-sufficient learning: “By employing reflective thinking skills to evaluate the results of one’s own learning efforts, awareness of effective learning strategies can be increased and ways to use these strategies in other learning situations can be understood. Reflection uses previous knowledge to gain new knowledge” (Ertmer & Newby, 1996, p. 18). As Simons (1993) proposes, “a learner’s reflection on the process of learning can lead to changes in future processing and increased metacognitive knowledge about learning” (as cited in Ertmer & Newby, 1996, p. 14). Similarly, White and Frederiksen (2005) argue that reflection leads to “developmental expertise” (p. 211)—that is, the knowledge and ability to improve one’s own capabilities. Expert learners are particularly adept at using reflection to inform and manage decision-making about their own learning (e.g., Bransford & Schwartz, 1999; Brown & Campione, 1996; Ertmer & Newby, 1996; Scardamalia & Bereiter, 1991).

Chapter 3: Design, Development and Iterative Refinement of the *Investigating Seasons* Inquiry Curriculum Unit

Introduction

Significant conceptual difficulties can arise when students attempt to combine their ideas from different sources into a cohesive, coherent whole. This is a task often encountered by students in the science classroom where experiential, intuited understandings are often at odds with formally introduced scientific ideas and evidence. The process of utilizing one's diverse repertoire of ideas to arrive at a scientifically valid understanding can be especially challenging in the case of a complex phenomenon such as Earth's seasonal temperature changes. In the case of seasons, students must coordinate between their observed firsthand personal perceptions (e.g., varying seasonal temperatures and the daily apparent movements of the Sun and Earth) and a less familiar, third-person perspective of the Sun-Earth system in order to understand why sunlight intensity changes throughout the year (the primary causal mechanism behind seasons) and furthermore, why a distance-based explanation (i.e., the Earth is closer to the Sun in the summer and farther from the Sun in the winter) does not and cannot account for yearly temperature patterns. Developing a complete and robust understanding of seasons thus requires students to reconsider firmly rooted and long-held ideas developed from personal interactions, experiences and observations with the physical world that would seem to support a distance-based explanation (e.g., it feels warmer closer to the fire than farther away from it—so Earth must be closer to the Sun during the summer and farther away from the Sun during the winter). This is not an insignificant challenge for both students and educators.

Carefully designed curricular materials can help to guide students in reconciling their ideas from multiple sources towards formulating a more coherent and normative explanation for seasons. In addition, the use of instructional technologies such as dynamic visualizations (i.e., student-driven scientific models designed for learning) can provide students with interactive opportunities for conducting “hands-on” inquiry investigations that encourage the reflection upon and revision of conceptual understandings.

This chapter describes my research work on the design, development and pilot testing of *Investigating Seasons* (abbreviated as *Seasons*; King Chen, 2011; King Chen et al., 2013), a web-based online inquiry curriculum unit for high school students. *Seasons* incorporates multiple dynamic visualizations and extensive instructional scaffolding to support students in collecting, evaluating, making sense of and integrating their diverse ideas for explaining seasonal temperature changes. Dynamic visualizations embedded within the curriculum function as critical learning opportunities for students to encounter important normative ideas and test their pre-existing beliefs. Supporting instructional scaffolds and prompts encourage students to monitor and evaluate their changing repertoire of ideas as they proceed through the unit. Two overarching goals guided the design and development of *Seasons*:

1. **Dynamic visualizations as focal learning resources for key scientific ideas.** The unit consists of five guided inquiry investigations that position the visualizations as important interactive learning tools for experimentation and data gathering.
2. **Supporting curricular instruction and prompts that explicitly scaffold the process of explanation and promote reflection.** The structure of instruction in the unit scaffolds and guides students through the process of drawing upon their repertoire of ideas to formulate an evidence-based explanation for seasons. Reflection prompts encourage students to periodically evaluate and assess their developing understandings.

In the sections that follow, I begin by problematizing and providing an instructional context for the teaching of seasons by first discussing an exemplar case from the video *A Private Universe* (Schneps & Sadler, 1987). I then present the inherent challenges and advantages of using seasons as a topic for science inquiry instruction before providing a brief review of the literature comprising the theoretical framework underpinning my work. I next explicate the theoretical and design commitments (Sandoval, 2014) that motivated and guided the design and development of the *Seasons* inquiry curriculum materials. I demonstrate the enactment of these commitments as evidenced by the design solutions implemented in the iterative refinement of the *Seasons* visualizations and instructional scaffolding; design cases provide additional context and an opportunity for further in-depth discussion. Finally, I share the study findings from classroom implementation and testing that demonstrate the unit's effectiveness and impact on student learning, and conclude with a discussion of the design principles and informative lessons that emerged from this research.

Reflections on *A Private Universe*

In the late 1980s, a documentary video created and produced by the Harvard-Smithsonian Center for Astrophysics became the subject of much discussion by members of the science education community. *A Private Universe* (Schneps & Sadler, 1987) showed several clips of interviews conducted with newly minted Harvard graduates (ostensibly still in their full graduation regalia) that clearly indicated that even highly educated, bright students could not give a correct explanation for the seasons:

Narrator: Despite a lifetime of the very best education, students in our classrooms are failing to learn science. Many of these students will graduate from college with the same scientific misconceptions that they had on entering grade school. To test how a lifetime of education affects our understanding of science, we asked these recent graduates some simple questions in astronomy. Consider, for example, that the causes of the seasons is a topic taught in every standard curriculum:

- Student 1:** Okay, I think the seasons happens because as the Earth travels around the Sun it gets nearer to the Sun, um, which produces warmer weather and gets farther away which produces colder weather and that's... and hence the seasons.
- Student 2:** How hot it is or how cold it is at any given time of the year has to do with the... the closeness of the Earth to the Sun during the seasonal periods.
- Student 3:** The Earth goes around the Sun. And it gets hotter when we get closer to the Sun and it gets colder when we get further away from the Sun.
- Narrator:** These graduates, like many of us, think of the Earth's orbit as a highly exaggerated ellipse, even though the Earth's orbit is very nearly circular, with distance producing virtually no effect on the seasons. We carry with us the strong incorrect belief that changing distance is responsible for the seasons.

The interviews conducted for *A Private Universe* revealed that “regardless of their science education, 21 of the 23 randomly selected students, faculty and alumni of Harvard University revealed misconceptions when asked to explain either the seasons or the phases of the Moon” (Schneps & Sadler, 1987). The realization that even college graduates and faculty from one of the nation's top universities could continue to hold on to non-normative ideas through years of formal schooling and instruction was received with much dismay and consternation by science educators. More than anything, *A Private Universe* raised the rather unsettling question, “How can students graduate from prestigious schools like Harvard or MIT and not know even some of the most basic ideas in science taught in grade school?” (Schneps & Sadler, 1987). While this question is certainly a provocative and troubling one, it is substantiated by a large body of research that clearly demonstrates that explaining seasons correctly is challenging for many individuals, regardless of age, education or cultural background (e.g., Atwood & Atwood, 1996; Baxter, 1989; Hsu, 2008; Hsu, Wu, & Hwang, 2008; Kalkan & Kiroglu, 2007; Kikas, 2004; Sharp, 1996; Trumper, 2000, 2001, 2006).

Consider the case presented in *A Private Universe* of Heather, an extremely bright ninth-grade student asked to share her explanation for the seasons. Although at first she responds to the interviewer's questions with nearly textbook-perfect responses, the interviewer soon discovers that “on probing, we see that Heather believes that the Earth travels in a bizarre, curlicue orbit” (Schneps & Sadler, 1987; Figure 3.1).



Figure 3.1. Screenshots of Heather's interview and explanatory drawings from *A Private Universe*.

Two weeks later (after her conceptions about the shape of Earth's orbit have changed after instruction), Heather mentions that her thinking may have been influenced by ideas she came across "on her own from books and other sources" (Schneps & Sadler, 1987). She recalls in particular a figure in her earth science textbook depicting an analemma (Figure 3.2). As Heather explains: "It was probably because I was looking in my earth science book in eighth grade and I looked at another chart and got it confused with this one."

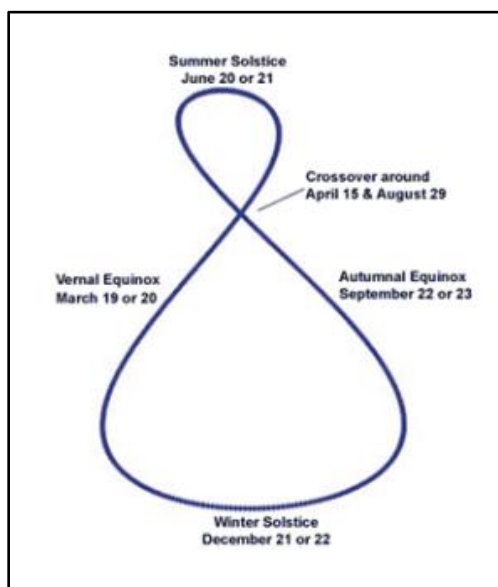


Figure 3.2. Drawing of an analemma.

As Heather's case illustrates, the process of combining ideas from different sources into a coherent account can be a conceptually challenging task fraught with difficulty, even for a student as highly motivated and bright as Heather. Clearly then, *how* learners engage in the process of integrating their pre-existing ideas with new ones encountered during instruction should be an issue of central importance and concern for science educators and instructional designers. Smith, diSessa and Roschelle (1993) argue that students' prior conceptions should be viewed as productive "resources for cognitive growth" (p. 116) and that instruction should focus on knowledge refinement and reorganization, rather than replacement (cf. McCloskey, 1983; Posner, Strike, Hewston, & Gertzog, 1982; Strike & Posner, 1985). Taking this view, if we value the richness and diversity of students' pre-existing ideas as useful starting points for instruction, I propose that an effective curriculum should both: (1) consider and build upon individuals' prior personal experiences and observations as well as (2) support the careful assimilation of learned information with those pre-existing beliefs. In developing the *Seasons* unit, I sought to gain insight into the following question: How can we design inquiry instruction about a complex phenomenon such as seasons that supports students in drawing upon their ideas to develop a scientifically valid and normative explanation?

Instructional Advantages and Challenges with Seasons

Despite (and possibly because of) the documented conceptual difficulties encountered by students, seasons is a popular topic of instruction for middle and high school science classrooms. National and state science education standards include a number of concepts integral for understanding seasonal temperature changes (e.g., the orientation and movement of objects in the Sun-Earth system, solar radiation and energy, light intensity) as important conceptual targets for learning and instruction (e.g., California Department of Education [CDE], 1998; National Research Council [NRC], 1996). My own personal view is that the topic (given its highly counterintuitive nature and multi-faceted complexity) offers unique instructional advantages and challenges that serve as a particularly rich context for promoting learning that requires self-aware, metacognitive and critical thinking skills (Next Generation Science Standards [NGSS], 2013). I present these advantages and challenges next (summarized in Table 3.1).

Advantages. Perhaps more so than any other area of science, astronomy and its array of esoteric phenomena (e.g., the seasons, the phases of the Moon, lunar and solar eclipses, exploding stars, comets, colliding galaxies, black holes, the Big Bang and the ultimate fate of the Universe) elicits students' natural curiosity, fascination and wonder. Often the first "Why?" questions children pose to their parents are aimed at understanding the wondrous world around them: "Why is the sky blue? Why does the Sun rise and set? Why does the Moon seem to follow our car home at night?" Furthermore, seasons is a unique astronomical phenomenon in that it is experienced and observed firsthand by most students. Consequently, unlike more abstract or "mysterious" scientific phenomena (black holes, photosynthesis, evolution or the electromagnetic spectrum, for example), for many students seasons feels like an accessible topic that they feel they have a wealth of ideas to immediately draw upon. Indeed, most students are able to offer with surprising conviction and confidence an explanation (whether correct or not) for the seasons (viz., Schneps & Sadler, 1987). From an instructional and educational research standpoint, the topic allows for relatively easy elicitation of students' pre-existing ideas to address and build upon during instruction, which aligns well with constructivist approaches for fostering learning and conceptual change (e.g., Linn, 2006; Smith, diSessa, & Roschelle, 1993).

Challenges. Ironically, students' unhesitating conviction in their pre-existing beliefs, while an asset, also present a significant obstacle for instruction. Research suggests that naïve conceptions arising from personal experiences are powerful and often highly resistant to instruction (Clement, 1982; diSessa, Elby, & Hammer, 2002; McCloskey, 1983; Posner, Strike, Hewston, & Gertzog, 1982; Shipstone, 1985; Windschitl & Andre, 1998) and that even when presented with plausible alternative viewpoints, students will often discount these in favor of their initial beliefs (Chinn & Brewer, 1993, 2001). Many students with distance-based explanations struggle to revise their thinking because their experiential observations of how the world works (e.g., it feels warmer closer to the fire than further away from it) would appear to confirm and give explanatory weight to their intuitive theories. Consequently, teaching seasons

necessitates the adoption of a “two-headed monster” approach in which instruction must attempt to address two aims simultaneously—that of de-privileging students’ long-held theories about the impact of distance while at the same time promoting students’ understanding of the impact of changing light intensity as the significant underlying causal mechanism for seasons. To complicate matters, achieving these instructional aims depends heavily on fostering students’ facility with spatial reasoning and manipulation, shifting between and coordinating different perspectives (Klatzky, 1998; Figure 3.3) and engaging in quantitative reasoning about relative size and scale. These activities are noted in the literature as being of significant cognitive difficulty for most students (e.g., Barab, Hay, Barnett, & Keating, 2000; Jones, 2013; Heywood & Parker, 2010; Parker & Heywood, 1998).

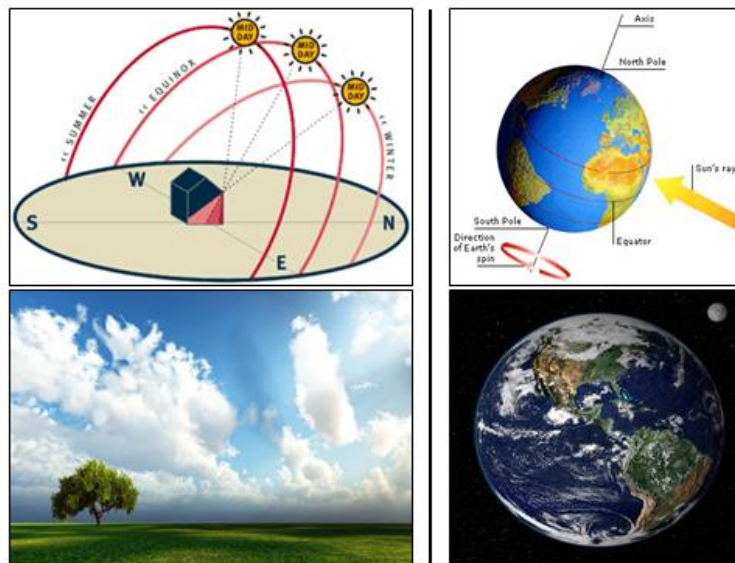


Figure 3.3. First-person (egocentric) and third-person (geocentric) perspectives of the Sun-Earth system.

Another complicating issue is that poorly-designed orbit diagrams that omit or provide unclear or confusing conceptualization cues (Lee, 2010) may cause students to assume a distance-based view of seasons. For example, many textbooks inadvertently mislead students by depicting the Earth’s orbit around the Sun from an extreme side perspective without making it clear how this representation distorts the true shape of the orbit—consequently, Earth’s nearly circular orbit appears at first glance to be a highly exaggerated elliptical one (Figure 3.4). (To see this for yourself, observe a large round dinner plate from above before slowly shifting your view from a top-down to nearly edge-on perspective.) Unfortunately, it is not unusual to encounter ambiguous, confusing (or even blatantly incorrect) “scientific” diagrams and depictions in even the most unexpected and innocuous of places (Figure 3.5). Finally, developing a valid scientific explanation for the phenomenon requires: (1) taking into account an array of intersecting knowledge pieces that comprise the different components underlying a robust knowledge framework for seasons and furthermore, (2) discerning and understanding the relative causal contribution of each component. I present this knowledge framework below (Table 3.2) in order to convey the high level of complexity that underlies a well-developed and

sophisticated understanding of seasons. From a logistical and practical standpoint however, teachers’ specified time limitations for spending classroom time on this topic dictated the knowledge components that were identified as design priorities for the *Seasons* unit. These priorities are noted in Table 3.2.

Instructional Issues	Advantage	Challenge
Component concepts and inquiry investigation skills necessary for formulating a complete understanding of seasons are mandated in national and state science education standards.	X	
High likelihood of existing student engagement and interest. Perhaps more than any other area of science, astronomy topics such as seasons tap into students’ natural curiosity and motivation to understand.	X	
Seasons is an accessible natural phenomenon that allows students to develop a rich repertoire of observations and experiences for instruction to build upon. Students are often comfortable with offering an explanation for seasons, unlike other more unfamiliar and abstract science topics. (Ironically, these same advantages also function as significant obstacles for addressing student ideas to productively advance learning.)	X	X
Developing a normative understanding requires that students discount their strongly-held intuitive beliefs developed from personal experiences and observations, making conceptual change notoriously difficult. (This is substantiated by a large body of existing research.)		X
Instruction must address two aims simultaneously—that of de-privileging students’ beliefs about the impact of distance while concurrently promoting understanding of light intensity as the primary underlying causal mechanism that accounts for seasons.		X
Requires that students successfully tackle a number of cognitive challenges: spatial reasoning and manipulation, shifting between and coordinating different perspectives and frames of reference, and developing a conceptual understanding of relative size and scale (quantitative reasoning).		X
Existing instructional material such as textbook diagrams of the Sun-Earth system are often badly designed or misleading.		X
Robust understanding requires competency and proficiency with the multi-faceted knowledge framework comprising seasons (Table 3.2).		X

Table 3.1. Summary of instructional advantages and disadvantages for teaching seasons.

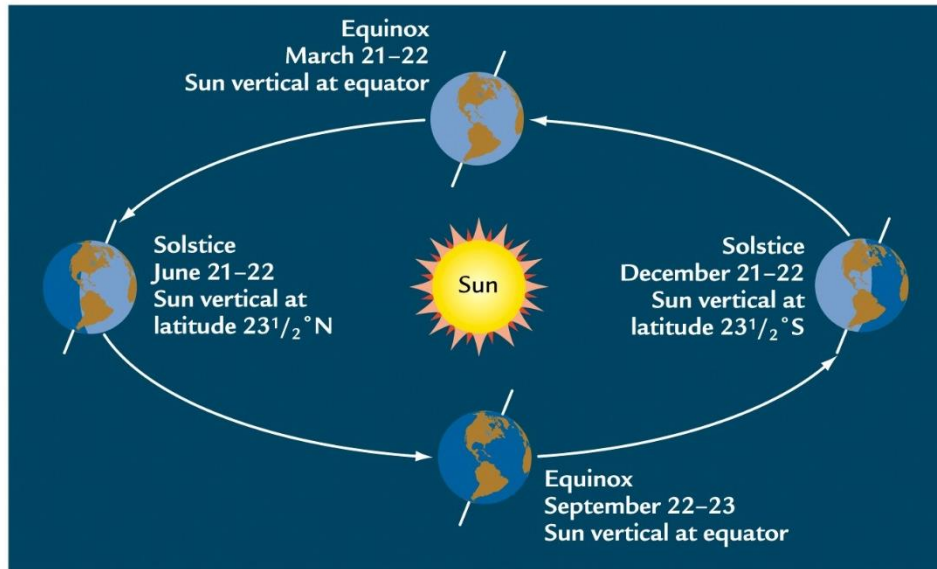


Figure 3.4. Example of a misleading diagram that inaccurately depicts Earth's orbit around the Sun.

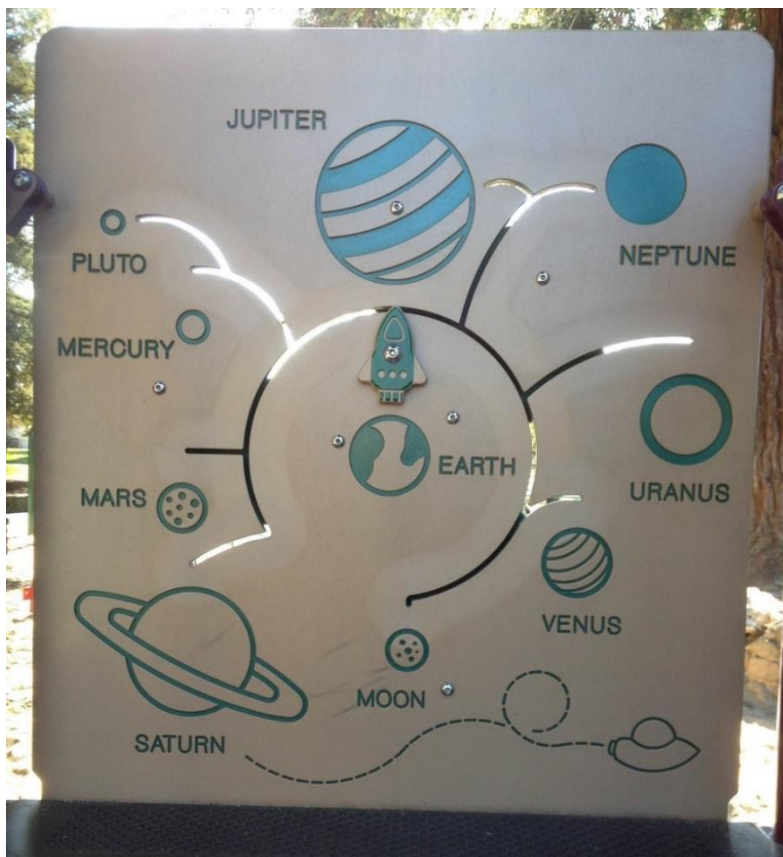


Figure 3.5. Incorrect and potentially misleading depiction of the Earth and other Solar System planets installed at a number of playgrounds in the San Francisco Bay Area. (How many inaccuracies can you find?)

Seasons Knowledge Component and Instructional Priority	Key Knowledge Pieces	Knowledge Types	Causal Contribution (1°, 2° or none)
<p>Sun-Earth system dynamics and definitions: Movements of the Sun and Earth</p> <p>These ideas are implicitly represented in the visualizations but are not explicitly taught in the unit, as most students will have encountered these basic concepts already through previous instruction.</p>	<ul style="list-style-type: none"> • Earth’s rotational axis is tilted 23.5° and is always oriented towards Polaris, the North Star. • One rotation of the Earth over a 24-hour period causes sunrise, day, sunset and night. • Earth’s path around the Sun defines the Sun-Earth orbital plane. One complete revolution (or orbit) of the Earth around the sun takes 365 ¼ days or a year. • The Sun is positioned at the center of Earth’s orbit. 	<ul style="list-style-type: none"> • Definitional • Factual • Spatial 	<p>Secondary:</p> <p>Changing positional configurations of the Sun and Earth relative to one another throughout the year results in changing light intensity.</p>
<p>Comparison of the Sun and Earth: Size and distance</p> <p>The visualizations provided key information when relevant, but the unit did not include explicit instruction about the difference in size between the Sun and Earth.</p>	<ul style="list-style-type: none"> • The Sun is considerably larger than the Earth with a diameter of 1.4×10^6 km (the equivalent of lining up 109 Earths in a row). • The distance between the Sun and the Earth is immense: approximately 1.5×10^8 km (the equivalent of lining up 11,760 Earths in a row). • Light from the Sun hits Earth in parallel rays because the Sun is so far away and so much larger than the Earth. 	<ul style="list-style-type: none"> • Factual • Mathematical • Spatial 	<p>Secondary:</p> <p>The physics of the Sun-Earth system results in sunlight hitting the Earth as parallel rays. In combination with Earth’s tilt and movement around the Sun, this causes the varying light intensity responsible for seasons.</p>
<p>Effect of distance: Shape of Earth’s orbit</p>	<ul style="list-style-type: none"> • Earth’s orbit around the Sun is very nearly circular. (Technically the orbit is an 	<ul style="list-style-type: none"> • Factual • Spatial 	<p>None</p>

<p>and changing Sun-Earth distance</p> <p>A significant and of key instructional priority for <i>Seasons</i>. These ideas are highlighted and prominently featured in the unit visualizations and instruction.</p>	<p>ellipse, but one with an extremely low eccentricity: $\epsilon = 0.02$.)</p> <ul style="list-style-type: none"> • Earth's orbit appears as a highly exaggerated ellipse in many representations because the orbit is shown from a nearly edge-on rather than top-down perspective. • There are minor Sun-Earth distance variations throughout the year. Most importantly, these variations <i>directly contradict</i> a distance-based explanation: Earth is closest to the Sun in December (1.46×10^8 km) and farthest from the Sun in June (1.52×10^8 km). 		
<p>Effect of Earth's tilt: Positional orientation between the Sun and Earth</p> <p>Another significant and key instructional priority for <i>Seasons</i>.</p>	<ul style="list-style-type: none"> • Earth's tilted rotational axis results in differing configurations of the Earth's spatial positioning relative to the Sun, resulting in changing light intensity and hours of daylight over the year. • The effect of Earth's tilt is differential, depending on latitude (e.g., equatorial, polar or somewhere in-between). 	<ul style="list-style-type: none"> • Spatial 	<p>Primary:</p> <p>Earth's tilt is directly responsible for changing light intensity throughout the year.</p>
<p>Effect of light intensity: Changing angle of incidence</p> <p>Also a significant and of key instructional priority for <i>Seasons</i>.</p>	<ul style="list-style-type: none"> • The tilt of Earth's axis affects the angle of incidence of incoming light from the Sun, resulting in changing light intensity throughout the year. This effect differs depending on latitude. • Light output from the Sun is relatively constant throughout the year. • The Earth receives parallel light rays from the Sun. (This 	<ul style="list-style-type: none"> • Factual • Spatial 	<p>Primary:</p> <p>Changing light intensity results in seasonal temperature changes.</p>

	is due to the enormous size of the Sun relative to the Earth, and the large distance between the Sun and the Earth.)		
Effect of hours of daylight: Earth’s tilt and orbital position and area of planet illuminated These ideas are implicitly represented in the visualizations but are not explicitly taught in the unit.	<ul style="list-style-type: none"> • The tilt of Earth’s axis affects the number of hours of daylight experienced at different latitudes. • Without the Earth’s tilt, every location on the Earth would experience 12 hours of daylight throughout the year. 	• Spatial	Secondary: Longer hours of daylight (when the Sun is in the sky) results in more time for the Earth to be heated by the Sun. But hours of daylight do not directly cause seasons.
Comparing global temperature patterns: Differing seasonal temperatures by latitude These ideas are implicitly represented in the visualizations but are not explicitly taught in the unit	<ul style="list-style-type: none"> • The tilt of Earth’s axis affects the angle of incidence of incoming light from the Sun, resulting in changing light intensity and consequently, temperature, throughout the year. This effect differs depending on latitude. 	• Spatial	None

Table 3.2. The different conceptual pieces that comprise a full and robust knowledge framework for understanding seasons. The relative causal weight of each component is indicated.

Important considerations for instructional design. As can be seen, the cognitive challenges inherent in supporting students’ learning of the seasons are many, varied and not insignificant. With these challenges in mind, educators and curriculum developers should be sensitive in providing instruction that minimizes the cognitive load placed on students (Chandler & Sweller, 1991) and provides explicit scaffolding for promoting frequent sense-making and reflection (Heywood & Parker, 2010; Quintana et al., 2004; Quintana, Zhang, & Krajcik, 2005). From the perspective of researchers and designers, acknowledging and working to address these challenges provides an opportunity to contribute to our collective understanding of how to design inquiry instructional materials that support student learning about a challenging and

complex scientific phenomenon. For this work, I sought to leverage the above identified advantages while also tackling some of the key challenges described.

Theoretical and Empirical Foundations

In this section I discuss the research perspectives that were instrumental in informing the theoretical framework that guided the design and development of the *Seasons* unit materials.

Knowledge integration (KI) supports students in reorganizing their repertoire of fragmented ideas towards more coherent understandings. We acquire our ideas and understanding about the world from varied settings (e.g., everyday experiences, informal learning opportunities, through formal schooling) and different sources (e.g., peers, family members, books and texts, multimedia and the internet). Consequently, learners' knowledge can be characterized as fragmented and incoherent (e.g., Minstrell, 2001), and students often struggle to reconcile their diverse repertoire of ideas into coherent and normative accounts. Furthermore, research suggests that students can hold contradictory ideas simultaneously and activate different ideas for explaining depending on perceived context and framing of the task or situation (diSessa, Elby, & Hammer, 2002; diSessa & Sherin, 1998; Russ, Lee, & Sherin, 2012).

This research work takes a constructivist perspective towards supporting and promoting student learning. As discussed previously, individuals draw upon a diverse pool of knowledge resources and ideas when reasoning about and generating an explanation for a complex phenomenon. In the case of seasons, students often have both intuitive, experiential ideas (developed from everyday interactions with and observations of their surroundings) as well as more formal ideas encountered during lessons in the classroom. From a constructivist perspective, the array of pre-existing ideas that learners bring to bear upon their thinking and understanding of things (even if flawed), can and should be used as productive starting points for building towards more normative understanding of challenging science concepts (e.g., Linn, 2006; Smith, diSessa, & Roschelle, 1993).

Aligned with the constructivist perspective is the *knowledge integration (KI) framework* (Linn, 2006; Linn, Davis, & Eylon, 2004; Linn & Eylon, 2006; Linn, Eylon, & Davis, 2004; Linn & Hsi, 2000), which frames learning as a "process of adding, distinguishing, organizing, and evaluating" one's diverse "repertoire of ideas" (Linn, Eylon, & Davis, 2004, p. 30). The *scaffolded knowledge integration framework for instruction* (Linn, Davis, & Eylon, 2004) specifies the following four interrelated processes for supporting knowledge integration and achieving instructional goals such as experimentation and reflection (Linn & Eylon, 2006, p. 523-525; Figure 3.6):

- **Elicit pre-existing ideas.** Prompting students to acknowledge and explicate their existing ideas ensures that new ideas can be considered alongside pre-existing ones so that students consider the "full range of [their] ideas rather than ignoring contexts and isolating new learning" (p. 524).

- **Add normative ideas.** Through instruction and inquiry activities, students encounter new and normative scientific ideas to add to their existing repertoire. The use of carefully designed “pivotal cases” (Linn, 2005) can stimulate students to discern key differences, thus directing attention to important concepts or prompting students to reconsider their ideas (Linn & Hsi, 2000).
- **Develop criteria for distinguishing ideas.** Learners need support in developing “coherent ways to evaluate the scientific ideas they encounter” (p. 524). Instructional activities can help students to develop criteria for distinguishing useful and relevant ideas from unproductive and irrelevant ones.
- **Sort and refine ideas.** Students reflect on their repertoire of ideas by applying criteria to evidence, making note of contradictions and identifying instances where additional information can help to resolve weaknesses, gaps or inconsistencies in understanding. In doing so, “students reformulate both their criteria and their accounts of scientific phenomena” (p. 525).

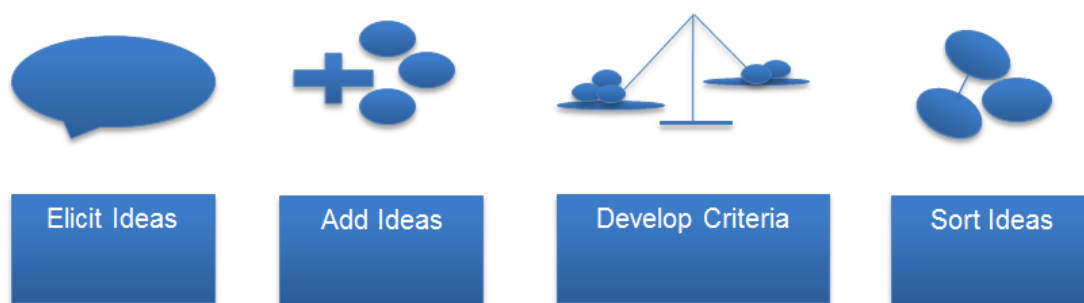


Figure 3.6. The four interrelated processes comprising the scaffolded knowledge integration (KI) framework for instruction.

A brief note of clarification: These four processes should not be considered mutually exclusive or as necessarily proceeding in a sequential progression as presented above—rather, “instruction typically interleaves the four processes, moving among them rather than following a linear sequence” (Linn & Eylon, 2006, p. 523). While one might design an instructional activity to emphasize a particular process over others, in practice the boundaries between processes can and are often blurred and nebulous. For example, the use of a pivotal case (Linn, 2005) or a critique prompt (Sato 2015; Zhang, 2010) might simultaneously introduce students to key ideas while also highlighting inconsistencies in understanding for further inspection or resolution.

The curriculum activities and prompts in *Seasons* were designed to engage students in the above described KI processes. Some exemplar instructional activities in the unit and the primary associated KI process they were designed to promote are given in Table 3.3.

Sample Instructional Activity in <i>Seasons</i>	Knowledge Integration Processes			
	<i>Elicit</i>	<i>Add</i>	<i>Distinguish</i>	<i>Refine</i>
Respond to a prediction prompt in preparation for interaction with a visualization.	X			
Explore the visualization with guiding experimentation goals and questions in mind.		X		
Use an idea organizer to categorize whether specific ideas can be used in support of or against a presented question.			X	
Reflect upon organized ideas to write a response (or revise a previous explanation) to the presented question.				X

Table 3.3. Examples of knowledge integration instructional activities in the *Seasons* curriculum.

The Web-Based Inquiry Science Environment (WISE) for designing inquiry instruction projects.

The *Seasons* unit was developed using WISE (Web-based Inquiry Science Environment), a free online and open-source platform available for designing science inquiry projects (<http://wise.berkeley.edu>; Bell, Davis, & Hsi, 1995; Linn, Clark, & Slotta, 2003; Linn & Slotta, 2000) that implement KI *curriculum design patterns* such as “orient, diagnose and guide” or “predict, observe and explain” (Linn & Eylon, 2006). WISE allows authors and developers to design customized instructional sequences of inquiry activities and prompts by offering access to various step type templates (e.g., curriculum or introductory text page, questionnaire or survey step, open-response reflection note, draw step, image annotator tool). Authors can also embed multimedia resources such as visualizations, animations and video clips as well as other technological tools into the project. In addition, the Teacher Dashboard allows teachers to easily track, monitor and manage their students’ progress through the project. By having real-time access to student work through the Dashboard, teachers can quickly identify problematic ideas that require attention as well as productive ideas to reinforce and build upon. Furthermore, WISE’s infrastructure and logging capabilities record and provide researchers with valuable information about student activity in projects (e.g., their responses to prompts) and associated metadata (e.g., the sequence of project steps visited, time spent on specific steps, revisions made to responses). Thus WISE is able to operate at multiple levels by simultaneously supporting inquiry learning for students, providing formative assessment opportunities for teachers (Shepard, 2005), and capturing informative data for researchers and developers.

Affordances and challenges of using dynamic visualizations in science instruction and inquiry.

For this work, I use the term *dynamic visualization* (occasionally shortened to just *visualization* for simplicity) to refer to an interactive, computer-based animation that simulates or models a scientific phenomenon for student-directed exploration and experimentation. Students might use a dynamic visualization to carry out any of the following inquiry activities: making

observations, generating predictions, testing variables, running experiments, collecting data and information, or interpreting and making sense of data.

Recent and continuing advances in technology allow for the representation of dynamic and complex phenomena in ever more interesting, innovative and ambitious ways. Consequently, dynamic visualizations have the potential to be powerful educational tools for science learning and exploration. They provide an opportunity for students to engage in more meaningful investigations of scientific phenomena that may not normally be accessible for direct examination in the classroom. By making difficult-to-visualize processes more explicit and visible, visualizations enable students to interact with and control the experimentation space in ways that are simply not possible with traditional inquiry methods (e.g., turning Earth's gravity on or off, adjusting the angle of tilt of Earth's axis of rotation, speeding up or slowing down time). Interactive user interfaces and controls encourage students to participate in more active learning such as manipulating models, making observations, testing hypotheses and generating virtual artifacts (Bakas & Mikropoulos, 2003; Corliss & Spitulnik, 2008). By making abstract concepts more concrete and accessible and by promoting creative and flexible learner-centered explorations, these alternative representations (in contrast to static diagrams or non-interactive animations) can help to increase student enthusiasm and motivation for learning.

Dynamic visualizations are thus particularly well suited for supporting the exploration of topics in astronomy, a branch of science that is by nature difficult to bring into the classroom for authentic "hands-on" inquiry (Bakas & Mikropoulos, 2003; Barab, Hay, Barnett, & Keating, 2000). In the case of seasons, visualizations can help learners to more easily visualize, coordinate and connect between different frames of reference or perspectives to attain a more complete understanding of the movements, orientation and positioning of the Sun and Earth relative to one another.

While dynamic visualizations provide many affordances for enhancing student learning, they also present potential challenges that should be acknowledged and addressed in order for instruction with visualizations to be effective and beneficial (Ainsworth, 2008; Chandler, 2004). Poorly-designed visualizations can easily overwhelm and overload students' cognitive processing by being too complex or too challenging to use or navigate (Ainsworth, 2006; Chandler & Sweller, 1991). In addition, visualizations can appear straightforward and easy to understand, thus inadvertently promoting *deceptive clarity* (Linn, Chang, Chiu, Zhang, & McElhaney, 2010); that is, students' overestimation of their own conceptual understanding of the material presented in the visualization. Embedding visualizations in instruction that features *desirable difficulties* (cognitive activities such as explanation or critique to highlight key information and clarify useful distinctions between ideas) can help learners to better make sense of their learning, thereby increasing the impact of the visualization (Linn, Chang, Chiu, Zhang, & McElhaney, 2010).

Earlier I discussed the many instructional obstacles that educators may encounter in supporting student learning about the seasons (refer back to Table 3.1). One significant challenge stems from the necessity of being able to coordinate and switch between different perspectives of the

Sun-Earth system (first- and third-person, or egocentric and geocentric; see again Figure 3.3) in order to understand what causes varying light intensity throughout the year. From a cognitive load perspective on learning (Chandler & Sweller, 1991), coordinating between different frames of reference can tax and deplete learners' cognitive resources "because material must be mentally integrated before learning can commence," creating an undesirable heavy cognitive load for students (p. 293). Accordingly, dynamic visualizations can productively redirect learners' cognitive resources towards more immediately useful and tractable learning goals by taking on the burden of depicting and connecting separate perspectives for students. However, in order for these visualizations to be helpful, they should be designed such that students are able to successfully master the cognitive tasks necessary for using the visualization to learn (Ainsworth, 2006), and any extraneous cognitive load on the student is reduced (Chandler, 2004).

These challenges point to the importance of designing both visualizations and supporting instruction to carefully scaffold student learning and understanding. McElhaney (2010) identifies the following three design principles for promoting KI processes and supporting students in using dynamic visualizations to achieve more coherent understanding:

- **Present multiple representations of phenomena.** The use of multiple representations can provide a range of different entry points for learners to engage with the visualization to develop understanding. Pairing a familiar or real-life representation with a less familiar one can help learners to more easily access their pre-existing ideas and to connect new information acquired from the visualization to prior knowledge. Using different representations to convey the same information can highlight and call attention to informative distinctions for students to make note of. However, caution must be exercised: Multiple representations can introduce undesirable complexity for students and furthermore, studies have shown that "learners tend to treat representations in isolation and find it difficult to integrate information from more than one source" (Ainsworth, 2006, p. 187). Designing multiple representations to *constrain interpretation* (e.g., using a simple or familiar representation to guide interpretation of a more complicated one), help *construct deeper understanding* (e.g., providing representations that encourage the identification of shared versus unique features to promote understanding) or assume *complementary roles* (representing the different aspects of a phenomenon using the most appropriate form of representation for each component) can help to ensure that they support rather than detract from desirable learning goals (Ainsworth, 1999, 2006, 2008). "Cognitive flexibility theory highlights the ability to construct and switch between multiple perspectives of a domain as fundamental to successful learning" (Spiro & Jehng, 1990, as cited in Ainsworth, 2008, p. 198).
- **Promote learner-initiated exploration.** Visualizations can serve as interactive and active learning spaces for students to explore questions of interest, generate predictions, run experimental trials and compare resulting outcomes to stated hypotheses. Unexpected

results can motivate learners to revisit their ideas to refine understanding or conduct follow-up investigations.

- **Provide record-keeping tools.** Records of interactions (in the form of notebooks, journals, experimental logs, multimedia scrapbooks, etc.) can help students to focus on and monitor their progress toward learning goals. The “visual records of interactions can make patterns in data more explicit” (McElhaney, 2010, p. 15), allow for comparisons of multiple inquiries to reveal important relationships or key distinctions, and encourage reflection on previous trials and collected data—all activities that are beneficial for promoting students’ integration of ideas.

These design principles served as main guiding influences on the development of the visualization activities for students in *Seasons*. The supporting instruction in the unit was designed to promote knowledge integration processes (Linn & Eylon, 2006) and featured metacognitive prompts and tools (described in more detail in the sections ahead) to encourage sense-making and self-aware learning (e.g., Quintana et al., 2004; Quintana, Zhang, & Krajcik, 2005; White & Frederiksen, 1998, 2000, 2005). Below I discuss some of the issues concerning the design of instructional scaffolds, in particular with respect to the use of explanation and reflection as metacognitive learning scaffolds for inquiry.

Designing instructional scaffolds to encourage explanation and reflection during inquiry. In Chapter 2, I reviewed the learning benefits of supporting students’ use of each of these activities as documented in the literature, and presented the rationale for considering explanation and reflection as instructional strategies that can help move learners towards more evaluative, self-aware and independent inquiry. Here I briefly revisit some of the main informative points from that earlier discussion—specifically as they relate to and influenced my work on the design and use of curriculum scaffolding and tools in *Seasons*.

Explanation

Although research shows that many individuals do not have a normative conceptual understanding of the seasons (e.g., Atwood & Atwood, 1996; Baxter, 1989; Hsu, 2008; Hsu, Wu, & Hwang, 2008; Kalkan & Kiroglu, 2007; Kikas, 2004; Schneps & Sadler, 1987; Sharp, 1996; Trumper, 2000, 2001, 2006), surprisingly many can nonetheless rather easily provide some sort of explanation (whether valid or not) for why they think seasonal temperature changes occur. In fact, a great deal of the shock value generated by the interviews featured in *A Private Universe* (Schneps & Sadler, 1987) came from seeing highly educated college graduates deliver with unwavering confidence and conviction *incorrect* explanations for the seasons. These interviews suggest an important question for educators: How can we help students to reassess or question understandings that they take to be normative and valid? Here, the use of explanation as a metacognitive scaffold for inquiry instruction may prove helpful.

Students often suffer from an “illusion of explanatory depth” (IOED; Rozenblit & Keil, 2002, p. 522), the mistaken belief that they understand with greater completeness, accuracy and

coherence than they actually do (diSessa, 1983). Engaging in explanation can help to counter IOED by highlighting inconsistencies or conflicts in thinking that require resolution, thus revealing weaknesses or gaps in understanding (Bell & Linn, 2000; Bielaczyc, Pirolli, & Brown, 1995; Chi, 2000; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Davis, 2003; Davis & Linn, 2000; Keil, 2006; Scardamalia & Bereiter, 1994). An astute reader might at this moment choose to point out an apparent contradiction here—that the individuals featured in the *A Private Universe* interviews were, in fact, *engaged in explaining* without any noticeable or obvious awareness of the problematic nature of their ideas. I raise this issue as a springboard for deeper discussion and clarification of my use of explanation as a form of instructional support for students.

As stated in the introduction to this chapter, one of the overarching instructional goals articulated for the design of the *Seasons* unit was that of providing designed support for students to develop evidence-based explanations. Thus in this work I make a distinction between explanation as the end *product* of explaining as opposed to explanation as the *process* of organizing one’s ideas into a coherent explanation (Kuhn & Reiser, 2005; Lombrozo, 2012; Wilkenfeld & Lombrozo, 2015). I further take the perspective that for explanation to function effectively as a learning task, it must be embedded within an intersecting system of supporting instruction that highlights inconsistencies and areas of unresolved understanding such that further questioning and reflection is encouraged. In this way, the instruction implicitly frames explanation as a *purposeful learning process for students to reflect upon and make sense of their ideas*. To illustrate, consider the following brief description of a segment of instruction from the *Seasons* curriculum that shows how different instructional components can be used in concert to support the implementation of explanation as a metacognitive, sense-making task.

Students interact with the visualizations and acquire new ideas, observations and evidence to add to their repertoire of pre-existing ideas. For example, some key ideas and observations that might serve to counter the validity of a distance-based understanding and provoke further reflection are:

- Earth’s orbit is very nearly circular.
- Earth is positioned in its orbit farthest from the Sun in June and closest to the Sun in December (because Earth’s orbit is not a perfect circle, there are minor changes in distance between the Sun and Earth throughout the year).
- Different locations on the Earth experience different seasons at the exact same time of year (e.g., in December it is wintertime in the United States and summertime in Australia).

An ensuing sequence of instructional prompts guide students in weighing their evolving repertoire of ideas to determine which ones might be appropriate to use as supporting or opposing evidence for say, a distance-based explanation for seasons. (As they complete the five investigations in the unit, students encounter and are asked to respond to an array of possible

alternative explanations—distance being just one out of a number of presented alternative viewpoints.) Students may realize as they work through these prompts that they lack sufficient evidence for certain claims (e.g., that the Earth’s orbit is highly elliptical), that some ideas may not be particularly useful for constructing a causal explanation (e.g., leaves change color in the autumn and flowers are in bloom in the spring), or that a number of their ideas can plausibly be applied as evidence for a particular claim (e.g., Earth’s tilt affects global temperature patterns). Afterwards, students write (and subsequently revise) their explanation for seasons, with the specified goal of developing an explanatory account that best incorporates all of the supporting evidence that they have accumulated.

Each instructional activity component described above underscores the overarching framing of explanation as a learning task aimed at supporting students in integrating their repertoire of ideas and resolving any inconsistencies that may arise during that process. As students work through the investigations in the unit, they continue to iteratively refine their explanations to better reflect their evolving pool of accumulated ideas. Providing an intersecting network of instructional scaffolds (all aligned towards the same instructional goal—in this case, to support explanation as a process for sense-making and developing coherence) ensures that students are not asked to explain in “isolation” as with an evaluative assessment task (i.e., can you demonstrate a correct understanding or not, as seen for the *A Private Universe* interviewees) but rather in response to a body of rich intellectual stimuli (i.e., conceptual food for thought) that students can react to and engage with. This approach more constructively frames explanation as an embedded formative assessment task (Shepard, 2005), one that promotes the view of explanation as a constantly evolving and iterative learning process.

Reflection

This work builds from the perspective that instruction should encourage students to view their own thinking and cognition as responsive to evaluation, reflection and improvement (Dweck & Leggett, 1988; Ertmer & Newby, 1996; Lin, 2001; White & Frederiksen, 2000, 2005). Aside from promoting the beneficial outcomes that can result from metacognitive learning (summarized in Chapter 2), “supporting reflection is critical... because learners are frequently adverse to reflection” (Quintana, Zhang, & Krajcik, 2005, p. 242). Students may find reflection difficult to engage in because of the abstract and obscure nature of meta-level cognitive processes, which are often not the primary focus of instruction or discussion in classrooms. In *Seasons*, I attempt to demystify reflection and other metacognitive processes by providing scaffolding that strives to make these activities more explicit, concrete and transparent to students (Quintana, Zhang, & Krajcik, 2005).

Interestingly, reflection and explanation both appear to function in similar ways to support sense-making and growth in knowledge. Much like explanation, reflection can help learners to become aware of and identify deficiencies or gaps in knowledge (Bell & Davis, 2000; Bielaczyc, Pirolli, & Brown, 1995; Chi, de Leeuw, Chiu, & LaVancher, 1994; Davis, 1996, 1998, 2003; Davis & Linn, 2000; Heywood & Parker, 2010). Thus like explanation, reflection can support the integration of new information with prior knowledge by directing the learner’s attention to

conflicts that require resolution or weaknesses that require strengthening. As I discussed in Chapter 2, the intersection between explanation and reflection may stem from the ability of explanation to operate on two levels—as a cognitive as well as metacognitive task (Alevan & Koedinger, 2002; Bielaczyc, Pirolli, & Brown, 1995; Chi, Bassok, Lewis, Reimann, & Glaser, 1989); that is, explanation can activate the meta-level awareness that supports self-evaluation and reflection.

In *Seasons* I build upon this natural synergy by using an interconnected network of scaffolding that weaves explanation with reflection to mutually reinforce one another: Reflection activities invite students to draw upon their ideas to explain (reflection supports explanation) and the explanations that students construct subsequently serve as tangible artifacts of understanding for students to reflect and improve upon (explanation supports reflection). Reflection prompts in the unit also motivate student interaction with the visualizations and promote knowledge integration by calling awareness to weak or missing links in knowledge (i.e., adding ideas) and drawing attention to the lack or misuse of evidence in explanations (i.e., reflecting upon and refining ideas).

Encouraging the use of meta-explanatory expertise (i.e., the mindful awareness and reflection upon the process of explaining itself) can support students in using explanation to improve understanding and learning. But perhaps just as importantly, the promotion of meta-explanatory expertise can lay a foundation for helping learners to develop their general skill and proficiency with constructing and evaluating scientific explanations. This work thus not only addresses the instructional domain and inquiry goals for seasons indicated by the national and California science content standards (California Department of Education [CDE], 1998; National Research Council [NRC], 1996; Next Generation Science Standards [NGSS], 2013) but the call to support the development of learners' scientific literacy as well (American Association for the Advancement of Science [AAAS], 1993; National Research Council [NRC], 1996, 2007).

Seasons Design Motivation and Objectives

This design work was motivated by the extensive body of research documenting the many difficulties encountered when teaching students about the seasons. It seemed that two of the most significant challenges—that of helping students to understand the impact of changing light intensity while relinquishing the erroneous perception of distance as being key—might be addressed by leveraging the unique capabilities and affordances of dynamic visualizations. In addition, the complex, multi-faceted knowledge framework that I presented for seasons earlier (refer back to Table 3.2) suggested a need for instructional scaffolding designed to address and work against these challenges. In particular, it seemed that instruction emphasizing explanation and reflection might prove helpful for getting students to re-evaluate their prior understandings and to become aware of the inconsistencies between their beliefs and the evidence obtained from the unit visualizations for explaining seasons.

About the Seasons unit. *Seasons* uses dynamic visualizations and supporting instruction to help students develop coherent explanations using their gathered observations and experimental data from the visualizations. Five guided inquiry investigations cover a set of conceptual topics critical for developing an integrated and robust understanding of the phenomenon of seasonal temperature changes (the key conceptual targets for each investigation are shown in Table 3.4). Each visualization is embedded within a network of supporting instructional scaffolds that encourage students to work towards coalescing their diverse repertoire of ideas into more coherent and normative explanatory accounts for seasons through iterative cycles of explanation and reflection. Embedded instructional prompts also guide students to engage with the four knowledge integration processes described earlier (Linn & Eylon, 2006). For example: (1) prediction or open brainstorm prompts preceding the visualization *elicit pre-existing ideas*, (2) experimentation questions and goals guide students to search for and *add normative ideas*, (3) use of an idea management tool for tracking and evaluating collected ideas and evidence helps students to *develop criteria for distinguishing ideas*, and (4) students write and reflect upon their own explanations as well as the explanations of other students to *sort and refine ideas*.

Seasons Inquiry Investigations	Key Conceptual Targets for Instruction
Investigation D Sun-Earth Distance and Shape of Earth's Orbit	<ul style="list-style-type: none"> • The shape of Earth's orbit is very nearly circular. • Earth's orbit can appear highly elliptical depending on the viewer's perspective. • Earth is closer to the Sun in December than in June.
Investigation F Earth's Tilt and Hours of Daylight	<ul style="list-style-type: none"> • Changes in hours of daylight occur because of Earth's tilt. • The hours of daylight observed vary according to latitude. • Without tilt, the hours of daylight would remain constant throughout the year at all latitudes.
Investigation L Light Intensity and Power Absorbed by a Solar Panel	<ul style="list-style-type: none"> • The percentage of light received by a solar panel depends upon the angle of incidence. • The power absorbed by a solar panel placed varies depending on latitude and the time of year.
Investigation P Temperature Patterns Around the World	<ul style="list-style-type: none"> • Temperature patterns for cities on Earth throughout the year are different depending on latitude. • Not all cities experience the four seasons. • Temperature patterns between the Northern and Southern Hemispheres are reversed. • A city at the Equator experiences very little temperature change throughout the year.
Investigation T Earth's Tilt and Temperature Patterns	<ul style="list-style-type: none"> • Earth's tilt results in seasonal temperature patterns. • Temperatures would remain pretty constant without tilt.

Table 3.4. Overview of key conceptual targets for the five guided inquiry investigations in *Seasons*.

The *Seasons* unit was authored using the Web-Based Inquiry Science Environment (WISE; <http://wise.berkeley.edu>; Bell, Davis, & Hsi, 1995; Linn, Clark, & Slotta, 2003; Linn & Slotta, 2000), a free, online and open-source platform available for designing and implementing science inquiry activities. WISE projects are structured by an “inquiry map” (Linn, 2006) that guides students through a designed sequence of activities and prompts (Figure 3.7). Teachers can monitor ongoing student work and progress through the WISE Teacher Dashboard.

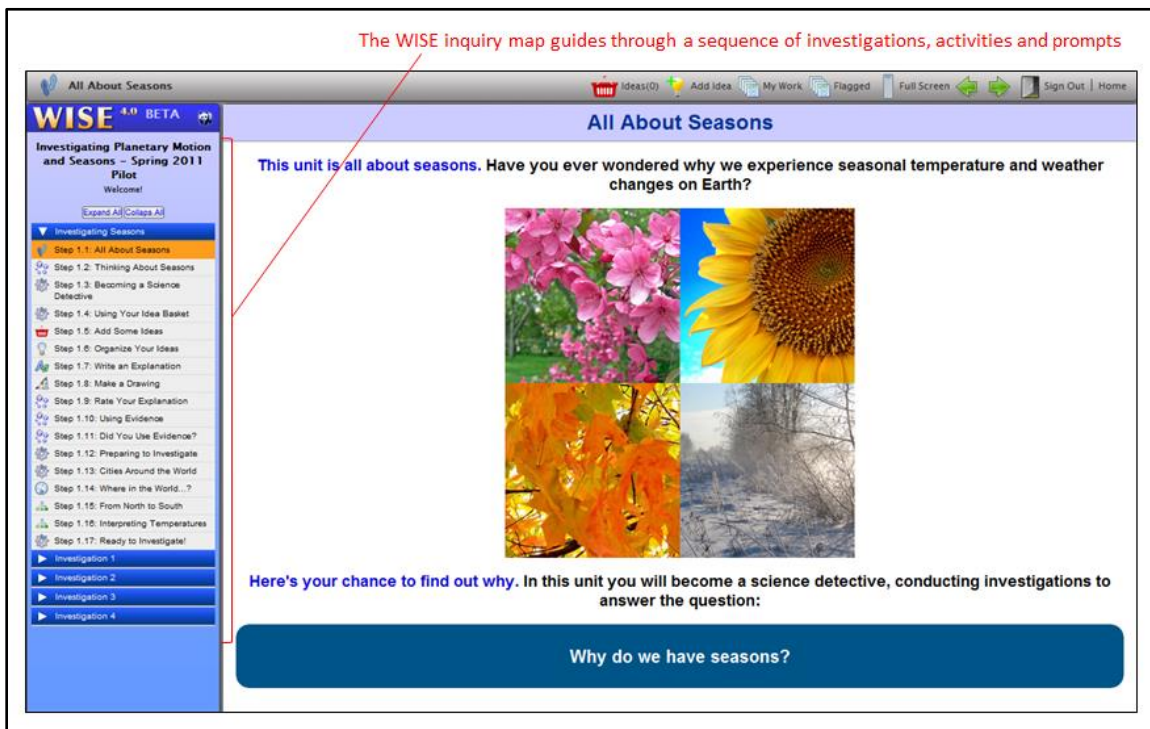


Figure 3.7. The WISE environment and inquiry map.

Theoretical and design commitments for *Seasons*. The work I describe in this chapter concerns the design and use of the curricular materials for *Seasons*—namely the dynamic visualizations and supporting instructional scaffolding. This work was guided by several theoretical and design commitments (Sandoval, 2014). I gave a general-level overview of these commitments in the conjecture map given in Chapter 2 (refer back to Figure 2.1). In this chapter I unpack some of the ideas presented in the conjecture map by providing further explication and detail about the commitments underlying the design work for the visualizations (Table 3.5 ahead) and the instructional scaffolding (Table 3.7 ahead).

Data sources for design decisions. The following data sources were used to inform the design iterations and decisions for the visualizations and instructional scaffolding in the unit: comments and feedback from research group members and colleagues during in-house testing,

observation notes made during classroom visits and my informal discussions with students, and videotaped data of student pairs working in the unit.

Development and Iterative Refinement of *Seasons* Visualizations

This section details the design process behind the development of the dynamic visualizations for *Seasons*.

The design team. The visualizations in the unit were designed and developed in partnership between members of the Linn Research Group at UC Berkeley's Graduate School of Education and educational technology developers at the Concord Consortium. As such, the team consisted of educational researchers and learning scientists as well as educational technologists and software programmers. As the main author and researcher for *Seasons*, I led and coordinated the development and refinement of the six visualizations in the unit. Our development approach was a highly interdisciplinary and collaborative one, with different team members bringing to the table complementary and relevant areas of expertise, including: deep science content and disciplinary knowledge (with physics, astronomy, and seasons in particular), extensive teaching and classroom experience, and backgrounds in educational research, inquiry curriculum development, modeling, programming and educational technology design.

Review of prior work and existing resources. We began by reviewing the research literature on seasons and astronomy education for middle and high school students. We also referred to our prior observations of students' (as well as our own!) conceptual difficulties in grappling with the topic. Drawing upon these sources of information, we identified a set of central scientific understandings that we wanted the visualizations (and consequently, the unit overall) to address. These are the key conceptual targets given previously in Table 3.4.

We then turned our attention to searching for and reviewing the multimedia resources already currently available. These included static diagrams (from traditional textbooks as well as online websites), videos and animations, and interactive models and visualizations (including the library of PhET interactive simulations developed at the University of Colorado Boulder; Wieman & Perkins, 2006). Although we were inspired by the wide number and diversity of available materials we came across (seasons is a highly popular topic for science instruction given students' documented difficulties), we did not discover a set of existing models or visualizations that adequately addressed our set of key targeted concepts as we had envisioned. It seemed that the development of a suite of interactive visualizations addressing these identified target concepts might be a useful and valuable contribution to the existing pool of resources for science and astronomy instruction.

Use of WebGL and NetLogo. We built the visualizations using WebGL (Web Graphics Library; a newly available JavaScript Application Program Interface when we began our development work on *Seasons*) and NetLogo (a multi-agent programmable modeling environment often used for simulating scientific phenomena for educational contexts). Although we were unaware of it

at the time, the decision to use WebGL was, in hindsight, ultimately an ambitious one that would take us down a path lined with a number of unexpected difficulties and challenges. From our initial brainstorming discussions however, we saw the new availability of WebGL as a unique opportunity to take advantage of its powerful affordances to design cutting-edge interactive 2D and 3D graphics—ones we thought might more effectively model and represent the complexity of seasons for supporting students’ investigations. As we eventually discovered later, using WebGL to build the visualizations impacted our development and implementation work in consequential ways that (again, with clear 20/20 hindsight) we had not foreseen but should have considered and weighed more carefully from the outset.

The visualizations and unit inquiry activities. In total, we developed, tested and iteratively refined a set of six visualizations (four with WebGL and two with NetLogo). These visualizations function as the primary investigation spaces for students in *Seasons* to explore and gain exposure to our identified key conceptual targets (see again Table 3.4). The unit uses the following inquiry activities to promote the development of students’ conceptual understandings:

- Identifying global temperature patterns (for different latitudes at different times of the year).
- Analyzing changes in Sun-Earth distance and the shape of Earth’s orbit.
- Examining the effect of Earth’s tilt on temperature patterns and hours of daylight.
- Observing why sunlight intensity changes over the year and the resulting impact of this change.

These inquiry activities served as a springboard for the development of the five inquiry investigations that comprise *Seasons*:

- **Investigation P:** Temperature Patterns Around the World,
- **Investigation D:** Sun-Earth Distance and Shape of Earth’s Orbit,
- **Investigation T:** Earth’s Tilt and Temperature Patterns,
- **Investigation F:** Earth’s Tilt and Hours of Daylight, and
- **Investigation L:** Light Intensity and Power Absorbed by a Solar Panel.

Inquiry learning goals motivating design work. With a basic structural outline in mind for the unit curriculum and investigations, we then brainstormed three inquiry learning goals that encapsulated *how* we envisioned the visualizations supporting student learning about and inquiry into the seasons. In short, we wanted to:

- Help students realize that the small changes in Sun-Earth distance throughout the year *cannot* explain seasons. (Earth’s orbit is nearly circular and in fact, Earth is closest to the Sun in December and farthest from the Sun in June.)

- Help students understand why Earth’s tilt causes the sunlight intensity we receive to change throughout the year (i.e., assist students in connecting between a first-person and third-person view of the Sun-Earth system), and what the impact of this change is on global temperature patterns.
- Help students manage their inquiry with the visualizations (e.g., making observations, experimenting with variables, understanding collected data) and conceptual sense-making.

In summary, we sought to develop an integrated set of visualizations that would help students to understand the importance of light intensity (a challenging normative conception for students to grasp) as well as the lack of impact of Sun-Earth distance (a common misconception that students struggle to let go of). We also wanted to include a number of user features to help students conduct and make sense of their inquiry experimentation activities with the visualizations.

User features to promote and support inquiry. Throughout the design process, we experimented with including a number of inquiry-supporting user features for the visualizations (indicated in a screenshot of a WebGL visualization in the unit, see Figure 3.8) that put into practice the design principles identified by McElhane (2010) for promoting KI and coherence:

- **Manipulable and linked representations of different perspectives of the Sun-Earth system.** Users can switch between preset “top” and “side” views for each perspective (“Earth from Space” and the “Sun-Earth System”). Clicking on a view choice moves *both* perspectives simultaneously to the desired view. Each perspective window also allows for interactivity and manipulability (Blumenfeld et al., 1991, as cited in Edelson, Gordin, & Pea, 1999); for example, in the “Earth from Space” perspective users can use the mouse to drag the Earth around to a desired orientation.
- **Features that encourage experimentation and sense-making.** Users can adjust variables (such as “month” and “city”) to run different experimental trials. Both perspective windows subsequently update to reflect the indicated variable choices (e.g., a latitude marker appears on the Earth indicating the location of the selected city). Prior to running each experiment, users are required to make a prediction (in this case, what temperature they expect to see for city “X” during month “Y”). Also, a column in the data collection table (labeled “season?”) encourages users to make sense of the data they have just collected in order to promote a more mindful and deliberate experimentation mindset (e.g., “Huh... If Canberra, Australia experiences 65 °F weather in December, maybe the season isn’t winter as I predicted... It looks like it’s really summer instead...”) rather than a rote “plug and chug” mentality (e.g., “Let’s just go through all the variable possibilities so we can move on to the next step...”).
- **User controls for data collection and analysis.** Users can keep track of their experimental trials with various user controls and “record-keeping tools” (Edelson,

Gordin, & Pea, 1999, p. 401) such as the data collection table (which allows for data sorting) as well as a user-controlled graph (e.g., students can select which data points to display for comparison and analysis).

Table 3.5 below summarizes the theoretical and design commitments that motivated and guided the design and development of the visualizations in *Seasons*.

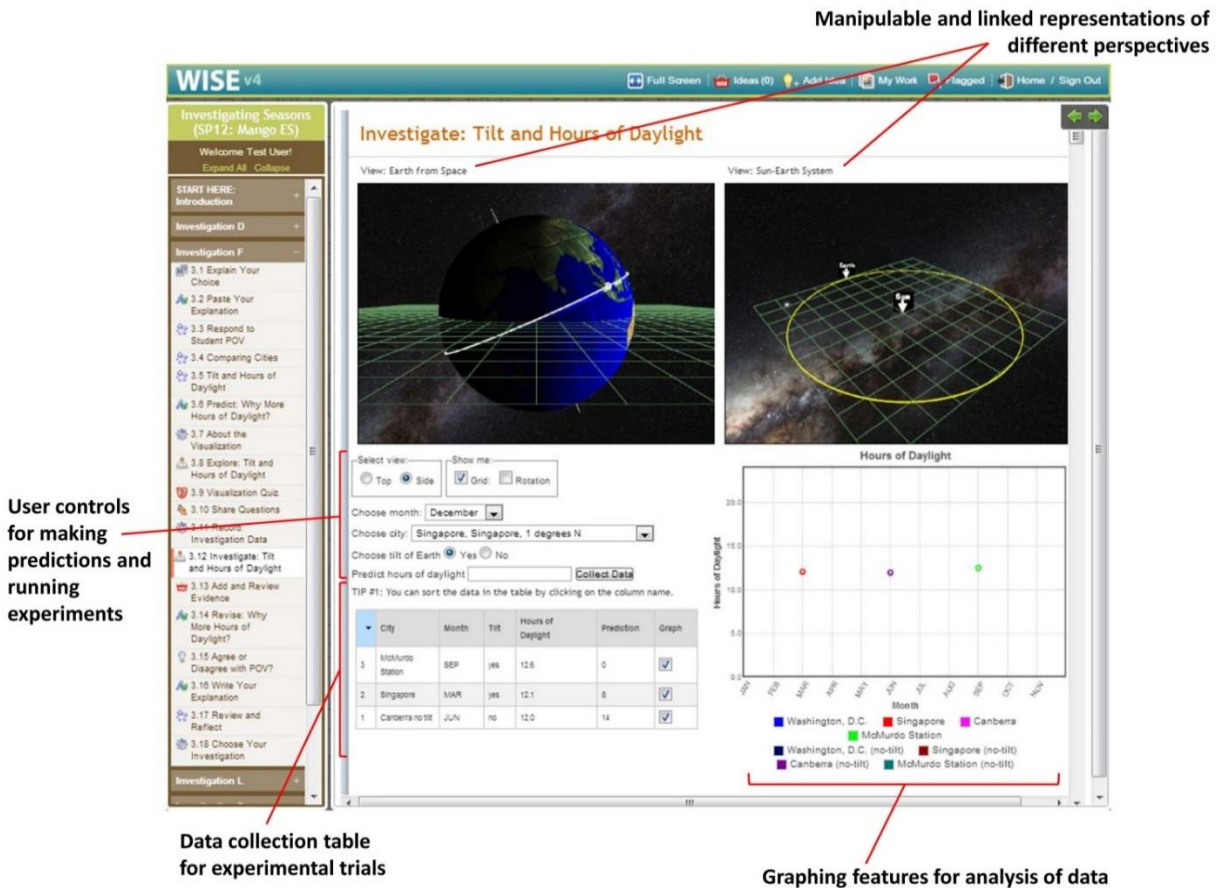


Figure 3.8. Screenshot of a WebGL dynamic visualization in *Seasons* with inquiry-supporting user features highlighted.

Instructional Goal <i>Desired cognitive task</i>	Theoretical Rationale <i>How the goal supports learning</i>	Design Objective <i>Specific approach taken to achieve goal</i>
Make connections between different perspectives	Comparing different representations can highlight informative similarities and distinctions for additional exploration and investigation	Present linked and interactive representations that give different perspectives of the same phenomenon for users to inspect and control

Engage in exploration and experimentation	Experiment results can provide evidence to support ideas, motivate follow-up investigations into questions of interest or encourage the refinement of understanding	Embed supports and interactive features within the visualization interface to promote learner-directed explorations
Reflect on and make sense of observations, ideas and evidence	Persistent visual records can allow for comparisons of different trials to reveal useful relationships or distinctions that support the integration of ideas	Provide record-keeping tools for tracking, monitoring and making comparisons between experimental trials

Table 3.5. The primary instructional goals, theoretical rationale and design objectives for the dynamic visualizations in *Seasons*.

Iterative testing and refinement towards design solutions. We took an iterative approach towards the design and refinement of the visualizations. Working from our specified design goals, we sketched our ideas for possible user interfaces using both high-tech (i.e., PowerPoint) and low-tech methods (i.e., pencil and paper), scrutinized and discussed any issues with the proposed interface, and then proceeded with creating software prototypes. Through weekly team discussions, frequent in-house testing (among ourselves and with research colleagues) and observations made during classroom implementations with teachers and students, we identified and made any necessary modifications (e.g., adjustments to improve ease of use, visual clarity or the underlying mathematics for modeling the phenomenon). We repeated this process of improvement and refinement periodically over a period of five years, from January 2010 through May 2015. Table 3.6 highlights some of the inquiry user features of the WebGL visualizations (organized by instructional goal as specified previously in Table 3.5) and the design solutions we implemented in response to the findings from in-house testing and classroom observations. A representative screenshot of the current user interface for the WebGL visualizations in *Seasons* is shown in Figure 3.9.

Inquiry-Supporting User Feature	Rationale for Feature	Findings from Testing and Classroom Observations	Design Solution Implemented
<i>Instructional goal: Make connections between different perspectives</i>			
Interactive perspective windows allow the user to select between “top” (polar) and “side” (equatorial) view options. User can drag each view 360 degrees in all directions.	Provides user the ability to manually explore and “look around” within each perspective window by using the mouse to grab and turn the view in any desired direction.	Students found the interactive views difficult to accurately manipulate and consequently confusing. We had expected this user feature to be one of the most informative and powerful advantages of using WebGL. Unfortunately, despite sustained efforts to debug and implement this functionality, we were unable to do so.	We constrained the dragging functionality to 180 degrees around predetermined axes or planes of rotation. (This ended up being much more informative for students.) We kept the “top” and “side” instant view options, which students used frequently during their explorations.

Perspective views refresh and update in response to inquiry variable inputs designated by the user (e.g., latitude line is highlighted by identifying color for the selected city; the orientation of Earth is represented for the selected month).	Visibly connects the state of the perspective view to selected variable outputs by the user. Links the experimental data to the Earth's corresponding physical position and orientation to promote spatial awareness and understanding.	Students attended to either the perspective windows (exploring or playing with the orientation of the Earth) or experimentation controls (adjusting variables and gathering data), but not the two in conjunction with one another (as we had hoped they would). This was the case even though we included highlighting features to connect between the views and experimentation displays.	We adjusted and tweaked the design of the highlighting features to more strongly call student attention to the real-time changes in the perspective views in response to variable selections (e.g., used brighter, more noticeable colors for the latitude lines and increased the contrast between the space background and the Earth).
A "spaceship" icon visible in the perspective windows helps the user to orient to and shift between the "Sun-Earth system" and "Earth from Spaceship" views.	Gives the user something concrete to orient around in order to more easily connect and translate between each perspective window.	Students either did not understand or missed the spaceship icon (most likely because the icon is not explicitly discussed in the instructional curriculum).	We redesigned the spaceship icon to make it more identifiable and useful as an orienting image between the two perspective windows.
<i>Instructional goal: Engage in exploration and experimentation</i>			
Pop-up hint screens provide important information and details for using the visualizations.	Directs attention to available interactive features for observation and experimentation and also reminds the user of key inquiry goals.	Students seemed to view the hint screens as unimportant obstacles to interaction with the visualization and often opted to bypass them in quick succession without reading any of the content.	We embedded important information and inquiry goals into the instructional pages and prompts (which required students to generate responses) preceding the visualization.
Controls give user the option to change the visualization running speed and turn the rotation of the Earth and Earth's tilt "on" or "off".	Allows the user to speed up, slow down or stop the visualization for closer inspection and to determine the impact of Earth's tilt on the variable of interest (e.g., temperature, hours of daylight).	Students appreciated the ability to stop and start the rotation of the Earth. They also found it informative to compare data collected between the "tilted Earth" and "no-tilt Earth" scenarios. Most students did not notice or make use of the visualization speed slider bar.	We kept the visualization speed slider bar as an optional control feature for students, but set the default rate at an optimal value (i.e., slow enough to encourage informative observations and fast enough to avoid long wait times and frustration).
<i>Instructional goal: Reflect on and make sense of observations, ideas and evidence</i>			
User must enter in prediction values and respond to reflection prompts before and after receiving data output for each experimental trial.	Requires user to slow down and make predictions or reflect upon each data trial to encourage more mindful and deliberate, directed experimentation.	Some students found the prediction and reflection features within the visualization interface tedious but others enjoyed seeing if their initial guesses matched up with the resulting data output.	We removed the reflection prompt but kept the prediction prompt since students enjoyed this feature more (and often intuitively reflected on discrepancies between their predictions and the data).
Data table and graph are populated as the user runs experiments and generates data. The user can sort the data using table column headers and can select which data rows to display in the graph.	Encourages the user to interact with and explore the collected data set to discern useful or interesting patterns for closer investigation.	Students did not engage with the interactive features available for sorting the data and displaying selected data points in the graph. Most students worked under the mentality of filling out the available experimental space (i.e., running through all of the possible variable combination) as quickly as they could without engaging in sense-making.	We increased the number of possible variable combinations to discourage a "plug and chug" approach to experimentation. Increasing the number of months to twelve from four (for each season) allowed students to observe completely yearly temperature graphs instead of four isolated time points.

Table 3.6. Iterative refinement of user features in the WebGL visualizations based on team testing and classroom observations.

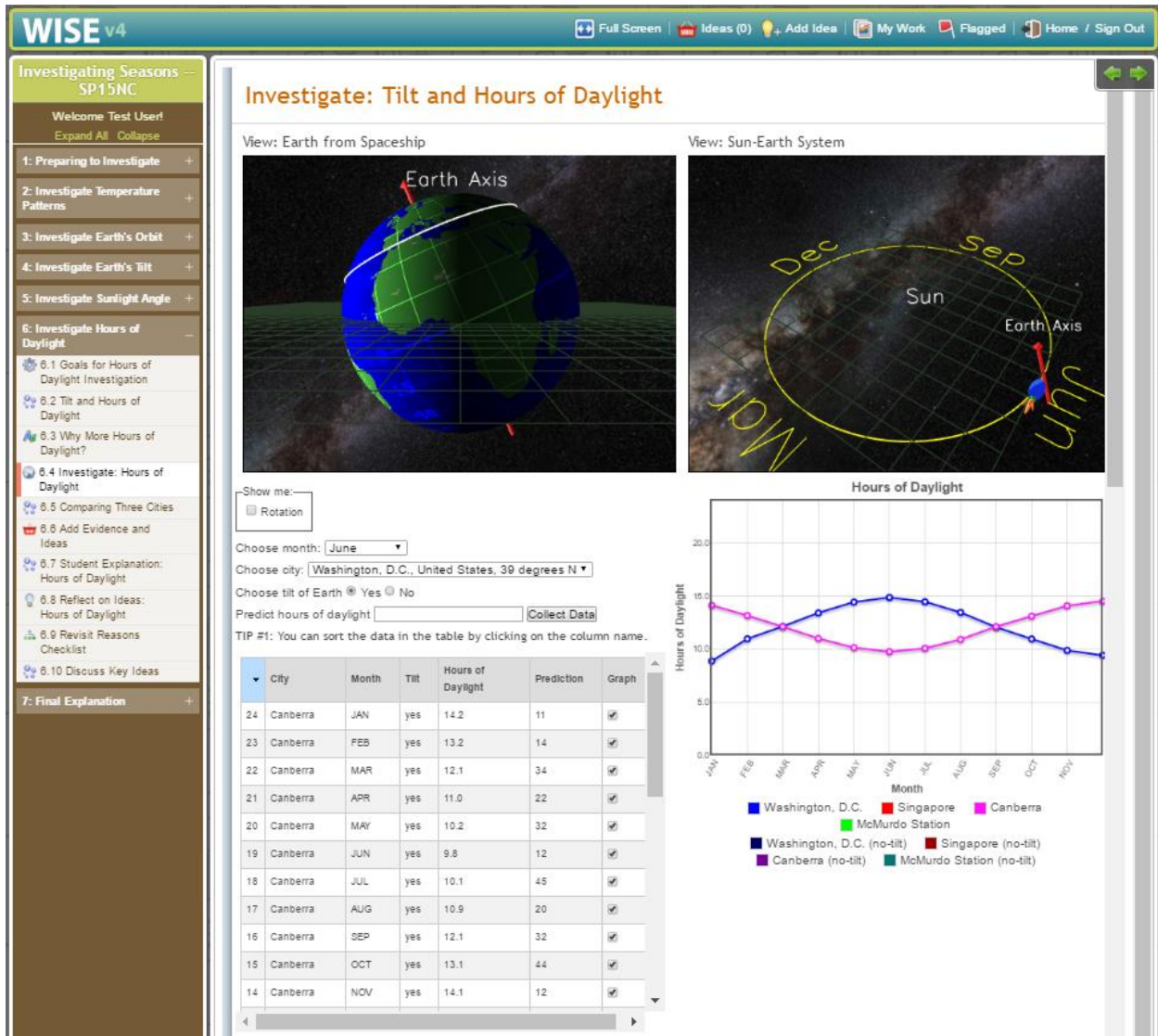


Figure 3.9. Screenshot showing the current user interface for the WebGL visualizations in *Seasons*.

Discussion of specific design cases. To further explicate the development work behind the refinement of the visualizations, I present and discuss next two specific design cases. The first one provides a closer look at the development of the WebGL visualization for Sun-Earth distance. The second case details the developmental evolution of the NetLogo visualizations that address sunlight angle of incidence and light intensity. I selected these two design cases to better illustrate and show the differences between the WebGL and NetLogo models and user interfaces. In addition, these two particular cases allow for an informative discussion of the design solutions we implemented to tackle the two central inquiry learning goals our team had

identified as being of high instructional priority: understanding the causal impact of light intensity (a difficult normative conception for students to grasp) and debunking the perceived effect of Sun-Earth distance (a frequent misconception that students struggle to relinquish).

Design Case: WebGL Visualization for Sun-Earth Distance

Figures 3.10 and 3.11 below allow for comparison of an early version of the WebGL distance visualizations with the final, iteratively refined version. A number of changes and additions were made to the early prototype (Figure 3.10) in order to arrive at the latest version of the visualization (Figure 3.11). I discuss the most interesting and impactful design modifications that we implemented below (while also providing the instructional context and rationale for our decisions):

- **Number of months available for data collection.** We thought initially that allowing students to collect four months of distance data would be enough to communicate the key message of the visualization—that Earth is closer to the Sun in December rather than in June. In later iterations however, we decided that providing access to twelve months of distance data, rather than creating a more tedious number of trials for students to run as we had initially feared, in fact allowed students to more deeply engage with and gain insight into the yearly variations in Sun-Earth distance that correspond with the nearly-circular shape of Earth’s orbit. Although we at first believed that constraining students’ focus to just four months of data would more clearly highlight the counterintuitive Sun-Earth distance information for December compared to June, we were instead nonplussed to discover that while students noticed this discrepancy, they integrated it into their existing beliefs in a rather surprising and unexpected way: Upon noticing that a difference in distance between months existed, many students immediately made the assumption that this difference *confirmed* their understanding of seasons as a distance-dependent phenomenon. Thus they erroneously assumed (without taking a second, closer look) that the data supported their pre-existing ideas without realizing that the direction of the distance difference in actuality presented evidence arguing *against* a distance-based understanding of seasons. Students were often oblivious to this inconsistency in their thinking until explicitly probed to explain by either the researcher or teacher. Even so, in some cases students continued to avoid direct reconciliation of this conflict by instead referring to other distance-based explanatory accounts under continued probing and questioning: “Okay, so maybe the Earth *is* closer to the Sun in December than in June, but that doesn’t matter too much because Earth’s tilt ends up moving where we are on the planet farther away from the Sun, so that’s why it’s colder in December.”
- **Availability and representation of distance data.** With the initial data set limited to just four input months (representing the four seasons), early versions of the visualization did not include a persistent data collection table for students to create a record of their data—only a simple readout display. We made this particular design decision because we wanted students to focus primarily on engaging with the interactive visual display

features for investigating the Sun-Earth distance (described next) rather than getting caught up in the process of data collection itself (i.e., changing inputs to fill out a data table without paying attention to actual data values). When we made the decision to expand the number of months from four to twelve, the inclusion of a data collection table and graphical display began to make sense. The visual representation of the distance data with a bar graph proved to be helpful for getting students to notice and examine monthly differences in distance (as compared to the basic numerical readout in earlier versions of the user interface) although again, many students often mistakenly assumed that the differences in distance observed provided confirmation for, rather than against, their distance-dependent explanations.

- **Appearance and user access of visual overlay features.** We included two overlay visuals (“orbital grid” and “circular orbit”) to help students more carefully inspect changes in the Sun-Earth distance over a year, to make judgements about differences in size and scale between the Sun and Earth, and to compare the shape of Earth’s orbit to that of a perfect circle. After observing students’ use of these features in the classroom, we opted to make the graphic of the Earth’s orbit more noticeable and informative by using a higher contrast, brighter yellow for drawing the orbit line and adding large month labels positioned accordingly. We also determined that the usefulness of the grid for students’ understanding of the minor variations in Sun-Earth distance throughout the year warranted including it as a persistent inquiry feature (rather than an optional “on/off” feature as it first appeared in earlier versions of the visualization).

WISE v4 Full Screen | Ideas (0) | Add Idea | My Work | Flagged | Home / Sign Out

Investigating Seasons (SP12: Mango ES)

Welcome Test User!
Expand All Collapse

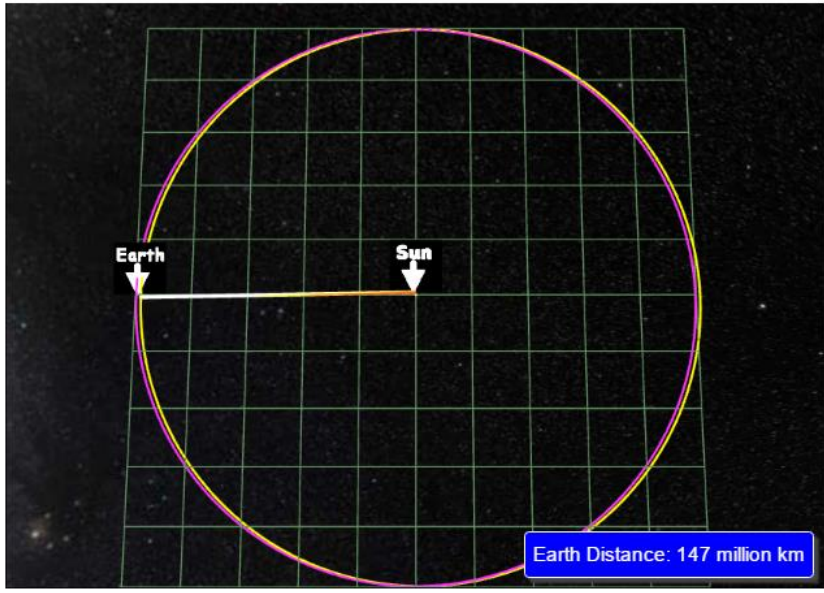
1: START HERE:
Introduction

- 1.1 Thinking About Seasons
- 1.2 Explaining Seasons
- 1.3 About This Unit
- 1.4 Choosing Investigations
- 1.5 Think Like a Science Detective
- 1.6 Three Mysterious Cases
- 1.7 Mysterious Case #1
- 1.8 Mysterious Case #2
- 1.9 Mysterious Case #3
- 1.10 Your Idea Basket
- 1.11 Add Some Ideas
- 1.12 Organize Ideas and Explain
- 1.13 Review and Reflect
- 1.14 Ready to Investigate
- 1.15 Choose Your Investigation

2: Investigation D

- 2.1 Explain Your Choice
- 2.2 Paste Your Explanation
- 2.3 Respond to Student POV
- 2.4 Shape of Earth's Orbit
- 2.5 Predict: Changes in Distance
- 2.6 Share Questions
- 2.7 Record Investigation Data
- 2.8 Investigate: Sun-Earth Distance and Shape of Earth's Orbit
- 2.9 Add and Review Evidence
- 2.10 Revise: Changes in Distance
- 2.11 Agree or Disagree with POV?
- 2.12 Write Your Explanation
- 2.13 Review and

Investigate: Sun-Earth Distance and Shape of Earth's Orbit



Choose view: Top Side Show me: Circular orbit Orbital grid:

Choose month: December

Figure 3.10. An early version of the WebGL visualization for the Sun-Earth distance investigation (Investigation D) in *Seasons*.

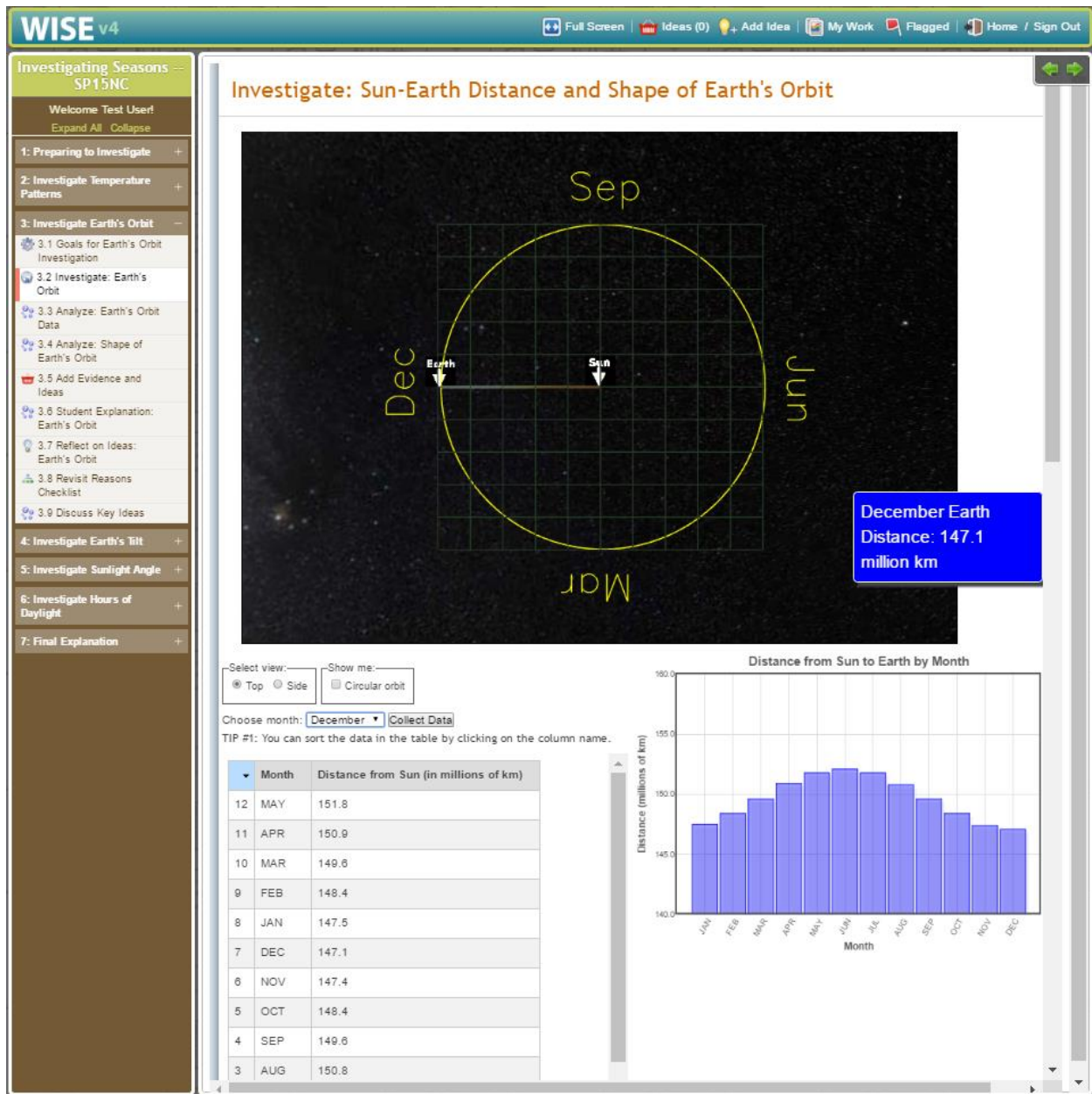


Figure 3.11. The latest version of the WebGL visualization for the Sun-Earth distance investigation (Investigation D) in *Seasons*.

Design Case: NetLogo Visualizations for Light Intensity

Our initial plan had been to build all of the *Seasons* visualizations using WebGL. In our early planning, we had envisioned a final suite of visualizations consistent in appearance, user interface and functionality across all of the unit investigations. However, as we began to encounter unanticipated obstacles that hinted at the greater challenges that might lie ahead, we made the decision to use NetLogo instead to build the light intensity models for the unit. (We had run into a number of difficulties in trying to successfully develop and debug a WebGL prototype for our planned light intensity model despite weeks of troubleshooting and

modifications.) The design trajectory underlying the evolution of the NetLogo visualizations was particularly significant and extensive, making it an interesting design case for deeper discussion. Several striking differences between the early versions of the light intensity models (shown in Figures 3.12 and 3.13) are clearly evident in comparison to their later, iteratively refined counterparts (shown in Figures 3.14 and 3.15).

We determined that in order to adequately represent and convey the concept of light intensity for students, two visualizations (rather than just one as initially planned) were necessary. The first model constrains students' focus to understanding the relationship between the angle of incidence of an incoming "unit" of sunlight and the resulting percentage of that light subsequently captured by a solar panel (i.e., the panel will detect 100% of sunlight coming from directly overhead with a 0° angle of incidence; the panel will detect 0% of sunlight coming in horizontally from either direction with a $+90^\circ$ or -90° angle of incidence). The second visualization extends upon this basic concept by allowing students to observe the angle of incoming sunlight (and consequently, the power absorbed by the solar panel for a set unit of time) for four different cities at four different representational times during the year. We used the same four cities (Singapore, McMurdo Station, Washington DC and Canberra to represent equatorial, polar, and mid-northern and mid-southern hemisphere latitude positions, respectively) and months (March, June, September and December to represent four seasonal time points during the year) as in the WebGL models to maintain consistency and encourage connections and sense-making across all of the visualizations in the unit. Also similar to the WebGL models, in NetLogo the perspective views refresh and update according to the selected variable inputs. However, one significant difference (which was a strong motivating factor behind our initial preference to build the models exclusively with WebGL) is the stark contrast between WebGL and NetLogo for designing flexible and more sophisticated record-keeping features and data visualization tools. For the NetLogo light intensity models, students use a simple text notepad to log and record select data trials of their choosing.

Screenshots of the "percentage of light" models can be seen in Figures 3.12 (early version) and 3.14 (latest version). Screenshots of the "power absorbed" models are shown in Figures 3.13 (early version) and 3.15 (latest version). The key modifications and additions we implemented in our refinement of the NetLogo light intensity visualizations were:

- **Availability of contextual and visual cues.** The first versions of the NetLogo visualizations did not contain any contextual clues to help students connect from the abstract scenarios presented to more familiar and informative contexts. In later versions we added in orienting visual cues (e.g., a blue sky, the grassy ground, yellow incoming sunlight rays, a standing person, and a more prominently visible and labeled solar panel) to help activate students' prior knowledge in order to better promote the contextualization of new ideas and support knowledge-building. We also updated the control features to appear more user-friendly and "clickable", and placed these features in more appropriate and intuitive spaces within each model interface. User interactions with the later versions of the models suggest that these changes were helpful

improvements upon their more minimal and bare-bone earlier counterparts, which many students often remarked were counterintuitive and somewhat clunky in design.

- **Design of sunlight angle selector user feature.** Early versions of the “percentage of light” model utilized a simple slider bar for students to set a value for sunlight angle. While perfectly functional, we redesigned this user feature to support students in developing a more intuitive and “embodied” (Abrahamson, 2009) understanding of how the angle of incoming sunlight translates to an on-Earth view of light from the Sun hitting the ground. The redesigned version of this feature lets students drag an indicator bar along a dial that runs from -90° to $+90^\circ$ to set the angle of incoming sunlight. The position of the set indicator bar on the dial thus corresponds exactly to the angle of incoming sunlight rays shown when the model is run, thereby situating and familiarizing an abstract concept for students (i.e., the connection between a numerical angle setting and how that translates to the visualization of the spatial positioning of incoming light rays relative to a person standing on the Earth).
- **Implementation of scaffolding features for sense-making.** For later versions of the models we added in some visual supports to scaffold students in engaging with and making sense of the visualizations. These included: highlighting an incoming “unit” of sunlight for students to better visualize and compare the percentage of light detected and undetected by the solar panel as a result of changing sunlight angle, and the addition of a “person” icon to help students situate and orient themselves within each perspective window (a “standing on Earth” view and an “Earth in space” view).
- **Clear pairing and sequence of the two models.** Although we viewed the “power absorbed” model as extending upon the “percentage of light” model immediately preceding it in the unit, our first iterations of these models did not present this connection in any obvious or explicit way. In the latest versions of these visualizations, that connection is explicitly and clearly made. The “power absorbed” visualization includes two linked perspective windows: One shows the same first-person (or *egocentric*) view students become familiar with during their explorations with the “percentage of light” visualization. The second view encourages students to connect between their understanding of the concept of the sunlight angle of incidence to a third-person (or *geocentric*) view of the Earth. This change more clearly conveys how the angle of incidence of sunlight (and the resulting amount of power absorbed by the solar panel) can differ at different latitudes for the same time of year.

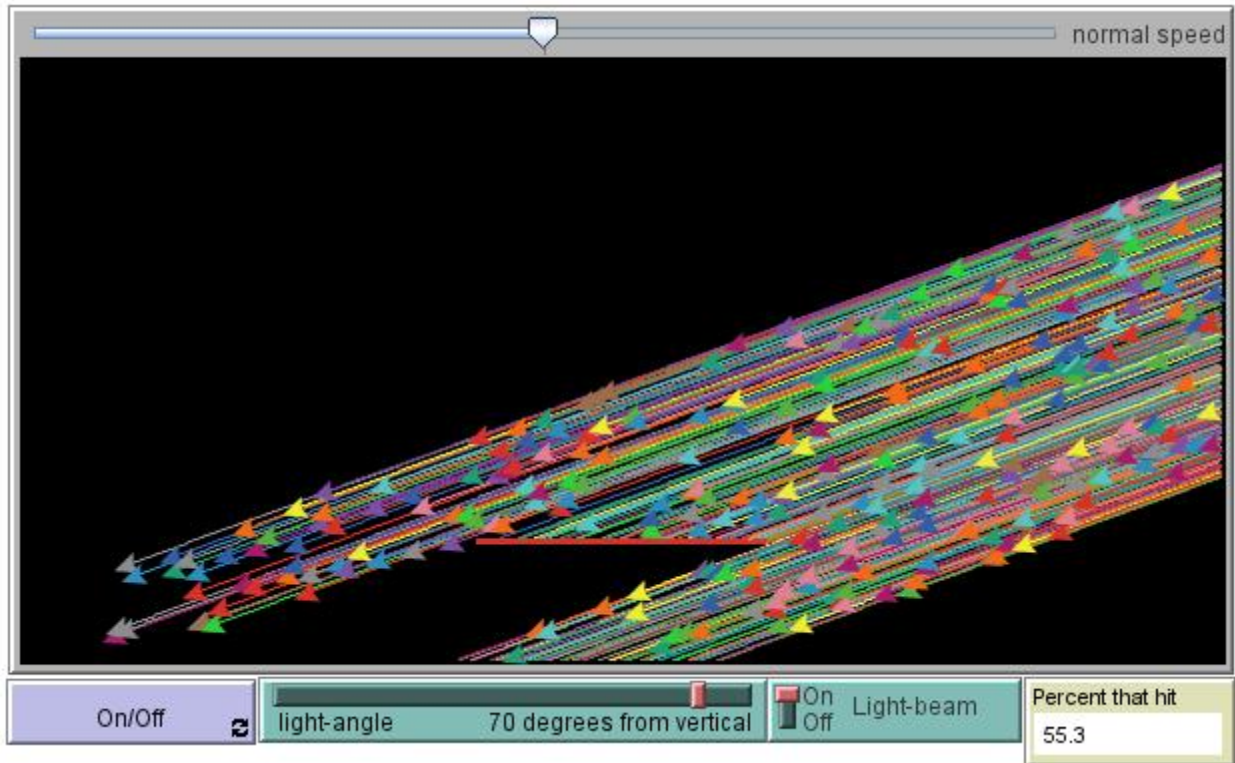


Figure 3.12. An early version of the “percentage of light captured by a solar panel” NetLogo visualization for the light intensity investigation (Investigation L) in *Seasons*.

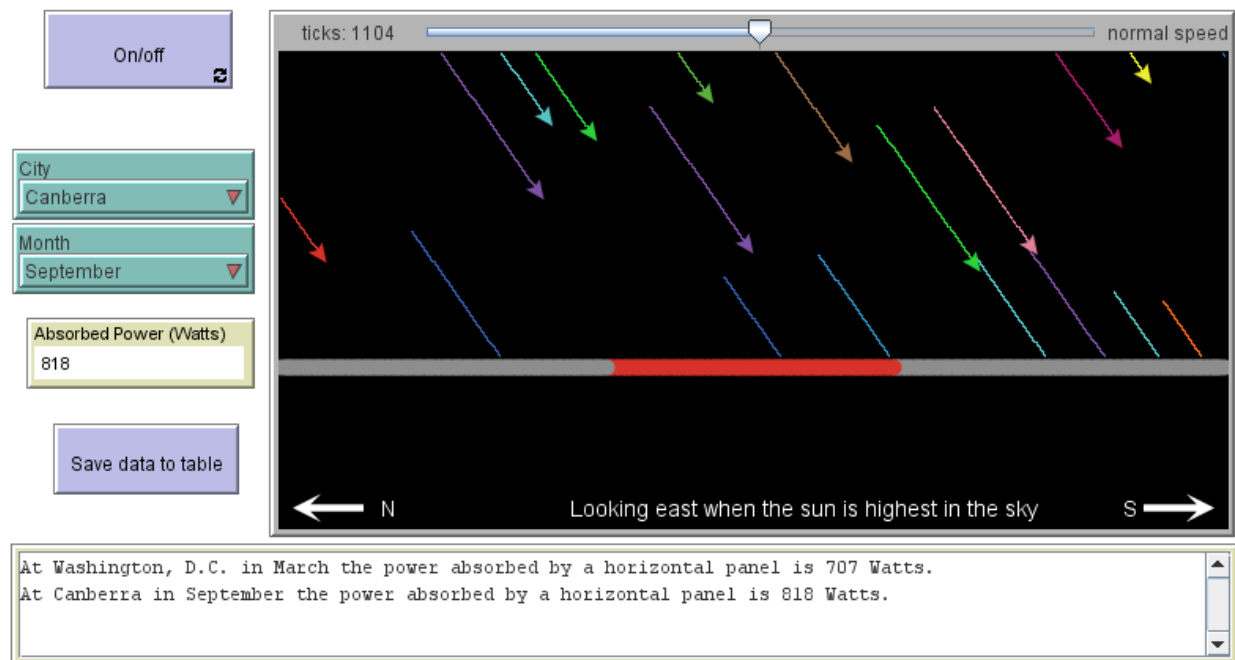


Figure 3.13. An early version of the “power absorbed by a solar panel” NetLogo visualization for the light intensity investigation (Investigation L) in *Seasons*.

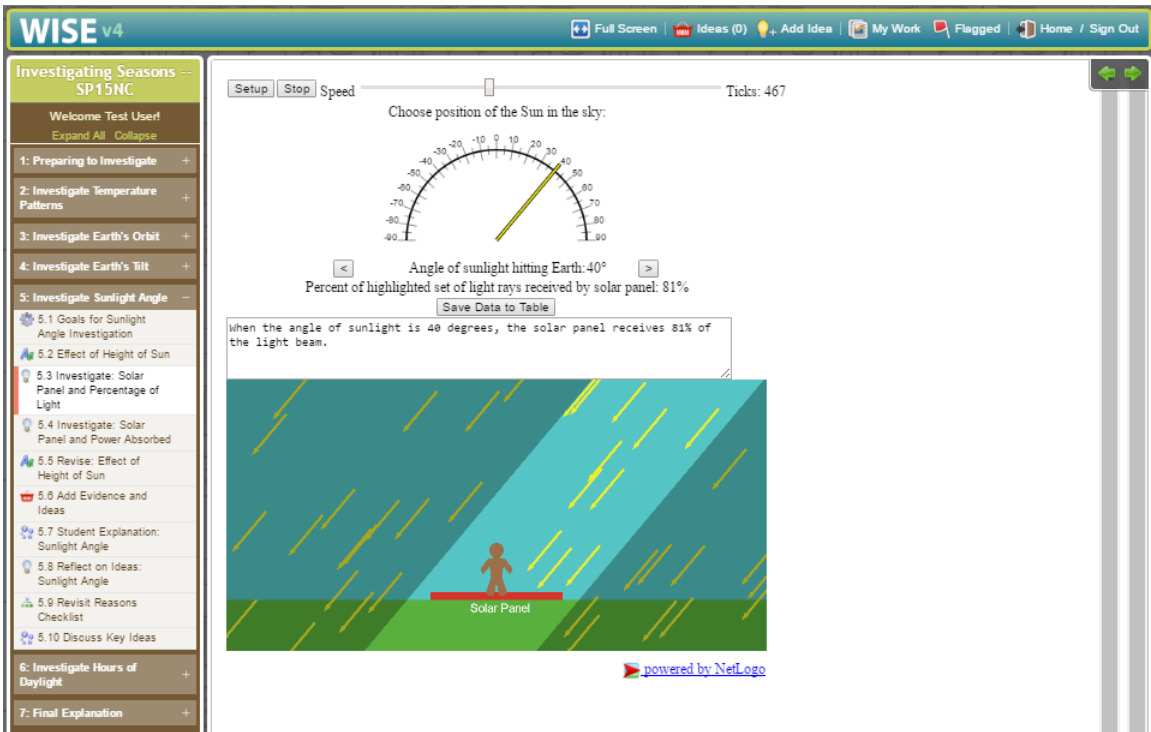


Figure 3.14. The latest version of the “percentage of light captured by a solar panel” NetLogo visualization for the light intensity investigation (Investigation L) in *Seasons*.



Figure 3.15. The latest version of the “power absorbed by a solar panel” NetLogo visualization for the light intensity investigation (Investigation L) in *Seasons*.

I conclude discussion of this design case by sharing some thoughts about possible directions for future development work to extend the usability of the NetLogo light intensity models. Reasonable (and potentially even more impactful) next steps would be to build upon the “power absorbed” model by implementing an expanded version that includes an “Earth’s tilt” on/off toggle button to allow students to compare the differences in power absorption for and between cities with and without the Earth’s tilt. Another desirable modification would be to convert the data output variable from “power absorbed” to “temperature” instead. This is something we tried at the beginning to implement; however, we discovered that far from being straightforward and simple to do, the underlying mathematical assumptions required to accurately generate a temperature output reading were surprisingly complex and nuanced. As a result, we made the decision for the time being to use the power absorbed by the solar panel as a proxy outcome measure for temperature. While we did not think that this was the best or most desirable choice from an instructional perspective (i.e., power absorbed is a more intangible and abstract concept than temperature for most students), from a realistic design and development perspective it was the most feasible workaround and expedient solution available to us at the time.

Design and Use of Instructional Tools and Scaffolding in *Seasons*

We designed the WebGL and NetLogo models not as standalone learning tools to be used in isolation, but as interactive inquiry spaces to be embedded within a supporting network of instructional scaffolds. In the context of education, *scaffolding* refers to the assistance given to a learner by a more knowledgeable “other” (whether a parent, teacher or peer), who modifies the learning task in such a way that the student can successfully complete it (Collins, Brown, & Newman, 1988; Wood, Bruner, & Ross, 1976). Thus “tasks that would otherwise be out of reach” given the learner’s current skills and capabilities become tractable and achievable with the appropriate assistance and guidance (Reiser, 2004, p. 274). With the advent of technology-enhanced learning environments, the notion of scaffolding and the more knowledgeable “other” has since been expanded to include the assistance that software tools can provide that allow learners to accomplish more ambitious tasks (Edelson, Gordin, & Pea, 1999; Reiser, 2004, p. 275). Examples of software scaffolds include tools that help learners to track and manage their inquiry processes (Quintana et al., 2004) and prompts that encourage students to pause and reflect (Davis & Linn, 2000). This section details the use and design of instructional scaffolds in *Seasons* to promote students’ engagement with explanation and reflection.

Theoretical and design commitments. As discussed previously, seasons provides a rich context for involving students in deep critical thinking and sophisticated scientific inquiry. Given the complexity of the topic, curriculum scaffolds should be designed with clear instructional goals in mind in order for students to benefit from instruction. Table 3.7 specifies the theoretical and design commitments underlying the design and use of instructional supports in the unit.

Instructional Goal <i>Desired cognitive task</i>	Theoretical Rationale <i>How the goal supports learning</i>	Design Objective <i>Specific approach taken to achieve goal</i>
Explanation	Reveals uncertainty or gaps in knowledge	Make the process of constructing an explanation using evidence visible and explicit
Reflection	Identification of lack of evidence in explanation or weaknesses in understanding	Provide reflection prompts and activities to help with awareness of weaknesses in understanding (i.e., lack of supporting evidence for explaining) to motivate learning (i.e., inquiry with the unit visualizations)

Table 3.7. The primary instructional goals, theoretical rationale and design objectives for the curriculum scaffolds in *Seasons*.

Instructional scaffolds in Seasons. As seen in Table 3.7, the instructional scaffolding provided in the unit places special emphasis on supporting students with explanation and reflection. Students are encouraged to take a more deliberate and mindful approach towards explanation through the use of the WISE Idea Manager (IM; Matuk et al., 2012, 2013, 2016; Matuk & King Chen, 2011), a scaffolding tool that deconstructs the process of explaining into explicit, visible and tractable steps for students (i.e., a “process visualization” scaffolding strategy; Quintana et al., 2004, as cited in Quintana, Zhang, & Krajcik, 2005, p. 239). By externalizing the process of explanation, the Idea Manager helps students to clarify, organize and restructure their knowledge (de Vries, Lund, & Baker, 2002, as cited in Kuhn & Reiser, 2005, p. 2-3). The second focus of scaffolding in the unit concerns helping students to improve upon their understanding and explanations through self-evaluation and reflection. Reflection prompts can assist students in identifying conceptual gaps where more information and evidence can help to strengthen and build understanding (Bell & Davis, 2000; Davis, 1996, 1998, 2003; Davis & Linn, 2000). A more detailed description of the IM tool and reflection activities in the unit follows next.

The WISE Idea Manager

Seasons makes extensive use of the WISE Idea Manager (IM), a software tool that scaffolds students in developing and writing evidence-based explanations. The IM makes the process of explaining explicit, breaking the task down into two primary components—the Idea Basket and Explanation Builder (Figure 3.16). The Idea Basket (IB) functions as a persistent and dynamic repository for students to store and track their evolving ideas over the course of the project. Ideas added into the Basket (which students can access at any time during their work in the unit) can be annotated (e.g., noting the primary source for the idea), flagged (e.g., indicating importance or uncertainty), tagged (e.g., applying labels to categorize and sort) and modified (e.g., revisiting to revise, delete or restore after deletion). The specific properties of the IB can be easily customized by WISE project authors to adapt to the instructional goals of different units (Figure 3.17). The Explanation Builder (EB) provides a structured organizing space for

students to evaluate, sort and reflect upon the ideas in their basket according to author-provided, relevant criteria. The EB thus supports students' writing of evidence-based scientific explanations by making explicit the connection between the evaluation of evidence and the use of appropriate evidence in an explanation. As with the Idea Basket, the EB organizing space and guiding explanation prompt can be tailored by project authors to meet the needs of different inquiry units (Figure 3.18). Figure 3.19 illustrates how the two components of the Idea Manager (the Idea Basket and Explanation Builder) are integrated as prominent KI learning tasks that support the implementation of the scaffolded knowledge integration framework for instruction (Linn, Davis, & Eylon, 2004) in *Seasons*. The IM serves the dual purpose of providing instructional scaffolding (i.e., supporting students in using their ideas to explain) as well as collecting research and assessment data (i.e., logging of students' evolving repertoire of ideas and how they use those ideas to generate explanations).

The development of the Idea Manager was undertaken by a team of educational researchers and technologists in the Linn Research Group at UC Berkeley's Graduate School of Education. As a core member of the design team, I contributed to the initial brainstorming and conceptualization discussions for the IM, participated in the development and review of prototypes, and implemented and tested the functionality of the tool in classroom studies with students. A more thorough and in-depth discussion of our design process for the IM (as well as the specific design moves we applied to iteratively refine the tool through repeated cycles of testing conducted in multiple classroom contexts) can be found in Matuk et al. (2016).

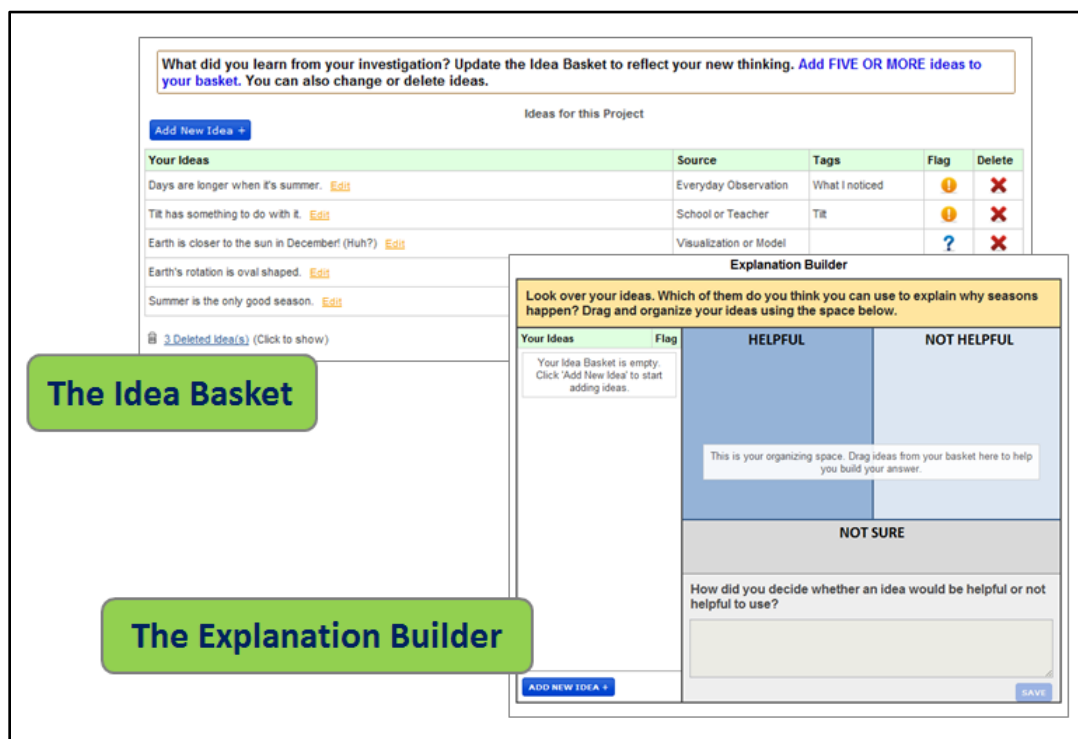


Figure 3.16. The WISE Idea Manager consists of two tools: the Idea Basket (a repository for students' ideas) and the Explanation Builder (an evidence-organizing space for constructing explanations).

WISE v4 Full Screen Ideas (1) Add Idea My Work Flagged Home / Sign Out

Investigating Seasons (SP12: Mango ES)
 Welcome Test User!
 Expand All Collapse

START HERE:
 Introduction
 Investigation D
 Investigation F
 3.1 Explain Your Choice
 3.2 Paste Your Explanation
 3.3 Respond to Student POV
 3.4 Comparing Cities
 3.5 Tilt and Hours of Daylight
 3.6 Predict: Why More Hours of Daylight?
 3.7 About the Visualization
 3.8 Explore: Tilt and Hours of Daylight
 3.9 Visualization Quiz
 3.10 Share Questions
 3.11 Record Investigation Data
 3.12 Investigate: Tilt and Hours of Daylight
 3.13 Add and Review Evidence
 3.14 Revise: Why More Hours of Daylight?
 3.15 Agree or Disagree with POV?
 3.16 Write Your Explanation
 3.17 Review and Reflect
 3.18 Choose Your Investigation
 Investigation L

ADD, REVIEW and REVISE the ideas in your Idea Basket:

- What new ideas did you learn about seasons from using the visualization? Add these ideas to your basket.
- Have any of your ideas changed? If so, you can edit the ideas already in your basket.
- Are there ideas you no longer want to keep? Delete them. (You can always restore them later.)
- Can any of these ideas be used to explain a Mysterious Case? Indicate which MC using the tags under "useful to explain MCs".

Ideas for this Project

Add Idea +

Your Ideas	Got this idea from	Helps me think about	Useful to explain MCs	Delete
Earth is far from the sun Edit	School or a teacher	Effect of Earth distance	Not sure yet if helpful	

[Trash \(0\)](#) (Click to show)

Add New Idea

Type your idea here:
 Sun is hot, which makes summer days warm.

Got this idea from*: Personal experience

Helps me think about* (select all that apply):
 Effect of Earth distance
 Effect of facing the Sun
 Effect of angle of light
 Effect of tilt of Earth
 Effect of city location
 Effect of time of year
 Effect of daylight hours
 None of these effects

Useful to explain MCs*: Choose One:

OK Cancel

Figure 3.17. Screenshot of an Idea Basket curriculum step in *Seasons*. The specific properties of the Basket can be customized by authors to align with the desired instructional goals for the unit.

WISE v4 | Full Screen | Ideas (3) | Add Idea | My Work | Flagged | Home / Sign Out

Investigating Seasons (SP12: Mango ES)
 Welcome Test User!
 Expand All Collapse

START HERE:
 Introduction
 Investigation D
 Investigation F
 3.1 Explain Your Choice
 3.2 Paste Your Explanation
 3.3 Respond to Student POV
 3.4 Comparing Cities
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 3.14 Revise: Why More Hours of Daylight?
 3.15 Agree or Disagree with POV?
 3.16 Write Your Explanation
 3.17 Review and Reflect
 3.18 Choose Your Investigation
 Investigation L

EXPLANATION BUILDER

When asked to explain what causes seasons, some students last year took the point of view (POV) that: "The season we're in depends on if we're facing towards the Sun or away from it." Do the ideas in your basket lead you to AGREE or DISAGREE with this POV? Organize your ideas by dragging them into the different spaces below. **Ready to Explain!**

Your Ideas	Helps me think about	Evidence that leads me to AGREE with POV	Evidence that leads me to DISAGREE with POV
We are close to the sun in December!	Effect of Earth distance	We are close to the sun in December!	
Sun is hot, which makes summer days warm.	Effect of time of year		
Earth is far from the sun	Effect of Earth distance		
Add Idea +		Evidence I am NOT SURE applies in this case	
		Sun is hot, which makes summer days warm.	

Figure 3.18. Screenshot of an Explanation Builder curriculum step in *Seasons*. The organizing space and guiding explanation prompt can be tailored to fit the goals of different inquiry units.

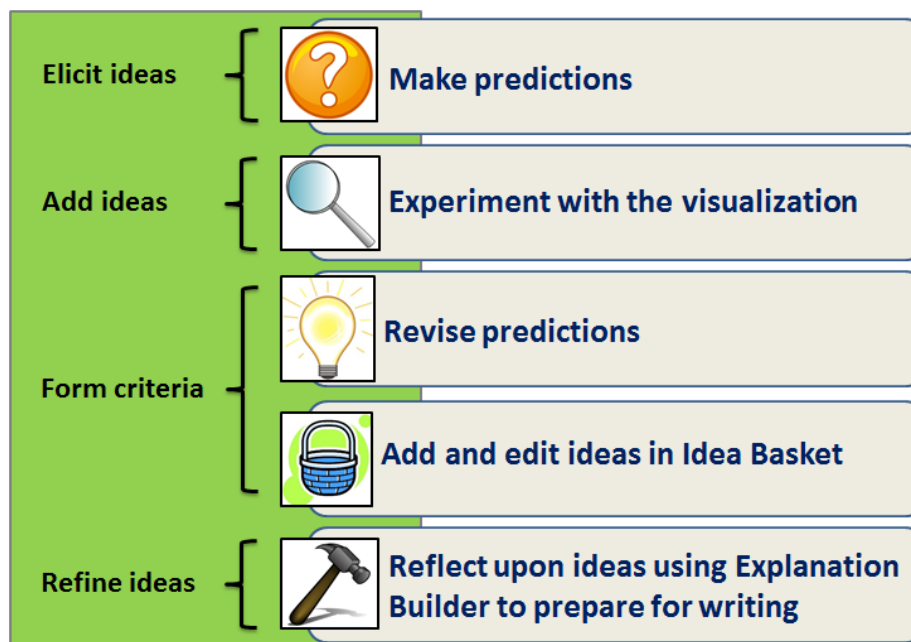


Figure 3.19. The IM (consisting of the Idea Basket and Explanation Builder) scaffolds students’ construction of explanations as integral KI learning tasks in *Seasons*.

Reflection Activities and Prompts

In *Seasons*, I use reflection to engage students in the deliberate thinking and evaluation of their learning experiences for the express purpose of making adjustments for improvement (Ertmer & Newby, 1996; Quintana, Zhang, & Krajcik, 2005; White & Frederiksen, 2005). Reflective learners are better able to adapt and respond to new learning situations (Hatano & Inagaki, 1986, 1992; Lin, Hmelo, Kinzer, & Secules, 1999). Furthermore, reflection can call attention to deficiencies in understanding (Bell & Davis, 2000; Davis, 1996, 1998, 2003; Davis & Linn, 2000), providing the awareness necessary to motivate learners to address identified weaknesses—thus resulting in increasingly more expert and self-improving learning experiences (Ertmer & Newby, 1996; Lin, 2001). For most students however, reflection is a difficult and unfamiliar activity. Consequently, the use of designed instructional scaffolds for promoting reflection becomes critical (Quintana et al., 2004; Quintana, Zhang, & Krajcik, 2005). As indicated already in Table 3.7, the reflection prompts and activities in *Seasons* are designed to help students become aware of weaknesses in understanding (e.g., to notice the lack of supporting evidence in their explanations) in order to motivate their learning efforts (e.g., students’ engagement and interaction with the unit visualizations). Table 3.8 presents the designed reflection activities learners encounter in the unit, organized by three specific instructional goals:

- **Reflection on the collection of evidence and learning with visualizations** to identify critical gaps in knowledge that need to be addressed (see design items 1-3 in Table 3.8). Instructional activities engage students in considering these questions: *What ideas and evidence did I gain from using the visualization? Did I miss any important or key pieces of*

information? Students are encouraged to revisit visualizations to address any identified weaknesses or gaps.

- Reflection on use of evidence for writing, evaluating and revising explanations** to assess how well students’ explanations are supported by confirming evidence, and whether additional support is necessary for strengthening or improving the explanation (see design items 4-5 in Table 3.8). Instructional activities engage students in considering these questions: *Does this explanation contain strong supporting evidence? What additional pieces of evidence would make this explanation more convincing?* Students are prompted to periodically revise their own explanations as they acquire new ideas from the visualizations. Sample peer explanations offer students the opportunity to evaluate an alternative explanation and to make suggestions for improvement.
- Reflection on students’ own evolving understandings about seasons** to determine if their ideas and thinking have changed based upon their investigations and interaction with the visualizations (see design items 6-7 in Table 3.8). Instructional activities engage students in considering these questions: *How has your thinking about the cause(s) of seasons changed? Which ideas do you think are the most relevant or important for explaining seasons?* These end-of-investigation reflection activities encourage students to periodically reflect upon their understandings with the goal of raising awareness of how their explanations for seasons may or may not be changing in response to the instruction. In my research studies examining the impact of a choice-guided model of inquiry, I use these reflection activities (i.e., the reasons checklist and two-step ranking task; see Table 3.8) to frame and motivate choice-making as an opportunity for students to decide for themselves how they wish to proceed with their learning (e.g., to confirm or challenge an existing belief; to investigate or become exposed to an alternative idea not previously considered). I present and discuss my work investigating choice using the *Seasons* unit in greater detail in Chapter 4.

Item ID	Instructional Scaffold for Reflection	Rationale for Design of Activity	Findings from Testing and Classroom Observations
<i>Instructional goal: Reflection on collection of evidence and learning with visualizations</i>			
Item 1	Guiding inquiry questions suggest experimentation goals for students’ use of the visualizations.	Focuses attention on the most informative questions to explore with the visualization— i.e., what data and evidence to collect.	Most students glanced or read quickly through the questions but few used them to guide their use of the visualizations. Many students sought out the researcher or teacher for guidance instead.
Item 2	Post-visualization challenge questions function as conceptual “gatekeepers”: Students must respond correctly to the prompt before being allowed to proceed ahead through the unit.	Allows students to quickly and easily check their understanding of the visualization by responding to a quiz-like item with immediate feedback. (Students who respond incorrectly are	Students who were unable to correctly respond to the challenge questions often did not use the visualization to gather more information. Instead, they resorted to “gaming” the question (i.e., rapidly running through all possible response combinations until hitting upon the correct response). In later iterations I redesigned the item prompts and activated random shuffling of the

		encouraged to return to the visualization.)	response choices to discourage students from mindlessly guessing to bypass the step.
Item 3	An Explanation Builder (EB) idea-sorting activity immediately following each visualization asks students to sort their repertoire of ideas according to specified conceptual categories.	The EB sorting space provides a visual “conceptual map” overview of the investigation topic to help students identify any gaps in knowledge (i.e., areas of the map without ideas).	Students seemed unconcerned about any gaps as evidenced by their work on the EB step. Many did not notice or were unaware of the metacognitive purpose underlying the activity (i.e., developing awareness of key conceptual areas missing ideas or evidence). An earlier iteration of this activity (that was an extension upon Item 1) used the Idea Basket: Students were presented with the list of guiding inquiry questions and asked: Does your Idea Basket contain at least one idea that addresses each inquiry question in this list?
Design Notes	The first iteration of this scaffold (Item 1) required no input from students. As a highly <i>passive</i> activity (i.e., reading only; no conceptual input required), it was easily bypassed and ignored by students. Items 2 and 3 represent subsequent design iterations upon Item 1 that moved towards making the instructional items more <i>active</i> (i.e., scaffolded activities that require a high level of conceptual engagement and effort from students).		
Instructional goal: Reflection on use of evidence for writing, evaluating and revising explanations			
Item 4	A questionnaire of sequenced prompts assists students with evaluating the use of evidence in their written explanations in preparation for conducting additional investigations and later, for revising their explanations.	A sequence of questions breaks down the process of evaluation into smaller, more manageable steps to help students determine whether their explanations are convincing (i.e., supported by ample evidence).	Almost all students found the process of periodically evaluating (and then subsequently revising) their explanations extremely frustrating and bothersome. As they progressed through the unit and were prompted at the end of each investigation to evaluate and revise, students quickly experienced irritation and item fatigue and stopped making substantive revisions, returning instead uninformative responses such as: “Why do I have to do this again?” and “What I already wrote earlier.”
Item 5	Guided assessment of sample peer explanations asks students to indicate agreement/disagreement and to suggest revisions for strengthening the explanation.	Similar to Item 4, the process of evaluation is deconstructed into a sequence of guided questions. The use of peer explanations allows students to critique alternative viewpoints (easier for most students than assessing their own explanations).	Students engaged with this activity (an iterated version of Item 4) substantially more than when asked to evaluate and revise their own explanations. They seemed to enjoy seeing the written explanations and drawings of others (actual student work that I pulled from a previous classroom study with <i>Seasons</i>). The alternative viewpoints shared introduced new ideas that students found more interesting to respond to than revisiting and revising their own ideas.
Design Notes	While an <i>active</i> item requiring a high level of input (similar to Item 4), Item 5 appeared to at least be more motivating in getting students to think about the use of supporting evidence in explanations. Although still a challenging task for many (the successful evaluation and critique of explanations are documented difficulties in the literature; Sato, 2015), students at least seemed more willing to engage with Item 5. This may be because of students’ affinity for holding onto their prior ideas and beliefs even when presented with conflicting ideas during instruction (Chinn & Brewer, 1993, 2001; de Jong & van Joolingen, 1998; Keil, 2006). Revising one’s own conceptual understandings (undergoing deep conceptual change) can be more challenging and discomfiting than noticing the deficiencies and inconsistencies in others’ explanatory accounts.		
Instructional goal: Reflection on students’ own evolving understandings about seasons			
Item 6	A simple checklist at the end of each investigation asks students to indicate which reasons they think correctly explain seasons.	Gives students the opportunity to quickly and easily “check in” at the end of each investigation to track how their thinking about seasons has changed (or not).	As an easy-to-complete item that required little conceptual heavy lifting by students (an item towards the <i>passive</i> end of the instructional scaffolding spectrum), students found this item quick and simple to respond to. Although the motivation factor for this item was quite high (i.e., it had a high response rate from students), I was concerned that its design did not do enough to engage students in mindful reflection (i.e., students might be choosing the same responses

			each time out of habit). This led to a revision of the item, resulting in Item 7.
Item 7	A two-step ranking task at the end of each investigation shows students a set of possible reasons for seasons. Students first indicate all the reasons they think apply, and then designate the one reason they think best explains seasons.	Much like Item 6, engages students at the end of each investigation in reflecting upon their current understanding of seasons. Their responses to the ranking task indicate which reasons they still view as relevant, and which one in particular they deem as the most important (i.e., the primary causal mechanism they believe is responsible).	This item appeared to strike an appropriate balance between being a conceptually and cognitively rich activity (an <i>active</i> scaffolded instructional item) and being low on the frustration scale for students (i.e., easy and simple to respond to). Students seemed to enjoy the drag-and-drop functionality of the item, and the two-step ranking process encouraged more mindful consideration of students' most relevant and top-priority explanations for seasons. Item 7 also had the advantage from a research perspective of providing more informative context and insight into students' evolving understandings about seasons.
Design Notes	The design of Item 6 was an iteration of Item 4, in response to the visible frustration and vocal protests I observed from many students irritated at being asked to continually evaluate and revise their explanations. Although from my perspective as a researcher Item 4 presented the possibility of collecting richer data (i.e., capturing the evolution of students' explanations at periodic time points set throughout the unit, thus gaining an overview of their learning trajectories from the beginning to the end of instruction), the extremely low response rate for Item 4 clearly negated any possible research benefit that I might have initially hoped for. Item 6 was consequently my attempt to enact a design solution that balanced the needs of research (my own) with the needs of the students (a beneficial learning task that did not require too much effort or trigger item fatigue).		

Table 3.8. Summary of the instructional scaffolds designed to promote students' reflection in *Seasons*.

Classroom Implementation and Study Findings

To assess the overall impact and effectiveness of the *Seasons* curriculum unit and students' use of the visualizations and Idea Manager in support of their learning, I conducted a classroom study at a local high school in California.

Study participants. Four classes of earth science students (N = 91) at a socially and economically diverse high school in California studied *Seasons* over the course of ten hours spread out over six class periods. More than three-quarters (76%) of the students were in the ninth grade; the remaining 24% of students were in either the tenth or eleventh grade. Most students worked in pairs to complete the unit. Unpaired students worked alone or joined a pair to work as a group of three.

Assessments and collected data. Pre- and post-unit tests, embedded assessment prompts within the unit, logged data of students' use of the Idea Manager tools (the Idea Basket and Explanation Builder), as well as recorded video footage of student pairs working together through the unit comprise the various sources of data collected for this study. The pre- and post-tests were administered to students individually immediately before and after the unit. Students' pre- and post-test explanations were scored on a scale from 1-5 using a knowledge integration rubric (Linn, Lee, Tinker, Husic, & Chiu, 2006) I designed to measure the coherence

of students' explanations (i.e., how successfully they linked and integrated ideas obtained from the visualizations into their explanations). A higher KI score corresponds to evidence of higher levels of integration between normative scientific ideas. Student work in the Idea Manager (with the Idea Basket and Explanation Builder tools) was coded to analyze how students used the IM and visualizations in the unit to support their learning.

Results and discussion. Our findings indicate that *Seasons* was highly successful in improving students' overall conceptual understandings and explanations. Students made large, significant pre- to post-test learning gains. Furthermore, analysis of logged work with the embedded Idea Manager tools revealed that both the visualizations and IM were used successfully by students to positively impact their learning in the unit. We have presented these findings at meetings and conferences, including at a poster symposium held during the 2011 meeting on Computer-Supported Collaborative Learning conducted by the International Society of the Learning Sciences (see Matuk & King Chen, 2011). I briefly review each study finding in turn below.

Analysis of Pre- and Post-Test Explanations

Student explanations for seasons demonstrated marked improvement after use of the curriculum unit. KI scoring of pre- and post-test explanations indicate that students made large, significant pre- to post-test gains ($M = 2.42$, $SD = 0.88$ (pre); $M = 3.35$, $SD = 0.94$ (post); $t(90) = 7.67$, $p < 0.001$, $d = 1.03$), suggesting that *Seasons* was successful in improving students' understanding of (and explanations for) seasons (Figure 3.20).

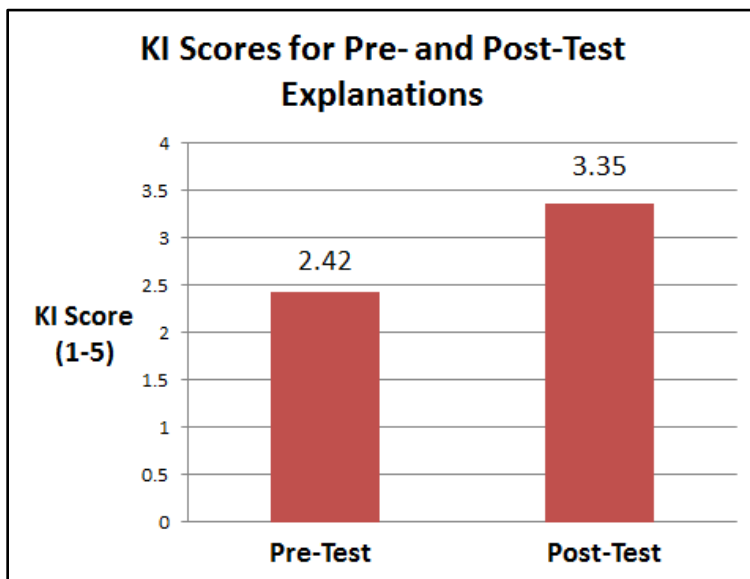


Figure 3.20. Comparison of pre- to post-test gains for students' explanations about the seasons.

Analysis of Use of the Idea Manager and Dynamic Visualizations

Students added more ideas using the Idea Manager than on any other curriculum step type in the unit. Close analysis of the contents of students' Idea Baskets (as they evolved over the

course of the project) revealed that students added significantly more ideas to their baskets during the Idea Manager-guided curriculum steps (i.e., an Idea Basket or Explanation Builder activity step) than during any other step in the project, including the visualization steps themselves—69% of ideas were added during Idea Manager steps, 25% during visualization steps, and 6% during other curriculum steps (see Figure 3.21). While this finding may appear on the surface to be rather unsurprising and expected (i.e., students add ideas when prompted to do so) I argue that it also points to the absolute necessity for providing instructional scaffolding that prompts students to track and monitor their developing ideas. Remember, the Idea Basket was accessible to students at all times during the project. Even so, students overwhelmingly chose to add ideas to their baskets only after being explicitly prompted to do so.

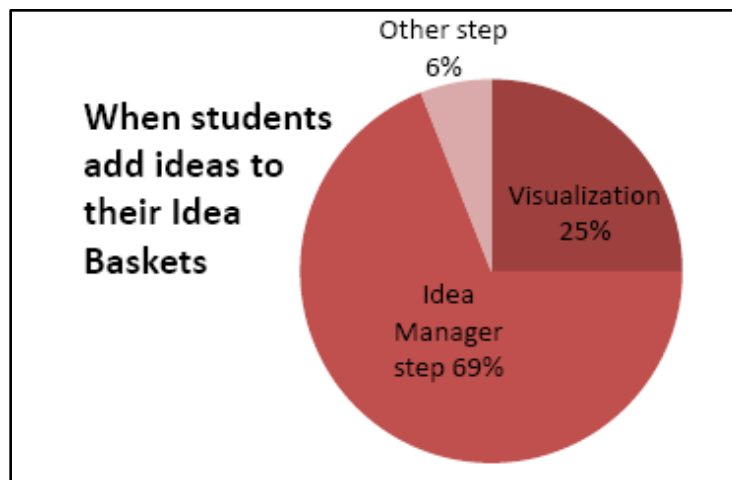


Figure 3.21. Students’ use of the Idea Basket in the project.

In addition, the ideas students attributed to being acquired from the visualizations were more likely to be normative than non-normative (74% normative, 16% non-normative, 10% irrelevant), suggesting that the visualizations fulfilled their designed roles as sources of key, normative ideas for students (Figure 3.22).

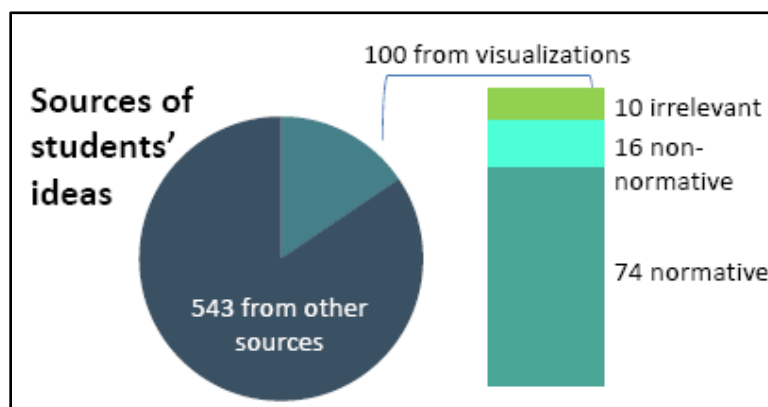


Figure 3.22. The dynamic visualizations were a source of normative ideas for students.

Furthermore, students viewed the ideas they gleaned from the visualizations as important (see Figure 3.23). Students flagged more of their visualization-based ideas as important (30%) than ideas derived from other sources (19%; e.g., peers or family members, personal experience, school, textbooks).

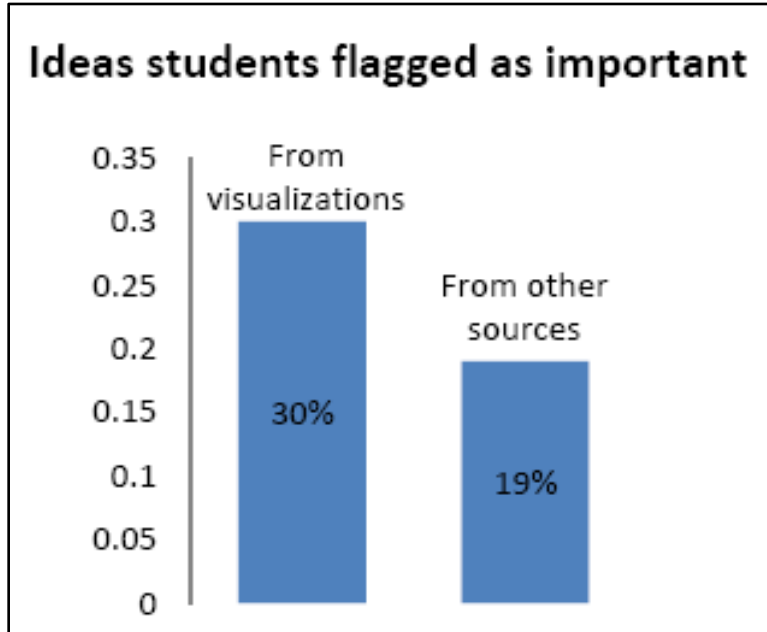


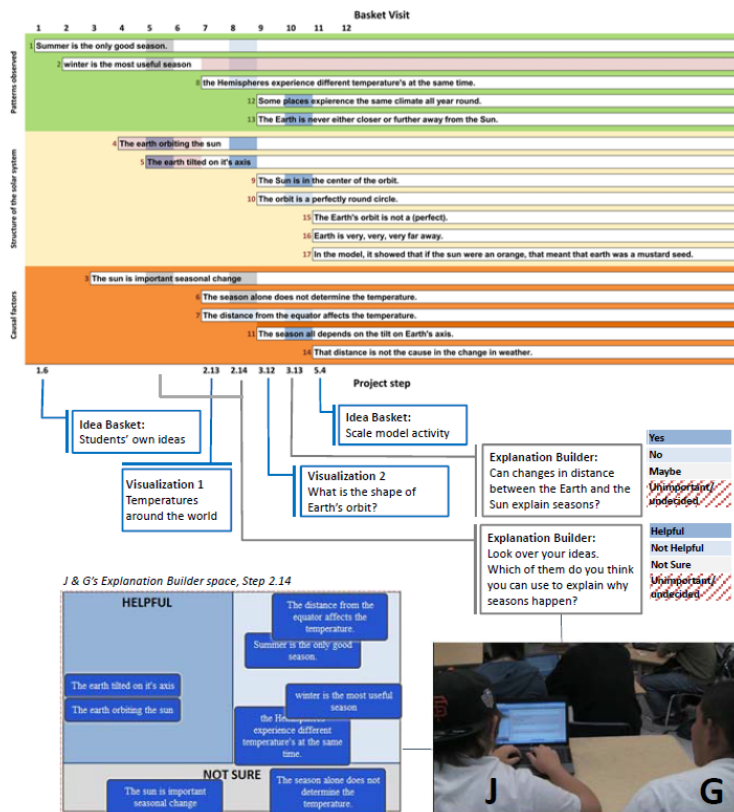
Figure 3.23. Students view the ideas they gained from interaction with the visualizations as more important information than ideas acquired from other sources.

Finally, a case study analysis of two students (Student J and Student G) using the Idea Basket and Explanation Builder in *Seasons* demonstrates how the IB and EB can function to make ideas and thinking visible and explicit for shared discussion and examination (see Figure 3.24). By providing a visual learning space that both students can access and manipulate, the EB supports the collaborative negotiation of evaluative criteria for reflecting upon ideas and engaging in joint meaning-making.

CASE STUDY: A record of students' thinking

Students' Idea Baskets provide a record of when and what ideas were generated over the course of a project, how they decided to categorize them,* and how and when ideas were flagged. Their Explanation Builders reveal how students evaluated their ideas in preparation to write a shared explanation.

*Although analysis of how students tagged their ideas is possible, the graphic below displays researcher-generated categories of students' ideas.



J&G coordinate their ideas

J: No, actually none of these, um, explain why seasons happen.

G: They're just reasons that —Reasons how--

J: The-- We're talking about temperature again.

G: Well, actually, the seasons happen, it's just--

J: OK, wait. No no no no no. "The hemispheres experience temperature --" that's like, "not helpful." OK, I'll show you how. OK, the Earth tilted on its axis [makes a C shape with his right-hand fingers and waves his hand up and down at the wrist] that determines um,--

G: -- where it's located.

J: --the seasons, right? 'Cause if the, um, when it's pointed up, you know what I mean? Or down --

G: Depends where it gets hot.

J: [reads ideas in the Idea Basket] "The Earth orbiting the sun--" Yeah. "The season alone does not determine the temperature."

G: That's not really helpful.

J: OK, "the distance from the equator helps us determine the temperature." Um, that's true, but it doesn't help us explain why seasons happen.

G: So the way we determine is whether it explains, it explains how the temperature--no, if it explains why the seasons happen, not the change in temperature.

The Idea Basket provides a visible record of all their generated ideas, and helps J & G quickly categorize them in response to a prompt.

J comments on the manner G organized their ideas in the Explanation Builder. This external representation makes G's thinking visible to J. The ability to alter the representation facilitates J showing G how his thinking differs.

Physically labeling and sorting ideas into categories facilitates organization and evaluation -- two important processes in planning explanations

Given a common task, students must negotiate shared criteria for evaluating their ideas.

Figure 3.24. The Idea Basket and Explanation Builder tools can make student thinking visible and provide a shared learning space for student pairs to negotiate criteria and engage in sense-making.

Continued implementation in classrooms and observed impact on student explanations. We have continued to test the effectiveness of *Seasons* and its visualizations with a diverse population of students and teachers in classrooms throughout California's San Francisco Bay Area. Every *Seasons* classroom study that I have implemented (with different iterations of the visualizations embedded and under different instructional conditions) has demonstrated statistically significant ($p < 0.05$) pre- to post-test learning gains and improvements in students' explanations for seasons, regardless of assigned study condition. For all studies, students' pre- and post-test explanations were scored (as described previously) using a KI rubric designed to evaluate the number of valid connections made between normative scientific ideas as an indicator of increasing explanatory coherence or knowledge integration. The findings from these studies have been disseminated at national and international conferences and published in conference proceedings and peer-reviewed journals (King Chen, 2011a, 2011b, 2012a, 2012b, 2013a, 2013b, 2014, 2016; King Chen & Matuk, 2011; King Chen et al., 2013).

An important note of clarification: Aside from the pilot study findings I describe above, these additional studies were not designed to assess the effectiveness of the visualizations directly per se, but rather the effectiveness of the surrounding curriculum scaffolds utilizing the visualizations. Since the visualizations are the only sources of normative scientific information in the unit for students, I put forward the argument that the learning gains we have seen in all studies across different instructional settings and contexts would suggest that the design of the visualizations (and their subsequent iterations) have been effective tools overall for supporting and promoting student learning about the seasons.

Chapter 4: Investigating the Impact of Choice-Guided Inquiry Instruction on Student Explanations and Learning

Introduction

Numerous state and national documents on science education reform (American Association for the Advancement of Science [AAAS], 1993; Board on Science Education, 2012; California Department of Education [CDE], 1998; National Research Council [NRC], 1996) emphasize the importance of helping students to become proficient with conducting inquiry investigations. However, despite these calls for more authentic inquiry-based approaches to science instruction, research has demonstrated that successfully engaging students in inquiry activities can be extremely challenging (e.g., McNeill & Krajcik, 2007; Sandoval, 2003; Sandoval & Reiser, 2004; Zimmerman, 2000). For example, students often have difficulty generating legitimate research questions for directing scientific investigation and analysis (Krajcik, Blumenfeld, Marx, Bass, & Fredericks, 1998), making instructional approaches in which students take ownership of and direct their own independent inquiry investigations difficult to successfully implement in most typical science classrooms (e.g., White & Frederiksen, 1998).

Novice learners often lack the necessary levels of prior and strategic knowledge required to competently tackle complex tasks (e.g., Bransford, Brown, & Cocking, 2000). Accordingly, when attempting to carry out open-ended inquiry activities independently without expert guidance, learners can become “overwhelmed by the complexity of options available, making it difficult [for them] to direct their investigations, see what steps are relevant and productive, and make effective activity decisions” (Quintana et al., 2004, p. 359). Quintana et al. (2004) recommend in their proposed framework for designing inquiry scaffolding that instruction should constrain the complexity of the activity presented to the student. By strategically “limiting the scope of the activity space” (Quintana et al., 2004, p. 359), the inquiry task at hand is appropriately structured to optimize and scaffold the student’s learning within his or her zone of proximal development (Vygotsky, 1978). In addition, offering a carefully curated, limited set of choices can promote higher satisfaction and prevent the sense of uncertainty and paralysis that can result from having too many options (Iyengar & Lepper, 2000; Schwartz, 2000).

This chapter presents the findings from two classroom comparison studies that I conducted to investigate the effect of a learner-directed, choice-guided model of inquiry (i.e., students are scaffolded in choosing from a set of five inquiry investigations which ones to complete and in what order) on students’ conceptual learning and understanding about the seasons. Both studies were implemented using *Investigating Seasons* (or *Seasons*), a Web-based Inquiry Science Environment (WISE; Linn, Clark, & Slotta, 2003) high school curriculum unit designed to support students in conducting key inquiry investigations using dynamic visualizations, and developing and reflecting on explanations for the seasons (King Chen, 2012, 2013).

Rationale

In most typical science classrooms, inquiry is often presented as a “one size fits all” procedural exercise—one in which all students complete the same sequence of steps to arrive at the same predetermined “correct” answer. Instruction that presents a constrained, linear view of inquiry discourages students from engaging in making mindful decisions about their own learning and does little to foster the critical thinking, adaptive and reflective learning skills that we know are essential for students to become autonomous, self-directed and self-aware lifelong learners (Ertmer & Newby, 1996; White & Frederiksen, 2005; Zimmerman, 1998). Furthermore, a linear model of inquiry fails to leverage the opportunity to capitalize upon the diversity of learners in two key respects: first, the nature of such instruction does not fully take advantage of the rich array of students’ prior ideas as productive starting points for instruction (Smith, diSessa & Roschelle, 1993) and second, the “one size fits all” instructional approach does not support the implementation of different learning trajectories for diverse learners with varying prior ideas and knowledge. Inquiry instruction should be “sufficiently open to allow for the flexibility that accommodates and values the diversity of the learners. By allowing for multiple entry points and multiple paths, all students ultimately come into proximity to core learning goals, with richer and deeper learning experiences” (Murata, 2013, p. 20).

This research attempts to address the need for more flexible and customized instruction by examining the impact of providing students with a set of guided inquiry investigation choices for learning about seasons. Students’ choice-making in the unit is supported by extensive instructional scaffolding that prompts students to first reflect on their understandings (e.g., what supporting evidence they have and what evidence they think they still need to write a better explanation) before choosing the next investigation (out of the five offered options) to complete.

Providing different investigation choices for students to choose from can make the learning experience feel more personally relevant for students (Cordova & Lepper, 1996; Katz & Assor, 2007), which can in turn lead to more effortful self-regulated and metacognitive learning (Flowerday, Schraw, & Stevens, 2004; Kamii, 1991; Pintrich, 1999). The benefits of supporting the development of self-aware and reflective learners has been demonstrated to help students not only learn the material at hand, but to become better overall learners as well (White & Frederiksen, 1998, 2005). Furthermore, Pintrich, Marx and Boyle (1993) noted that the typical structure of instruction in classrooms, in which students are given little choice or control over their learning activities, was less likely to support the development of an intrinsic desire to gain knowledge. Conceptual change was found to more likely occur for students with an intrinsic, or mastery orientation towards learning (Pintrich, 1988, 1989; Pintrich & De Groot, 1990). However, it should be noted that simply providing students with the option to choose is not a guarantee for facilitating conceptual change. Offering choice is motivating (and more likely to enhance intrinsic motivation) only when the options provided satisfy the inherent psychological needs of learners, such as the desire for autonomy and competence (Deci & Ryan, 1987, 2000; Katz & Assor, 2007). The *Seasons* curriculum aims to promote a sense of: (1) autonomy by framing choice-making as an opportunity for students to direct their own learning and (2)

competence by providing a network of designed instructional supports (i.e., metacognitive explanation and reflection activities) to inform and scaffold students’ engagement with choice. In this way, the unit strives to assist students’ cognitive learning efforts by acknowledging and addressing important and relevant affective needs (Bandura, 1997; Belland, Kim, & Hannafin, 2013; Brown, 1988; Brown, Bransford, Ferrara, & Campione, 1983; Garcia & Pintrich, 1994, 1996; Pintrich, 1994, 1999, 2003; Pintrich & Schrauben, 1992).

Although the role of choice has been studied in a number of educational contexts (see Table 4.1), authentic classroom studies investigating the impact of choice within a complex, conceptual learning endeavor such as scientific inquiry are rare (refer to: Flowerday & Schraw, 2000; Reber, Hetland, Chen, Norman, & Kobbeltvedt, 2009).

Research Context	Citation(s)
School	McLaughlin (2005) and Paquette (2005) discussed issues relevant to school choice in the context of public education in a democratic society.
Course or subject matter	Research by Stokking (2000) investigated the factors underlying the differences between choosers and non-choosers of physics in secondary education.
Homework assignments	Patall, Cooper and Wynn (2010) examined the effects of giving students the choice between two similar homework assignment options.
Example choice	Reber and his colleagues studied the impact of using “example choice” (the contextualization and situation of formal theoretical principles using scenarios with personal interest; e.g., students choose between “gambling” or “becoming a crime victim” text examples to learn about probability) on students’ interest, sense of control and learning outcomes (Reber, Hetland, Chen, Norman, & Kobbeltvedt, 2009).
Physics computer game	Kim and Shute (2015) assessed the impact of linear versus non-linear gameplay on student learning and enjoyment using <i>Physics Playground</i> , a computer-based game for teaching qualitative physics principles.

Table 4.1. Examples of previous choice studies identified in the literature.

This research contributes to the existing body of work by examining the feasibility and impact of choice embedded in an inquiry instructional unit that supports students’ conceptual learning and explanations for developing understanding of a challenging and complex scientific phenomenon.

Theoretical Framework and Research Objectives

This work draws from several lines of theoretical and empirical research. As I have already previously covered these topics in some detail in Chapters 2 and 3, I touch on only the most salient points in an abbreviated discussion below.

Students’ diverse ideas about seasons and other astronomical phenomena. As discussed in Chapter 3, many learners, irrespective of their educational background or age, experience considerable difficulty in understanding and correctly explaining the reasons for seasons (e.g., Atwood & Atwood, 1996; Baxter, 1989; Kalkan & Kiroglu, 2007; Kikas, 2004; Schneps & Sadler, 1987; Sharp, 1996; Trumper, 2000, 2001). In fact, students bring many prior ideas into the classroom with them about an array of astronomical phenomena ranging from the shape of the Earth and gravity to the phases of the Moon (e.g., Sneider & Ohadi, 1998; Stahly, Krockover, & Shepardson, 1999; Vosniadou & Brewer, 1992). In the case of seasons, most students mistakenly believe that the Earth travels around the Sun in a highly elliptical orbital path, which results in changes in distance from the Sun that are responsible for seasonal variations in temperature (e.g., Bakas & Mikropoulos, 2003). Indeed, a pre-unit assessment item (“What causes seasons? Write an explanation and make a drawing to support your explanation.”) that I administered to 102 high school earth science students three months prior to their use of the *Seasons* unit also confirmed this finding (see Table 4.2). Although I had expected that many students would reference a distance-based view about the seasons, I was surprised by the array of other alternative viewpoints students included in their responses as well. In fact, the diverse range of response categories that I saw in students’ responses (e.g., depends on the changing output of the Sun; depends on which direction Earth is “facing”) appeared to align with the observations of other researchers as summarized by Hsu (2008). It is important to note however, that while students may respond with one primary idea when pressed to identify a main causal mechanism, in reality they often hold a number of ideas (sometimes conflicting ones) simultaneously, and will refer to or discuss one or the other when cued under different contexts and circumstances. Consequently, although it would appear that distance is (and should be) of high priority for a curriculum module about the seasons, I felt that a unit designed to explicitly allow students to explore and learn about the topic from a number of other alternative viewpoints would be worthwhile and of important instructional value.

% of Responses	Response Category
31%	Changing distance between the Earth and the Sun
29%	Whether Earth faces towards or away from the Sun
13%	Effect of Earth’s tilt (on distance and/or Earth’s orientation facing the Sun)
12%	Student response difficult to categorize
6%	Change in output from the Sun
4%	More hours of daylight
4%	Student response falls under multiple categories
1%	Other phenomena responsible (e.g., wind, solar flares, weather)

Table 4.2. Responses obtained from high school earth science students (N = 102) asking about the primary cause of seasons.

Promoting coherent understanding by building on prior knowledge. Students' prior knowledge can be used to build towards more scientifically valid and coherent understandings of challenging science ideas and concepts (Linn, 2006; Smith, diSessa, & Roschelle, 1993). The knowledge integration (KI) framework (Linn, 2006; Linn, Davis, & Eylon, 2004; Linn & Eylon, 2006; Linn & Eylon, 2011; Linn, Eylon, & Davis, 2004) describes learners as having fragmented and often conflicting ideas. *Seasons* was designed using the *scaffolded knowledge integration framework for instruction* (Linn, Davis, & Eylon, 2004), which specifies four iterative processes that can help students to integrate new ideas with their existing understandings as they engage in inquiry (Linn & Eylon, 2006): elicit prior ideas, introduce normative scientific ideas, help establish criteria for evaluating ideas, and encourage the sorting and refinement of one's repertoire of ideas. In *Seasons*, designed curriculum prompts engage students in all four knowledge integration processes as they proceed through each investigation.

Use of explanation and reflection to expose explanatory weaknesses and gaps in conceptual knowledge. The curriculum aims to promote student learning through the use of explanation and reflection activities embedded within the KI framework for instruction. I presented detailed discussions of the explanation and reflection literature previously in Chapters 2 and 3. In addition, in Chapter 3 I gave an in-depth account that illustrated how this literature informed the design of the dynamic visualizations and instructional scaffolding that supports students' investigations in *Seasons*. Thus I provide below just a brief review of the main ideas concerning explanation and reflection that are relevant to my research examining the impact of choice-based instruction (Table 4.3). This model of choice-guided inquiry uses explanation and reflection as metacognitive learning supports for framing and informing students' choice-making in the unit.

Embedded explanation activities in instruction can assist in exposing the "illusion of explanatory depth" (IOED; Rozenblit & Keil, 2002, p. 522) by calling attention to inconsistencies or conflicts in thinking that require resolution, thus revealing weaknesses or gaps in understanding (Bell & Linn, 2000; Bielaczyc, Pirolli, & Brown, 1995; Chi, 2000; Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Davis, 2003; Davis & Linn, 2000; Keil, 2006; Scardamalia & Bereiter, 1994). Engaging in reflection and evaluative activities can lead to increased expertise about how to improve one's own learning and understanding as well as improved learning outcomes (Bransford & Schwartz, 1999; Brown & Campione, 1996; Ertmer & Newby, 1996; Hatano & Inagaki, 1986, 1992; Lin, 2001; Scardamalia & Bereiter, 1991; Simons, 1993; Quintana, Zhang, & Krajcik, 2005; White & Frederiksen, 1998, 2005). My work on choice seeks to promote the perspective that instruction should encourage students to consider their own thinking and cognitive processes as subject to continual evaluation, reflection, and improvement (Dweck & Leggett, 1988).

Identified Learning Benefits from the Literature	
Explanation	Directs focus to causal structure of a phenomenon and guides generalization for future explaining (Keil, 2006; Lombrozo, 2006, 2011, 2012).
	Helps to integrate new information with existing knowledge (Chi, de Leeuw, Chiu, & LaVancher, 1994).
	Reveals gaps in understanding (Bell & Linn, 2000; Bielaczyc, Pirolli, & Brown, 1995; Chi, 2000; Davis, 2003; Davis & Linn, 2000; Scardamalia & Bereiter, 1994).
	Activates metacognitive monitoring skills (Chi, de Leeuw, Chiu, & LaVancher, 1994).
Reflection	Supports learning that is flexible and adaptable to different situations and contexts (Lin, Hmelo, Kinzer, & Secules, 1999; Hatano and Inagaki; 1986, 1992).
	Promotes higher levels of awareness and expertise about the “self-as-learner” (Ertmer & Newby, 1996; Lin, 2001; White & Frederiksen, 1998, 2005).
	Encourages the integration of ideas by identifying weaknesses in knowledge (Bell & Davis, 2000; Davis, 1996, 1998, 2003; Davis & Linn, 2000).

Table 4.3. Summary of identified learning benefits for explanation and reflection as documented in the research literature.

Implementing a Choice-Guided Model for Inquiry Instruction

Providing choices during learning can result in a number of positive effects, including higher levels of intrinsic motivation, a greater sense of autonomy and competency, better test performance and more self-aware, self-regulated learning (e.g., Bandura, 1997; Flowerday, Schraw, & Stevens, 2004; Patall, Cooper, & Wynn, 2010; Pintrich, 1999; Pintrich & Schrauben, 1992; Reber, Hetland, Chen, Norman, & Kobbeltvedt, 2009). Much of the existing literature has focused on exploring the affective and motivational value of choice (e.g., Cordova & Lepper, 1996; Katz & Assor, 2007). However, as I described previously, few studies have examined the value and impact of choice on complex cognitive tasks such as students’ development of a scientific explanation or engagement with conceptual learning during inquiry (Flowerday & Schraw, 2000; Reber, Hetland, Chen, Norman, & Kobbeltvedt, 2009; refer back to Table 4.1 for examples of previous choice studies). In my conceptualization of a choice-guided model of inquiry instruction, I acknowledge the importance of students’ motivation and positive affect for promoting more fruitful and effortful learning (Belland, Kim, & Hannafin, 2013; Brown, 1988; Brown, Bransford, Ferrara, & Campione, 1983; Garcia & Pintrich, 1994, 1996; Pintrich, 1988, 1989, 1994, 2003; Pintrich & De Groot, 1990; Pintrich, Marx, & Boyle, 1993; Pintrich & Schrauben, 1992). I further propose to expand the scope of existing choice research by presenting the following additional hypotheses as potentially informative avenues of exploration for developing a more complete understanding of the role and impact of choice on learners—particularly those engaged in conceptual inquiry learning. Choice implemented during inquiry instruction might be beneficial because it:

- **Imparts an increased sense of perceived control, resulting in a positive impact upon focus and motivation** (e.g., choosing based on one’s own interests and desires; i.e., students’ sense that they are more important or responsible for their own learning than the teacher).
- **Primes the learner to assimilate new information acquired during learning** (e.g., choosing based on curiosity or the desire to answer a question; i.e., in considering the available possibilities and choosing one option the student activates expectations for what the ensuing instruction might cover, thus priming existing knowledge for refinement or reorganization).
- **Provides exposure to and consideration of alternative viewpoints and other possibilities** (e.g., the available choice options expose students to other relevant ideas; i.e., students acquire a sense of the “lay of the land”—that is, they see all of the investigation options that constitute a robust understanding of the topic of investigation).

My research explores whether a choice-based inquiry model can engage students in developing their conceptual understanding of seasons by allowing them to select investigations that are of higher immediate relevancy for moving their learning forward. By using explanation and reflection activities to support choice-making, *Seasons* provides an opportunity for students to evaluate and choose (as their learning is underway) those investigations that best address the identified gaps or weaknesses in their evolving knowledge and understanding. The unit embeds investigation choice as an instructional scaffold for engaging students in more reflective and self-directed inquiry and learning. The advantage of a choice-based inquiry instructional model is the flexibility it offers for unique inquiry paths that can support a range of learners with differing levels of prior knowledge and understanding (Murata, 2013). The two classroom studies described in this chapter were designed to address two research aims:

- **To test a choice-based model of inquiry instruction:** How can we design choice-based inquiry instruction that effectively builds on the prior ideas and knowledge of students?
- **To investigate impact of choice on student learning:** How does providing students with choices for inquiry investigations affect their learning and conceptual understanding of seasons?

Investigating Seasons Instructional Materials

The *Seasons* unit consists of a set of five guided inquiry investigations that help students develop evidence-based explanations for Earth’s seasonal temperature changes. Interactive dynamic visualizations embedded within each investigation serve as focal learning activities for students to build upon their initial ideas and to encounter key normative concepts. The progression of visualizations, activities, embedded prompts and instructional scaffolds in the

unit encourages students to track, evaluate and reflect upon their ideas with the goal of developing a well-supported explanation for seasons. I summarize in brief the main instructional components of the unit. (Refer back to Chapter 3 for a detailed description of the unit visualizations and instructional scaffolds.)

Dynamic visualizations. The visualizations in the unit contain various user inquiry features that encourage observation and experimentation. While dynamic visualizations can serve as powerful tools that enhance student learning, they present a number of challenges for instruction as well (Ainsworth, 2008). In particular, they may inadvertently promote “deceptive clarity” (Linn, Chang, Chiu, Zhang, & McElhaney, 2010); that is, students’ overestimation of their own conceptual understanding of the material. It is therefore imperative that students’ interactions with visualizations be carefully supported by the use of instruction and prompts that promote the articulation and reflection of ideas and observations (e.g., Linn & Eylon, 2006; Quintana et al., 2004; White & Frederiksen, 1998). The use of explanations and reflection have been demonstrated as effective ways to support learning, the development of deeper understanding (e.g., Chi, de Leeuw, Chiu, & LaVancher, 1994), and the identification of gaps in knowledge (e.g., Keil, 2006). Consequently, *Seasons* includes extensive instructional scaffolding (detailed in Chapter 3) that supports students in reflecting on the evidence they collect from the visualizations for developing and constructing explanations.

The WISE Idea Manager tools. The Idea Manager makes the process of explaining explicit and consists of two tools—the Idea Basket and Explanation Builder (Matuk et al., 2012, 2016). The Idea Basket functions as a persistent repository for students to track their evolving ideas over the entire course of the unit. The Explanation Builder provides an organizing space for students to evaluate and reflect upon the ideas in their baskets in preparation for generating an explanation.

Instructional scaffolds for reflection and KI. The five inquiry investigations in *Seasons* address key concepts central to developing a highly integrated explanation for seasons (see Table 4.4, ahead). Prompts and instruction embedded within the curriculum guide students to evaluate and integrate their ideas (Linn & Eylon, 2006, 2011; Linn, Davis, & Eylon, 2004; Linn, Eylon, & Davis, 2004). Within each investigation, students predict what they will learn from the visualization, experiment and collect data using the visualization, reflect on and revise their earlier predictions, add new ideas or revise existing ones using the Idea Basket, evaluate their ideas for explaining using the Explanation Builder tool, write their explanations using evidence sorted with the Explanation Builder, and reflect on their own or other’s explanations and use of evidence (Figure 4.1).

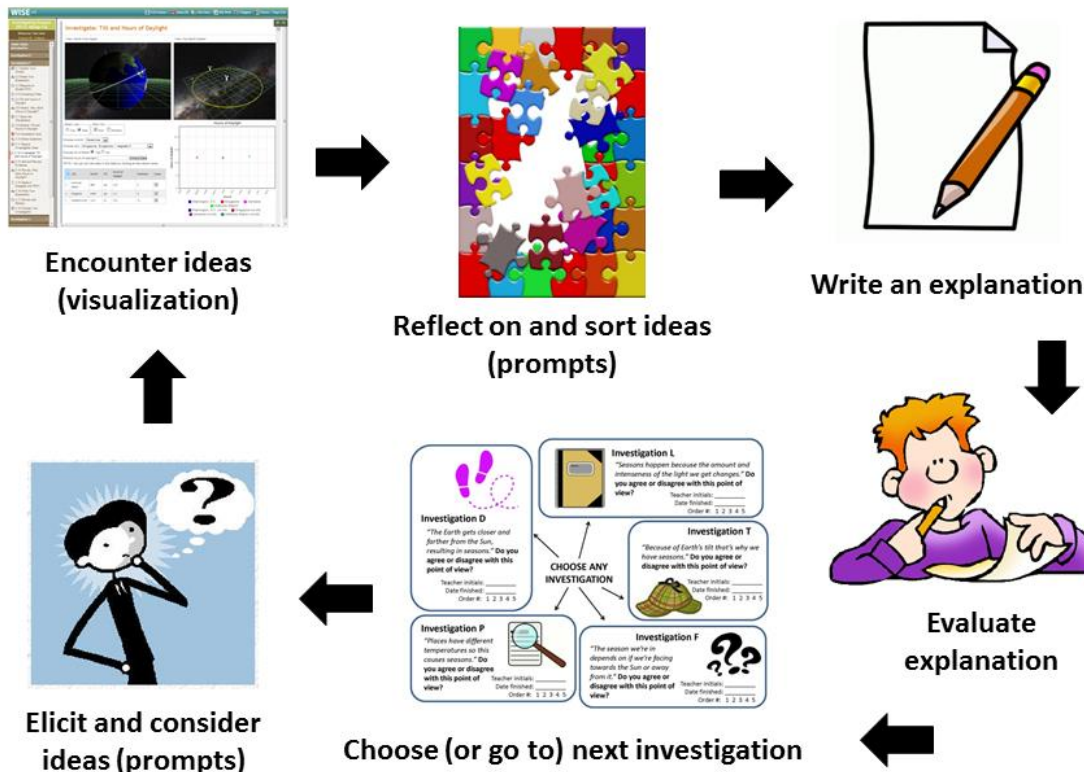


Figure 4.1. Iterative and cyclical sequence of instructional support implemented in *Seasons*.

Study Design and Methods

To assess the feasibility and impact of a choice-guided model of inquiry instruction, I conducted two classroom comparison studies (a pilot study and follow-up replication study) using two versions of the *Seasons* curriculum unit (one offering students investigation choices, the other without choice-making). Before discussing the specific analyses and findings for each individual study, I present first a general overview of the study design and methods implemented for both studies.

Primary objectives of design-based research. Design-based research (DBR) aims to inform and advance the development of theories of learning as well as the design of innovative learning environments. Researchers seek to acquire a “greater understanding of a *learning ecology*—a complex, interacting system involving multiple elements of different types and levels—by designing its elements and by anticipating how these elements function together to support learning” (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003, p. 9). Primary hallmarks of DBR include iterative cycles of implementation and evidence-supported refinement (Barab & Squire, 2004; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Sandoval, 2014; Sandoval & Bell, 2004; Wang & Hannafin, 2005).

Choice and no-choice versions of the curriculum. The *no-choice* version of the *Seasons* unit presents students with a predetermined sequence of inquiry investigations similar to more traditional, teacher-directed models of science instruction. (The specific no-choice investigation sequences used for each study are given in the relevant sections that follow.) I anticipated the no-choice order of instruction as being informative for most learners based on my teaching experiences and background in the design of astronomy curricular materials, the seasons research literature, my prior classroom observations and survey of student ideas about seasons (see again Table 4.2), and in consultation with teachers. Students do not make choices or direct their own inquiry in this condition. By having all students complete the same linear sequence of investigations, the no-choice condition was designed to imitate as closely as possible most typical inquiry instruction settings, in which the teacher determines the sequence of learning content for students.

In contrast, the *choice* version of *Seasons* does not require students to complete the investigations in any predetermined order; rather, students are presented at the end of the introductory section (and later, at the end of each subsequent investigation chosen) with a “choose your investigation” curriculum page that prompts students to choose between the five investigations available (Figure 4.2). Before choosing an investigation, students first complete an evidence assessment activity to help them reflect on the ideas they currently have about seasons as well as to identify any gaps in their knowledge (Figure 4.3). After completing their first selected investigation, students are prompted to reassess their collection of ideas and evidence before being redirected back to the choice page to select from the remaining investigation options (four, then three, and so on). Students in the choice condition are thus able to choose which investigations they want to do, and in what order. For example, by the end of the instructional intervention period, one student pair might have completed all five investigations in one particular order (e.g., D, L, P, F and T), while another student pair might have gone through the investigations in a different order (e.g., P, T, D, L and F). Yet another pair of students might have moved through the instruction at a slower pace than their peers and covered only investigations D, T and L.

With the exception of the “choose your investigation” step in the choice version of the curriculum, both study conditions had access to the same investigations and instructional content. Like their choice peers, students in the no-choice condition also completed the evidence assessment step for each investigation to reflect on their understandings before moving on to or selecting the next investigation; the only difference between the two versions of the unit was that the no-choice students were constrained to complete the investigations in a predetermined order. Slower moving no-choice student pairs might complete only the first three investigations in the unit, similar to the situation I described above for a sample choice student pair. Students were allowed to progress through the unit at their own pace, although in both studies the teachers would encourage and remind students to get through as much of the curriculum as they could in the time available for the intervention.

Seasons Inquiry Investigations	Key Conceptual Targets for Instruction
Investigation D Sun-Earth Distance and Shape of Earth's Orbit	<ul style="list-style-type: none"> • The shape of Earth's orbit is very nearly circular. • Earth's orbit can appear highly elliptical depending on the viewer's perspective. • Earth is closer to the Sun in December than in June.
Investigation F Earth's Tilt and Hours of Daylight	<ul style="list-style-type: none"> • Changes in hours of daylight occur because of Earth's tilt. • The hours of daylight observed vary according to latitude. • Without tilt, the hours of daylight would remain constant throughout the year at all latitudes.
Investigation L Light Intensity and Power Absorbed by a Solar Panel	<ul style="list-style-type: none"> • The percentage of light received by a solar panel depends upon the angle of incidence. • The power absorbed by a solar panel placed varies depending on latitude and the time of year.
Investigation P Temperature Patterns Around the World	<ul style="list-style-type: none"> • Temperature patterns for cities on Earth throughout the year are different depending on latitude. • Not all cities experience the four seasons. • Temperature patterns between the Northern and Southern Hemispheres are reversed. • A city at the Equator experiences very little temperature change throughout the year.
Investigation T Earth's Tilt and Temperature Patterns	<ul style="list-style-type: none"> • Earth's tilt results in seasonal temperature patterns. • Temperatures would remain pretty constant without tilt.

Table 4.4. Overview of the five guided inquiry investigations in *Seasons*.

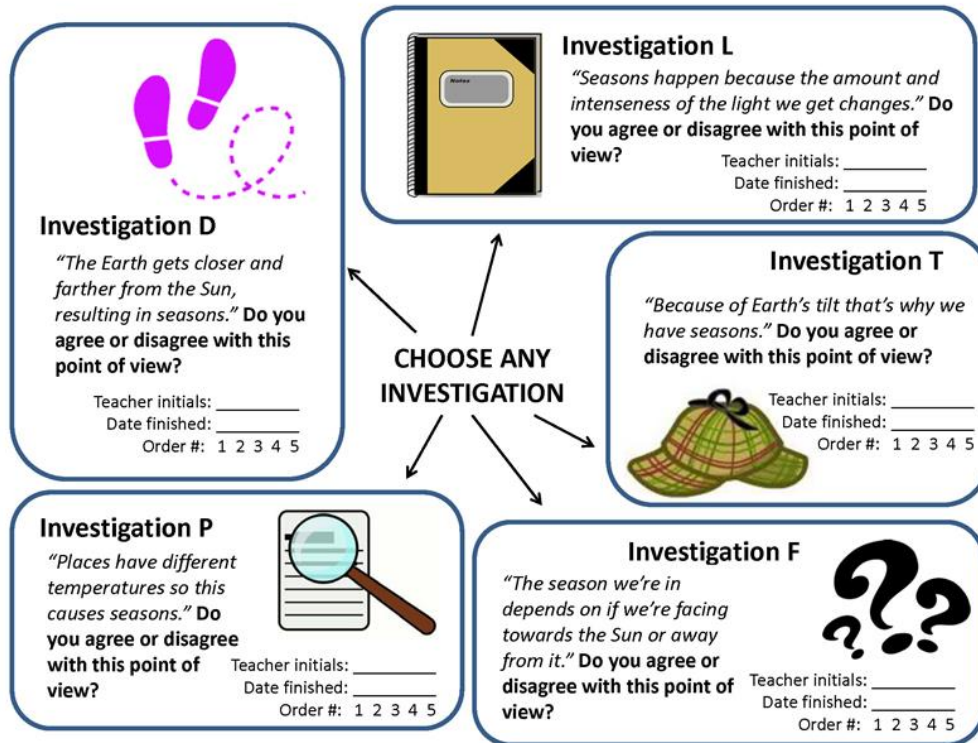


Figure 4.2. The five investigation options presented on the “choose your investigation” curriculum page in the choice version of *Seasons*.

WISE v4 | Full Screen | Ideas (0) | Add Idea | My Work | Flagged | Home / Sign Out

Investigating Seasons -- SP15CH

Welcome Test User!
Expand All Collapse

1: Preparing to Investigate +

2: Investigating Seasons -

- 2.1 Choose Your Investigation
- 2.4.1 Goals for Sunlight Angle Investigation
- 2.4.2 Effect of Height of Sun
- 2.4.3 Investigate: Solar Panel and Percentage of Light
- 2.4.4 Investigate: Solar Panel and Power Absorbed
- 2.4.5 Revise: Effect of Height of Sun
- 2.4.6 Add Evidence and Ideas
- 2.4.7 Student Explanation: Sunlight Angle
- 2.4.8 Reflect on Ideas: Sunlight Angle
- 2.4.9 Revisit Reasons Checklist
- 2.4.10 Discuss Investigation Choices
- 2.4.11 Review or Choose

3: Final Explanation +

EXPLANATION BUILDER

Use the organizer below to check whether you learned some key ideas from the visualization. Go back to the visualization steps if you need more ideas.

Your Ideas

Your Idea Basket is empty. Click "Add Idea" to start adding ideas.

Ideas comparing the angle of light hitting a panel for Washington D.C. in JUN and in DEC:

This is your Organizing Space. Drag ideas here to help you build a response to the question or instructions above.

Ideas comparing the angle of light hitting a panel for Canberra in JUN and in DEC:

Ideas about how the angle of light hitting a panel and absorbed power are related:

Add Idea

Figure 4.3. Example of an evidence assessment and reflection activity in *Seasons*.

Assessments and collected data. Pre- and post-unit tests, embedded assessment prompts within the unit, logged data of students’ use of the Idea Manager tools (the Idea Basket and Explanation Builder), as well as recorded video footage of student pairs working together through the unit comprise the various sources of data collected for this study. Pre- and post-tests were administered individually to students before and after completion of the unit. Open-response explanation items were scored on a scale from 0-4 using a knowledge integration (KI) rubric (Linn, Lee, Tinker, Husic, & Chiu, 2006; Table 4.5) that looks for scientifically valid connections between ideas. In addition, the WISE environment logs all student activity within the unit, including submitted responses to the embedded instructional prompts as well as time-stamped data about each investigation students complete. Analysis of the logged data indicated the number and order of investigations completed by students in the choice condition.

Score	Level	Description
9	Missing Response	Student never saw the question.
0	No Links (No Answer, Off-Task or Irrelevant Response)	Student gives no response, an off-task or irrelevant answer, or responds with “I don’t know”. (Student may have written some text, but it does not address the question being asked.)
1	Invalid Link (Non-normative Response)	Student gives a response that is completely non-normative. The response contains no connections or scientifically invalid connections, such as: <i>We get seasons when Earth moves closer and then farther away from the Sun.</i>
2	Partial Link (Basic Response)	Student gives a basic response that is relevant to the question and normative. The response is unelaborated without any valid connections made between response and supporting evidence, such as: <i>Seasons happen because of Earth’s tilt.</i>
3	Single Link (Normative Response)	Student gives an elaborated response that is relevant to the question and normative. The response contains one valid connection made between response and supporting evidence, such as: <i>Earth’s tilt causes seasons because the fact that we are tilted means we get different light angles at different seasons.</i>
4	Multiple Links (Complex,	Student gives a fully elaborated response that is relevant to the question and normative. The response contains two or

	Normative Response)	more valid connections made between response and supporting evidence, such as: <i>We have seasons because Earth's tilt makes the Sun appear higher in the sky in the summertime and lower in the sky in the wintertime. This means we have higher temperatures in summer and lower temperatures in winter. Tilt also causes changing hour of daylight, which is why summer days are longer than winter days.</i> (3 connections.)
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Table 4.5. Knowledge integration rubric used to score students' pre- and post-test explanations.

Choice Pilot Study: Results and Discussion

This first classroom study assessed the feasibility of a choice-guided inquiry approach to students' learning of the seasons. The study was also used as an opportunity to make observations to inform subsequent modification and refinement of the choice curricular materials.

Study participants and overview. Ten classes of ninth-grade earth science students taught by two teachers (N = 207) used the choice (N = 123) and no-choice (N = 84) versions of *Seasons*. Class periods for each teacher were randomly assigned to each study condition. Students in each condition worked through the unit in pairs for approximately six hours over five class periods. The no-choice investigation sequence presented to students was: D – F – L – P – T. My analysis of students' pre- and post-test explanations and the WISE logged data revealed promising findings pointing to a possible trend favoring the choice condition over the no-choice condition. I observed this positive trend on a number of different learning and outcome measures.

Comparing scored pre- and post-test explanations. Knowledge integration coding and analysis of students' pre- and post-test explanations (looking for valid connections made between scientific ideas) revealed that the *Seasons* curriculum materials improved students' explanations in both study conditions (Figure 4.4), with the choice students showing a higher pre- to post-test average gain in KI score than the no-choice students (0.39 for choice compared to 0.27 for no-choice). Students in the choice condition made moderate, significant pre- to post-test gains (M = 1.48, SD = 0.81 (pre); M = 1.87, SD = 0.92 (post); $p < 0.001$, $d = 0.45$). Similarly, students in the no-choice condition also demonstrated moderate, significant pre- to post-test gains (M = 1.42, SD = 0.71 (pre); M = 1.69, SD = 0.83 (post); $p = 0.03$, $d = 0.35$). The difference in the mean gain scores between the two conditions was not found to be statistically significant (M = 0.27, SD = 0.93 (no-choice); M = 0.39, SD = 0.75 (choice); $p = 0.37$, $d = 0.12$).

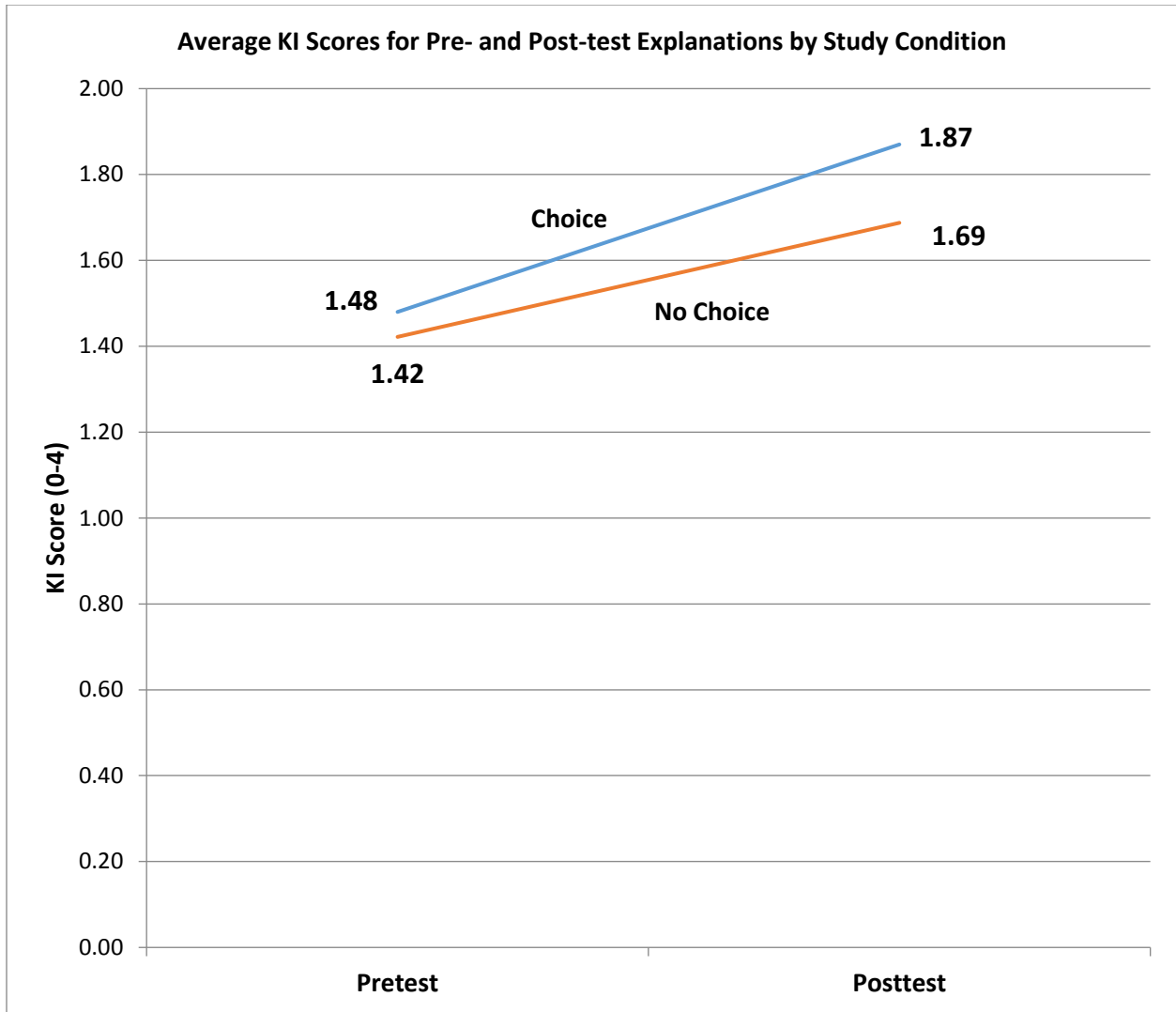


Figure 4.4. Comparison of KI scores for students' pre- and post-test explanations.

Categorizing explanations by primary causal mechanism. Categorization of students' explanations according to the primary mechanism for seasons given (e.g., changing distance, Earth's tilt, solar flares from the Sun, increased hours of daylight, etc.) showed that students in the choice condition had a higher percentage increase in scientifically valid explanations (from 24% on the pre-test to 41% on the post-test) and corresponding decrease in non-normative explanations (from 63% on the pre-test to 50% on the post-test) compared to their no-choice counterparts (who showed no noticeable differences in percentage increase or decrease; Figure 4.5). This finding was not determined to be statistically significant ($\chi^2 (1, N = 188) = 1.56, p = 0.212$).

Categorization of Explanations by Study Condition

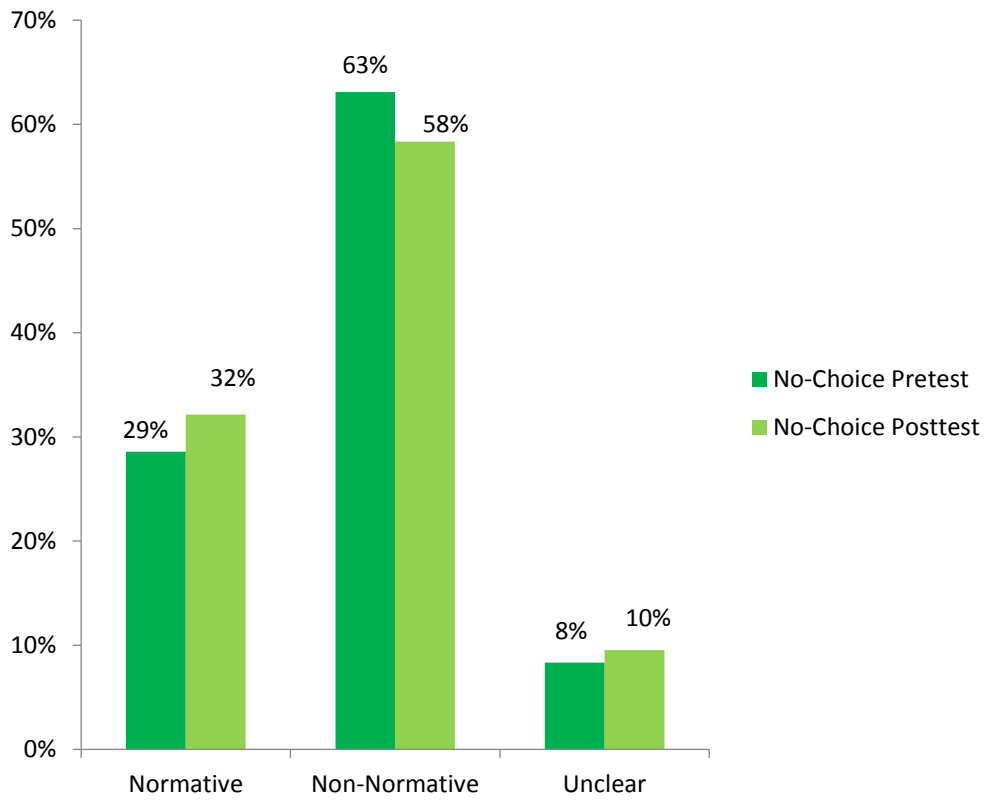
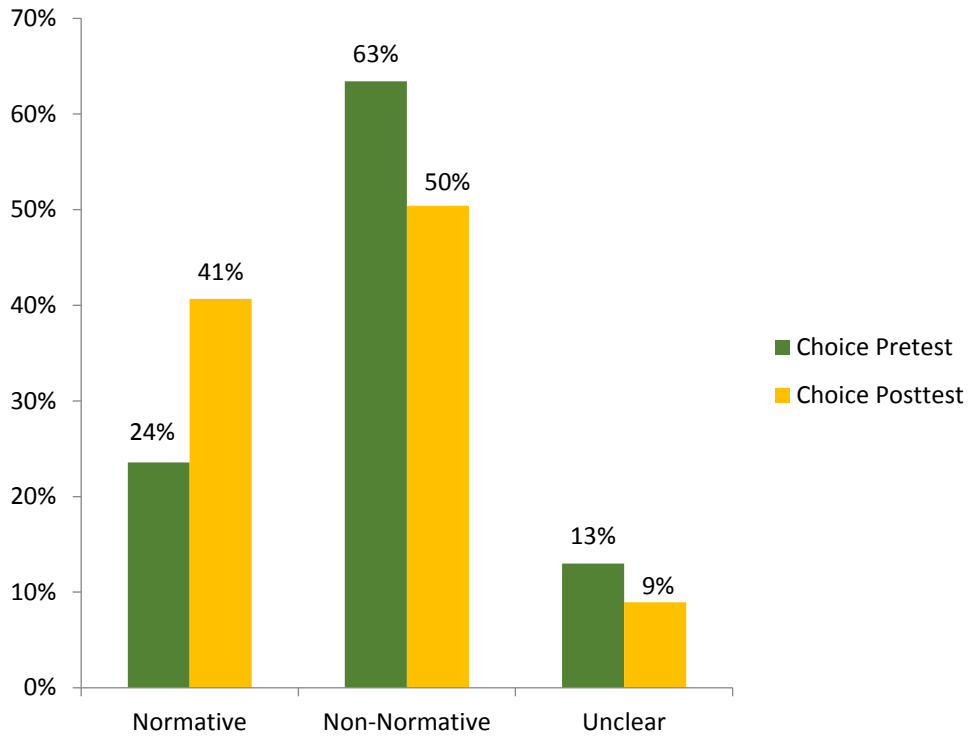


Figure 4.5. Percentage of normative and non-normative explanations from pre- to post-test by study condition.

Examining time spent on choice-making and overall learning gains. Finally, I conducted an analysis to determine whether students’ pre- to post-test KI score gains might relate to the time they spent on the choice-making step. In other words, did students who were more engaged with choice-making (using time spent as a proxy for gauging engagement) experience greater learning gains? Analysis results suggest a potentially beneficial relationship between the amount of time spent on choice-making and the impact on pre- to post-test learning gains (Figure 4.6). No-choice students (who effectively spent no time with choice-making) experienced the lowest pre- to post-test KI score gains (0.27). Choice students who spent 40 seconds or less on the choice-making page had modest pre- to post-test gains (0.38), and choice students who spent more than 40 seconds on choice-making demonstrated the highest gains (0.51). The criterion of $t = 40$ seconds that I used to create the time groups for this analysis was determined by inspecting a bimodal histogram I created of the time spent on choice-making by all student pairs in the choice condition. One possible explanation for the relationship between time spent on choice and learning gains is that the student pairs who spent more time on choice might more often been engaged in collaborative discussion with their partner in order to negotiate understandings and to reach consensus about which investigation to select next.



Figure 4.6. Relationship between average KI gains and the time student pairs spent on choice-making.

Choice Replication Study: Results and Discussion

This second classroom study utilized refined versions of the *Seasons* choice and no-choice curriculum units (i.e., modifications were made to address identified issues with the curricular materials during the pilot study) and sought to replicate the findings obtained from the first classroom study.

Study participants and overview. Five periods of high school chemistry students (N = 112) taught by one teacher participated in this study comparing the choice and no-choice versions of *Seasons*. Students within each period were randomly assigned to either the choice (N = 47) or no-choice (N = 65) study condition. (Despite our efforts to assign an equal number of students within each class period to the two conditions, it appears that some students may have accidentally selected the wrong version of the unit to complete when first logging into the WISE student user interface.) Students in each condition worked through the unit with a teacher-assigned partner for approximately six hours over four class periods. The no-choice investigation sequence presented to students was: P – D – T – L – F. As with the first study, my analysis of students' pre- and post-test explanations and other responses in the unit indicated again a possible trend favoring the choice condition over the no-choice condition, providing additional support for the positive impact of choice on study learning.

Comparing scored pre- and post-test explanations. Scoring of students' pre- and post-test explanations for seasons using a KI rubric (see again Table 4.5) found that *Seasons* improved students' explanations in both study conditions. Choice students made significant pre- to post-test gains (M = 2.09, SD = 1.46 (pre); M = 3.38, SD = 1.66 (post); $p < 0.05$). Similarly, students in the no-choice condition also showed significant pre- to post-test gains (M = 1.82, SD = 1.39 (pre); M = 3.06, SD = 1.50 (post); $p < 0.05$). Although the choice group demonstrated a slightly higher mean gain from the pre- to post-test (M = 1.25, SD = 1.32 (no-choice); M = 1.30, SD = 1.32 (choice)), the difference in the mean gain scores between the two conditions was not found to be statistically significant. One possibility is that the grain size of the KI scoring rubric, which rewards valid links made between ideas, might be too large for this (and the previous) study to capture any differences in learning gains between the two conditions, especially given the choice group's higher level of prior knowledge at the start of this study—compare $M_{\text{CHOICE}} = 2.09$ (a basic, unelaborated normative explanation) to $M_{\text{NO-CHOICE}} = 1.82$ (between a non-normative and basic normative response). In addition, given the deeply entrenched nature of students' personal conceptions about seasons (e.g., Baxter, 1989; Schneps & Sadler, 1987, etc.) it is unlikely that significant shifts in conceptual understanding might be obtained (or observed) after only six hours of instruction, especially at the level of a written explanation. At the very least, comparison of students' pre- and post-test explanations suggests that incorporating choice into inquiry instruction (which may offer a potentially more engaging and proactive learning experience for students) does not disadvantage or take away from student learning compared to the more traditional approach towards science instruction.

Considering students' investigation choices and effect on conceptual learning. Typical classroom instruction, in which students have minimal input over their learning activities, does not promote motivated learning (Pintrich, Marx & Boyle, 1993) and consequently, students are far less likely to undergo conceptual change (Pintrich, 1999). As discussed earlier, this work considers whether a choice-based instructional model might positively impact learners' developing conceptual understandings by providing students with a self-directed—and thus potentially more engaging and relevant—learning experience. The following finding offers some insight into this issue. Review of the WISE logged data indicated that the most popular choice of investigation was the activity on Sun-Earth distance and the shape of Earth's orbit (Investigation

D, selected by 40% of choice students first, followed by 27% of students second). Consequently, 67% of choice students had completed the distance investigation by the end of their first two investigations. For the no-choice students, distance appears as the second investigation in the sequence of instruction. Thus for both conditions, most students had completed the distance activities by the end of their second investigations. However, by the end of the unit the choice students demonstrated greater improvement on a pre/post-test distance item (asking about the near-circular shape of Earth's orbit) compared to the no-choice students (24% choice compared to 7% no-choice), despite the fact that the majority of students in both groups had encountered the distance investigation at the same time early on (within the first two investigations) in the unit. This finding is especially interesting given students' well-documented difficulties with explaining seasons; a distance-based explanation citing the highly elliptical shape of Earth's orbit is the most popular misconception voiced by students. One might argue that the first choice students complete in the unit is likely to be the most impactful and meaningful compared to students' subsequent choices in the unit (when there are fewer investigation options left and the experience of choosing becomes less novel). While this finding requires support from more in-depth analyses of additional data sources, it suggests a potentially powerful impact on students' conceptual learning through the inclusion of choice in inquiry instruction.

Concluding Thoughts

There is a need for research that investigates the impact of a choice-based inquiry learning model in authentic classroom settings. Schwartz and Arena (2009) note that if it is possible to "track different patterns of learning choices and tie these to learning outcomes, there is the question of how to guide students to make more effective choices. There is very little evidence on this question" (p. 35). Murata (2004) states that "different sequences may suit different learners' needs in ways that instructional designers and learning theory have yet to predict" (as cited in Schwartz & Arena, 2009, p. 33). The choice-based instruction in *Seasons* allows for learners to take different inquiry investigation paths and learning trajectories. The potential benefits of successfully engaging students in reflective choice-making are numerous. They include: supporting customized instruction for diverse students with a wide range of prior ideas, scaffolding student-directed independent learning trajectories, and the promotion of inquiry instruction that seeks to be more personally relevant and engaging for all students.

Chapter 5: Conclusion

Summary

As science educators consider how best to prepare today's students to become tomorrow's informed and knowledgeable citizens, many view exposure to authentic scientific inquiry experiences that engage students in critical thinking and independent learning skills as vital. Open-ended and student-directed models of instruction such as project-based learning (PBL) aligns well with the outlined key skills indicated in reform documents, but the reality is that for many teachers and students, the divide between current instructional approaches and innovative forms such as PBL is simply too wide a gap to easily traverse without significant resources and support. There are considerable challenges for both teachers and students to adopt this new approach towards inquiry. In this dissertation, I proposed a model of choice-based inquiry that can bridge between instruction that is highly structured and teacher-led and instruction that is more open-ended and student-directed. In a choice-guided approach to inquiry instruction, the use of explanation and reflection as metacognitive instructional strategies engages students in a form of inquiry that promotes more self-directed, reflective and independent learning. Bringing choice into the classroom exposes students to a new way of participating in learning, one that helpfully will help to prepare them for more advanced forms of independent inquiry.

Findings from choice classroom studies. I conducted two classroom studies to examine the impact of incorporating choice into inquiry instruction. The collection of findings from the two choice studies presented in Chapter 4 suggest that further investigation into the contribution of choice in the classroom is well warranted and worthwhile. Although statistically significant differences *between* the two groups was not obtained, it is of note that like their no-choice peers, the choice students benefited from the unit instruction. In essence, the two groups performed equally (i.e., the change in pre-test to post-test gains was observed to be statistically significant for each group). Furthermore, it is worth noting that across a range of outcome measures for both studies, a consistent trend was seen of students in the choice group exhibiting positive learning benefits. A possible relationship between the time spent on choice-making and pre- to post-test gains would seem to provide some intriguing evidence for the hypothesis that students invested and engaged in choice reap some benefit from doing so. Taken together, the set of findings from the two studies combined with the known affective advantages of choice documented in the literature provide a promising indication of the value of choice for supporting the design of curriculum that provides students with the opportunity to pursue independent and unique inquiry learning trajectories.

Contribution and significance. This work contributes to the aims and goals of the educational research community by proposing and demonstrating the feasibility and potential benefits of enacting an innovative model of inquiry instruction that utilizes metacognitive instructional supports (explanation and reflection) for promoting students' learning through choice-making. The two classroom comparison studies provide preliminary evidence for the promise and

usefulness of choice-guided inquiry for supporting inquiry learning, a complex cognitive task. To my knowledge, there has been no similar work done in this area of research. Prior work with choice has occurred in either simple “choose A or B” situations (e.g., deciding between homework assignment options, selecting which example problem to look at) and focused primarily on the effect of student affect (i.e., motivation, engagement or sense of autonomy and control) through mainly self-report survey data. In some instances studies have been done investigating the effect of choice in gaming contexts (e.g., Kim & Shute, 2015), but the methods and goals of learning through games differ (sometimes significantly) from that of formal science instruction in classrooms. As of this writing there are no existing studies that embed and utilize choice as a metacognitive support for helping students to learn in a complex instructional setting such as during inquiry in the classroom.

Why Choice Matters

As is evident from the existing literature, choice can enhance engagement and intrinsic motivation, and provide learners with a sense of autonomy and control. Educational psychologists have long made the claim that instruction focuses too heavily on cognitive issues, to the detriment or exclusion of equally important affective factors (Belland, Kim, & Hannafin, 2013; Brown, 1988; Brown, Bransford, Ferrara, & Campione, 1983; Garcia & Pintrich, 1994, 1996; Pintrich, 1994, 2003; Pintrich & Schrauben, 1992). It is hard to deny the argument that a student’s mental mindset—for example, whether he is having a good or bad day, how he feels about himself and his intellectual abilities, or the ongoing environment at home, whether positive or negative—is left at the doorway of the classroom. Affective factors necessarily play an important and impactful role on students’ learning experiences, and the value of bringing choice into the classroom is that the model of choice-guided inquiry that I have proposed attempts to support students’ cognitive learning through the implicit acknowledgment of equally important underlying affective factors. While not the main focus of this dissertation, I fully expect that the benefits of choice stem from both cognitive factors (e.g., productive collaborative discussions with peers, exposure to alternative viewpoints and perspectives, the activation and priming of prior knowledge for new ideas to build upon, the identification of areas of curiosity or weaknesses for further investigation and inquiry) as well as affective ones (e.g., engagement in learning that seems a little more personal and relevant, the ability to control or choose what to study next, the novelty of making decisions for oneself instead of mindlessly following the teacher). Choice thus promotes more personal, autonomous and self-directed learning by acknowledging affective factors alongside cognitive ones. The model of choice that I have implemented for my dissertation studies interweaves the three components for self-regulated learning proposed by Schraw and his colleagues: cognition, metacognition and motivation (Schraw, Crippen, & Hartley, 2006).

The role of motivation sustaining engagement and effort with learning (the idea of perseverance or “grit”) is a paramount one for education today. As many parents can observe firsthand, children start out with an exuberant and delightful abundance of motivation and curiosity to explore and understand the world around them. Sadly, by the middle and upper

grades many adolescents have lost their natural interest and willingness to participate in science and thoughtful investigations. This is a distressing issue that educators must factor into their efforts to promote sustained engagement with science inquiry and learning. With a choice-based model of learning I put forward that instruction that strives to be responsive to individual students, that seeks to be relevant and engaging for different learners, is likely to appeal and motivate more than instruction that remains impersonal and designed from the perspective that “one size fits all”. As Reber, Hetland, Chen, Norman and Kobbeltvedt (2009) note: “In traditional teaching, there often exists a gap between what students have to learn at school and what they are really interested in. Karl Popper (1945) described this gap as being the difference between the Platonic ideal of education and an ideal of education in which students are encouraged to devote themselves to their studies for the sake of studying, for the real love of their subjects, and for inquiry... This gap continues to exist, and one of the most important challenges of education at the beginning of the new millennium is motivating students to learn and to stay in school” (Hidi & Harackiewicz, 2000, as cited in Reber et al., 2009, p. 510).

Implications for Design of Choice-Based Instruction

Although the work described in this dissertation embeds choice within a technology-enhanced curriculum, the implementation of choice does not necessitate the use of technology. As such, it is an accessible intervention that can help to bring more independent inquiry experiences into all classrooms, especially perhaps the ones that would benefit the most from exposure to more open-ended forms of learning experiences. However, many questions remain about how best to design for choice in instruction. For example, when is choice an appropriate instructional model or strategy to use? Are some topics more amenable for choice-guided instruction than others? What role does the teacher and classroom culture play on the effectiveness of implementing choice in school? I consider and share my thoughts about these and other issues next.

When is choice likely to be effective? Katz and Assor (2007) propose a framework for understanding when choice is likely to be effective and when it is likely to not. In their paper, the authors review a number of choice studies, and discuss how this framework can account for the inconsistent findings from these studies about choice and its impact on engagement and intrinsic motivation. Building upon the self-determination theory of human motivation (SDT; Deci & Ryan, 2000; Ryan & Deci, 2000), Katz and Assor (2007) note that choice is most likely to be effective if it satisfies the three needs described by SLT: the need for autonomy (an understanding of the value and relevance of the task), the need for competence (choice options that are at the optimal level of difficulty to engage students) and finally, the need for relatedness (addressing students' needs for either independence or interdependence). Katz and Assor argue that when choice meets these needs, motivation is enhanced, with positive effects seen as well for both learning and well-being. Below I consider how their framework might translate into relevant issues for educators to consider when implementing choice during inquiry instruction in the science classroom.

Need for Autonomy

A sense of autonomy is satisfied when one can “understand the value or relevance of the task in which they are engaged” (Katz & Assor, 2007, p. 431), thus identifying with it. The more one perceives the task as being in line with one’s values, interests and goals, the stronger the feeling of autonomy. Katz and Assor (2007) suggest that the alignment of choice options to one’s goals (i.e., relevance) may in fact play a more significant role than the simple act of choosing itself (i.e., control). If we consider what this might mean for students in the science classroom, the need for autonomy would seem to connect to the importance of acknowledging and addressing students’ epistemological beliefs. Epistemological beliefs inform what knowledge a learner values or believes is useful or relevant, and can consequently impact the use (or conversely, the lack of use) of that knowledge during a cognitive endeavor (such as explaining). Furthermore, epistemological beliefs refer to not only beliefs about the utility of knowledge, but also its origin and nature (Reiner & Gilbert, 2000). To illustrate, consider two students with very different epistemological world views (Elby & Hammer, 2001; Hammer & Elby, 2002). The student who views knowledge as simple, unchanging and straightforward (a “realist” perspective) is likely to take a very different approach towards learning and explaining than the student who considers knowledge as messy, continuously changing and derived from personal experience (a “relativist” perspective). In fact, studies conducted by Kuhn and her colleagues (Kuhn, 1991; Kuhn, Cheney, & Weinstock, 2000) with individuals having diverse perspectives on the nature of knowledge revealed that epistemological beliefs affected not only the ability to construct a persuasive argument, but also the use of metacognitive skills and knowledge for self-regulation as well. Individuals with a more relativist perspective of knowledge were more likely to generate alternative theories, to come up with stronger counterarguments, and to engage in critical reflection. It would seem that these individuals would be more likely to fully engage with choice during instruction than those individuals who hold a realist perspective towards learning and knowledge construction. In terms of instructional design, it might be beneficial to frame choice for students as an opportunity to explore questions of interest, to take control and guide one’s own learning, or to convey that developing more sophisticated understanding comes from continually evaluating and reflecting upon one’s thinking in order to think about how to build upon current knowledge (in other words, to promote a more relativist perspective).

Need for Competence

One has a sense of competence when the choice task at hand is neither too overwhelming and difficult nor too simple and straightforward. Either end of the spectrum can be demotivating. Katz and Assor (2007) observe that the need for competence is satisfied when individuals are provided choice options at just the right level of challenge (similar to the story of Goldilocks)—that is, “just right”. Providing a limited set of choices, rather than an overwhelmingly large array of options, results in higher satisfaction (Iyengar & Lepper, 2000; Schwartz, 2000). Too many alternatives results in a “complex decision-making environment” (Payne, 1976, as cited in Katz & Assor, 2007, p. 434) and under these “complex cognitive conditions, people tend to defer decisions, choose the default option, or choose not to choose” (Katz & Assor, 2007, p. 434). This

type of “choice overload” situation (Iyengar, Huberman, & Jiang, 2004, as cited in Katz & Assor, 2007, p. 434) can lead to both frustration and dissatisfaction. I see the issue of addressing the need for competence with a choice-based model of instruction in a few interesting ways. In this dissertation I discussed why I see the implementation of choice-guided inquiry as an instructional approach that holds promise: Choice allows for more relevant, customizable learning pathways that strives to meet students conceptually where they are at the beginning of instruction. Furthermore, the various investigation options acknowledge the different ideas of students’ prior conceptions, thus providing a number of options for students to begin engagement with the material. In fact, I argue that there is no obvious, “right” linear sequence of the five investigation options in *Seasons*. In my own experiences teaching and developing curriculum materials for astronomical topics and seasons in particular, I found that I could make a plausible case for any number of ordered sequence combinations of the five investigations. (A note of clarification here: This is not to say that any sequence would be an ideal, effective sequence for *all* students; rather, in practice I might suggest different progressions of investigations for one student compared to another, based on my real-time observations and diagnoses of their respective learning and understanding at different moments during instruction. The main point I am trying to make here is that any sequence of the five investigations *could* make sense for an imagined hypothetical student, with different sequences ultimately being more ideally suited to different students, depending completely on the specific needs on the identified target student.) As I tried to demonstrate with Table 3.2 in Chapter 3, seasons is an especially complex, rich and challenging instructional topic to tackle with students. Possibly too complex; with a choice task involving the weighing and consideration of five options (representing five key conceptual areas of understanding), perhaps many students felt that they were being asked to engage in complex decision-making that they felt ill equipped to tackle, even with all of the instructional scaffolding designed to prepare and support students with choice-making. It is worth considering whether a more “simple” content topic might better meet students’ needs for a choice task that presents a more optimal level of challenge. In other words, a level of difficulty that is “just right”. But how do we determine what might be an ideal level of challenge for different students? And how do we determine the “simplicity” of a learning topic? One might argue that for a simpler topic, choice might be less compelling because with less “conceptual space” between choice options, each one becomes less distinctive or weighty from the others. If fewer choices are presented, one danger is the loss of the novelty of choice, and possibly the loss of what makes choice inherently interesting or appealing as an instructional intervention (i.e., choosing between only two options might give the sense of “less choice,” or not much of a sense of choice to begin with compared to having three or more options to consider against one another). Another related issue that bears thinking about is whether choice might be more effective for some students over others. Lawless and Brown (1997) examined how the interaction between learner characteristics (such as prior knowledge, self-efficacy and interest) and external factors (such as instructional design, learner control and level of control) affected students’ learning in an educational multimedia context. They found that sufficient prior knowledge was required in order for learner control to increase students’ performance on learning tasks. Novice learners benefited more from teacher control because they could focus on learning the content, rather than being distracted by choices (which required more cognitive resources to process). More advanced learners, on the

other hand, were able to benefit from choice when they had a sufficient level of prior knowledge that made choice-making less resource intensive.

Need for Relatedness

As Katz and Assor (2007) note in their paper, the connection between choice and relatedness is more ambiguous and harder to define and consequently, has not been examined as closely in the existing research literature. However, in their discussion they point to the impact of cultural preference for either independence or interdependence as central to the issue of relatedness. In studies examining this issue, it was found that in western cultures, the higher premium placed on achieving independence causes students to value and appreciate choice more than in eastern cultures, where interconnectedness and an emphasis on harmony with family leads students to focus on their relationship with others, rather than on one's own needs and desires. A study by Iyengar and Lepper (1999) examined the effects of these cultural differences on choice and motivation. In their study, the authors found that choice enhanced motivation more for independent rather than interdependent students: American students showed less intrinsic motivation when choices were made for them; in contrast, Asian children were most intrinsically motivated when choices were made for them by a trusted authority or peers (Iyengar & Lepper, 1999). Another study conducted by Assor, Kaplan and Roth (2002) further speaks to the importance of classroom culture and norms: In their work, they found that teacher actions—whether they were autonomy-enhancing or autonomy-suppressing—held more significance for students as a form of autonomy support, outweighing the impact of simply providing choice. In fact, perhaps these studies provide insight into the differences in average KI gain I observed between the two choice classroom studies: The pilot study was conducted in two classrooms where the teachers did not go to great lengths to expressly support and promote students' autonomy. This stands in contrast to the classroom for the replication study where the teacher managing the class visibly encouraged and explicitly and frequently stated her belief in students' abilities to achieve and be autonomous and independent. (It is worth noting however, that regardless of the classroom culture, choice as implemented in the *Seasons* studies still demonstrated benefits for all students.) My own observations and the literature on relatedness suggest the critical role of the teacher in communicating expectations and seeding the classroom culture and norms adopted by their students. Important issues for teachers to be mindful of include: the promotion of students' views of themselves as lifelong learners capable of continuous improvement (Lin, 2001), the framing of failures as productive and informative opportunities to support and move learning forward, the value of tenacity and persistence in working through difficulties and larger obstacles to achieve worthwhile long-term goals (i.e., the idea of "grit") and finally, the mutual understanding that learning tasks set forward for the student are tractable, and within their means to tackle and overcome (e.g., as in gaming contexts, where there is the implicit understanding that with enough hard work and persistence, each game level can be successfully completed). The list of beliefs that I've provided here is, of course, not exactly simple or straightforward to bring about. The changes suggested here are difficult ones to enact and it is not my intention to give the impression that these are easy changes to implement quickly. However, awareness of these important factors and the potential role they play in

supporting choice (and consequently, more independent and reflective forms of learning) is a necessary first step towards moving teachers, classrooms and students towards more ambitious learning goals and endeavors.

Limitations and Future Directions

This dissertation explored the feasibility and impact of a choice-guided model of inquiry for supporting student learning. The work discussed in this document is an initial investigation into a different instructional approach towards promoting more independent and reflective inquiry experiences for students. Clearly however, more work and studies are required to better understand how choice works in learning, and how educators and researchers can best design choice-learning experiences for students. Here are some of the outstanding questions that remain for future research and investigation.

Considering a simpler model of choice-guided inquiry. The advantage of embedding choice in a less complex topic of investigation (i.e., one that inhabits a smaller, less ambitious conceptual space) is that doing so provides a better opportunity of discerning the impact of choice separate from the confounding factors that presented itself in the present studies with *Seasons*. Using a simpler topic (but still within the context of inquiry and conceptual learning) might give a clearer picture of the impact of choice, uncontaminated by the effect of when specific content knowledge pieces are learned and in what order. These and other similar issues ended up being challenging and complicating factors in making sense of the impact of choice in my present work. Furthermore, one might also consider presenting equivalent choices (i.e., choices that represent two sides of the same conceptual coin) rather than conceptually different options (i.e., different conceptual content and learning goals as with each investigation option in *Seasons*) to further isolate the effect of choice from the effect of access of content (i.e., what is learned and in what order). Another possibility would be to embed choice as an instructional element only after students have completed a set of introductory activities that expose students to the same baseline knowledge pieces underlying the targeted key concepts. (In *Seasons* the baseline was assumed to be students' prior instruction in the topic, which is first usually introduced in either elementary or middle school. In hindsight however, I'm not sure if most students entered the unit with a strong enough foundation of knowledge to fully engage with and benefit from choice-making. Introduction of a choice activity at a later stage could then shift the role of choice during learning (i.e., acquiring knowledge to develop coherent understanding as framed in the *Seasons* studies) to instead the final integration of knowledge for application to a design project or other application challenge instead (a less ambitious, more tractable learning task). In this scenario, the choices offered to students might consequently be more equivalent to one another (presenting the same basic conceptual challenge framed in different ways), thus minimizing the interfering impact of different levels of timing of exposure to key content knowledge. The ideas described above might give more direct insight into the effect of choice and present less of an analytical challenge than the considerably messier, complex studies conducted with *Seasons*.

Acknowledging the difference between authentic choice and school choice. Is “authentic choice” possible in the science classroom? Up until this point I have discussed the implementation of choice in various academic contexts and settings without once acknowledging the elephant in the room: Can we really design for authentic choice in education and in particular, during science instruction? By using the term “authentic choice,” I attempt to make a distinction between choice that truly appeals and resonates with students deeply on a personal, intrinsic level and the far less intrinsically appealing choices that we as educators often offer to students. In the context of classroom instruction, for most students, choosing whether to study topic A, B or C is not really a deeply motivating or interesting decision. A student might have a preference to study topic C out of all of the options presented, but one would be hard pressed to argue that such a choice is as inherently engaging as asking that same student whether she would prefer to spend an evening out with a friend or at home with a favorite book. An appropriate analogy for contextualizing this discussion might be the following scenario: A parent asks her child to choose between two dinner options—say, chicken and broccoli (choice A) or pork and carrots (choice B), when deep down what the child really wishes Mom would present as dinner options are pizza and chips (choice C) or hamburgers and fries (choice D). Thus an unspoken conceit of choice in the classroom is that as currently embodied, it rarely touches upon students’ innermost intrinsic motivations. Choices A and B as presented in the dinner example above are constrained by what the parent values as and believes are healthy and nutritious options, but unfortunately these are not the same options that are always exciting or enticing for the child (choices C and D).

This quandary touches on a deeper, underlying issue—that of the nature of science instruction and what we expect students to learn in the classroom. Much of the scientific knowledge taught to students in schools today are validated theories that have (so far) stood the test of time. Scientific information and facts are often presented as immovable, not up for dispute or debate. As a result, science learning as it is undertaken in the classroom does not capture the true nature of scientific discovery and investigation, where things are far messier, uncertain, and up for continuous debate and interpretation. In sharp contrast, students in the classroom are aware in fact, that the answers are already known, the final destination of understanding already predetermined (i.e., there is a “right” and a “wrong” answer). In essence, students are merely being caught up on centuries of collective scientific knowledge that has already been discovered, investigated and tested over the years. Understandably, students consequently feel ambivalence and even disinterest in the final outcomes of assigned labs and research projects. In thinking about this issue, three possible solutions come to mind. One addresses the above-stated concerns on an immediate, short-term scale, one focuses more on the bigger, long-term picture, and the third occupies a space in the middle. The short-term suggestion is to consider whether choice might appear more authentically appealing if situated within a learning context where no one clear and obvious “right” answer exists. For example, students might be asked to choose between various tradeoff investigation options such as: “Which hand-drying option is better for the environment—using electric air dryers or recycled paper towels? Choose one and gather enough evidence to argue your case convincingly.” With this type of choice-based inquiry challenge, the goal of students’ explanations would shift from sense-making to place more emphasis on the other facets of explanation, that of argumentation and persuasion. The

longer-term solution raises the issue of whether our institutional, high-stakes evaluative assessments align and place proper importance on the things we hope students leave school being able to do (i.e., to be independent learners capable of making good decisions for supporting their own learning). Schwartz and Arena (2009, 2013) argue that assessments and the design of learning environments should be aligned to promote and assess the decisions learners make as a better, more accurate measure of independent learning. The third, mid-term solution poses the possibility of reframing our expectations of motivation and engagement in the classroom. That is, if we assume that most of the learning experiences students encounter at school may never reach the same intrinsic levels of motivation and engagement that students have for leisure pursuits and social activities, then perhaps we as educators need to rethink how we perceive and measure “engagement” and “motivation” in the classroom. Perhaps a better indicator (and potentially more valuable skill that underlies lifelong learning) might be students’ demonstrated persistence (or “grit”) during difficult leaning tasks. In the context of my choice work in *Seasons*, “persistence” measures might be: the time students spend on particular instructional steps (e.g., the visualizations or an Explanation Builder step), the number of experimental trials students choose to carry out with the models, or whether or not students revisit the visualizations.

Making use of automated guidance technologies. Earlier I mentioned that implementing choice can be a low-tech instructional strategy, without the need for software or computer-based resources. But with ever-impressive advances in technology such as AI and the affordances of computer-automated guidance, implementing choice within a technology-enhanced learning environment opens the door to some intriguing possibilities for further, deeper exploration of this topic. For example, autoscoring of student responses can provide immediate diagnosis of conceptual difficulties and provide real-time recommendations for what might be the most helpful or illuminating choice to pursue next. Using technology, we could investigate whether the positive impact of choice is mainly affective (i.e., benefit stems from having the power to choose, regardless of whether the choice is “correct”; the sense of autonomy resulting in higher engagement or increased desire to participate and learn) or whether the advantage of choice is attributable mainly to one’s timely access to the appropriate content at the right time (that is, choosing “right” to access critically needed information matters). In other words, is choice effective because students (more than anyone else) know best about how to customize the learning to their current needs? And if so, is a threshold of metacognitive awareness necessary for students to reap the value of choice? Or is the real issue how designers design instruction to support students in self-evaluation and choice? Say perhaps that in being asked to choose, one is “prepped” to access or build upon prior knowledge for learning the content. That raises the larger question of what, exactly, a “right” choice looks like. As far as we know, learning does not happen in a predictable, easily mappable way. What defines a “good” choice for any particular learner? Does such a thing really exist, when the specifics of how conceptual change occurs remains still mysterious and relatively unclear? How do we, as instructional designers, make an argument for the next best choice for a student’s learning? And is the end state more important than the trajectory of learning itself? I would argue that the mental processes to get to the desired end state are the most important (i.e., the journey is more important than the destination), and that choice

encourages students to activate those mental processes compared to more passive forms of learning.

Constraining choice to better support thoughtful and reflective choice-making. Using some insights gleaned my classroom studies, here is an example of an alternative study design approach to better support students in making investigation choices that are reflective and informed by self-assessment of their own understanding and prior knowledge. While in the classroom, I observed that many students seemed uncertain about how to decide which investigation to choose next. This resulted in students also finding it challenging to articulate why they had selected a particular investigation. One possibility is that presenting students with a set of options can be more overwhelming and confusing than helpful for a complex topic such as seasons. Perhaps in this case, constraining students' focus to deciding between two options might make choice-making more tractable. To better help students engage with choice, a computer algorithm could present customized pairs of investigations for students to choose between. (Providing only two investigation options at a time is more likely to encourage students to compare and contrast the options against one another, possibly making it easier for them to choose as well as articulate their reasons for choosing one investigation over the other.) The customized choice pairs would be determined by a "smart" computer algorithm that analyzes students' responses to a pre-unit prior knowledge task. The task asks students to decide which two investigations (out of the five) they think will be the most beneficial for their learning, based on their self-assessment of what they think they understand and don't understand about seasons. Using the students' responses, the algorithm generates and presents customized choice pairings (e.g., "Would you like to complete Investigation F or Investigation L?") for students to choose between. The algorithm uses a ranking system (which notes students' indicated top two investigations) to create meaningful and interesting investigation choice pairs for students to decide between, thus making the choice task consequential and potentially more engaging (see Appendix A for an illustrative example). In summary, students are presented with customized choice pairs, based on an algorithm that determines optimal choice pair options using students' responses to a pre-unit prior knowledge task.

Concluding Remarks

Choice is a model of instruction that aims to empower students to be aware of and take charge of their own learning. The intended result of implementing choice in instruction is to bring elements of personalized and adaptive instruction into the classroom, where one teacher is often tasked with the learning of 30 (and often more) students, all with varying needs, backgrounds and interests. With its emphasis on self-assessment through explanation and self-improvement through reflection, the vision of choice instruction that I have for students seeks to help them exercise and develop the skills needed to become self-sufficient and proactive lifelong learners. While in this dissertation I make the specific case for fostering these skills through scientific inquiry experiences, I see these skills as useful ones that translate outside the boundaries of the science classroom, and vital for enriching all other areas of one's life. The

idea of metacognitive learning is what first brought me to graduate school (and UC Berkeley specifically), and what has always been of highest interest and priority for me and the work I envision doing. If a student can be taught to manage and improve upon his own learning, then he is better equipped to succeed than he would be otherwise, even under challenging or undesirable circumstances that may be beyond his control. He is empowered as his own self-sustaining teacher and continues to mature as a learner as a result. The ultimate goal of education is to equip students with the skills to sustain independent, self-improving and self-sufficient lifelong learning. In this way learners can continue to grow, to explore, to question, to seek to understand, and to be successful in finding the answers that lead them to yet other questions of interest—resulting in rich, intellectual stimulation and enrichment to sustain a lifetime.

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Appendix

Appendix A: Example Illustrating the Customized Choice Pairs Algorithm

