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Designing Critique for Knowledge Integration

by

Mie Elissa Sato

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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Science and Mathematics Education

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of the

University of California, Berkeley

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Designing Critique for Knowledge Integration

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by

Mie Elissa Sato

Abstract

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Doctor of Philosophy in Science and Mathematics Education

University of California, Berkeley

Professor Marcia C. Linn, Chair

Generating explanations is central to science and has the potential to have a powerful impact on students' conceptual understanding in science instruction. However, improving conceptual understanding by generating explanations is a fraught affair: students may struggle with the sense of false clarity that may arise from generating explanations, fail to detect gaps in their understanding, and dismiss salient information that contradict their beliefs. Critiquing explanations has the potential to counteract these pitfalls by exposing students to alternative ideas to contrast with their own. This dissertation seeks to clarify how to design critique in technology-enhanced science instruction to support students in revising their explanations about scientific phenomena, and in doing so, refining their conceptual understanding.

Using the Knowledge Integration framework, I revised two technology-enhanced curriculum units, *Plate Tectonics* and *Global Climate Change*, in a design partnership between teachers, researchers, and technologists. I conducted a series of studies with sixth-grade students to investigate the conditions under which guided critique of explanations can support revision. The pilot critique study investigated the impact of the revised *Plate Tectonics* unit on students' understanding of convection, as well as of a preliminary design of critique where students generated and applied their own criteria for what makes a good explanation in science. The guidance study explored how incorporating a complex selection task that features meta-explanatory criteria into critique supports students in distinguishing among different criteria, as well as how students use peer or expert guidance on their initial explanation during revision. The critique study investigated how designing critique with a complex selection task that features plausible alternative ideas and giving guidance on students' critiques support students in distinguishing among a range of relevant ideas and making productive revisions to their initial explanations.

These studies clarify how critique can be designed to help students sort through various ideas in their conceptual repertoire, be they ideas about meta-explanatory criteria or science ideas about a specific phenomenon. The study findings illuminate the challenges of guiding students to examine or re-examine the full range of ideas for knowledge integration. Students struggle to identify salient, missing, or normative ideas in their own or another explanation, and to incorporate their insights in a coherent way through revision. The studies demonstrate that embedding complex selection tasks in critique encourages students to consider a broad range of ideas and supports them in making conceptual revisions of their explanations. The results have implications for the design of critique in technology-enhanced science instruction.

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Chapter 1: Introduction and Rationale

This dissertation investigates how guided critique can be designed to support students in revising their initial explanations in technology-enhanced science instruction and emerge with a more coherent, integrated understanding of scientific phenomena. Guided critique is the prompting of students to evaluate their own or another's ideas with the goal of revising and refining their conceptual understanding, a practice that is common in science, yet increasingly rare in today's test-driven classrooms. My research shows how we can take advantage of technology in inquiry science instruction to provide students with guided opportunities to reconsider and revise their ideas in explanations.

This dissertation research seeks to further our understanding of how guided critique in technology-enhanced instruction can support students in making sense of their own existing and new ideas and refine their understanding. Students become entangled in multiple, often conflicting ideas about scientific phenomena as they interact with the natural world and struggle to distinguish new ideas from existing beliefs (e.g., Clark, 2007; diSessa, 1988). Critique can help students reassess their understanding by providing opportunities to examine specific ideas. Many students find it challenging to effectively engage in and learn from critique.

How can critique be designed to help students evaluate and revise their science explanations to reflect their evolving understanding? Critique may fail to address conceptual entanglements if it does not attend to confirmation bias, or if it overwhelms and further confuses students with new information. In designing critique, I draw on the constructivist knowledge integration (KI) framework (Linn & Eylon, 2006) that addresses the difficulties students have in making sense of their multiple, conflicting ideas. KI calls for building on the repertoire of ideas students develop in their lives by designing inquiry experiences. In my research, I explore ways to use critique to help students distinguish among existing and new ideas and refine their repertoire of ideas through reflection and revision. The goal is to support students in a) distinguishing among ideas in an explanation, and b) making sense of the ideas in a critique. By testing alternative activity designs through a series of comparison studies, I seek to combine these activities into a powerful instructional sequence that will help students emerge with a more coherent understanding of scientific phenomena.

I conducted studies in two middle school earth science curriculum units, *Plate Tectonics (PT)* and *Global Climate Change (GCC)*. Both units have been classroom-tested and iteratively refined in multiple middle school classrooms (Varma & Linn, 2011; Sato & Linn, 2010a, 2010b, 2011; Visintainer & Svihla, 2010; Sato & Svihla, 2012). In my dissertation, I investigate how critiquing explanations, receiving guidance, and being prompted to revise based on critique and/or received guidance can help students reflect on and refine their ideas after generating an initial explanation. In addition to analyzing the impact of these activities on students' written explanations, I examined video records and data logs of students' navigation through the units to better understand how these activities impact students' learning processes. My dissertation integrates insights from research on explanations, critique, and guidance to address the following questions:

1. How can we design guided critique in technology-enhanced science inquiry instruction to help students distinguish among their ideas and revise their explanations about scientific phenomena?
2. How can guidance on students' initial critiques or explanations help students reflect on their understanding and make progress during revision?

3. How are students' learning processes impacted when prompted to critique explanations, receive guidance, and revise their explanations?

This chapter reviews pertinent research that addresses how students benefit conceptually from critiquing explanations, receiving guidance, and revising their initial explanations in science instruction. I first review the benefits and challenges of improving students' conceptual understanding of scientific phenomena through generating explanations. I then synthesize research on critique and formative guidance in science instruction as a means to address some of the difficulties students experience when learning from generating explanations. Lastly, I contextualize my research for designing instruction within the Knowledge Integration framework.

Generating Explanations

The learning benefits of generating explanations have been well-documented in prior research (Lombrozo, 2012). Generating explanations can help students make connections among existing and new ideas, as well as help students recognize and repair gaps in their understanding (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher, 1994; Chi, 2000). For example, Chi and colleagues (1989) found that prompting eighth-grade students to self-explain while reading text about the circulatory system significantly increased their learning gains compared to students who read the text twice, with higher learning gains correlated with more frequent self-explanations. However, even with carefully designed scaffolds, students often do not recognize gaps in their understanding when generating explanations (Chinn & Brewer, 1993; Keil, 2006). Students may be content with simplistic and superficial explanations. They can discount alternative causal accounts once they have an initial plausible explanation (Oppenheimer, 2004). Thus, effective instruction involves both eliciting explanations and ensuring that students can accurately evaluate explanatory quality such that they can refine their understanding.

Providing scaffolded opportunities for students to construct and evaluate explanations has shown promise for technology-enhanced science education (e.g., McNeill, Lizotte, Krajcik, & Marx, 2006; Sandoval & Reiser, 2004). For example, Reiser and colleagues (2004) created a tool called ExplanationConstructor to guide students' inquiry learning in BGuILE, a technology-enhanced learning environment designed to support students' investigations about evolution on the Galapagos Island. However, designing effective scaffolds to promote revision remains an elusive goal. In my research, I conceptualize explanations as students' attempts to express their ideas about mechanisms underlying scientific phenomena in writing. Allowing students to examine their ideas in explicit activities such as critiquing explanations and applying external feedback has the potential of strengthening their understanding.

Critiquing Explanations

Research shows that critique combined with generation has benefit over generation without critique for certain tasks (e.g., Chang, Quintana, & Krajcik, 2010). For example, Chang and colleagues (2010) found that middle school students learning chemistry demonstrated significantly larger learning gains when asked to generate, interpret, and critique molecular animations of chemical reactions in comparison to students prompted to generate and interpret the animations. Students who critiqued the animations also produced higher-quality animations than students who did not. Their findings indicate that critique adds value to learning activities involving generation.

In science education, critique of explanations is considered a core component of argumentation, where students evaluate and challenge other students' explanations and defend their own explanation against criticism (Berland & Reiser, 2009). Osborne and colleagues (2004) argue that argumentation is a central practice when constructing explanations in science and involves the explicit consideration of alternatives in light of available evidence. Critique in argumentation may therefore prompt students to examine the ideas in their own explanations and distinguish among multiple alternatives. Students may learn to detect and repair gaps in their understanding as a result of engaging in argumentation and having their ideas challenged by others.

Although the practice of argumentation is an important skill to foster in students, it is a complex task that requires making sense of and challenging the ideas of others through structured discourse while contrasting those ideas with their own. It may therefore distract students from the task of reflecting on and applying their critique-derived insights to their own ideas. For example, Berland and Reiser (2011) found that while middle school students became more proficient in argumentation practices with extensive guidance and training, they did not necessarily revise their ideas even when engaging in argumentation with each other over ideas in opposition. The authors attributed the probable cause of this outcome to several challenges, such as students remaining neutral during the evaluation of other students' ideas and not debating whose ideas were scientifically correct, or students debating each other's contradicting ideas but failing to reach a resolution before the instruction's conclusion. Similar challenges are echoed by Chang and Linn (2012), where students were reluctant to critique their peers' ideas.

These findings suggest that critiquing a known peer's work, especially in the context of learning argumentation, may focus students on the structure and practices of argumentation and detract from reflecting on their own ideas during that process. In my research, I therefore investigate the potential benefits of critiquing both peer and assigned explanations presented outside of the argumentation context. Studies in higher education report promising findings when students critique their peers' writing (Cho & MacArthur, 2011; Nicol, Thomson, & Breslin, 2014). For example, Cho and MacArthur (2011) found that critiquing peer essays, compared to reading peer essays, allowed undergraduate students to write higher quality essays without receiving additional guidance. An in-depth analysis of critiques generated by students revealed that critique comments qualifying as problem detection were significant predictors of students' writing quality. Their findings support the idea that engaging in critique and examining ideas in the writing of others supports students in examining their own ideas. I examine how carefully designed critique can support middle school students in leveraging their critique experience to revise their own thinking.

Using Guidance to Revise Explanations

Research suggests that compared to providing guidance such as starter sentences during the initial explanation generation process, providing natural language guidance on students' initial explanations may be more effective in prompting students to reflect on the ideas expressed in explanations and to distinguish and refine their ideas (Alevin, Ogan, Popescu, Torrey, & Koedinger, 2004). In addition, research has identified several characteristics and dimensions of guidance that affect its effectiveness in prompting revision such as prompt specificity (e.g., Shute, 2008; Underwood & Tregigdo, 2010). However, designing guidance to prompt successful revisions that go beyond stylistic and mechanical improvements and improve the conceptual content of student writings remains a persistent challenge (Cho & MacArthur, 2011; Walker, 2015; Sato & Linn, 2011). Even students who have been trained in critique and generating guidance struggle to apply received guidance to their own work (Walker, 2015). These findings align with

the literature on the difficulty students have recognizing and reconciling conflicts in their conceptual understanding (Chinn & Brewer, 1993; Clark, 2006).

In addition to discounting evidence that contradicts their beliefs, students may fail to connect inferences across different activity contexts such as generating guidance to others' explanations and applying received guidance to their own explanations (Sato & Linn, 2011; Walker, 2015). Thus, the challenge lies not only in how to design the guidance itself but in how to design the activity context such that students are motivated to reflect on their understanding. My research therefore seeks to understand how to design and combine critique and revision with guidance so that there will be a synergistic effect on students' learning.

Designing Instruction and the Knowledge Integration Framework

Prior research has documented the importance of well-designed supports for effective learning in technology-enhanced inquiry science instruction (Quintana et al., 2004; Donnelly, Linn, & Ludvigsen, 2014). This dissertation conceptualizes learning as an integration of one's existing ideas with new ideas introduced through instruction. I draw on the knowledge integration framework (Linn, Davis, & Bell, 2004; Linn & Eylon, 2006) to guide my development of critique and guidance to support student through this process. Consistent with existing literature on students' conceptual learning (e.g., diSessa, 1988; Strike & Posner, 1992; diSessa, 2008), the knowledge integration perspective frames learning as an iterative, constructivist process that acknowledges and leverages the rich repertoire of ideas students bring with them to instruction. Minimizing or ignoring students' existing ideas carries risk; students may develop isolated, fragmented knowledge. The knowledge integration instructional pattern thus consists of eliciting students' existing ideas, adding new ideas through instruction, helping students develop criteria and distinguish among their and new ideas, and refining their conceptual repertoire to emerge with a more coherent, sophisticated understanding of the scientific phenomenon being studied.

The cognitive processes involved in knowledge integration are neither linear nor mutually exclusive. For example, prompting students to generate explanations can involve eliciting their existing ideas, as well as adding new ideas from instruction and distinguishing among ideas as students connect ideas to answer the explanation prompt. However, an activity can be framed to emphasize certain processes more than others. In this context, my research frames critiquing and revising explanations as activities that promote the development of criteria and helps students distinguish among ideas. This premise drives the instructional designs in my empirical studies (see Chapters 2 and 3 for specific design considerations).

Dissertation Overview

This dissertation investigates the impact of iteratively refined critique and guidance on supporting students' revision of their explanations in middle school technology-enhanced inquiry science units. I synthesize insights from research on explanations, critique, and guidance to implement and test different approaches to supporting students in critique and revision of explanations through a series of comparison studies. I examine the impact of each guidance design decision on student revisions, critique, and learning processes. Each study builds on the preceding study's analytical findings.

I first discuss the curriculum design of the primary unit used to explore critique, *Global Climate Change*, and the methodology employed across the three empirical studies (Chapter 2). In the first empirical study (Chapter 3), I describe the redesign and overall impact of the *Plate Tectonics* unit on students' understanding of convection, as well as the implementation of a pilot

critique design and its results. The findings demonstrated the overall effectiveness of the unit, and characterize the students' understanding of criteria for science explanations, their ability to critique explanations using minimal guidance, and their ability to generate guidance for their peers. The findings also highlight the importance of providing effective guidance during revision.

Building on these insights, the second study (Chapter 4) explored the impact of a revised critique design using a complex selection task framework, and the role of guidance during revision following critique. A comparison of peer versus expert guidance found that successful revision was dependent on well-designed expert guidance. Findings pointed to the improved effectiveness of the redesigned critique for prompting students to distinguish among their ideas about criteria, with case studies demonstrating how the redesigned critique led students to engage in sensemaking discussions. Findings also illuminated the continuing challenge of guiding students to articulate their critique insights in their guidance to peers, and to revise their explanations based on the guidance provided. Portions of Chapter 4 have been published in Sato & Svihla (2012).

These results indicated that designing critique with complex selection engages students in distinguishing among ideas about criteria, mainly by creating a *desirable difficulty* that prevents gaming behavior and motivates discussion. However, the findings also suggested that students struggle to leverage insights gained during critique and make conceptual revisions to their explanations. In particular, the findings raised the possibility that students are likely to benefit more from being assigned explanations designed to align with their initial understanding. The third study (Chapter 5) used these findings to further refine the critique design to promote sensemaking of scientific concepts relevant to the target explanation, and compared two different approaches to designing the explanation assigned for critique. Results indicate that the current iteration of the critique design is robust enough such that it is effective for both types of designed explanations. Portions of Chapter 5 have been published in Sato & Linn (2014).

Chapter 6 discusses the overall impact of the empirical studies and outlines implications for the value of critique in instruction, critique design principles, and instruction. Directions for future research are discussed with regard to possibilities for additional refinements to the critique design and guidance provided to students. A summary of the three empirical studies in terms of research questions, key methods, and major findings are provided in Table 1.1.

Table 1.1

Summary of Empirical Chapters.

Chapter	Research Questions	Key Methods	Major Findings
Chapter 3: Pilot Critique and Guidance Study in the Redesigned Plate Tectonics Unit	<ul style="list-style-type: none"> • How did students' ideas about convection shift? • How does peer guidance, in comparison to teacher guidance, affect students' Energy Stories about convection in the Plate Tectonics unit? • What criteria do students use to critique an Energy Story? 	<ul style="list-style-type: none"> • Compared initial and revised explanations for students receiving peer guidance and students receiving teacher guidance • Embedded assessments, pre- and posttests • Guidance generated by students and the teacher • Classroom observations 	<ul style="list-style-type: none"> • Students in both conditions made significant gains in their understanding of convection • No difference was found between conditions for student revisions of explanations • Students can list criteria about explanations in the abstract, but struggle to articulate and apply them during actual critique
Chapter 4: Comparing Peer and Expert Guidance as Supports for Explaining in Science	<ul style="list-style-type: none"> • How do peer and expert guidance impact revision of student explanations in science? • How does peer guidance differ from expert guidance and typical teacher guidance? • Does the quality of the explanation that students critique (high and low) impact the gains from guidance? 	<ul style="list-style-type: none"> • Compared initial and revised explanations for students receiving peer guidance and students receiving expert guidance • Embedded assessments, pre- and posttests • Guidance generated by students and the teacher • Videoanalysis • Student interviews • Classroom observations • Student log data 	<ul style="list-style-type: none"> • Students receiving expert guidance made significantly higher gains during revision than students receiving peer guidance, regardless of the quality of explanation critiqued • Content specificity in guidance alone does not support knowledge integration and conceptual revision • Critique design employing complex selection among criteria prompted students to engage in sensemaking

	<ul style="list-style-type: none"> • How might student engagement with critique vary and relate to their feedback? 		
Chapter 5: Designing Critique to Improve Conceptual Understanding	<ul style="list-style-type: none"> • How do students benefit overall when they critique (a) an incomplete explanation with normative ideas to identify a missing idea (<i>incomplete</i>) or (b) an incomplete explanation combining normative and non-normative ideas to identify a non-normative idea (<i>non-normative</i>)? • How do students' ideas, as expressed in their explanations, shift in response to critique and revision? • How do students benefit when provided with automated guidance on their critique? 	<div style="border: 1px solid black; padding: 5px; margin-bottom: 10px;"> <p>[Grab your reader's attention with a great quote from the document or use this space to emphasize a key point. To place this text box anywhere on the page, just drag it.]</p> </div> <ul style="list-style-type: none"> • Compared initial and revised explanations for students critiquing explanations with a missing idea and students critiquing explanations with a non-normative idea • Embedded assessments, pre- and posttests • Case studies • Videoanalysis • Classroom observations 	<ul style="list-style-type: none"> • Students in both conditions benefitted from critique and made significant gains during revision • Critique design employing complex selection among relevant science ideas prompted students to engage in distinguishing among those ideas • Students' final revisions were not dependent on successful critique • Automated guidance checkpoint provided another opportunity to reconsider ideas • Potential of critique to serve as formative assessment

Chapter 2: Curriculum Design

In this chapter, I describe the methodologies underlying the design of the *Global Climate Change* unit, which was iteratively refined and tested in classroom implementations by collaborators prior to the two empirical studies in which the unit was used (cf. Chapters 4 and 5). The design and refinement of the unit used in the pilot study, *Plate Tectonics*, is described separately in Chapter 3. I also explain the assessment design and general analytical approaches taken in each of the empirical studies.

Design-Based Research

Design-based research aims to study learning in authentic contexts and investigates how learning theories translate to and inform instructional design through a process of iterative enactment, experimentation and evidence-based refinement (Sandoval & Bell, 2004; Collins, Joseph, & Bielaczyc, 2004; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). The refinement can target the conceptual learning goals of a particular topic, such as global climate change (cf. Chapter 4), or the design of a particular type of learning activity, such as critique and revision of explanations. My dissertation focuses on the latter, with findings from each experimental study informing the refinement of the critique activity design in the subsequent study. The goal of my dissertation research is to test and refine principles for designing guided critique and revision of explanations in technology-enhanced inquiry science instruction.

Curriculum Focus: Role of Energy in Global Climate Change

Global Climate Change is a week-long middle school earth science unit with a focus on energy processes, specifically energy transformations that are key to understanding the underlying mechanism of the greenhouse effect. The unit also addresses how human actions amplify the natural greenhouse effect to the detriment of the global climate. The unit leverages powerful NetLogo visualizations to make the different forms of energy visible and accessible to students.

Global climate change is a complex phenomenon in which energy transformations play a key role as the mechanism underlying the warming effect of greenhouse gases. (Rye, Rubba, & Wiesenmayer, 1997; Andersson & Wallin, 2000). Both the California science standards and the Next Generation Science Standards (NGSS, 2013) require middle school students to understand how human activity contributes to global climate change by raising the global mean average temperature. Energy is vital to all phenomena and one of the unifying concepts in science, but it is also abstract, and in most of its manifestations, invisible, making it one of the most challenging concepts for students to learn in science. Many studies document the diverse and non-normative ideas students develop about energy concepts (e.g., Driver, Squires, Rushworth, & Wood-Robinson, 1996; Clark, 2006; Liu & McKeough, 2005). Energy is typically taught in superficial, fragmented, isolated contexts in middle school curricula, which may lead students to develop a superficial understanding of the energy-driven mechanisms and thus the overarching phenomena (Nordine, Krajcik, & Fortus, 2011; Kesidou & Roseman, 2002).

Despite the pivotal role energy plays in global climate change, typical instruction focuses on the impact of human energy use on the levels of greenhouse gases in the atmosphere, and deemphasizes how energy transformation is involved in the underlying global warming mechanism. Students may believe that human actions increase greenhouse gases and mean global temperature, but do not connect the increase of greenhouse gases to the increased frequency of

energy transformations that result in warming. Instead, students may infer that the global mean average temperature increases because greenhouse gases are warm, or because greenhouse gases destroy the ozone layer (Shepardson, Niyogi, Choi, & Charusombat, 2009, 2011; Andersson & Wallin, 2000; Lee, Lester, & Ma, 2007; Papadimitriou, 2004; Groves & Pugh, 2002; Österlind, 2005). Understanding energy transformation is critical for understanding how increases in greenhouse gas levels actually contribute to global climate change.

Curriculum Design

The existing *Global Climate Change* unit has been refined in a design partnership of researchers, content experts, teachers, and technologists (Shear, Bell, & Linn, 2004). As reported elsewhere (Svihla & Linn, 2011), the unit was revised to address the issue that students in previous implementations struggled to gain a deep understanding of the role energy transformations play in the greenhouse effect. Additionally, the redesigns aimed to facilitate comparisons of different human activities' impacts on the greenhouse effect through NetLogo experimentation.

The redesign focused on supporting student learning from key NetLogo visualizations depicting energy transformations and how greenhouse gases interacted with different forms of energy. Given the complexity of the visualizations, researchers observed students struggling to take note of when and how certain forms of energy transform into another form of energy in NetLogo. For example, students often did not notice that solar radiation did not transform when it simply reflected off the Earth's surface, but did transform into heat when it was absorbed into the Earth's surface. The visualization activities were therefore redesigned to support students in linking symbolic energy representations to their corresponding energy forms and to highlight transformation conditions.

Activity 1: Global and Local

The first activity introduced students to the issues of scale in global climate change with regard to relative time scale and geographic scale (Figure 2.1). Framed as a student's question to her teacher about an unseasonably warm winter day, this activity served to familiarize students with the idea that global climate change goes beyond local weather patterns and short-term extremes.

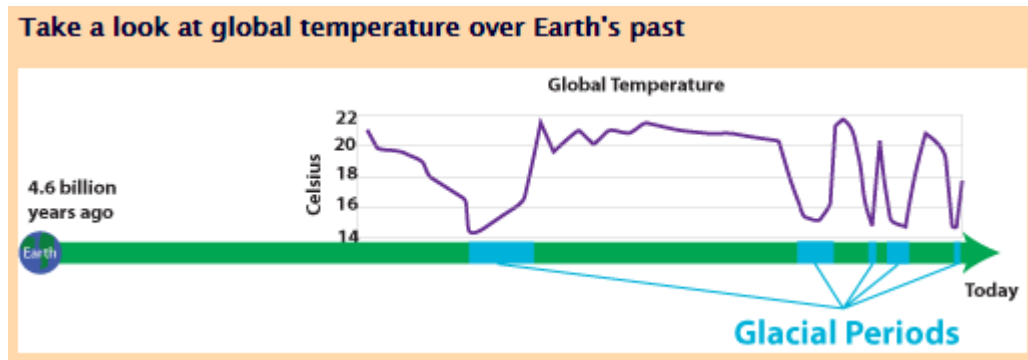


Figure 2.1. Temperature and Timeline Graphic Used in Activity 1

Activity 2: Energy from the Sun

The second activity prompted students to consider how and where Earth gets its warmth. Students were introduced to solar radiation, how solar radiation travels through space to reach Earth's surface, and under which circumstances the energy transforms into other forms of energy (Figure 2.2). The activity also served as an introduction to the first NetLogo visualization with pared-down features to support student interactions with more complex NetLogo visualizations in subsequent activities.

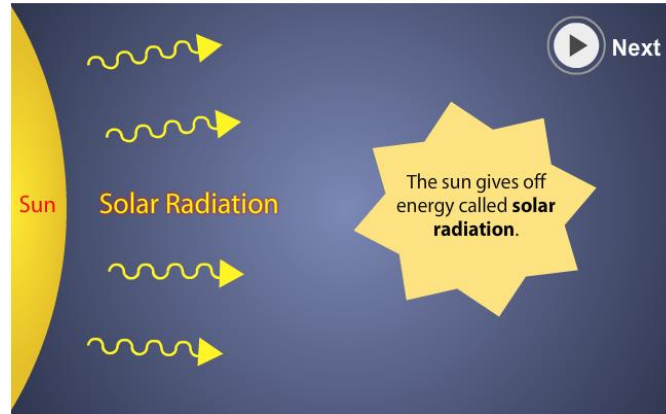


Figure 2.2. Visualization Used in Activity 2

Activity 3: Reflected Light

The third activity guided students to link their understanding of energy transformation conditions from Activity 2 to albedo, the degree of surface reflectivity, as a variable that impacts the frequency of energy transformation and corresponding fluctuations in global temperature (Figure 2.3). Students were directed to conduct a virtual experiment using NetLogo by choosing different environments with corresponding shifts in albedo values. The activity employed a predict-observe-explain pattern (White & Gunstone, 1992) to support students in extracting the relationship between environment type, albedo, energy transformations, and global temperature.

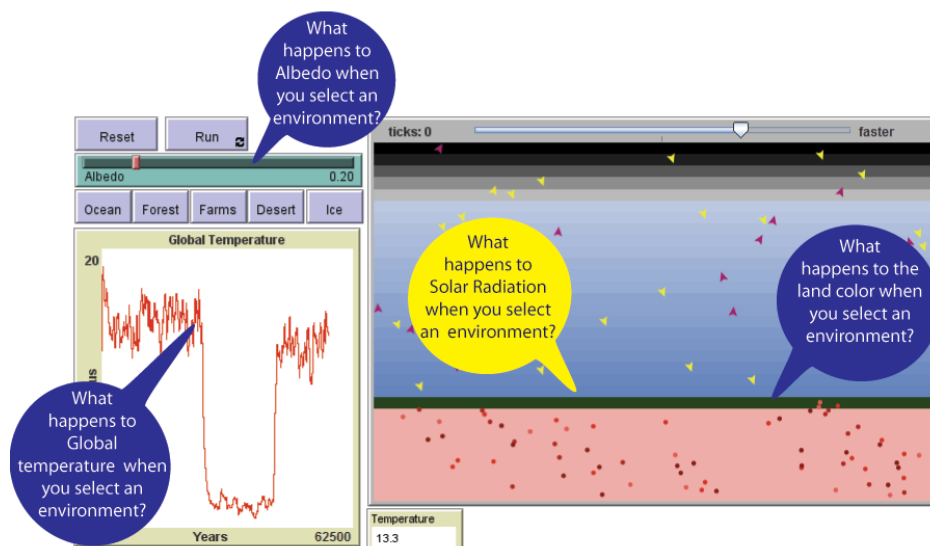


Figure 2.3. Visual NetLogo Guidance Used in Activity 3

Activity 4: The Natural Greenhouse Effect

The fourth activity continued to build on ideas about energy transformations, energy transformation conditions, and albedo from the previous activities by introducing how the natural greenhouse effect impacts how much energy leaves Earth's system. The activity focused on distinguishing between forms of energy involved in the greenhouse effect (solar radiation, infrared radiation, and heat) and which forms of energy interact with greenhouse gases. Students were first introduced to the greenhouse metaphor, in which the greenhouse's roof blocks infrared radiation from exiting the greenhouse and sends the energy back into the greenhouse, where it will transform into heat upon absorption. The metaphor was then mapped to the Earth system, with greenhouse gases acting as the roof. Finally, students interacted with a complex NetLogo simulation allowing them to add greenhouse gases through natural phenomena (volcanic eruptions) and observe their impact on global temperature to emphasize that the amount of greenhouse gas in the atmosphere can fluctuate due to natural as well as human activities (Figure 2.4).

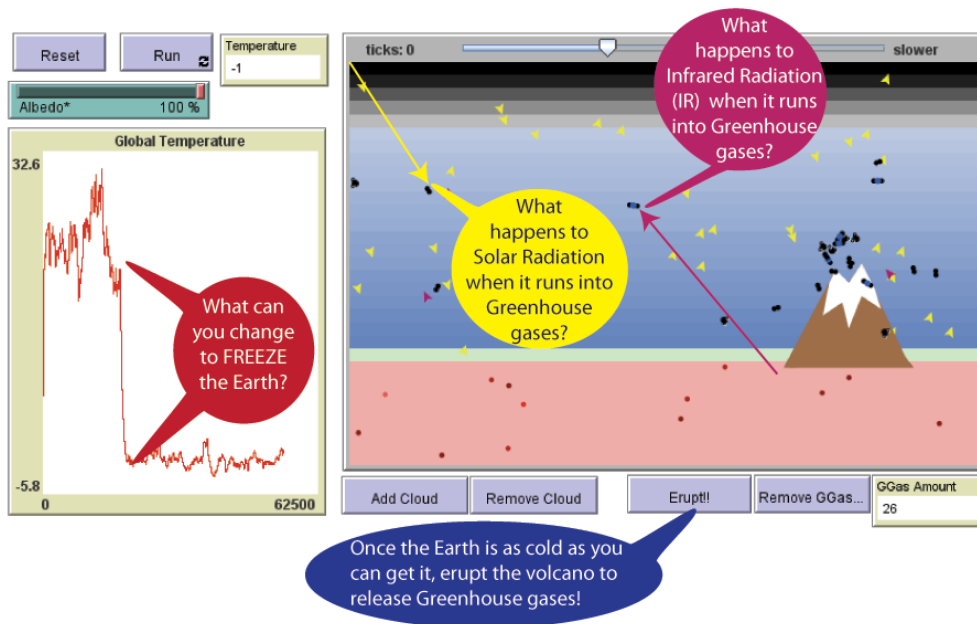


Figure 2.4. Visual NetLogo Guidance Used in Activity 4

Activity 5: Your Actions

The fifth activity addressed how human actions impact the amount of greenhouse gases in the atmosphere by introducing the natural carbon cycle and how humans directly (e.g., driving) or indirectly (e.g., consumption of meat) disrupt the balance (Figure 2.5). The activity also served as part of an extended predict-observe-explain sequence by guiding students to predict which human activities had a greater impact in the form of advising a fictional student on how to reduce her energy use.

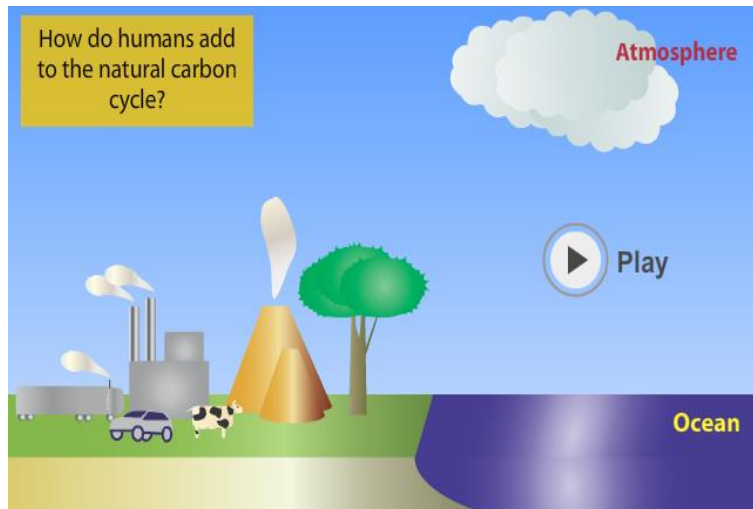


Figure 2.5. Visualization Used in Activity 5

Activities 6 and 7: Littering or Eating Meat; Walking or Reducing Electricity Use

The sixth and seventh activities comprised the observe and explain portion of the extended predict-observe-explain sequence begun in Activity 6. Students tested their predictions by running NetLogo simulations for the chosen human activities, with one comparison being littering versus eating meat and the other being walking versus reduced electricity use. In the former, the comparison was to determine which activity resulted in a greater increase in greenhouse gases; in the latter, it was to determine which activity resulted in a greater decrease in greenhouse gases. The NetLogo simulations allowed students to select each activity, then see changes in atmospheric greenhouse gas levels and global temperature (Figure 2.6). Based on their experimental findings, they were then asked to finalize their advice to the student.

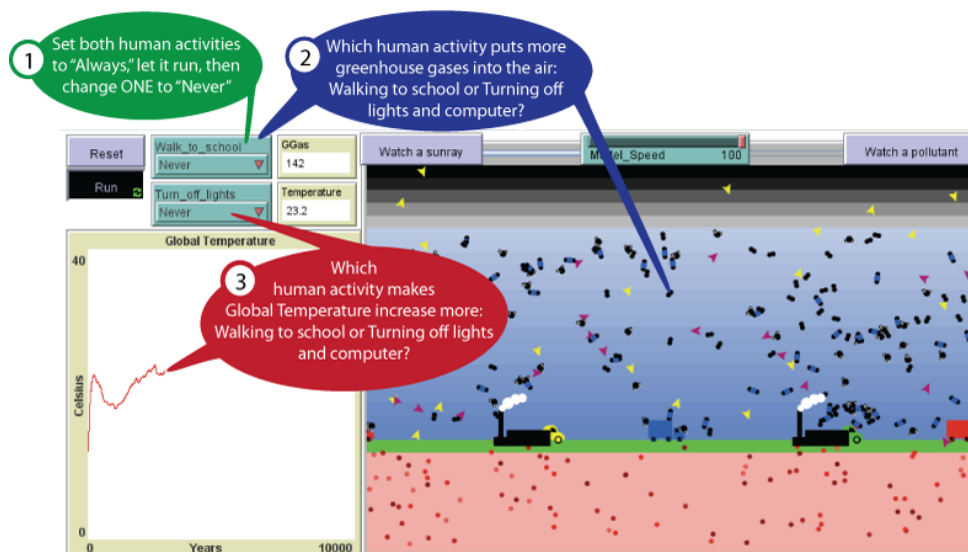


Figure 2.6 Visual NetLogo Guidance for Activity 7

Assessments

The pre- and post-test assessments, as well as embedded assessments, were iteratively refined through cycles of implementation (cf. Svihla & Linn, 2011). The pre- and post-test items mainly consisted of constructed response explanation items, some of which were multiple choice plus explain items shown to be good valid measures for knowledge integration (Liu, Lee, & Linn, 2011). In addition, students answered an extended constructed response item called the Energy Story, for which students wrote narrative explanations of energy-drive phenomena (see Table 2.1). Students also generated a MySystem diagram, which allowed them to visually depict energy flows and transformations (Figure 2.7). The MySystem diagram addressed the same concepts as the Energy Story, and served as a counterpart. Pretest and posttest items can be found in Appendix A.

Table 2.1
MySystem and Energy Story Prompts

	MySystem	Energy Story
Prompt	<p>Explain to Gwen how the Earth is warmed by energy. Be sure to include the following information as you label all arrows:</p> <ul style="list-style-type: none"> • Where the energy comes from • How the energy moves/transfers from one place to another • Where energy goes • How energy changes/transforms 	<p>Write a story to explain how the Earth is warmed by energy. Include:</p> <ul style="list-style-type: none"> • Where energy comes from • How energy moves • Where energy goes • How energy changes/transforms

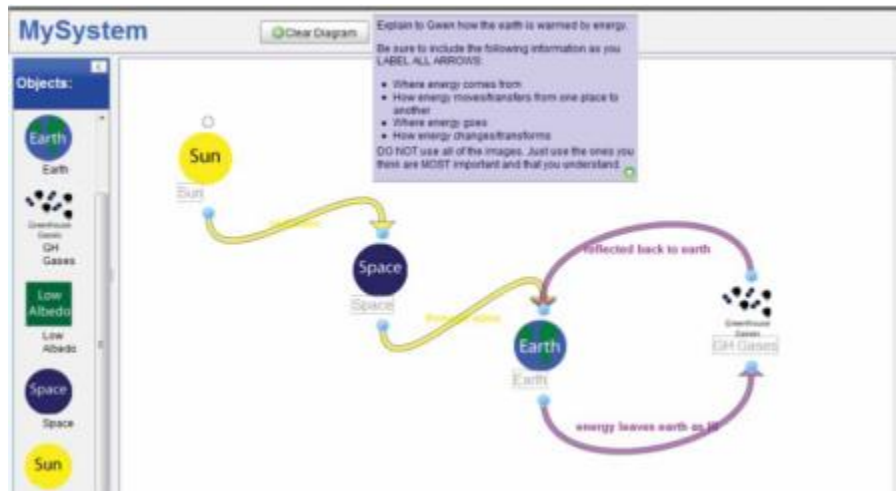


Figure 2.7 Sample MySystem diagram for the GCC unit

Embedded assessments consisted of a variety of item types, including multiple choice checkpoints to guide students to attend to salient features of NetLogo simulations, but items were predominantly constructed response explanation items. Each of the two main empirical studies in this dissertation looked closely at a constructed response explanation item targeting key energy concepts in the GCC unit (Table 2.2; for a description of the explanation item used in the Pilot Study, see Chapter 3, Table 3.1).

Table 2.2

Core Embedded Explanation Prompt used in Empirical Studies with GCC unit

Study	Prompt	Target Concepts/Links
Chapter 4: Guidance Study	How did adding greenhouse gases change global temperature? How did adding greenhouse gases change what happened to infrared radiation?	<ul style="list-style-type: none"> • Relationship between greenhouse gas levels and global temperature • Interaction between greenhouse gases and infrared radiation • Energy transformation of infrared radiation to thermal energy
Chapter 5: Critique Study	Where did infrared radiation (IR) come from in the model? Give as much detail as you can.	<ul style="list-style-type: none"> • Energy transformation sequence (solar radiation to thermal energy to infrared radiation) • Energy transformation conditions (absorption and release instead of reflection)

Analysis**Knowledge Integration Assessments**

All assessment items were scored using Knowledge Integration rubrics, which rewards coherence of ideas as represented by the number and complexity of connections students make between valid scientific ideas (Linn et al., 2006). Higher scores represent increased number of connections students made among scientifically valid ideas to explain the target phenomenon and therefore represent greater explanatory depth. Each rubric was developed by analyzing student responses gathered in pilot implementations to categorize the range of student ideas, following the grounded methodology of Strauss and Corbin (1990), then iteratively refined by sorting student responses into levels of coherence: irrelevant (KI score of 1), no link (2), partial link (3), full link (4), and complex link (5).

From the KI perspective, students are not penalized for connecting relevant but scientifically invalid ideas, as their attempt is part of the knowledge integration process. For that reason, responses linking non-normative ideas receive a score of 2 as opposed to irrelevant, off-topic responses that receive a score of 1. Similarly, if a student response contains both scientifically valid and invalid links, the response is scored based on the strength of the valid link and no deductions are taken. For example, for the core embedded explanation item used in the Chapter 5 (Table 2.2; see Table 2.3 for rubric), a student may write that “infrared radiation happens when heat energy bounces off the Earth’s surface and transforms into infrared radiation.” Although the student’s idea that thermal energy transforms into infrared radiation is scientifically valid, the energy transformation condition (“when heat energy bounces off the Earth’s surface”) is incorrect. The response would be credited for the valid energy transformation idea, but not penalized for the invalid energy transformation condition idea.

The KI rubric also seeks to differentiate between full, complete connections and partial connections between the target concepts. In the Chapter 5 item’s case, some students may have a full grasp of the energy transformations occurring in sequence (i.e., solar radiation to thermal energy to infrared radiation), but others may write that infrared radiation comes from solar

radiation without indicating the intervening phase. Such responses, in the absence of other complete valid links, would therefore be credited as having partial understanding.

Table 2.3

Knowledge Integration rubric used to score key item in Chapter 5.

Explanation Prompt:		
Where did infrared radiation (IR) come from in the model? Give as much detail as you can.		
Score	Description	Student Examples
1 (Irrelevant)	No answer or irrelevant answers	I don't know
2 (No Link)	Non-normative ideas or links	It came from the sun and space.
3 (Partial Link)	One relevant and normative idea	IR came from conduction, under the earths crust. The Solar Radiation transforms into heat energy that bounces off earths crust and is trapped by the greenhouse gases and unable to escape earths atmosphere.
4 (Full Link)	Scientifically valid and fully elaborated link between two relevant and normative ideas	It comes from heat energy when heat energy is released it goes into the Infrared radiation, so it becomes heat energy.
5 (Complex Link)	At least two links among three or more relevant and normative ideas	Some solar radiation is reflected back into space, and some is absorbed. The SR that is absorbed becomes heat energy, and heats up the Earth. It is in there for a while, and is eventually is released back into the atmosphere as infrared radiation.

Note. Examples are actual unedited responses by students.

In addition to analyzing the scored written assessments to track overall learning gains from pre- to posttest, or from initial to revised explanations, I analyzed the scored assessments for types and/or normality of ideas (e.g., Chapter 3, Figure 3.12; Chapter 5, Figure 5.4) to track shifts in students' understanding at a smaller grain size than raw KI score gains. I investigated possible associations between shifts in students' understanding and other metrics, such as the association between types of guidance received and successful revisions to their explanation (Chapter 4, Tables 4.10, 4.13); revisits of key evidence steps and successful revisions (Chapter 4, Table 4.14); and successful critiques and successful revisions (Chapter 5, Figure 5.5). This analysis aimed to address alternative interpretations of the core data and account for additional factors that may have impacted student engagement with the writing, evaluation, and revision.

Qualitative Case Studies

To assess the effectiveness of the critique guidance design in the two main empirical studies (Chapters 4 and 5), I conducted illustrative case studies to capture how student pairs engaged with key activities investigated in my studies (Yin, 2013). For each empirical study, I conducted a video case study and a written assessment case study looking more in-depth at specific student revisions of explanations based on intervening steps such as their critiques and received guidance (see Table 2.4 for summary of case studies conducted). For the video case studies, I selected video cases from the available video corpus that illustrate the kinds of wide variations in student engagement during critique that were observed in the data corpus as a whole. Video data were transcribed using a modified version of Och’s conventions (1979, p.63-6), and contrasting cases were summarized, then compared to glean further insights from a specific design’s implementation results for additional refinement. Similar selection and analysis processes were employed for the embedded assessment case studies, where I selected student pairs from the available written data corpus and summarized and compared their work to inform the next iteration of the activity design.

Table 2.4
Summary of qualitative case studies

Study	Focus of Case Study	Data Sources
Chapter 4: Guidance Study	Engagement with critique	Video
	Engagement with revision	Written assessment, guidance received
Chapter 5: Critique Study	Engagement with guidance checkpoint	Video, written assessment
	Engagement with revision	Written assessment

Chapter 3: Pilot Critique and Guidance Study in the Redesigned Plate Tectonics Unit

This chapter discusses the design, implementation, and impact of guided critique in a revised technology-enhanced *Plate Tectonics* unit. The unit was designed to help students relate surface geological features and events to underlying processes deep within the Earth. In addition, there was special emphasis on helping students understand how thermal energy is transferred in fluids through convection.

This chapter reports on the general redesign of the unit and incorporation of an extended sequence designed to target convection, as well as a pilot study conducted with the redesigned unit featuring a preliminary guided peer critique activity sequence. Specifically, the chapter investigates the following questions:

1. How do students' ideas about convection change?
2. How does receiving peer guidance, in comparison to teacher guidance, after guided peer critique impact students' Energy Stories about convection in the *Plate Tectonics* unit?
3. What criteria do students use to critique an Energy Story?

Rationale

Plate tectonics is a causal theoretical framework for past, current, and future geographical phenomena (Bencloski & Heyl, 1985). It is currently taught as an earth science unit in sixth grade in the state of California. It has traditionally been a difficult concept for middle school students (Gobert & Clement, 2002), requiring students to learn about abstract processes and phenomena that lie outside of their direct experience and to integrate spatial, causal and dynamic information (Gobert, 2000).

One way to support students' knowledge integration in plate tectonics is by asking them to generate explanations. Prompting students to generate explanations have been shown to help students integrate ideas in science (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher, 1994). However, prior research has shown that generating explanations can provide the explainer with an illusion of explanatory depth (IOED, Keil, 2004). Students may gain a false sense of understanding a given topic upon generating a partial explanation. One factor contributing to IOED may be lack of experience with assessing explanations, as students may not have developed criteria for what constitutes a good explanation.

Designing activities that support students in developing criteria and assessing explanations may therefore have a positive impact on their knowledge integration. Findings from previous research on student assessment are mixed with regard to its benefits (Falchikov & Goldfinch, 2000). Furthermore, students need substantial guidance in order to critique effectively (Tsivitanidou, Zacharia, & Hovardas, 2011). Thus study investigates the efficacy of an initial design for critique guidance.

Research in writing also suggests that prompting students to revise their initial explanations based on direct conceptual guidance on their explanations may help students further distinguish their ideas. Since generating guidance for revision requires evaluating initial written work, this study examines guidance generated by students after guided critique or by teachers and how each contributes to revision. While prior research has identified some guidelines for guidance on students' writing (e.g., Underwood & Tregidgo, 2006; Hattie & Timperley, 2007), further clarification is needed as to when and how guidance can support students in refining their written conceptual understanding. In particular, current studies focus on students at the post-secondary

level, making it difficult to extrapolate findings to younger students in K-12 contexts. The pilot study therefore sought to characterize typical guidance generated by students and teachers for student explanations, and how the peer or teacher guidance impacted subsequent student revisions.

To explore what conditions are necessary for students to benefit from critiquing their own or peer explanations, I conducted a design study using a six-day technology-enhanced curriculum project developed using the Web-Based Inquiry Science Environment (WISE, Linn, Davis, & Bell, 2004). The curriculum design is guided by the Knowledge Integration (KI) framework (Linn, Eylon, & Davis, 2004). The KI framework identifies instructional patterns to support students in developing a more integrated, normative understanding, with an emphasis on developing students' criteria in order to help students distinguish among their initial ideas and new ideas encountered through instruction. From a KI perspective, developing criteria will enable students to evaluate their conceptual repertoire and distinguish between their normative and alternative ideas.

In this study, I extend the instructional pattern to support students in developing criteria about a particular type of explanation, the Energy Story. Energy Stories are narrative explanations (Norris et al., 2005) in which students describe how energy processes manifest in a given context. Energy Stories extend typical Knowledge Integration explanation items by prompting students to connect more concepts into a cohesive causal narrative about the target phenomenon. In the Plate Tectonics unit, students are asked to explain how energy within the earth affects changes in the mantle. The Energy Story is considered to be a core assessment item in the project, requiring students to integrate various types of information at both macro- and microscopic scales.

Overall Redesign of Plate Tectonics Unit

The existing *Plate Tectonics* unit was heavily revised in accordance with current KI design principles. The KI framework involves designing a non-linear, recursive learning process through eliciting student's existing ideas, adding new ideas through instruction, distinguishing among the existing and new ideas by developing criteria, and refining their conceptual repertoire through reflection. Given that plate tectonics is an abstract process involving geological time scales, I reorganized the *Plate Tectonics* unit to progress from the exploration of more familiar and concrete surface features and processes to that of more abstract and invisible processes underneath Earth's surface while supporting students in making connections between the surface and sub-surface processes.

Activity 1: What's Our Country Like?

The first activity introduced students to a series of maps of the United States highlighting differences in features between the East and West Coast, as well as Northern and Southern California (Figure 1.1). This activity served as the gateway to learning about plate tectonics by presenting a familiar context (their country and state), and prompting students to notice that different regions of the same country or state can have different distributions of geological features, such as mountains, and processes, such as volcanic activity. The activity's intent was to elicit students' ideas about why these differences might exist.

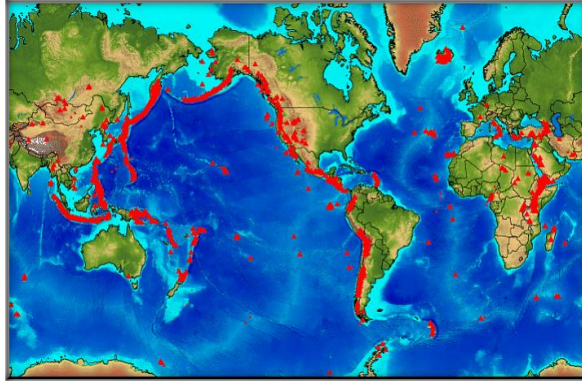
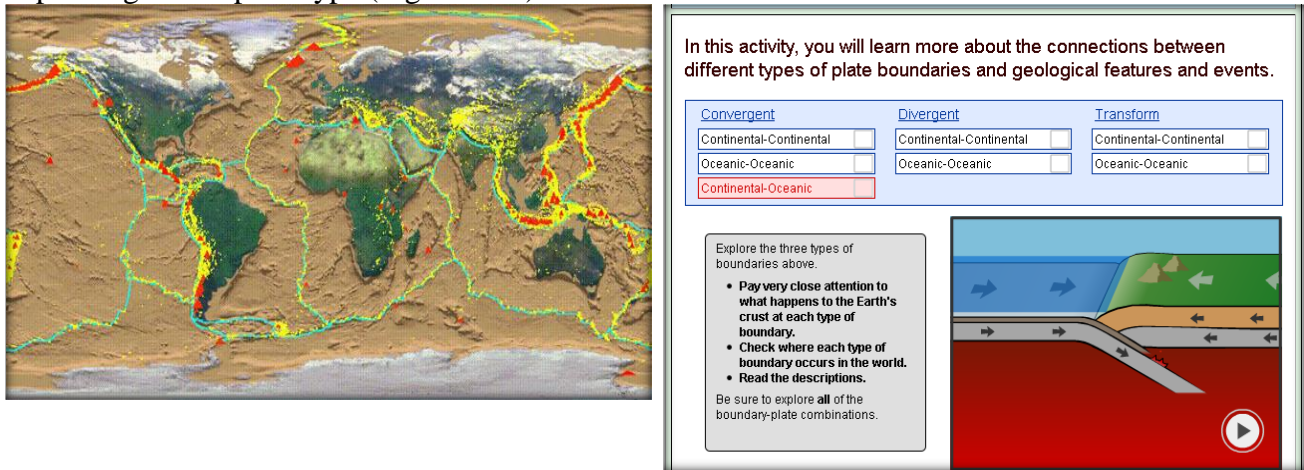


Figure 3.1. Screenshot of Map Used in Activity 1

Activity 2: What's Happening Outside?

The second activity prompted students to build on their observations of surface features and processes in Activity 1. After introducing plate boundaries, which are both surface and sub-surface structures, students were prompted to correlate the features and processes with plate boundaries in general (Figure 3.2a). Then, they were introduced to the idea that plates are in motion, which result in different types of plate boundaries (convergent, divergent, and transform), and explored a visualization showing what geologic features and events occur at each type of boundary depending on the plate type (Figure 3.2b).



(a) (b)
Figure 3.2. Screenshots of Map and Visualization Used in Activity 2

Activity 3: What's Going on Inside?

The third activity continued the progression toward more abstract, sub-surface features by prompting students to consider why plates move. At the time of implementation, convection was still emphasized as a driving force underlying plate movement, although advances in geologic research had identified ridge push (gravity acting on cooling lithosphere on a downward slope at a midocean ridge) and slab pull (gravity acting on subducting lithosphere) as primary causal factors. Thus, the activity focused mostly on convection. After students explored the underlying mechanisms of convection in the context of water (the design will be explained in depth in a subsequent section), they were prompted to reconnect their insights to the context of plate tectonics

by mapping conceptual elements underlying convection onto Earth's layers (Figure 3.3a). Students then revisited a key visualization from Activity 2 showing different plate boundaries and associated geologic features and events, where the visualization now also showed the associated convection cells and provided additional information about the feature or event shown (Figure 3.3b).

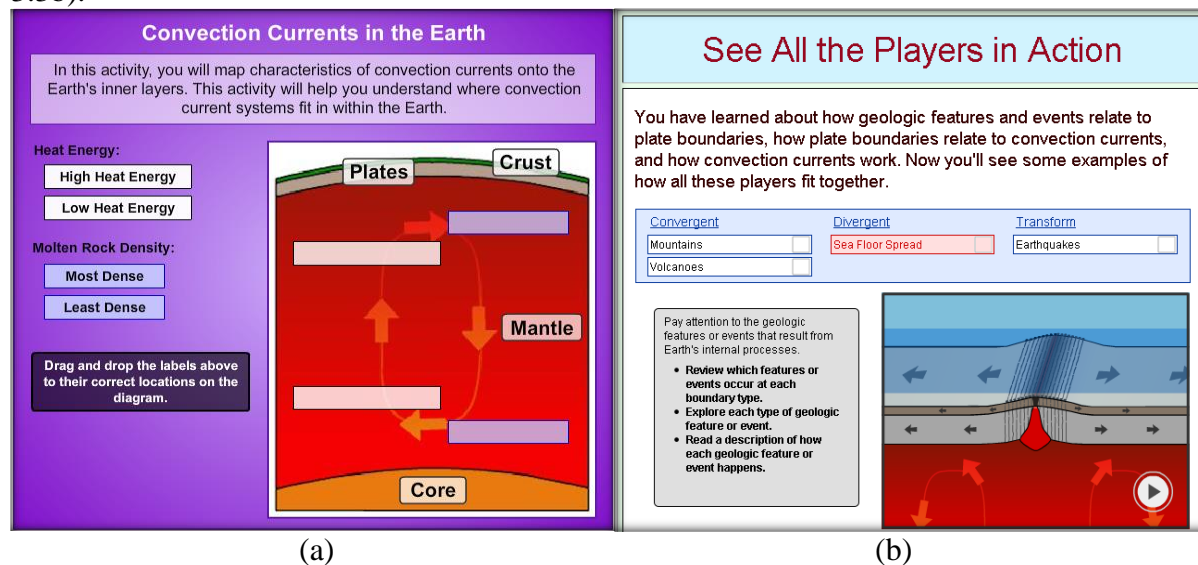


Figure 3.3. Screenshots of Visualizations Used in Activity 3

Activity 4: Express Your Knowledge

Activity 4 was implemented in previous versions of the Plate Tectonics unit as an opportunity for students to consolidate their understanding by drawing a model of a geologic feature or event of their choice showing both surface and sub-surface processes. This activity was retained in the revised Plate Tectonics unit so that it would serve as an initial attempt by students to distinguish among a variety of ideas they may now have about surface and sub-surface geologic processes before proceeding to generate a concept diagram and the Energy Story.

Activity 5: Reflection

Activity 5 presented students with additional opportunities to refine their understanding by generating two complementary representations: a concept energy flow diagram called MySystem, and an Energy Story about a geologic feature or event of their choice, with an emphasis on energy flow. Both items asked students to depict the same phenomenon, but the MySystem diagram prompt asked students to focus on energy flow, while the Energy Story prompt asked students to focus on describing changes due to energy flow (Table 3.1; see Figures 3.4 and 3.5 for examples).

Table 3.1

MySystem and Energy Story prompts

	MySystem	Energy Story
Prompt	Create a MySystem diagram that shows the <u>energy</u> involved in convection currents in the Earth. Make sure your diagram shows:	Based on the convection current exploration activities, write a story about changes in the mantle as it moves from the Earth's core towards the crust and back

	<ul style="list-style-type: none"> ○ Where the energy comes from ○ How the energy moves ○ Where the energy goes 	<p>down to the core. Make sure you include as much detail as you can to describe the following information:</p> <ul style="list-style-type: none"> ○ Where does the energy come from? ○ Where does the energy go? ○ How does the energy move? ○ How does the energy change? ○ What role does the energy play in changes in the mantle?
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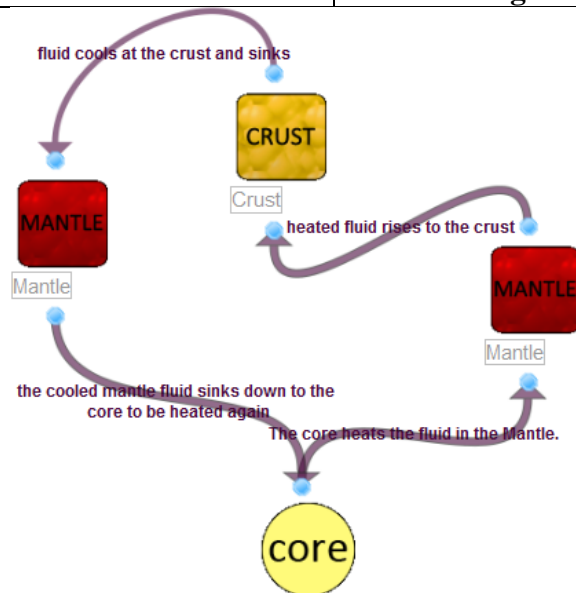


Figure 3.4. Sample MySystem Diagram

The energy comes from the core and goes through the mantle, the upper mantle, the crust and back down to the core. It goes through the core by convection currents. This is how convection currents work. Well, the core is so hot and has so much heat energy it makes the molecules less dense than the air around it so it goes up. Once it goes up it doesn't have that heat source so it cools down and the molecules get less dense than the air around it so it goes back down. When it goes back down it is near the core, or its main heat source. So it goes again and the process keeps repeating. Whenever the energy goes through the upper mantle it then goes near the crust and it turns into kinetic energy. So beneath the crust the energy is going up and down and it eventually, (depending on which direction it's going), it will spread the crust through kinetic energy. So through convection currents it creates all sorts of new geological features, in the mantle, crust, and in the whole world.

Figure 3.5. Sample Energy Story

Design of Activity 3 Sequence Emphasizing Convection

I also strengthened the convection component of the curriculum unit and the connections between convection and other concepts in plate tectonics and other disciplines. Whereas the processes involved in convection were described in a single paragraph in the original project, I

expanded the section to allow students to explore and visualize the process of convection at both macro- and micro- levels to contextualize their understanding of convection to plate tectonics, and to extend their understanding of the principles involved in convection to other contexts such as lava lamps and hot air balloons.

Because convection is a macro-scale phenomenon arising from micro-scale changes, students explored convection at both macro- and microscopic levels of representation. Convection is also an invisible, unfamiliar process, so students were introduced to convection through the predict-observe-explain (POE) sequence with a demonstration commonly employed in classrooms using a tank of water, colored dye, and a heat source (Figure 3.6). Students viewed a short video clip of the demonstration setup and then predicted what would happen to the dye. They then viewed a video of the actual demonstration and explained why the dye rose and fell in the tank of water.



Figure 3.6. Screenshots of Activities with Demonstration Video

Following the predict-observe-explain sequence, students re-investigated the convection demonstration at the molecular level by “zooming in” to the pool of dye inside the water tank (Figure 3.7) and simulating the addition and removal of a heat source in a Molecular Workbench visualization. A follow-up activity prompted students to link what happened at the molecular level to the macro level phenomenon by taking virtual molecular “snapshots” of a macro-level convection current animation (Figure 3.8).

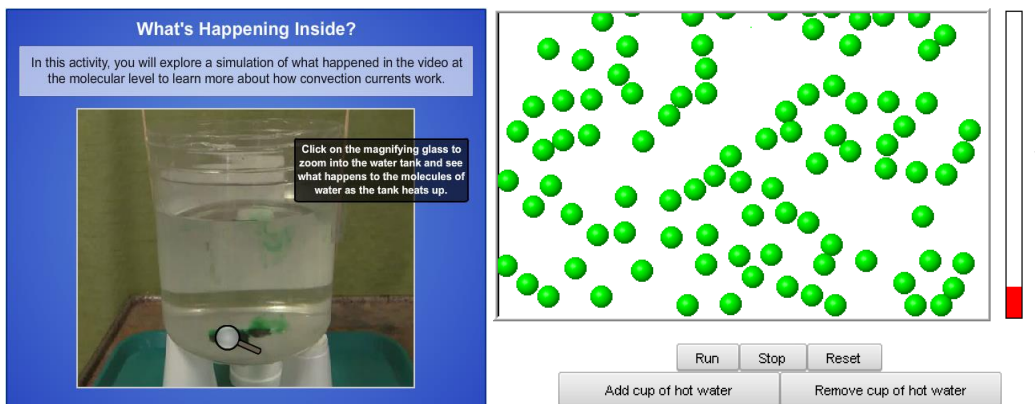


Figure 3.7. Screenshots of Activities with Molecular Workbench Simulation

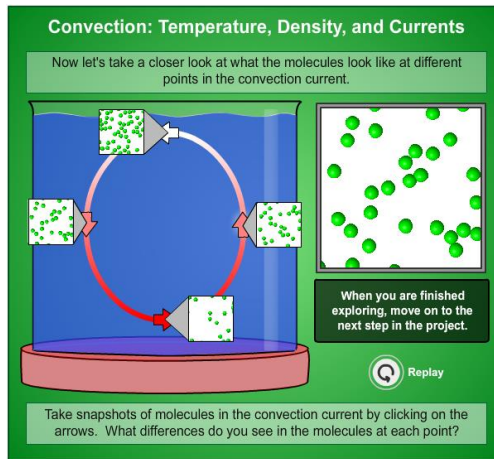


Figure 3.8. Screenshot of Activities with Macro-Scale Animation of Convection

Methods

Participants and Study Design

The seven-day *Plate Tectonics* unit was completed by 82 middle school students in four intact classrooms taught by the same teacher, who had more than 10 years of experience teaching science using web-based inquiry instruction and had taught previous versions of the unit. Students had completed at least one web-based inquiry unit prior to the *Plate Tectonics* unit, and had not received classroom instruction on plate tectonics. The pre- and post-tests were each completed within a 50-minute classroom period. Students worked on the unit in pairs, but completed the online pre- and post-tests individually.

Two classroom periods were assigned to the *peer guidance* condition, and two classroom periods were assigned to the *teacher guidance* condition. I used a pretest/posttest experimental design with embedded assessments and two comparison conditions. Based on the design research paradigm, the study sought to investigate whether one condition is better than the other. In the *peer guidance* condition, students critiqued a randomly assigned peer Energy Story, then revised their own Energy Story. In the *teacher guidance* condition, students critiqued an Energy Story pre-selected from a previous implementation of the unit.

Critique Activity Sequence

The critique activity sequence was embedded in Activity 3 of the redesigned *Plate Tectonics* unit (Figure 3.9). After generating a short explanation about how convection makes fluids move, students' ideas about criteria for what makes a good explanation in science were elicited in a brainstorm step. The step asked students for three criteria they considered to be important for explanations in science. The teacher then led a whole-class discussion around students' initial brainstorm, and encouraged students to think about using evidence from the curriculum, detecting missing ideas in order to achieve sufficient explanatory depth, and connecting relevant ideas with reasoning. Following the discussion, students revisited their list of criteria and chose the final two criteria in addition to one criteria that were provided to students: "Complete science content (Is anything missing?)." In addition to science content criteria, students were also prompted to list stylistic criteria based on discussions with the teachers that students tend to focus on stylistic criteria and may need to explicitly distinguish between stylistic and science

content criteria. Students then generated their Energy Story, critiqued the randomly assigned or preselected Energy Story, then revised their initial Energy Story based on either *peer* or *teacher guidance*.

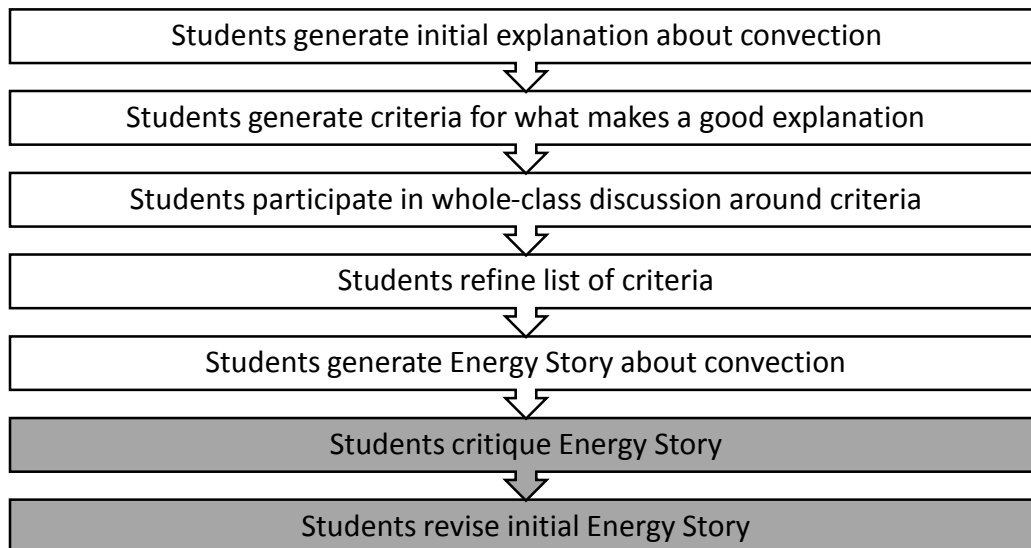


Figure 3.9 Outline of the overall activity sequence. The shaded step indicates where the activity sequence differed between the two versions.

Design of the Critique Guidance

During critique, students were prompted to use their final criteria list for what makes a good explanation in science to evaluate the randomly assigned or preselected Energy Story, which were both presented as work from an anonymous pair of peers (Table 3.2). They were asked to provide both positive comments (“What are the things that make this a good energy story?”) and constructive critique (“What are the things that could be improved?”). The guidance was designed to support students in using their refined criteria about explanations in science to evaluate an Energy Story and write detailed guidance to actual (*peer guidance*) or fictitious (*teacher guidance*) peers.

Table 3.2
Critique guidance provided to students

Instruction	Now that you and your partner have chosen common criteria for Energy Stories, use the list of criteria to help one of your peers improve their Energy Story. Be specific! <ul style="list-style-type: none"> • What are the things that make this a good Energy Story? • What are the things that could be improved?
Energy Story Prompt	
Work Submitted by Team Anonymous	[Preselected or randomly assigned Energy Story]
Your Feedback for Team Anonymous	- What are the things that make this a good Energy Story? (Use your criteria list in 3.15!)

	- What are the things that could be improved? (Use your criteria list in 3.15!)
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Data Sources

Student work formed the core data source, with the individually completed pre- and posttests, as well as the pair work on initial and revised explanations, and the peer critiques. Student responses were coded using a rubric based on the KI framework, which rewards coherence of ideas as represented by the number and complexity of connections students make between their ideas (see Table 3.3). I analyzed students' responses for links between ideas about heat, density, and movement to explain convection. The following rubric emerged from the larger student data corpus. Additional data sources included classroom observations and student and teacher interviews to explore alternative interpretations of data.

Table 3.3

Knowledge Integration rubric used to code convection assessment items

Sample Prompt: [image] Lava lamps are special lamps full of fluid. [image] Every so often, a blob of colored fluid will go up to the top of the lamp, then go back down again. How do you think lava lamps work? Using what you know about HEAT and DENSITY, explain how you think lava lamps work.			
Main Links			
Link between heat and density		When the “blob” is heated up, it becomes less dense. When the “blob” cools down, it becomes denser.	
Link between heat and movement		When the “blob” heats up, it rises. When the “blob” becomes cooler, it sinks.	
Link between density and movement		When the “blob” becomes less dense, it rises. When the “blob” becomes more dense, it sinks.	
score	Level	Description	Examples
1	Off-task or Idk. Student writes, but the response does not answer the question being asked.		no idea!
2	Non-normative ideas or links, Scientifically non-normative ideas (misconceptions), vague ideas, or scientifically invalid connections between ideas	Non-normative/irrelevant: Token mechanism only ("by heat" "by convection") with no elaboration. Heat as an active agent (e.g., heat causes pressure that makes the lava rise. Heat pushes the lava up.).	I think lava lamps work by the heat of electricity heating up the lamp. The reason it goes up and down is because the gob of heat is denser than the air so it will end up sinking down and going back up
3	Partial link Unelaborated connections using relevant features OR Scientifically valid	Only link(s) w/in ONE category. Links in multiple categories, but isolated.	I think the heat comes from the bottom, and the blobs capture some of the heat and rise. When they reach the

	connections that are not sufficient to solve the problem.		top, they cool and sink back down. (only heat+mvmt links)
4	Full link One scientifically complete and valid connection	Links in THREE categories for one direction (up or down).	As the colored fluid on the bottom of the lamp heats, it becomes less dense and rises to the top. (heat+density, heat-density+mvmt links for UP)
5	Complex links Two or more scientifically complete and valid connections	Links in at least THREE categories for ONE direction (up or down) with links in at least ONE category for the other direction.	The goo goes up as it gets hotter, getting less dense. As it cools it gets more dense, sinking. (heat+density, heat+mvmt & density+mvmt links for both UP and DOWN) The heat is less dense then cold temp. so it rises but then it cools down so it starts going to the bottom of the glass. so its basically like a cycle. (heat+density, heat+mvmt & density+mvmt for UP, only heat+mvmt for DOWN)

A full understanding of convection (KI score of 4) was characterized as a coherent description of movement in one direction by linking ideas about heat and density. A complex understanding of the phenomenon (KI score of 5) was characterized as having the elements of full understanding with an additional relevant idea indicating at least a partial understanding of causal factors driving movement in the opposite direction.

Results

The *Plate Tectonics* unit was implemented as planned. Classroom observations indicate that students were engaged during the whole classroom discussion about criteria. While the manual assignment of peer explanations during critique presented a logistical challenge, no technical mishaps occurred and students were able to complete the unit within the expected time of seven class periods. Overall, students benefitted from the instruction in all conditions. There was no difference between expert guidance and peer guidance on students' revisions or on their pre- and post-test performance.

Impact of the Plate Tectonics Unit on Overall Learning Gains

Analyses of student responses using the KI rubric indicate that students made significant gains overall with a medium effect size ($d=.55$, see Table 3.4). There were no significant differences between conditions after controlling for pretest scores ($F(1,79)=0.26$, $p>.05$).

Table 3.4

Means and standard deviations for pre- and post-test scores by condition

	N	Pretest		Posttest		t	Effect	p
		M	SD	M	SD		Size	
							d	
All	82	2.62	0.99	3.22	1.17	5.09	0.55	<.001
Peer Guidance	42	2.52	0.94	3.21	1.20	4.37	0.64	<.001
Teacher Guidance	40	2.73	1.04	3.23	1.14	2.86	0.46	<.01

On average, students began with non-normative ideas about convection, but were able to achieve partial understanding. A breakdown by KI score shows that while an overall shift toward normative understanding of convection occurred, approximately one-third of students (32%) retained non-normative ideas about convection in the post-test, and only 28% of students expressed a full or complex understanding of convection (Figure 3.10).

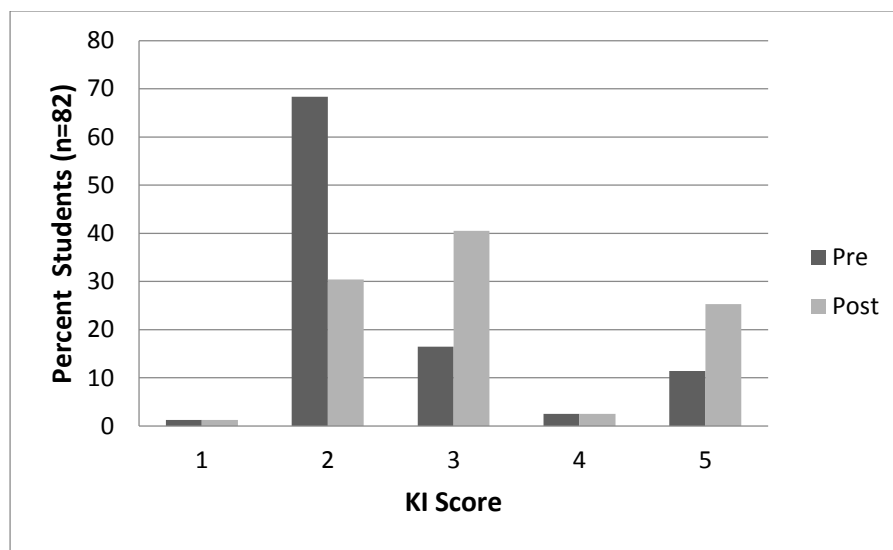


Figure 3.10. Distribution of KI scores of student responses by percent in pre- and post-tests.

When KI score gains were analyzed, it was found that half of student responses expressed no gains or even negative gains in understanding (Figure 3.11). Although 24% of those responses had already expressed a full or complex understanding at the pre-test, the majority of those responses (60%) had expressed a non-normative understanding in the pre-test (16% partial understanding). Overall, 53% of students who wrote non-normative responses in the pre-test did not show gains, indicating that the unit can be further refined to help students with alternative ideas about convection achieve a more normative understanding.

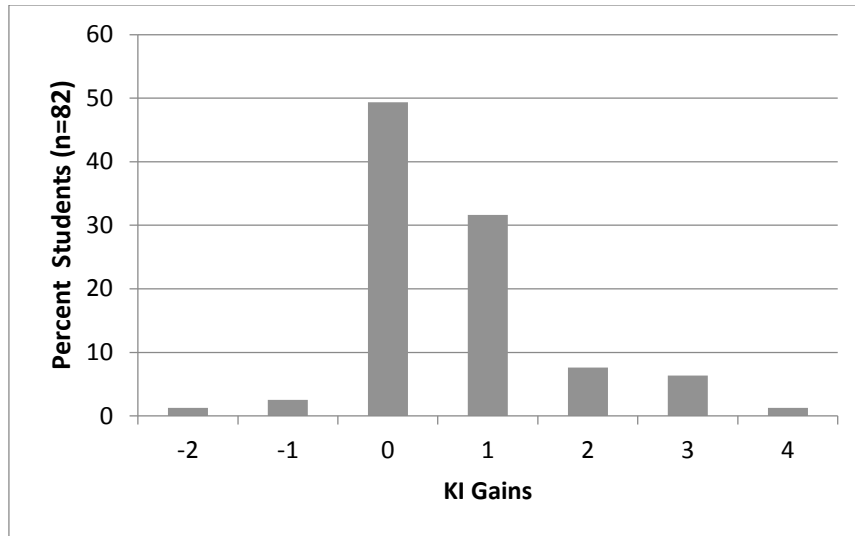


Figure 3.11. Distribution of gains in KI scores in student responses from pre- to posttests by percent

To analyze which ideas may have been more difficult for students to integrate into their understanding of convection over the course of the curriculum unit, I analyzed student responses for specific links as specified in the rubric for the item targeting convection (Figure 3.12; see Table 3.3 for links). Non-normative ideas about heat and movement were primarily ideas that heat directly exerted an upward force or pressure on lava lamp blobs. Some student responses were teleological in nature, attributing the blob’s movement to the blob’s desire or need to “go away from” or “go back to” the heat source in the lamp. Non-normative ideas about heat and density as well as about density and movement generally consisted of confusing the relationship to be the reverse (e.g., increased heat in a substance increases the substance’s density, increased density of the blob causes the blob to move up). Although the majority of students (61%) were able to connect normative ideas about heat and movement of fluids in their responses, only a third were able to connect normative ideas about density with either heat or movement (32% and 35%, respectively), which were necessary in order for the students’ responses to receive a KI score of 4 or 5. Of the post-test responses with a KI score of 3 (partial understanding), 70% only expressed heat-movement links and 24% only expressed density-movement links. These findings suggest that of the normative links needed to explain convection, density presented the greater difficulty.

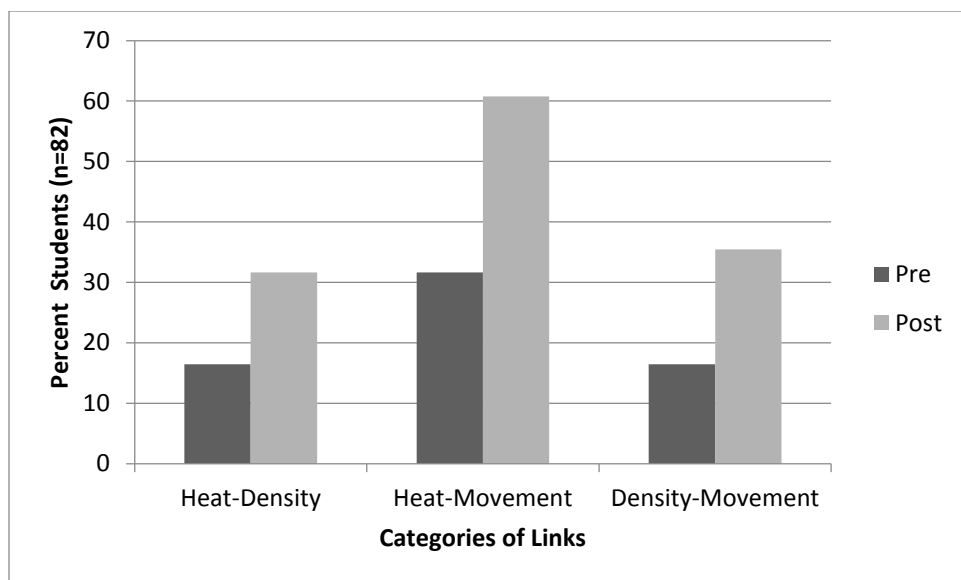


Figure 3.12. Percent of student responses containing scientifically valid links from pre to post.

Student Explanation and Revision

A larger sample of students ($n=55$ pairs), some of whom did not complete the pre/post-tests but did complete the critique activity sequence and received teacher or peer guidance before revision, were included in this analysis. On the embedded assessments, there was no significant improvement from the students' original to revised explanation for either condition (Table 3.5). There were no significant differences between conditions after controlling for their initial explanation scores ($F(1,52)=0.26$, $p>.05$).

Table 3.5

Means and standard deviations for original and revised explanation scores by condition

	N	<u>Original</u>		<u>Revised</u>		<u>t</u>	<u>Effect</u>	<u>p</u>
		M	SD	M	SD		<u>Size</u> <i>d</i>	
All	55 pairs	2.38	0.80	2.76	1.53	2.05	0.31	<.05
Peer Guidance	25 pairs	2.36	0.75	2.64	1.55	0.96	0.23	>.05
Teacher Guidance	30 pairs	2.40	0.86	2.87	1.53	1.92	0.38	>.05

Student Criteria

I analyzed the finalized list of criteria students generated following the classroom discussion to examine which criteria students felt were relevant for good explanations in science. As mentioned previously, the classroom discussion prompted students to consider the use of evidence, achieving sufficient explanatory depth, and using reasoning to connect ideas to generate a coherent explanation consistent with Knowledge Integration principles. Students' submitted criteria were coded along the dimensions of evidence, explanatory depth, reasoning, demonstrating sufficient knowledge, salience, and miscellaneous criteria (see Table 3.6 for category examples). Criteria were grouped under miscellaneous if less than five percent of student pairs included the criteria in their final list. Of the 59 pairs who submitted a final list of criteria, 28 (47%) cited

evidence, 14 (24%) explanatory depth, 21 (36%) reasoning, 9 (15%) demonstrating sufficient knowledge, and 5 (8%) salience. Only 6 pairs (10%) did not include any of the criteria emphasized during the classroom discussion (evidence, explanatory depth, or reasoning), whereas 41 pairs (69%) cited one of the three criteria, 11 (19%) two, and 1 pair (2%) all three. These findings indicate that most students identified at least one explanatory criteria as being relevant.

Table 3.6
Categories of criteria generated by students for explanations in science

Dimension	Sample Criteria Listed
Evidence	“Proof”; “Facts”
Explanatory Depth	“Details”
Reasoning	“Has to be clear”; “Logic”
Sufficient Knowledge	“Know what you’re talking about”; “Do your research”
Salience	“Answer the question”; “Have a topic”
Miscellaneous	“Give examples”; “Know your topic”; “Use science vocab”

Peer Guidance

To examine how students applied their criteria during critique, I analyzed how student pairs critiqued Energy Stories. Recall that during critique, students were prompted to draw on their finalized criteria list to evaluate the Energy Story. Critique was framed as providing guidance to their peers to help them improve their initial Energy Story, and sub-prompts guided students to provide both positive and constructive guidance (Table 3.2). Of the 51 pairs who submitted a critique, 9 (18%) declined to provide constructive guidance and stated that the Energy Story needed no improvement, and 15 (29%) focused exclusively on stylistic dimensions such as spelling and grammar for improvement.

Although students were prompted to be as specific as possible, only 13 (25% of total), or 45% of student pairs who wrote constructive guidance, referenced specific science content (see Table 3.7). Most student pairs therefore listed criteria with no elaboration. In fact, 12 (24%) submitted their critique where the criteria were in a list format (e.g., “details, evidence, know what you’re saying.”) without indication of how they applied the critique to evaluate the Energy Story. Indeed, classroom observations note that during critique, students were not observed discussing whether and which criteria applied to their assigned explanation. Students were observed suggesting which criteria to include in their evaluation, whose partners then would simply agree without requesting elaboration. These findings point to the difficulties students have in evaluating their own or another’s explanation. Interviews and classroom observations indicate that the teacher and the students had prior familiarity with criteria for written explanations in science, with the teacher stating that she reinforces the importance of evidence, reasoning, and so forth to her students when writing explanations. The written guidance generated by students during critique suggest that though they may be familiar with the abstract meanings of each criterion as described by their teacher, they may not have much experience applying those criteria in concrete ways that allow them to achieve a deeper understanding of what the criteria mean and how to embody those criteria in their own explanations.

Table 3.7
Categories of student guidance

Category	Example
Needs No Improvement	<p>- What are the things that make this a good energy story? (Use your criteria list in 3.15!) They tell you everything you need to use. They tell a good explanation, they supported the details, and they explained good enough to have evidence</p> <p>- What are the things that could be improved? (Use your criteria list in 3.15!) Better thought everything else is good.</p>
Stylistic Improvement Only	<p>- What are the things that make this a good energy story? (Use the criteria list in 3.15!) Good job using correct vocabulary: energy</p> <p>- What are the things that could be improved? (Use the criteria list in 3.15!) Capitalize the beginning of sentences, spell words correctly, and use complete sentences.</p>
Not Referencing Specific Science Content	<p>- What are the things that make this a good energy story? (Use your criteria list in 3.15!) facts evidence</p> <p>- What are the things that could be improved? (Use your criteria list in 3.15!) fix spelling more detailed facts.</p>
Referencing Specific Science Content	<p>- What are the things that make this a good energy story? (Use your criteria list in 3.15!) Things that make this a good energy story is that it talks about all of the layers of the earth.</p> <p>- What are the things that could be improved? (Use your criteria list in 3.15!) things that could have improved is that they could have explained a little bit more about how things form.</p>

Teacher Guidance

I also analyzed teacher guidance provided to students' Energy Stories in the *teacher guidance* condition to compare with peer guidance. Overall, teacher comments were far more likely to reference specific science content than peer guidance. Of the 26 total comments provided by the teacher to student responses, 5 (19%) indicated a job well done and that no further improvements were necessary, of which 1 was an Energy Story with a KI score of 4, 2 had a KI score of 5, and 2 were a KI score of 2. The last two Energy Stories with a KI score of 2 were long and contained distracting elaborate descriptions without necessarily including key ideas, which may explain why the teacher felt the Energy Stories were adequate. Of the 21 remaining comments indicating improvements to be made, 19 (90%) referenced specific science content by prompting students to add ideas such as how energy moves, how convection works, and how energy transforms; and 6 (29%) referenced criteria such as evidence and reasoning (see Table 3.8 for examples).

As expected, the teacher was more proficient than students in evaluating students' Energy Stories and providing guidance referencing specific science content. However, out of 20 student pairs in the *teacher guidance* condition who did not already demonstrate a sophisticated understanding in their initial explanation and who received teacher guidance prompting them to

improve their answer, only 4 pairs (20%) managed to do so. In many cases, the teacher specifically indicated alternative ideas and provided students with normative ideas as a starting point for revision (see Table 3.8 for examples), but this was not sufficient for students to make productive revisions, which is consistent with current findings that directly providing students with normative ideas through guidance is not effective (e.g., VanLehn et al., 2003; Koedinger & Alevan, 2007).

Table 3.8.
Sample teacher guidance

Category	Example
Referencing Criteria	<p>Very good! You can add further evidence about WHY the energy changes from the core to the mantle, and what causes it to move away from the heat source.</p> <p>HOW does the heat energy move? Explain with more details and evidence...</p> <p>The energy that heats the earth's core does not come from the sun. It comes from the core of the earth. Read the info again and explain, using evidence, how the process of convection works within our earth.</p>
Indicating Alternative Ideas	<p>The energy that heats the earth from within comes from our own core, not the sun. The sun's radiant energy only heats the surface of the earth and our atmosphere. Please rewrite this using accurate information which explains how that heat energy from the core convects up through the mantle to transfer the energy enough to move the crust's plates.</p> <p>the energy doesn't come from convection currents. It originally comes from the core of the earth and then conducts through to the mantle, where the convection begins - please reread about this entire process and revise your story.</p>

Summary and Discussion

The pilot study results suggest that, overall, the revised Plate Tectonics unit was effective in supporting students' learning of convection and its underlying processes. However, in-depth analyses showed that students find it challenging to learn density's role in convection and energy transfer. Given that density was taught in eighth grade in California at the time of the study (California Department of Education, 1998), this is not surprising. These findings led to further revisions to the unit to better support students in understanding the relationship between changes in thermal energy and density, as well as how local changes in density of fluids can lead to fluid movement. The unit also strengthened connections between density and plate tectonics by adding activities connecting differences in density to plate subduction.

In terms of the pilot critique design, findings revealed no differences in students' revisions between the *peer* and *teacher guidance* conditions. These findings resonate with existing research illuminating the difficulty of supporting students in making conceptual revisions in their writing (Cho & Macarthur, 2011; Hattie & Timperley, 2007; Gielen et al., 2010; van Zundert, Sluijsmans,

& van Merriënboer, 2010). In particular, while teacher guidance referenced specific science content and pointed students toward relevant information, thus meeting many of the principles for good guidance enumerated in the literature (e.g., Underwood & Tregigdo, 2006; Hattie & Temperley, 2007), this was not sufficient to provoke productive revisions. One possible explanation for this difficulty may be that students lacked sufficient understanding of criteria to take advantage of teacher guidance. The analyses of students' criteria lists and student comments generated during critique indicate that, while students may be familiar with criteria such as evidence in the abstract sense, they lack opportunities to apply and internalize those criteria in practice. Gaining more expertise with applying criteria through critique may also support students in taking advantage of guidance and revising their explanation.

The findings also yielded valuable insights into next steps for refining the critique design in the subsequent study. The analysis of student comments generated during critique demonstrated that few students elaborated on specific science content, and several listed multiple criteria in their comments without indicating that they had distinguished what each criterion meant. While research has shown that generation tasks can support students in distinguishing among their ideas (e.g., Chi, 2000; Linn, Lee, Tinker, Husic, & Chiu, 2006), these findings indicate that the learning process for distinguishing among criteria is more fraught. Rather than asking students to apply abstract criteria that they generated in list form through a brainstorm and finalized through a whole-class discussion, I decided to prompt students to make sense of abstract criteria through discussion. To do so, I drew on Zhang and Linn's (2013) work on complex selection tasks, which found that students benefited equally from generating drawings of chemical reactions at the molecular level as selecting among drawings representing plausible alternative ideas. I consequently redesigned the critique activity guidance by asking students to select a "best fit" criterion from a list of non-mutually exclusive criteria pertaining to explanations in science (See Chapter 4, Figure 4.2). I also drew on Gielen and colleagues' work (2010) on peer assessment and guidance, which results suggested that justifying the guidance with evidence from the evaluated work was more important than the guidance's accuracy. The redesigned critique activity therefore prompted students to generate their comment for the authors of the assigned explanation based on their choice. This redesign problematized the critique task such that students would be more motivated to discuss with their partners which one criterion out of several candidates should be selected for the assigned explanation. Thus, a multiple choice selection task was repurposed to serve not as an assessment tool but as a knowledge integration tool to help students distinguish among criteria.

Based on findings that approximately a third of the students focused entirely on stylistic elements in their critique comments, I made additional refinements to the critique guidance and to the activity sequence in the subsequent study. First, I separated the critique task into two parts: scoring the explanation for stylistic elements (i.e., spelling, grammar, and punctuation) and scoring the explanation for science content. The purpose was to implicitly alert students that explanations in science can be evaluated along those two dimensions. Second, I created an additional critique activity to serve as practice critique where students evaluated two explanations designed by the researcher in succession. Using the same two-part task design for the critique itself, students were presented with one explanation that had good stylistic elements and poor science content, and another explanation that had the opposite attributes, with poor stylistic elements but rich science content. As with the first modification, this modification was intended to support students in distinguishing between the stylistic elements and the science content in an explanation.

Lastly, the finding that students in the *teacher guidance* condition were not more likely to make productive revisions raised questions as to what successful expert guidance might look like.

Despite teacher comments embodying many elements associated with effective guidance, as discussed above, students still found it challenging to make revisions. In the subsequent study, I therefore explore the impact of expert versus peer guidance, where I draw on knowledge integration principles to design and provide expert guidance to student explanations.

In the next chapter, I build on findings from this study and investigate the impacts of the above refinements on students' revisions to their explanations. In my in-depth analyses, I examine whether the redesigned critique guidance supports students in distinguishing among various criteria and in attending to the content of the explanations being critiqued, as well as whether and how expert guidance supports students in making productive revisions.

Chapter 4: Comparing Peer and Expert Guidance as Supports for Explaining in Science

In this chapter, I investigate the impact of expert and peer guidance on the revision of student-generated explanations following a peer critique activity in a five-day technology-enhanced inquiry unit on global climate change. Sixth-grade middle school students (n=55 pairs) worked in pairs to critique peer explanations, then revised their initial explanations based on peer or expert guidance. Building on the results presented in Chapter 3, I wanted to evaluate the effectiveness of the refined critique guidance, and explore ways to provide expert guidance to student explanations to foster productive revisions. I focus on using complex selection tasks (Zhang & Linn, 2013) during critique to support students in distinguishing among different criteria about explanations in science by asking students to select a best fit criterion for a given explanation. I hypothesized that having to distinguish among different criteria in the context of a specific explanation during critique will also help students to attend more closely to the science content of the assigned explanation and thus better support students in integrating and refining their ideas during revision.

I also compare the effectiveness of two forms of guidance on students' revisions: peer guidance generated by students during critique, and expert guidance generated by the researcher based on knowledge integration principles. I wanted to explore what characteristics of guidance can best support students in leveraging their peer critique experience and making productive conceptual revisions to their explanation. Specifically, this study asks the following questions:

1. How do peer and expert guidance impact revision of student explanations in science?
2. How does peer guidance differ from expert guidance and typical teacher guidance?
3. Does the quality of the explanation that students critique (high and low) impact the gains from guidance?
4. How might student engagement with critique vary and relate to their guidance?

To foreshadow the results, the findings show significant differences between peer and expert guidance conditions. Only the expert guidance group demonstrated significant gains in conceptual understanding when they revised their initial explanations. The quality of the explanation critiqued by students did not have an effect on the ability of the students to make revisions. Analysis of guidance and subsequent revisions suggested that content or task specificity alone does not provide sufficient guidance for students. Students who were informed what to change in their responses did not benefit from the information, whereas students who were prompted to reconsider and build upon specific science ideas and causal relationships were more likely to integrate new information and make progress in their revisions. This study builds on previous research showing the value of peer assessment for improving student understanding by characterizing what elements of guidance are helpful for making conceptual revisions. These results show that well-designed guidance enables students working in pairs to make conceptual revisions to their explanations following peer critique.

Introduction

Generating explanations is considered a foundational practice in science (Next Generation Science Standards). In instruction, generating explanations has been found to help students integrate ideas (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher,

1994) and identify gaps in their understanding (Linn, Lee, Tinker, Husic, & Chiu, 2006; Chi, 2000). Yet learning from generating explanations can be difficult when the topic involves complex science concepts. For example, prior research has also shown that generating explanations may provide the explainer with an illusion of explanatory depth (Keil, 2006), where students believe they can explain complex science phenomena when they actually have a very simplistic and superficial understanding. Other studies reveal how confirmation bias, where students dismiss evidence that conflicts with their beliefs, can interfere with the benefits of learning from explanations by preventing students from detecting gaps in their conceptual understanding in light of new contradictory evidence (e.g., Chinn & Brewer, 1993; Clark, 2006). Determining how to best take advantage of explanations to promote student learning in science remains an ongoing endeavor.

This study investigates how a combination of critiquing an explanation and receiving peer or expert guidance helps middle school students refine their explanation and develop a more integrated understanding of global climate change. In this study, the expert guidance group explains their idea, critiques an archived peer idea, and gets expert guidance while the peer guidance group explain their idea, critique a peer idea, and then gets peer guidance. Prior research has shown that critique activities can contribute to learning from a variety of student-generated representations in technology-enhanced instruction, including animations (Chang, Quintana, & Krajcik, 2010), virtual experiments (Chang & Linn, 2013), models (Chang & Chang, 2013), and concept maps (Clark et al., 2012), as well as explanations (Reiser et al., 2001). Research in peer assessment has documented the value of students evaluating written work by their peers as a means for helping students examine their own writing with a more critical eye (Black, Harrison, Lee, & Marshall, 2003). Previous studies have demonstrated that receiving detailed instructor or expert guidance as well as peer guidance can be beneficial for making conceptual revisions to written student work by providing information that helps students attend to and remediate gaps in their work (Hattie & Timperley, 2007; Swanson & Lussier, 2001; Gielen et al., 2010; van Zundert, Sluijsmans, & van Merriënboer, 2010).

Although engaging in peer critique and generating peer guidance can be beneficial for the learner, receiving and implementing peer guidance may not always be beneficial. Numerous studies document the challenges of guiding students to generate quality peer guidance, particularly when the students are new to the practice of peer critique or the domain under study (e.g., Tsivitanidou, Zacharia, & Hovardas, 2011; Gan & Hattie, 2014; van Zundert, Könings, Sluijsmans, & van Merriënboer, 2012). Further, the quality of peer guidance can be impacted by the quality of the critiqued response (Topping, 2003, 2005; Falchikov & Goldfinch, 2000; Cho & Cho, 2011), which adds to the challenge of providing beneficial peer critique experiences for students in authentic classroom settings. Studies on formative peer assessment have investigated the value of engaging in peer critique and receiving peer guidance, but the potential benefit of engaging in peer critique and receiving expert guidance, in comparison to peer guidance, has not been explored. This study therefore seeks to address the value of engaging in peer critique and receiving expert guidance. Formative assessment and guidance from experts can be a powerful form of support for student learning, but expert guidance is not always successful and carries the risk of limiting the learning benefits if students apply the guidance without reflecting on their understanding (Hattie & Timperley, 2007; Lee, 2008; Yang, Badger, & Yu, 2006). Thus, there is a need to study whether and how peer and expert guidance can help or hinder students' efforts to build on their peer critique experience and revise their initial explanation.

This study builds on prior work on peer assessment by comparing the impact of peer and expert guidance when students critique peer explanations before revising their work based on external guidance. I seek to identify what aspects of peer critique and guidance impact students when revising their explanations after critique.

Rationale

Generating Explanations for Conceptual Understanding

The learning benefits of generating explanations have been well-documented in prior research in a variety of domains (e.g., Lombrozo, 2012; Roy & Chi, 2005). Generating explanations can help students make connections among existing and new ideas, as well as help students recognize and repair gaps in their understanding (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & Lavancher, 1994; Chi, 2000; Linn & Eylon, 2011; Ainsworth & Loizou, 2003; Ryoo & Linn, 2014). However, even with carefully designed scaffolds, students often do not recognize gaps in their understanding when generating explanations (Chinn & Brewer, 1993; Keil, 2006). Students may be content with simplistic and superficial explanations. Thus, effective instruction involves both eliciting explanations and ensuring that students can accurately evaluate explanatory quality such that they can revise and refine their understanding. Providing scaffolded opportunities for students to construct and evaluate explanations has shown promise for science education (e.g., McNeill, Lizotte, Krajcik, & Marx, 2006; McNeill & Krajcik, 2008; Sandoval & Reiser, 2004; Ryoo & Linn, 2014), but designing effective scaffolds to promote conceptual revision remains an elusive goal. Allowing students to examine their ideas in explicit activities such as critiquing explanations and applying external guidance has the potential of strengthening their understanding.

Critiquing Explanations

Research on student-generated representations has shown that critique combined with generation has benefit over generation without critique for certain tasks (e.g., Chang, Quintana, & Krajcik, 2010; Chang & Chang, 2013; Chang & Linn, 2013). In science education, critiquing explanations is considered a core component of argumentation (Erduran, Simon, & Osborne, 2004; Berland & Reiser, 2009). In argumentation, students evaluate and challenge other students' explanations and defend their own explanation against criticism (Berland & Reiser, 2009). Critique in argumentation may therefore prompt students to examine the ideas in their own explanations and distinguish among multiple alternatives. Students may learn to detect and repair gaps in their understanding as a result of engaging in argumentation. Although the practice of argumentation is an important skill to foster in students, it is a complex task that requires making sense of and challenging the ideas of others through discourse while contrasting those ideas with their own. It may therefore distract students from the task of reflecting on and applying their critique-derived insights to their own ideas (Berland & Reiser, 2011; von Aufschnaiter, Erduran, Osborne, & Simon, 2008). Students may also be reluctant to critique their peers' ideas (Chang & Linn, 2013; Chinn & Brewer, 2001). This study therefore investigates the potential benefits of critiquing explanations presented outside of the argumentation context.

Revising Explanations Using Guidance

Research suggests that compared to providing guidance such as starter sentences during the initial generation process, providing natural language guidance on students' initial explanations may be more effective for prompting students to reflect on and distinguish among the ideas in their explanations (Aleven, Ogan, Popescu, Torrey, & Koedinger, 2004). In addition, research has identified several characteristics and dimensions of guidance that affect its effectiveness in prompting learning such as prompt specificity (e.g., Shute, 2008; Underwood & Tregigdo, 2010; Hattie & Timperley, 2007; Hattie & Gan, 2011). However, designing guidance to prompt successful revisions that go beyond stylistic and mechanical improvements and improve the conceptual content of student writings remains a persistent challenge (Cho & MacArthur, 2011). Students can miss the opportunity to reflect on and refine their understanding if they dismiss the guidance as not being useful or if they disagree with the guidance. These findings align with the literature on the difficulty students have recognizing and reconciling conflicts in their conceptual understanding (Chinn & Brewer, 1993; Clark, 2006). Thus, the challenge lies not only in how to design the guidance itself but in how to design the activity context such that students are prompted to go beyond assessing whether the guidance can be used to revise their explanation, and also reflect on their understanding. Engaging in peer critique and generating guidance may prompt students to reflect on their own ideas and the ideas in the critiqued explanation, and help them take advantage of guidance during revision. We therefore combined peer critique and peer and expert guidance to investigate the potential synergistic effects of guiding students to generate their own guidance during peer critique prior to revising their own explanations based on external guidance.

Scaffolding Critique and Designing Guidance: the Scaffolded Knowledge Integration Instructional Framework

To support students in critiquing and revising explanations, we turned to the knowledge integration (KI) framework (Linn, Eylon, & Davis, 2004). The KI framework identifies effective instructional patterns to support students in developing a more integrated, normative understanding by building on their existing ideas and reflecting on their understanding. It involves eliciting existing ideas in students' conceptual repertoire about a target phenomenon, adding new ideas through instruction, prompting students to sort through their ideas by developing criteria, and helping students refine the connections among their ideas and transition toward a more normative, coherent understanding. In this study, we investigate how pairing peer critique with revision based on guidance can support students in distinguish among their own and new ideas. From a KI perspective, developing and using criteria during peer critique will enable students to evaluate their conceptual repertoire and distinguish between normative and alternative ideas. Based on research documenting the difficulties students have with unguided critique (e.g., Tsivitanidou et al., 2011), we guided students by providing a list of criteria to consider during critique, consistent with studies showing the value of providing students with rubrics and criteria to focus their efforts (Chang, Quintana, & Krajcik, 2010; Chang & Chang, 2011).

The KI framework also informed our guidance design in the expert guidance condition. From a KI perspective, guidance can promote knowledge integration by referencing students' existing ideas that were elicited in their initial explanation and indicating how students can further refine their understanding by considering new ideas or extending or elaborating upon those ideas (Gerard & Linn, 2013; Gerard, Ryoo, McElhaney, Liu, Rafferty, & Linn, 2014). The approach is

consistent with research showing that students benefit when guidance indicates their current progress, the goal of the activity, and next steps (Hattie & Temperley, 2007).

Methods

Participants and Study Design

The five-day *GCC* unit was completed by 198 middle school students in five intact classrooms taught by the same teacher, who had more than 10 years of experience teaching science using web-based inquiry instruction. Students had completed at least one web-based inquiry unit prior to the *GCC* unit, and had not received classroom instruction on global climate change. Although the teacher regularly reviewed student responses within the *GCC* and prior web-based inquiry instruction units, students reported during interviews that neither revising their responses nor critiquing peer responses was a common practice. Students worked in pairs throughout the unit, including the pre- and post-test. The pre- and post-tests were each completed within a 50-minute classroom period. Students were assigned to each treatment group by classroom period, with two classroom periods assigned to the *expert guidance* condition (n=29 pairs), and four to the *peer guidance* condition (n=70 pairs). Although it would have been possible to evenly distribute three periods to each condition, we chose to allocate four periods to the *peer guidance* condition due to peer guidance being our primary focus of study. Overall, students in condition spent the same amount of time on the unit. We removed a total of 44 pairs who did not complete the pretest or posttest from the analysis.

Web-based Inquiry Global Climate Change Unit

We drew on the KI framework to design and revise a five-day technology-enhanced, Web-Based Inquiry Science Environment (WISE, Linn, Davis, & Bell, 2004) curriculum unit, *Global Climate Change* (*GCC*, Figure 4.1; see Chapter 2). Global climate change is a complex phenomenon in which energy transformations play a key role as the mechanism underlying the warming effect of greenhouse gases. (Rye, Rubba, & Wiesenmayer, 1997; Andersson & Wallin, 2000). In the *GCC* unit, students are provided with multiple opportunities to explain causal subsets of this complex system (Table 4.1). Students were expected to achieve a certain level of explanatory, or mechanistic, depth in their explanations by elaborating on their ideas about the target phenomenon. The unit had been tested and iteratively refined through multiple classroom trials (Svihla & Linn, 2011). For this study, we focused on a particular prompt that asked students to explain the impact of increased greenhouse gases on global temperature and on infrared radiation in Earth's atmosphere.

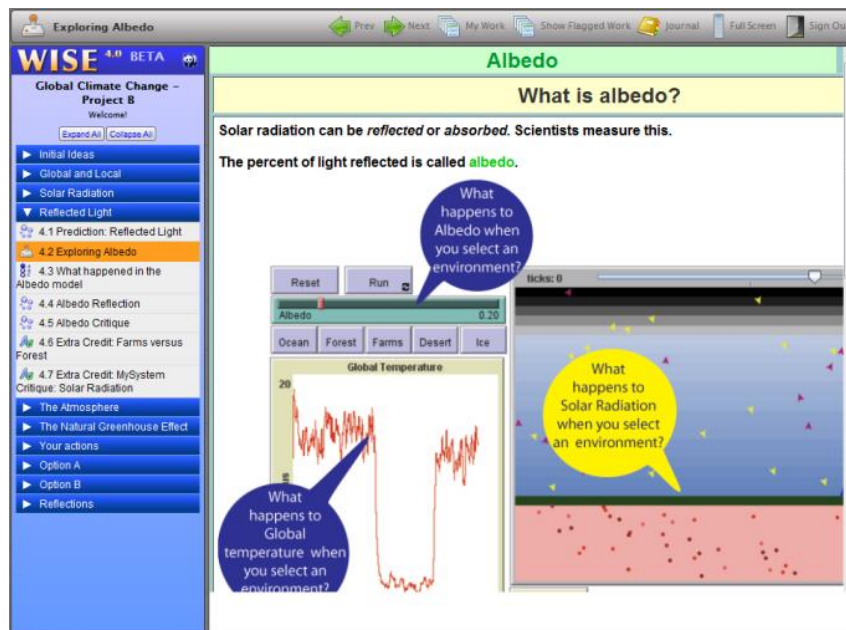


Figure 4.1. The WISE *Global Climate Change* unit. Students navigate the unit using the inquiry map to the left, and investigate the processes involved in global climate change via embedded interactive visualizations and pedagogical tools such as predict-observe-explain sequences and embedded notes to elicit, add, and refine their ideas.

Table 4.1

Activity structure of the Global Climate Change unit

Activity 1 Initial Ideas	Students' initial ideas about global climate change are elicited (pretest).
Activity 2 Global and Local	Students investigate weather and climate along the dimensions of relative time scale and geographic scale.
Activity 3 Solar Radiation	Students investigate how solar radiation transfers and transforms within the Earth's system.
Activity 4 Reflected Light	Students compare the effects of different degrees of surface reflectivity (albedo) on solar radiation and global temperature.
Activity 5 The Atmosphere	Students reflect on the role of Earth's atmosphere on global temperature.
Activity 6 The Natural Greenhouse Effect	Students investigate the natural greenhouse effect and the impact of increased greenhouse gas emissions through human activity on global temperature.
Activity 7 Your Actions	Students investigate the ways in which human activity can contribute to increased greenhouse gas emissions.
Activity 8 Littering or Food	Students investigate the impact of altering two subsets of human activity, littering and food consumption habits, in depth.
Activity 9 Walking or Electricity	Students investigate the impact of altering two subsets of human activity, walking versus driving and saving electricity, in depth.

Activity 10 Reflections	Students reflect on what they learned and revised their initial ideas (posttest).
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Conditions: Peer vs. Expert Guidance

Two versions of the unit were created to investigate the effects of expert versus peer guidance and the quality of the explanation critiqued (Table 4.2). In the *peer guidance* condition, peer explanations were randomly assigned to student pairs. In the *expert guidance* condition, students were assigned either low- or high-KI score explanations, which were archived from student responses in a previous implementation of the project.

In all conditions, students' ideas and criteria about explanations were elicited during the *first critique*, followed by delayed *second critique* (Table 4.2). Both critique steps consisted of two parts: students first generated their own explanation about the target phenomenon before proceeding to critique explanation(s) answering the same prompt. During critique, they were prevented from referencing and revising their initial explanations.

During each critique step, students rated each explanation for both style (spelling and grammar) and science content from a predetermined list of options, then generated guidance for the science content by explaining their choice for science content with an illustrative example from the explanation (Figure 4.2). Our goal was to prompt students to discuss criteria often encountered during instruction, so there was no correct choice per se among the list of science content criteria, which were not mutually exclusive. By asking students to choose the criterion they felt best captured the science content in the explanation, students were motivated to consider the subtleties of each criterion.

The *first critique* served as practice critique. All students evaluated two archived explanations chosen from student responses in a previous implementation of the project (Table 4.3). To address concerns that students tend to focus on surface features rather than the underlying ideas in an explanation, examples were selected to represent different dimensions of an explanation. One example was stylistically sound in terms of spelling and grammar, but sparse in terms of science content; the other had imperfect spelling and grammar, but described the phenomenon in detail. Students were not explicitly instructed to compare the two sample explanations along surface and content dimensions, but they were asked to critique the two sample explanations one after the other. Our goal was to implicitly prompt students to compare the two explanations and help students distinguish between their existing ideas about what makes a good explanation.

Table 4.2
Critique activity sequence

	Expert Guidance	Peer Guidance
First Critique	Students generate an explanation	
	Students critique two peer explanations addressing the same prompt	
Second Critique	Students generate an explanation	

	Students critique preselected low- or high-KI score explanation	Students critique anonymous pair's explanation
Revision	Students revise their initial explanation based on expert guidance	Students revise their initial explanation based on peer guidance
	Students reflect on how they used guidance to revise their explanation	

Table 4.3

Preselected explanations critiqued by students during the first critique

Question: What happens to global temperature in an environment with low albedo? What happens to solar radiation (SR) in the model in step 4.2 that supports your answer?	
Characteristics	Preselected Explanation
Good style (spelling/grammar), vague science content	It changed a lot. It went down then bounced.
Imperfect style (spelling/grammar), detailed science content	The globe temperture went down when the albedo was low, like for the ocean, or when the albeod reflected only 5 percent of the solar radiation. When the soler radiatoin was reflecting, it coud not change into heat energy it just went back to space.

2. Score this response for spelling, grammar, and punctuation:

- Very Good: No spelling, grammar, or punctuation errors
- Good: Few spelling, grammar, or punctuation errors
- Not so good: Many spelling, grammar, or punctuation errors

3. Score this response for SCIENCE content and clarity:

- The response does not answer all the questions.
- The response needs evidence to explain why.
- The science ideas are wrong or vague.
- The science ideas could be described in more detail.

4. Explain your choice for SCIENCE CONTENT and CLARITY and give an example from the response to help the student improve the explanation.

Figure 4.2. Screenshot of guidance provided during the *First* and *Second Critique* steps.

The *second critique* was the core activity. After generating an initial explanation, *expert guidance* students evaluated a preselected explanation with either a low- or high-KI score for science content; *peer guidance* students evaluated a randomly assigned explanation by an anonymous pair. All students generated explanations and provided guidance the same number of times across conditions, but revised their explanation based on instructor or peer guidance. Expert

guidance was created by the researcher to address concerns raised in prior research with regard to validity issues in teacher guidance (Falchikov & Goldfinch, 2000) and focused on conceptual guidance to promote knowledge integration (Gerard & Linn, 2013); students in the *expert guidance* condition believed the guidance came from their teacher. Expert guidance prompted students to elaborate on their ideas about the causal mechanism and referenced specific wording in student responses, indicated when students had incorrect ideas, and requested elaboration (see Table 4.8 for examples).

Data Sources

We collected student and teacher work, student log data, observation notes, and student interviews (Table 4.4). Student work formed the core data source. The embedded notes were generated during the critique activity sequence (Table 4.2), where the original explanation occurred. The unit of analysis was the dyad. We developed embedded and pretest/posttest assessments using the knowledge integration framework aligned with the instruction.

Table 4.4

Data sources

Data Type	Characteristics
Student Work	Pretest/Posttest results and embedded notes from critique activity sequence (original and revised explanations, peer guidance, post-revision reflection).
Teacher Work	Comments provided by the actual teacher to student responses within the project, and expert guidance provided by the researcher to the targeted response.
Student Log Data	Automatically generated logs of how much time dyads spent on steps and in which sequence over the course of the project, and of submitted work and of revisions to original work.
Observation Notes	Dyads working on project and teacher instruction during project.
Student Interviews	Two interviews of videotaped dyads, one given after critique and one given after revision, probing student perceptions of generating and evaluating explanations in science, of peer critique and guidance, of typical teacher versus peer guidance, and of implementing guidance.
Video	Five dyads working on project and teacher instruction during project.

Student responses such as the original and revised explanations and the pre- and post-test items were coded using a rubric based on the KI framework, which rewards coherence of ideas as represented by the number and complexity of connections students make between their ideas (Table 4.5; see Chapter 2). Higher scores represent increased number of connections students made among scientifically valid ideas to explain the target phenomenon and therefore represent greater explanatory depth (Linn et al., 2006).

Remaining data sources (teacher comments, log data, observation notes, student interviews, and video data) were analyzed to address alternative interpretations of the core data and account for additional factors that may have impacted student engagement with the writing, evaluation, and revision of explanations. Video data were transcribed using a modified version of Och's conventions (1979, see Appendix B for transcription scheme) for comparison case studies.

Table 4.5

Knowledge Integration rubric used to score students' original and revised explanations

Question:		
How did adding greenhouse gases change global temperature? How did adding greenhouse gases change what happened to infrared radiation?		
Score	Description	Examples
1 (Irrelevant)	No answer or irrelevant answers	Idk
2 (No Link)	Non-normative ideas or links	When there were more greenhouse gases, global temperature increased because the greenhouse gasses destroy the o-zone layer, and the Sun's rays more room to enter Earth's atmosphere.
3 (Partial Link)	One relevant and normative idea	When there were more greenhouse gases, global temperature increased. When there were more greenhouse gases, infrared radiation collided with greenhouse gases and went into space.
4 (Full Link)	Scientifically valid and fully elaborated link between two relevant and normative ideas	When there were more greenhouse gases, global temperature increases. When there were more greenhouse gases, infrared radiation changes into heat energy.
5 (Complex Link)	At least two links among three or more relevant and normative ideas	When there were more greenhouse gases, global temperature increased because greenhouse gases trapped infrared radiation in the atmosphere. When there were more greenhouse gases, infrared radiation was bounced around by greenhouse gases and trapped in the atmosphere. Also, infrared radiation can be absorbed by Earth, and changed into thermal energy.

Results

The *GCC* unit was implemented as planned. There was no significant effect of low or high-KI score explanation on gains for the *expert guidance* condition after controlling for the original score ($F(1,24)=.04, p>.05$) so responses for both explanation types were combined. This suggests the science content quality of the critiqued explanation does not affect the students' revision quality.

Overall, students benefitted from the instruction in all conditions. Expert guidance was more effective than peer guidance for helping students revise their original explanation. The quality of the explanation critiqued by students did not impact their ability to benefit from the experience and revise their explanation. In-depth analyses of guidance generated by students during critique and revisions provided further insights into when and how guidance supports students in revision. Revisiting a preceding step with salient information was not shown to be strongly correlated with successful revisions. Case studies illustrated that providing students with specific ideas to incorporate or change in their response did not support students in integrating those ideas and emerging with a more coherent understanding.

Pretest to Posttest Learning Gains

Students made significant pretest to posttest gains in both the expert and peer guidance conditions (Table 4.6). There was no significant effect of treatment after controlling for pretest scores ($F(2,51)=1.13, p<.05$). The lack of significant differences between conditions is not surprising, given that all versions contained a variety of instructional activities to support student learning. The analysis suggests all students benefited from critique and guidance.

Table 4.6

Means and Standard Deviations for Pretest and Posttest Scores by Treatment

		<u>Pretest</u>		<u>Posttest</u>			<u>Effect</u>	
	N	M	SD	M	SD	<u>t</u>	<u>Size</u>	<u>p</u>
All	55 pairs	2.71	0.35	3.20	0.53	7.34	1.09	<.001
Expert Guidance	27 pairs	2.74	0.41	3.19	0.56	4.64	0.92	<.001
Peer Guidance	28 pairs	2.68	0.28	3.21	0.52	5.67	1.28	<.001

Explanation Revision: Expert Guidance More Effective than Peer Guidance

In this analysis, we analyzed a larger subset consisting of 58 pairs who revised their original explanations. There was a significant advantage for expert guidance on gains after controlling for the quality of the original explanation, with a medium effect size ($F(1,55)=7.96, p<.01, d =.59$). There was significant improvement from the students' original to revised explanation across groups (Table 4.7).

Table 4.7

Means and Standard Deviations for Original and Revised Explanation Scores by Treatment

	N	<u>Original</u>		<u>Revised</u>		<u>t</u>	<u>Effect Size</u>	
		M	SD	M	SD		<i>d</i>	<i>p</i>
All	58 pairs	3.34	0.69	3.55	0.71	2.69	0.34	<.01
Expert Guidance	21 pairs	3.67	0.58	4.00	0.55	2.65	0.59	<.05
Peer Guidance	37 pairs	3.16	0.69	3.30	0.66	1.41	0.21	>.05

Comparison of Teacher, Peer, and Expert Guidance and Impact on Revision

We analyzed a larger sample of student and associated teacher data to investigate how expert and peer guidance given during the *second critique* activity compared to teacher guidance provided elsewhere in the GCC unit. The main difference between teacher guidance, expert guidance, and peer guidance was the use of *science content specificity* to promote knowledge integration (Table 4.8). Of the 440 comments given by the teacher to five student responses elsewhere in the unit, 70% stated “Good response,” at times regardless of the actual content of the student response. Of the remaining 132 guidance comments in which the teacher prompted students to improve their response in some form, 21% addressed spelling and/or grammar (e.g., “Capital letters?”), 7% addressed procedural errors (e.g., “Please complete.”), and 72% addressed the science content. However, of the teacher comments addressing science content, 91% was generic and did not guide students to consider specific science content (e.g., “Are you sure about your response?”). Only 9% addressed specific science content in student responses, but they were terse and did not prompt students to revise their answer (e.g., “Do oceans have the highest albedo?”). Similar characteristics were observed in the teacher’s comments provided in other WISE units used over the course of the school year. These characteristics are consistent with the literature on written teacher guidance provided to student responses. Given time constraints or gaps in content knowledge, teachers often struggle to provide written guidance that helps students with knowledge integration (Gerard & Linn, 2013). In this case, the teacher had a single subject teaching credential in earth and planetary science and therefore had content knowledge specific to the GCC unit. However, the teacher commented to the researcher that he was often pressed for time, which may explain the characteristics of his guidance comments. During instruction, the teacher was observed reminding students that he had reviewed their responses and that he would like them to review and revise their answers. However, none of his comments resulted in a revision.

Table 4.8

Comparison of Teacher, Peer, and Expert Guidance Comments within the GCC Unit

Guidance Source	Sample Guidance Comments
Teacher	<ul style="list-style-type: none"> • Good response. • Are you sure about your responses? • Check your responses; it is confusing? • Spelling, punctuation....etc. • Are you sure about your answers to #3 and #4 given the data and evidence?
Peer	<ul style="list-style-type: none"> • The other team could have said how the temperature rose. • There should be more details in the second sentence and the sentence itself is a run-on sentence which makes it hard to understand. • They did fine but forgot a bit of punctuation at the end called a period. • They need to have evidence to back up what they say. • Instead of saying it bounced off all over the place say it was reflected back. Also, use evidence from the model.
Expert	<ul style="list-style-type: none"> • Good start! Try to describe what happens to the infrared radiation in more detail. Why does the infrared radiation linger longer? Does anything else happen to the infrared radiation? • You have some incorrect ideas about the relationship between greenhouse gases, global temperature, and infrared radiation. Please review what you learned and try to be as detailed as possible about what happens to the infrared radiation and why.

Despite the explicit prompts for students to reference specific science content when giving peer critiques, most students did not do so. We analyzed all guidance comments written by students across conditions during *second critique*. Of the 63 total written student comments, 8% stated that the response did not need improvement. Of the remaining 57 comments in which the student pair made suggestions for improvement in some form, 7% commented solely on spelling and grammar, and 93% addressed the science content. Of the student comments addressing science content, 55% repeated the science content criterion without elaboration (e.g., “You need to more detail to explain why.”), and 45% provided specific guidance on science ideas. Thus, the comments generated by students during *second critique* were more likely than those generated by the teacher to be helpful to their peers during revision based on current recommendations for guidance in the literature. However, students in the *peer guidance* condition still struggled to improve their initial explanation.

The use of specific science content to promote knowledge integration in expert guidance may explain why students in the *expert guidance* condition were more likely to improve their initial explanation compared to students in the *peer guidance* condition. We conducted an in-depth analysis of 58 pairs who engaged with peer and expert guidance to investigate what kinds of guidance were received and how students responded to the guidance during revision. Pairs who did not submit a revision but indicated that they read the guidance by submitting a response on the guidance reflection step, such as, “we did not agree with the guidance so we didn’t change our

response,” were also included in this analysis. We categorized expert and peer guidance that prompted students to improve their initial response into several categories and found general patterns in students’ trajectories through the activity (Figure 4.3).

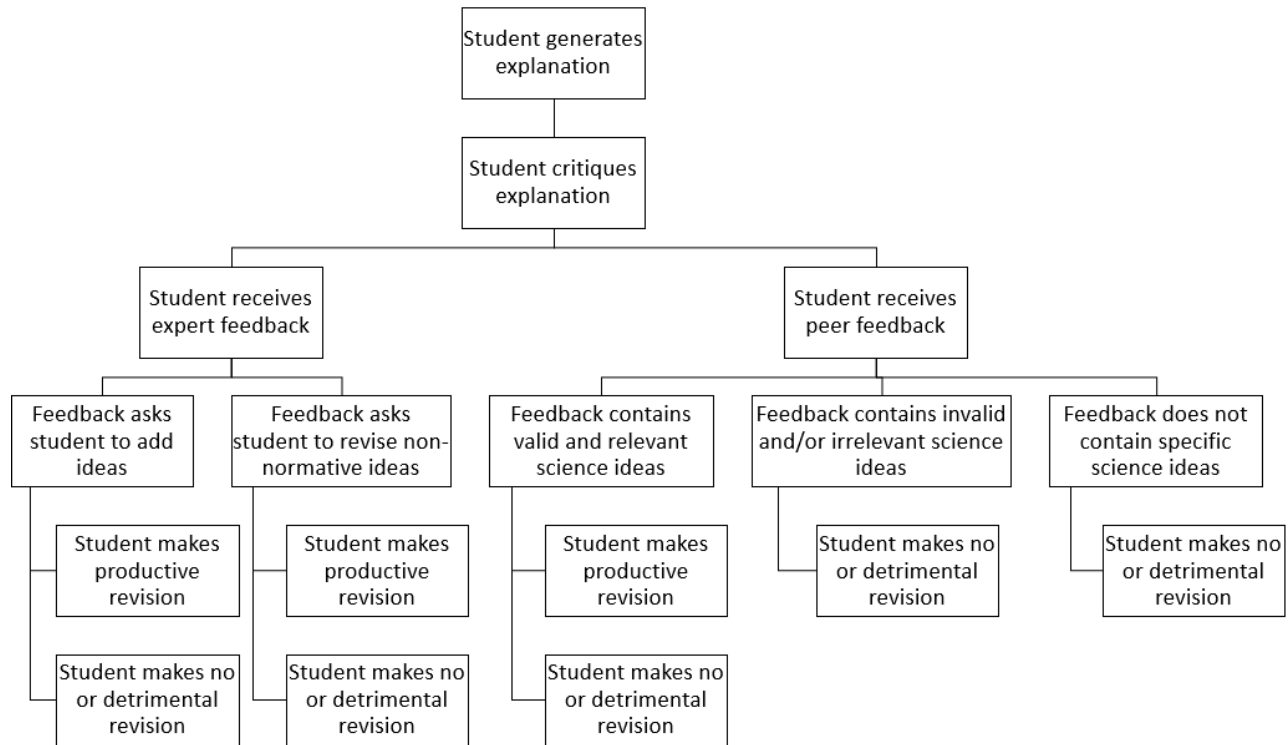


Figure 4.3. Flow diagram of student pathways through critique and revision.

Overall, 29% of student pairs in the *expert guidance* condition made successful revisions as measured by improvements in KI score, in comparison to 11% of student pairs in the *peer guidance* condition (Figure 4.4). Only student pairs in the *peer guidance* condition (3%) made detrimental revisions. In the *peer guidance* condition, only those who received guidance containing valid and relevant science ideas made successful revisions. The *expert guidance* comments were designed to guide students to consider and revise specific ideas in their initial explanations. This replicates findings by Gerard and Linn (2013) that knowledge integration guidance is more effective than generic guidance in supporting students in revising explanations.

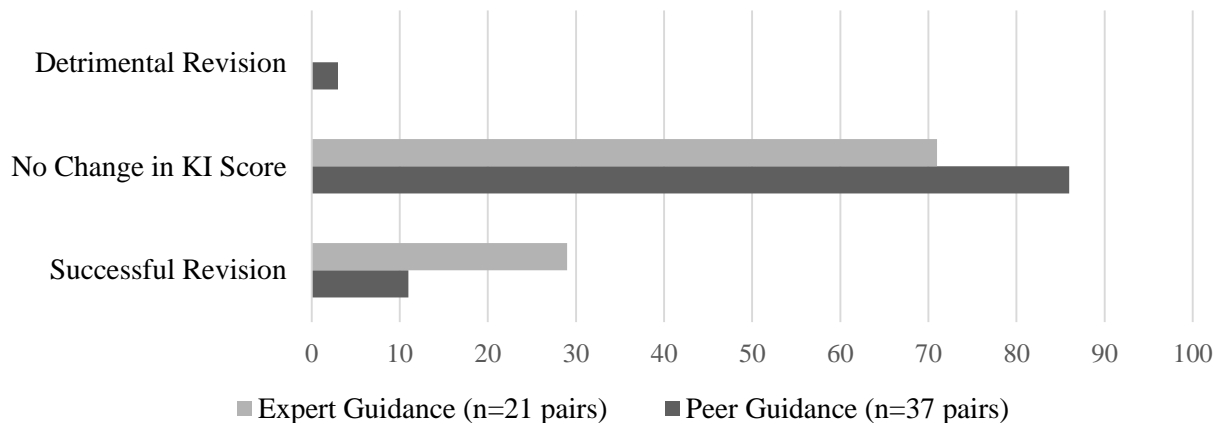


Figure 4.4. Frequency of revisions by condition.

Impact of Peer Guidance Referencing Specific Science Ideas

To further examine how students engaged with peer guidance containing specific science ideas, we scored whether the received guidance was scientifically valid and relevant to the explanation, whether it resulted in substantive revisions, and how students reflected on their use of peer guidance after the revision. In this analysis, revisions that improved the conceptual quality of the response without resulting in a gain of KI score, such as further elaboration of a valid science idea already present in the initial response, were coded as improvements. Revisions that removed an existing valid science idea and/or added a non-normative idea were coded as detrimental revisions. Of the 14 pairs who received peer guidance with specific science ideas and subsequently attempted to revise their responses, 8 pairs, or 57%, received valid and relevant guidance. Overall, 2 pairs improved their response, 4 made detrimental revisions, and 8 made no substantive changes (Figure 4.5).

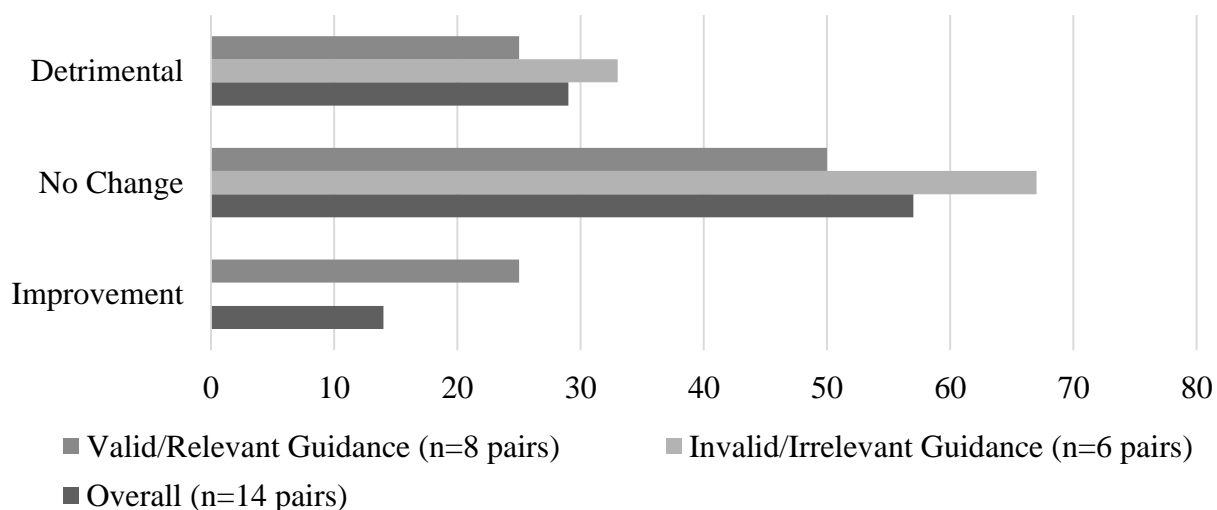


Figure 4.5. Frequency of revisions in response to receiving peer guidance with specific science ideas.

Both pairs who improved their response had received scientifically valid and relevant peer guidance. This is not surprising, given that scientifically invalid and/or irrelevant guidance would be likely to confuse students and hinder them from revising their response. However, two pairs who received valid and relevant guidance made detrimental revisions to their original response. To gain insights into why this may have been the case, we analyzed the specific content of the original and revised explanations of the two pairs, the guidance received, and student reflections on how they used the guidance (Table 4.9).

Table 4.9

Summary of Student Responses, Peer Guidance Received, and Reflection on Guidance for Two Pairs Who Made Detrimental Revisions

Original Response	Peer Guidance	Revised Response	Reflection
When there were more greenhouse gases, global temperature decreased. When there were more greenhouse gases, infrared radiation rose.	When there are more green house gases the temperature rises not decreases. "Infrared radiation rose" does not make any sense. Infrared radiation escaped the atmosphere as well as reflected off the green house gases.	When there were more greenhouse gases, global temperature decreased. When there were more greenhouse gases, infrared radiation <u>escaped the atmosphere as well as reflected off the greenhouse gases.</u>	We used the guidance. [I]t told us the correct answer.
When there were more greenhouse gases, global temperature increased. When there were more greenhouse gases, infrared radiation bounced off the green-house gasses, causing it to stay inside the atmosphere.	We think this response needs evidence to explain why global temperature increased , because it's described in detail what happened, but the answer didn't describe how it increased.	When there were more greenhouse gases, global temperature increased <u>because the greenhouse gasses destroy the o-zone layer, and the Sun's rays more room to enter Earth's atmosphere.</u> When there were more greenhouse gases, infrared radiation bounced off the green-house gasses, causing it to stay inside the atmosphere.	We used the guidance. We used the guidance to improve our answer.

Note. Specific science ideas referenced within the guidance are in **bold**; changes made during revisions are underlined.

The first pair generated a terse, non-normative response that incorrectly described the causal relationship between greenhouse gases and global temperature, and vaguely described the causal relationship between greenhouse gases and the amount of infrared radiation in the atmosphere. The specific guidance addressed both, essentially stating what the response should say, at least partially—the guidance corrected the change in global temperature and described how infrared radiation interacts with greenhouse gases, although it did not elaborate on the outcome (e.g., “infrared radiation increases”).

In response, despite two corrections being specified, the students implemented just one by copying the guidance’s description and replacing the corresponding vague description of how greenhouse gases affect infrared radiation in their original response. Because this led the students to remove a relevant, if vaguely described, idea about infrared radiation, their revision resulted in a lower score. The students’ reflection on the guidance indicate that they also thought the guidance was “[telling] the correct answer.” However, their ad hoc implementation of the normative ideas provided in the guidance signifies that the students did not use this opportunity to reassess their understanding. This aligns with current findings (e.g., VanLehn et al., 2010; Koedinger & Alevan, 2007) that specific, elaborated guidance that tells students which ideas are incorrect and which normative ideas to add may not support students in refining their ideas.

The second pair generated a relatively elaborate response with normative ideas that did not explicitly link the increase in global temperature to the greenhouse gas mechanism increasing infrared radiation levels. Thus, the two causal relationships remained isolated. The specific guidance addressed this gap by suggesting that the response be revised to explain why the global temperature increased.

In response, instead of connecting the two causal relationships together in their revision, the students elaborated their initial explanation of the increase in global temperature to add non-normative ideas about ozone. Following revision, the students reflected on the guidance and said they used the guidance to improve their response. They did in fact do as the guidance suggested by elaborating on why the global temperature increased, but they did not build on their existing valid ideas. Their revision suggests that the guidance, while referencing valid science ideas and prompting students to think more deeply about why the global temperature might increase, did not support them in integrating their understanding of the mechanism with increased global temperature. In this case, while the guidance avoided providing the answer, the students needed more guidance on which ideas to build on and consider when revising their response.

These case studies illustrate some of the challenges in guidance design. While providing students with specific information on how to improve their responses may help students focus on salient features of the phenomenon being explained, it may also lead students to incorporate those ideas into their explanations in isolation without distinguishing them from their own ideas. On the other hand, providing students with opportunities to reflect on specific aspects of their understanding may not be sufficient. As the second case illustrates, some students may incorporate non-normative ideas despite having promising ideas in their conceptual repertoire that can be developed to help explain the target phenomenon. In such cases, students may need an additional “hook” where the guidance points them to a productive idea already present in their original response so that students can build on the existing idea and refine their understanding.

Impact of Expert Guidance Referencing Specific Science Ideas

The expert guidance was designed to promote knowledge integration by prompting students to elaborate on their ideas about the causal mechanism and referenced specific wording in student responses where elaboration was possible (Table 4.10). Students were not explicitly prompted to review previously encountered information unless the guidance addressed alternative, non-normative ideas. When student responses were largely non-normative, the guidance alerted students and prompted students to reconsider a specific causal relationship without specifying any given step within the GCC unit to review. Thus, the expert guidance may also have encouraged students to revisit preceding steps to review salient information. To investigate the impact of expert guidance on students' revisions, I analyzed the original and revised explanations, the expert guidance provided, and student reflections on how they used the expert guidance.

Table 4.10
Sample Expert Guidance to Student Responses

Original Response	Expert Guidance	Revised Response	Reflection
When there were more greenhouse gases, global temperature increased. When there were more greenhouse gases, infrared radiation increased.	[Guidance Prompting Adding of Ideas] Good start. Try to describe what happens to the infrared radiation in more detail. Where does the infrared radiation increase ? Does anything else happen to the infrared radiation? How are green house gases involved?	When there were more greenhouse gases, global temperature increased <u>from an increase in IR which heated up the earth from being reflected back to the ground</u> . When there were more greenhouse gases, infrared radiation increased <u>because if was reflected by pollution</u> .	We used the guidance. We adjusted it to what the teacher suggested to us and we both agreed that we needed to change the changes the teacher told us to change.
When there were more greenhouse gases, global temperature increased. When there were more greenhouse gases, infrared radiation was reflected by earth more than being absorbed.	[Guidance Prompting Revision of Non-Normative Ideas] Good start. <i>You have some incorrect ideas about the relationship between greenhouse gases and infrared radiation</i> . Review what you learned and try to be as detailed as possible about what happens to the infrared radiation and why.	When there were more greenhouse gases, global temperature increased <u>because there is more infrared radiation being trapped</u> . When there were more greenhouse gases, infrared radiation was <u>trapped inside the Earth heating the planet itself</u> .	We used the guidance. We had the wrong ideas about infrared radiation so we used our guidance to change our response.

Note. Specific student wording echoed by expert guidance is in **bold**; wording alerting students about non-normative ideas is *italicized*. Changes made during revision are underlined.

None of the students in the *expert guidance* condition made detrimental revisions (Figure 4.6). Overall, of the 33 pairs analyzed, 13 (48%) improved their response. Most revisions involved adding more ideas (74%), which 40% of student pairs were able to do if they attempted revision. The majority of those who were asked to revise incorrect ideas and attempted to make a substantive revision were able to improve their response (71%). This suggests that the design features of expert guidance—prompting students to build on specific productive ideas and/or re-evaluate their understanding of specific aspects of the target phenomenon—are beneficial (see Figure 4.3 for summary of student pathways toward revision upon receiving guidance with science content specificity).

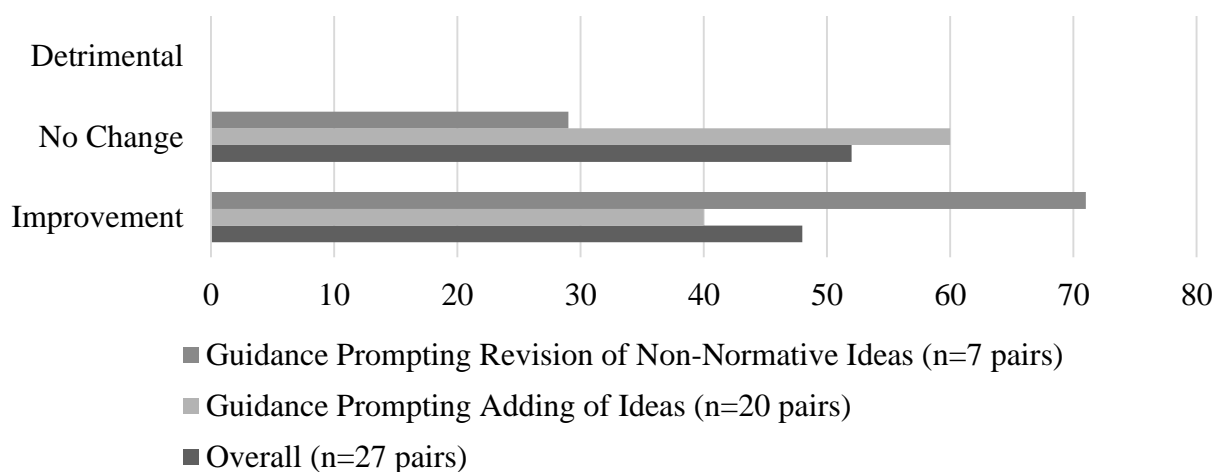


Figure 4.6. Frequency of student revisions in response to expert guidance.

Recent research has found that students were more likely to make successful revisions to their work upon receiving expert guidance if they revisit a key step (Ryoo & Linn, 2014b). To examine the possibility that students' greater success in revision after receiving expert guidance may have been due to students revisiting earlier steps in the unit, I analyzed student data logs to see if successful revisions were correlated with spontaneous step revisits. Student visits to previous steps were counted as significant and not accidental if students spent longer than seven seconds based on prior research (Svihla, Wester, & Linn, submitted). All step revisits in this study were characterized as spontaneous, as the unit did not require students to revisit a particular step. Only guidance prompting revision of non-normative ideas made a general suggestion to review ideas. When comparing both types of expert guidance, neither prompted significantly higher frequencies of spontaneous revisits (Table 4.11), with 45% of students receiving guidance prompting adding of ideas making revisits versus 57% of students receiving guidance prompting revision of non-normative ideas.

Overall, 48% of students made spontaneous revisits upon receiving expert guidance. 77% of students who revisited and 79% of those who did not revisit were able to improve their responses. These results suggest that revisiting evidence is not critical to successful revision when students receive well-designed guidance. However, there are several confounds. First, the step immediately preceding the revision step required students to review what they learned and consolidate their understanding by asking them to revise a separate response. Thus, students proceeding to the

revision step may have felt that they have already reviewed salient content in earlier steps to a sufficient degree. Second, of the students who revisited a prior step, 43% revisited the step that was linked in the prompt as a reminder of the prompt they were revising their original response to, or the step in which they critiqued a fictitious student’s work. Students were prevented from seeing actual responses to those steps upon submission to prevent copying of ideas, which means students who revisited the linked step would not have been able to review critical information. However, it is still possible that they used the revisit opportunity to jog their memory and discuss ideas.

Table 4.11

Summary of Students’ Spontaneous Revisits after Receiving Expert Guidance

	% Revisit (% Improved Response)	% No Revisit (% Improved Response)
Overall (n=27 pairs)	48% (77%)	52% (79%)
Guidance Prompting Adding of Ideas (n=20 pairs)	45% (78%)	55% (82%)
Guidance Prompting Revision of Non-Normative Ideas (n=7 pairs)	57% (75%)	43% (66%)

Students’ Post-Revision Reflections

Students’ post-revision reflection was a poor indicator of actual revision. Many responded they agreed with or discussed the guidance, but did not revise their explanation even if the peer or expert guidance comment was valid, included concrete suggestions for improvement, and/or explicitly stated the explanation contained incorrect ideas. In some cases, students explicitly stated that they disagreed with the guidance when they chose not to revise their initial explanation. Student logs indicate many students spent time on the reflection, suggesting students spent time discussing the guidance with their partners, but did not necessarily revise their explanations. This suggests that although guidance using specific science content to promote knowledge integration is helpful, further refinement of guidance during revision is necessary in order for students to fully take advantage of the opportunity to reconsider their ideas.

Additional Factors Impacting Quality of Guidance and Revision

Students elaborated on specific reasons in interviews when asked to explain the guidance comments they generated during *second critique*. They cited a variety of reasons for not elaborating their written guidance, such as not wanting to give the answer to their classmates and not wanting to discourage their classmates with a harsh critique. Furthermore, the discrepancy between the content of students’ discussions during critique and of the resultant written guidance suggests students need more support when concretizing their discussion in writing.

Interview data also indicate that students did not leverage their critique experience during revision. During interviews, students who did not successfully revise their explanations based on received guidance were able to detect areas for improvement in their own explanation when explicitly prompted to reflect on their critique experience. Given that some students reflected after the revision step but did not revise their answer because they had disagreed with the provided guidance, this suggests that generating guidance during critique and applying guidance during

revision may be tapping different cognitive processes. This aligns with Bangert-Downs et al. (1991) and Gielen et al. (2010)’s recommendation to cultivate *mindful reception* of guidance, and suggests students need support in distinguishing criteria for explanations and guidance.

Variations in Student Engagement during Critique: Case Studies

To examine the impact of the critique design on student engagement, we turned to our video data. In this chapter, we characterize student engagement as the types of discussions students had with each other and their interactions with the activity scaffolds. In this section, we focus on *first critique*. As the first stage of the peer critique and revision sequence, it affords insight into how students initially come to understand the different criteria presented in the task and apply these criteria to specific explanations. Of the six videotaped dyads, we have selected three contrasting cases that illustrate the kinds of wide variations in student engagement during critique that were observed in the data corpus as a whole (Table 4.12). In each selected dyad, the students were engaged with each other, but the degree to which they engaged with the critique activity and the nature of their engagement varied. Although the orientations of these dyads were neither one-dimensional nor fully consistent throughout the critique activity, the orientations were generally representative of each dyad’s engagement with the task.

Table 4.12
Summary of Cases

Case	Students	Treatment
Sensemaking Pair	Kostas and Ted	<i>Peer guidance</i>
Disengaged Pair	Meilin and Emily	<i>Expert guidance</i>
Task-Oriented Pair	Tammy and Giulia	<i>Expert guidance</i>

Note: all names are pseudonyms.

Case 1: The Sense-Making Pair. Kostas and Ted studied the *peer guidance* version of the *GCC* unit. Though they began the *GCC* unit in the bottom quartile of their treatment group, they were both highly motivated students who engaged with the unit and held extended discussions before deciding on responses to explanation prompts. Ted controlled the computer throughout the critique and typed the responses, but it was common for Ted to incorporate Kostas’ suggestions in the response and to confirm Kostas’ agreement with the response before submitting the final version. Kostas actively engaged with Ted; it was common for Kostas to raise questions and objections if he did not share Ted’s opinion or understanding of a particular activity.

Kostas and Ted engaged in sensemaking discussions of both surface (i.e., spelling, grammar, and punctuation) and content criteria throughout the *first critique* step. During both instances of surface critique—recall that in *first critique*, students critique two preselected explanations for surface and science content—Kostas and Ted discussed and negotiated whether accurate spelling and grammar can be judged independently of science content. Specifically, as the excerpt below demonstrates, Kostas appeared to grapple with the distinction between stylistic clarity and its impact on the clarity of science content, as opposed to simply the surface stylistic concerns of spelling and grammar. Prior to the transcript below, the pair had begun critiquing surface aspects of the sample explanation with good surface characteristics and vague science

content (“It changed a lot. It went down then bounced,” Table 2). Ted had asserted his rating (“good: few mistakes”), and after an initial assent, Kostas had reversed his position.

- 1 T: What would you give it? Out of three?
2 On a scale //of//—
3 K: //One?//
4 T: One? (incredulously)
5 K: Yeah, this is like, so bad. (sweeps finger across the explanation)
6 T: No, it’s not—
7 K: It’s not good English, you know?
8 Like, “It changed a lot. It //bounced and//”—(reads out loud in a singsong)
9 T: //That’s in// “scientific content and clarity.” (points to
10 next critique prompt for science content and clarity)
11 That’s what it means.
12 Here, “the science idea could be described in,” “some ideas are wrong or vague.”
13 (reads some of the science content criteria; K leans in toward the monitor as T
14 reads)
15 K: Like, what changed, though? (points to “It changed” portion of first explanation)

Although Kostas was unable to specify his misgivings other than to identify that it was not due to spelling, he elaborated his position by explaining that the explanation had “bad English (lines 7-8).” Ted countered that Kostas was referring to science content and clarity, not spelling and grammar (lines 9-12), and oriented Kostas to the next critique prompt and its list of criteria targeting science content and clarity. By asking Ted, “*what* changed? (line 14)” Kostas seemed to have been trying to identify what was bothering him about the explanation on a more specific level. Given that the explanation did not fully specify what “it” was that changed, this problem can be viewed simultaneously as an issue of vagueness in language and of lack of clarity in content. Here, Kostas was focusing on the vagueness of the language. In effect, then, Kostas may have been alluding to sophisticated ways in which the surface and content criteria can be considered to overlap. Although they eventually chose “good” as their response, the discussion re-emerged during the surface critique of the second explanation, indicating that making sense of the surface and content criteria was important for Kostas.

Kostas and Ted continued to engage in sense-making discussions during the science content critique for both explanations. In the example below, the pair had formed initial impressions about whether each criterion was applicable to the particular explanation before reaching the last criterion on the list, “the science ideas could be described in more detail.” The ensuing discussion illustrates the rich conversations they had as they negotiated the meanings of the criteria vis-à-vis each other:

- 1 K: This is... This is it. (points to “needs more detail” criterion)
2 In more detail... 'cause [the explanation] just said, "It changed a lot. It went down
3 then bounced."
4 So it needs like, more support... evidence [another criterion], and like, more
5 detail.

6 T: Yeah, it's more evidence.
7 It's... No, it doesn't need more detail. 'Cause, I mean... [it] has a LOT of detail.
8 Well, not that... well—(sighs)
9 It has like, a 4 out of 5 detail.
10 It said, "It went down, then bounced." That's kind of describing it in detail.
11 But it's not describing it in like, proper grammar.
12 K: I think this is right. (points to “needs more detail”)
13 T: I think... no.
14 This is “need more detail.” I think it’s “needs to have evidence.”
15 K: I’m really confused between both of those. (points to “needs more detail” and
16 “needs to have evidence” criteria)
17 I don’t know. [inaudible]
18 I think what you chose is right.
19 T: I don’t think there’s, like, a wrong answer in this question.

Although the explanation prompt explicitly asked students to provide information, or evidence, from a previously explored model (Table 4.3), Kostas and Ted did not discuss the evidence criterion in terms of whether the explanation contained explicit references to information in the model. Instead, they discussed how to distinguish evidence from detail. Ted struggled to clarify why he believed that “needs to have evidence” was the more appropriate critique over “needs more detail (lines 5-9).” Ted’s concluding remark, “But it’s not describing it in like, proper grammar (line 9),” is notable in light of the fact that they had already evaluated the grammar and spelling of the explanation to be “good.” It may suggest that he had some ideas about what counts as evidence in science explanations as opposed to simply descriptive detail. His struggle is similar to Kostas’ earlier attempt to distinguish between surface stylistic clarity and content clarity in that Ted also struggles to articulate why he believes one criterion is more applicable than the other. In this case, however, Kostas and Ted did not pursue this line of thought to the same extent as they did previously for Kostas. After Kostas professed his uncertainty about what evidence and detail meant (line 14), Ted responded that any of the criteria may be acceptable answers (line 18). Unable to pin down what exactly they felt was lacking in the explanation, they eventually decided on “the science ideas are wrong or vague” and wrote, “We think that the student needs to add more detail and support his answer because we can’t understand the answer, it is vague and needs to become clearer.”

Kostas and Ted also undertook the critique of the second sample explanation in light of the first. Recall that the *first critique* step was designed to cue students to the idea of surface and content dimensions by using two sample explanations that contrasted with each other on these dimensions (Table 4.3). The first explanation in the *first critique* step was intended to serve as an exemplar for good style and vague science content, whereas the second explanation was intended to serve as an example for poor style and detailed science content. As such, the second explanation was rife with spelling and grammatical errors. It may therefore seem a similarly straightforward task to score the spelling and grammar for that explanation, perhaps even more so than the first explanation due to the obvious errors. However, the confusion between stylistic and content criteria reemerges in Kostas and Ted’s exchange. In the following transcript, Kostas and Ted had just finished identifying numerous spelling errors in the second explanation and were about to

decide its score for spelling and grammar. As in the first explanation, they disagreed, but this time, Kostas used the first explanation as a point of reference when questioning Ted's assessment of "Not so good." This prompted Ted to repeat his earlier attempt to orient Kostas toward science content criteria to address his concerns with the explanation.

- 1 K: //U::h//
2 T: //U::h//
3 T: N:::not good. (selects "Not so good" criterion with pointer)
4 K: No, uh, it's, //it's good// (points to "Good" criterion with finger)
5 T: //It has many spelling//
6 T: Has //many// spelling.
7 K: //Ohh// Uhh.
8 K: Yeah, but this like, so you're saying the, the one before that has like one sentence,
9 is "good... few spelling and //the"//—(points to first explanation, then to "Good"
10 criterion)
11 T: //That's// for grammar and spelling. (traces "grammar
12 and spelling" in critique prompt; K drums fingers on desk)
13 T: I like this, the idea that it was, the— (points to second explanation)
14 K: Yeah, you—oh, oh. (nods, points to science content and clarity criteria list)
15 T: I like, for science clarity, "response," uh, "needs evidence to explain," so—(points
16 at criterion)
17 And the::n, "ideas could be elaborated."
18 I think...
19 I think yeah.

In questioning Ted's "not so good" surface critique of the second explanation, Kostas drew attention to the brevity of the first explanation relative to the second (lines 8-10). This indicates that Kostas was still struggling to distinguish between surface and content criteria. From this, his earlier dissatisfaction with the first explanation for "not good English" seemed to have remained unresolved. In response, as in the first case, Ted repeated his assertion that Kostas' issue with the first explanation pertained to science content and not spelling and grammar (lines 11-12). This time, Kostas nodded and pointed to the science content criteria list as if to accept and affirm Ted's claim. In Kostas' case, critiquing two explanations with contrasting dimensions seemed critical for making progress in teasing apart surface and content issues.

In Kostas and Ted's case, although they engaged in sensemaking discussions about both surface and content criteria, their rich conversations and oral critique were not fully captured in their written guidance. However, their active engagement with the critique tasks and sensemaking-oriented discussions seem to indicate that the critique activity provided them with multiple opportunities for beginning to make sense of and distinguish among the criteria.

Case 2: The Disengaged Pair. Meilin and Emily studied the *expert guidance* version of the GCC project. Like Kostas and Ted, they began the GCC unit at the bottom quartile of their treatment group. They took turns typing responses, but the one not typing the response would often engage in off-topic conversations with the typist. Although they had good rapport as a team, they were relatively disengaged from the GCC project as a team.

During both *first* and *second critique*, Emily typed the responses while Meilin looked around or made off-topic commentary into the wireless microphone. The following excerpt exemplifies the pair’s engagement with the critique tasks.

- 1 Emily: (reading snippets from critique prompt) “Score this response for spelling... Very
2 good...”
3 (reading first example explanation) “It changed a lot. It went down then
4 bounced.”
5 Uh::h.
6 (Emily works in silence for 27 seconds while Meilin looks around.)
7 Emily: What is it? (turns around, presumably in response to an inaudible distraction) Ew.
8 (Meilin turns around)
9 Meilin: Ew.
10 Emily: Wait, why are the [inaudible]?
11 (Emily and Meilin turn right to look at something, then turn back. Emily
12 continues to work while Meilin looks around.)
13 Emily: “Score this response for SCIENCE content and clarity.”
14 (Emily reads the choices for science content criteria to herself while Meilin looks
15 around.)
16 Emily: (asking Meilin) What’s “elaborated” mean?
17 Meilin: What? I don’t know.
18 Emily: (asking camera) What’s elaborated mean?
19 Meilin: Do you know that answer, America? (asking camera, then giggling)

Emily therefore worked mostly independently, with little input from Meilin (e.g., lines 1-6). They did not discuss Emily’s responses, and moved on to the next step once Emily seemed to be satisfied with her own response. Although Emily was on-task, she did not engage her partner in the critique, nor did she take additional initiative in seeking clarification for aspects of the task (e.g., what “elaborated” means) if the answer was not immediately available (lines 16-19).

In Meilin and Emily’s case, they were not engaged as a team with the critique tasks. In the above example, Meilin seemed content to have Emily complete the critique tasks and made minimal effort to help Emily when Emily asked her a question about one of the criteria (lines 16-19). It is unclear to what degree Emily engaged with the critique task on her own, but her lack of initiative in reaching out to the teacher or the researcher to resolve her confusion with one of the criteria seems to indicate that she did not find it important to make sense of the criterion in question. In fact, although log files indicate that Emily spent approximately three and a half minutes on the *first critique* step, for both sample explanation content critiques, her final responses were the two letters “sd.” Unlike the case of Kostas and Ted, the critique activity therefore did not lead to Meilin and Emily making sense of and distinguishing among the criteria, or even completing the task.

Case 3: The Task-Oriented Pair. Tammy and Giulia studied the *expert guidance* version of the *GCC* unit. They began the unit at the top quartile of the treatment group. They were highly motivated students who remained on-task during the *GCC* project. They typically approached each prompt from what might be characterized as a “What can we put down to complete the task?”

orientation, with statements starting with task completion-oriented remarks such as “We could say...” and “We could put...” when beginning to formulate their responses. Regardless of who controlled the computer for a given prompt or activity, both students engaged in the discussion.

During critique, Tammy and Giulia discussed the criteria until they reached agreement, after which Tammy typically dictated the response to Giulia as she typed. When choosing the criterion, one of the pair would immediately suggest a candidate, often without an accompanying rationale and without subsequent disagreement, as the following example of content critique illustrates:

- 1 T: “Score this response for SCIENCE content and clarity.”
2 (Reads list of criteria out loud (Figure 3))
3 T: I like the last one. [“The science ideas can be described in more detail.”]
4 G: Yeah.
5 T: “Explain your choice for SCIENCE CONTENT and CLARITY and give an
6 example from the response to help the student improve the explanation.”

In the example, Talia immediately declared that she liked the last criterion (line 3) but without stating why. Giulia agreed without providing her own rationale (line 4), and the pair moved on to the next prompt (line 5). Similar episodes were observed for both surface and content critiques. Thus, if one student did not find cause to disagree with the other’s proposal, there was no further discussion, and the pair moved on to the next task without elaborating on their decisions.

In the event of a disagreement, there were some instances that could have led to an exploration of a criterion’s meaning in the context of the explanation. However, the pair did not pursue those opportunities if they were able to come to some agreement and generate what they felt was a satisfactory response and could move on to the next task. The following excerpt is an example of one such instance during the content critique of the second sample explanation (bad surface characteristics and good science detail, with inaccurate science; Table 4.3):

- 1 G: (After reading the list of criteria) I think it’s the second one [“The response needs
2 more evidence to explain why”].
3 T: Yeah.
4 G: “The response needs evidence.”
5 T: “...to explain wh::y.”
6 G: (Reading prompt)
7 “Explain your choice for SCIENCE CONTENT and CLARITY and give an
8 example from the response to help the student //improve the exp—”//
9 T: //Wait, wait, go back.//
10 T: Go up, please. (G scrolls up)
11 T: I want to see something.
12 T: Um, //(inaudible)//—
13 G: //Yeah, it’s the same thing.//
14 T: “When the solar radiation was reflecting, it could not change into heat energy it
15 just”—
16 T: Well, then, no.

- 17 T: They explained, so I think they did well.
18 T: They explained; they just have grammar.
19 G: But they just, they didn't really (.) have evidence. Do they have evidence?
20 T: Yeah, they said that, //um//—
21 G: //Oh, yeah.// OK.
22 T: So, we could just say, u::::h.

In the above example, similar to the previous episode, one student declared that she liked a particular criterion, and the other agreed readily with neither of them providing a rationale (lines 1-5). However, when they moved on to the next prompt (lines 7-8), Tammy asked Giulia to “scroll up” for her, reread the explanation, and seemed to reverse her earlier decision and conclude that the other team explained well and only had grammatical issues (lines 9-18). When Tammy stated, “They explained; they just have grammar (line 18),” Giulia asked back if their explanation actually had evidence (line 19). When Tammy began to explain her rationale (line 20), Giulia interrupted her with an agreement (line 21). Tammy then switched immediately to “So, we could just say... (line 22);” neither mentioned evidence for the remainder of the content critique task. Given Giulia’s direct inquiry about whether there is, in fact, evidence in the explanation, it is notable that they do not pursue this nascent sensemaking discussion once they seemingly achieve an agreement. It is possible that the two students knew each other well and felt themselves so aligned with each other that they were not motivated to explicate their reasoning. Given that their sensemaking stopped immediately once Giulia agreed with Tammy, another possible explanation is that the pair did not engage in sensemaking beyond what was necessary to complete the task. Giulia and Tammy achieved a consensus, but it is unclear whether their rationales for their opinions actually aligned because neither of them explicated the basis for their respective opinions. Similar episodes during their critique tasks were observed, suggesting that, while Tammy and Giulia both engaged with the critique tasks and collaborated with each other, they missed several opportunities to delve more deeply into the criteria.

However, these missed opportunities do not necessarily mean that the critique activity was without value for this pair. Immediately after they conclude that the example does have evidence in the previous excerpt, Tammy and Giulia notice the inaccurate science in the sample explanation. The following excerpt is a continuation of the previous excerpt.

1 T: So, we could just say, //u:::h//
2 G: //Mm// wait, “The global temperature went down when
3 al—”
4 T: //(Inaudible)//
5 G: //Doesn’t// it— Isn’t that wrong? (begins highlighting section of explanation with
6 cursor)
7 G: The first line? (highlights first line of sample explanation, “Global temperature
8 went down when albedo was low”)
9 G: Global temperature went down when albedo was low. Shouldn’t it be high? (T&G
10 look at each other)
11 T: The (inaudible)—
12 T: “When the albedo was”—
13 T: Yeah, no, it’s supposed to be the—
14 T&G: The global temperature went up(G: high)...
15 T: Yeah, so they’re wrong. Yeah.
16 G: //Like, for the ocean//—
17 T: //So, they, u:::mm//—
18 T: “The science ideas are wrong or vague.”
19 G: Uh, “wrong or vague.” Yeah.
20 T: ’Kay, so we can write what they did.

Having identified the error in the sample explanation, they then went on to answer the next prompt, which asked students to explain their choice for science content critique and give an example from the explanation (Table 4.2). Although Tammy and Giulia had identified the specific error, they did not explicate what that was in their response and wrote, “They had grammar mistakes some of the information was wrong.” The inclusion of “grammar mistakes” in their guidance may indicate that they have not distinguished between surface and content criteria, but it is unclear to what extent they understand the criteria, given that they did not engage in explicit sensemaking. Despite the lack of specificity and mention of surface critique in their written guidance, in some ways, Tammy and Giulia’s response is an accomplishment: they identified the presence of a scientific error that was buried in a very complex explanation rich in detail. However, an examination of their conversations during the task also suggests that the critique activity did not elicit rich sensemaking discussions.

Summary and Cross-Case Comparison. The range of engagement observed in the videotaped dyads, as illustrated in the above cases, indicates that it is important to consider how students initially engage with critique when designing critique activities if students are to distinguish between and among surface and content criteria (Table 4.13).

Table 4.13

Summary of Cases with Dimensions of Engagement

Case	Students	Engagement as a Team	Sensemaking	Task Completion
Sensemaking Pair	Kostas and Ted	Yes	Yes	No
Disengaged Pair	Meilin and Emily	No	No	No
Task-Oriented Pair	Tammy and Giulia	Yes	Yes/No	Yes

Some, like Meilin and Emily, may be disengaged as a team. They may be content to have one student complete each task with minimal discussion and little evidence of engagement in sensemaking, at least together. At the other end of the spectrum in terms of engagement and sensemaking may be teams like Kostas and Ted. Although Kostas and Ted did not generate detailed guidance, their discussions illustrated rich instances of criteria sense-making that are arguably at least one of the essential first steps students must take before they can engage productively in critique and generate good guidance. In contrast, although Tammy and Giulia were similarly highly engaged with the critique tasks as a team, their discussions did not lead to rich sense-making. Unlike Kostas and Ted, who engaged in cross-explanation comparisons in their discussions, Tammy and Giulia seemed to approach each explanation critique as a separate task to complete in isolation, which may have inhibited the activity's potential to elicit more sensemaking of criteria. The pair also correctly identified inaccurate science content and engaged in some sensemaking in the event of a disagreement, but they did not appear to leverage these opportunities to delve deeply into the criteria and try to understand the nuanced distinctions to the same extent as Kostas and Ted. The two pairs' orientations, as observed through their interactions with the activity sequence, therefore seem to be at odds with each other.

Summary and Discussion

The findings of this study demonstrate that students who received expert KI guidance were better able to make conceptual revisions to their original explanations after engaging in peer critique than students who received peer guidance. While this guidance did not significantly affect their overall learning in the unit, it is possible that KI guidance on more responses would lead to overall learning gains. These findings build on previous studies demonstrating the value of well-designed guidance for supporting students in refining their understanding in technology-enhanced STEM instruction (Aleven et al., 2004; Narciss, 2004; Narciss & Huth, 2004). These findings can also contribute to the design of automated guidance in technology-enhanced instruction that adds value to typical instruction (Gerard, Ryoo, McElhaney, Liu, Rafferty, & Linn, submitted).

Further, the comparison of peer and expert guidance in terms of how specific science ideas are presented to students suggests several promising design principles of guidance that go beyond

content or task specificity. Being told their responses were incorrect and being provided with the correct information did not necessarily help students consolidate their understanding in light of new information and improve their explanation. When provided with correct information, students may elect to adopt the information in their revision without integrating it into their current understanding, which results in a piecemeal, incoherent explanation. Although expert guidance did not provide correct information, narrowing students' focus by providing students with specific ideas and causal relationships to reconsider and build upon seemed to support students in making progress with their revisions. These findings contribute to the existing body of work on formative guidance (Hattie & Timperley, 2007; Gielen et al., 2010; van Zundert, Sluijsmans, & van Merriënboer, 2010) by clarifying what types of content- or task-specific guidance may promote mindful reception and guard against the propensity of students to take the path of least resistance.

Referencing students' own words in the guidance may also promote students' metacognition by guiding students to reflect on their own understanding (Schraw, Crippen, & Hartley, 2006). When expert guidance prompted students to add ideas and elaborate on their initial response, it was framed as "How?" and "Why?" questions building on words used by students (e.g., "Why does the infrared radiation linger longer?"), thus focusing students on evaluating their own expressed understanding. Although students were only given one round of expert KI guidance in this study, receiving more KI guidance over time may foster more spontaneous metacognition by guiding students to self-monitor their own understanding.

In terms of critique guidance design, the study findings demonstrate the potential for using complex selection tasks to promote distinguishing among ideas. This resonates with Zhang and Linn (2013)'s findings that complex selection tasks can be as beneficial as generation tasks in technology-enhanced science instruction. In this study, video analysis revealed that prompting students to select among plausible alternatives without a clear correct answer can promote sensemaking discussions. Students negotiated their understanding of various criteria for explanations in science that they had previously encountered in instruction with each other, which led them to examine the explanation and using ideas in the explanation as evidence. Although the analysis also revealed the current design's weaknesses in terms of supporting students in consolidating their insights from the critique and expressing those ideas in writing, complex selection for guided critique remains a promising approach that merits further study.

These findings also have implications for science teachers, who are often pressed for time during instruction. Although research has shown that formative assessment is valuable for student learning, it is difficult for teachers to provide personal guidance to each student (Shepard, 2000). This study's approach to designing guidance based on common student ideas for a given explanation can potentially become customizable "templates" for teachers. Doing so may greatly reduce the burden on teachers and add value to their instruction with research-tested guidance guidelines.

The generalizability of these findings is limited, given that the study was not implemented across multiple domains and grade levels. In addition, as previously mentioned, students reported having minimal, if any, experience in peer critique or revision of explanations. Studies with populations having more familiarity with peer critique and revision practices may yield different

findings. While engaging in guided peer critique has been found to support students in making sense of criteria and detecting conceptual problems with the explanation being critiqued (Sato & Linn, 2012), students need more support and experience before they can fully benefit from the opportunity and provide effective guidance to their peers. Future work will help clarify the effects of extended training and classroom culture on guided peer critique and revision.

This study yielded promising insights into the design of expert guidance and the value of supporting students in guided peer critique and in generating more expert guidance. Further research is needed to test the value of providing students with guided critique opportunities and with expert guidance to revise their explanations for different grade levels and science domains. Future research should also investigate how expert guidance supports student revision of explanations. Although recent studies (Ryoo & Linn, 2014b; Gerard & Linn, 2013) have found that prompting students to revisit critical steps and find salient information in guidance can be beneficial for students, our findings were inconclusive with regard to whether revisiting is critical for revision. Future work will clarify when and how guidance designed to promote knowledge integration support students in reconsidering and refining their ideas.

Chapter 5: Designing Critique to Improve Conceptual Understanding

In this chapter, I test the robustness of the refined critique guidance against two approaches to designing explanations for critique. I also adjust the design of the activity structure in two ways. First, after critiquing another explanation, I asked students to revise their initial explanation based on a guided critique of their own response designed to prompt students to distinguish among a range of ideas. I hypothesized that basing their revision on critique will enable students to consider a range of ideas in their explanation, in contrast to providing guidance focused on a specific idea. Second, I provided conceptual guidance on the students' critique of another explanation. The critique task could then serve as a formative assessment opportunity to diagnose misconceptions based on the students' critique choice. Furthermore, given the literature documenting the propensity of students to discount ideas that contradict their beliefs, I hypothesized that students may be less likely to discount guidance if the guidance addressed the students' evaluation of another explanation, rather than the students' own explanation.

In addition, I changed the design of the critique guidance in two ways to enhance the distinguishing of ideas. First, whereas the critique task in the previous study consisted of selecting among a list of criteria for science explanations in general (e.g., "response needs more evidence"), I adjusted the list to become a list of science ideas specific to the explanation (see Methods). Just as selecting among a range of criteria supported students in criteria sensemaking, I hypothesized that selecting among a range of science ideas relevant to the explanation will support students in distinguishing among their and alternative ideas.

Second, I designed the critique artifact—the explanation assigned for critique—itsself in terms of what ideas each assigned explanation contained. Although the previous study did not find that the quality of the assigned explanation had an impact on students' ability to revise based on guidance, it is unclear whether the ideas contained in the assigned explanation will impact students' ability to revise based on critique. I designed explanations that contained different sets of ideas based on the hypothesis that students expressing a certain conceptual understanding or misunderstanding may benefit from considering a specific subset of ideas when critiquing an explanation. Put differently, critique may be more beneficial if the assigned explanation is aligned to the students' prior knowledge. I chose to investigate two different approaches to aligning the assigned explanation to student's prior knowledge.

Thus, this study seeks to advance our understanding of how critique can support students in revising their explanations by comparing two different approaches to designing explanations for critique. The conditions of this study are designed to address the following research questions:

1. How do students benefit overall when they critique (a) an incomplete explanation with normative ideas to identify a missing idea (*incomplete*) or (b) an incomplete explanation combining normative and non-normative ideas to identify a non-normative idea (*non-normative*)?
2. How do students' ideas, as expressed in their explanations, shift in response to critique and revision?
3. How do students benefit when provided with automated guidance on their critique?

I hypothesized that I would observe significant differences between conditions in students' learning gains if the potential benefit of critique depended upon carefully designing an accessible

yet *desirably difficult* critique artifact that was aligned to the students' prior knowledge. On the other hand, I hypothesized that students in both conditions would make comparable progress in their learning if the potential benefit of critique were less dependent on the complexity of the critique artifact and more dependent on whether students were appropriately supported in considering alternative ideas.

To foreshadow the results, the findings of this study show that students can equally benefit from critiquing explanations of varying complexity when guided to consider a range of alternative ideas during critique. The results show the value of designing critique to support students in distinguishing among their own and alternative ideas. Case studies illustrate how students engaged with opportunities provided by the guidance, and indicate areas where further research is necessary to refine the design of critique as a means to support conceptual learning in science.

Rationale

Students develop multiple, often conflicting ideas about scientific phenomena as they interact with the natural world and struggle to distinguish new ideas from existing beliefs (e.g., Clark, 2006). Both children and adults resist and discount evidence that contradicts their existing beliefs (Chinn & Brewer, 1993). Yet, citizens need to develop the ability to use scientific evidence to critique ideas of others and to interpret critiques of their own ideas. Efforts to date offer some promise for critique but also reveal the need for clarification of how, when, and why critiques are beneficial for conceptual learning (e.g., Shen, 2010).

In designing explanations for critique, I draw on the constructivist knowledge integration (KI) framework (Linn & Eylon, 2006) that addresses the difficulties students have in making sense of their multiple, conflicting ideas. KI calls for building on the repertoire of ideas students develop in their lives by designing inquiry experiences that support students in considering alternatives and refining their conceptual repertoire. However, students' ability to distinguish among alternatives during critique may be dependent on the complexity of the critique artifact. I draw on the notion of the zone of proximal development (Vygotsky, 1978), which suggests that students are most likely to benefit when the learning task is designed to align with their prior knowledge such that the task is accessible and allows students to make progress with appropriate guidance. However, additional perspectives such as desirable difficulties in psychology (Bjork, 1994) and productive failure in mathematical problem solving (Kapur & Bielaczyc, 2012) suggest that reducing the complexity of cognitive tasks may have a detrimental impact on student learning by deemphasizing the need to distinguish among ideas in their conceptual repertoire. The goal is therefore to adjust the sophistication of the assigned explanation while retaining the desirable difficulty of the critique task.

In previous chapters, I explored how critique can support students in revising their explanations by testing different designs for guided critique and revision. The videoanalysis findings highlighted the potential of guided critique for supporting students in distinguishing among their existing ideas and plausible alternative ideas. Prompting students to choose a "best fit" criterion among a list of alternative criteria for what makes a good science explanation can support students in criteria sensemaking and noticing specific ideas in the explanation being critiqued. However, the studies also demonstrated the difficulty students have in leveraging that

experience when they are subsequently given an opportunity to revise their initial explanations based on additional guidance.

In my previous studies, I found that students who revised their response based on expert guidance were more likely to improve their response than those who revised their response based on peer guidance. When asking students to revise based on direct guidance on the students' response, the quality of guidance is clearly important. However, analysis of post-revision reflection notes revealed that some students chose not to revise their response because they did not agree with the guidance provided. Their reflections indicated the possibility that when students are asked to revise based on external guidance, they do not draw on their broader experience of having critiqued another experience. Further, the guidance seemed to focus them on reconsidering whether they agree with the specific ideas targeted by the guidance, rather than reconsidering the range of ideas in their overall response. I address these issues by focusing on how I can strengthen critique to better support students in distinguishing among ideas.

From the KI perspective, conceptual critique involves distinguishing among normative and non-normative ideas. A successful critique involves identifying which relevant normative ideas need to be added to the explanation, as well as identifying which ideas in the explanation are irrelevant or non-normative. Guiding students in critiquing a normative response that is incomplete yet slightly more sophisticated than their current explanation could support students in distinguishing among ideas without being overwhelmed by complexity. Critiquing a slightly more sophisticated normative response may not support students in this process because the non-normative ideas are not explicit. Students may be content with addressing the more obvious flaws and neglect to reflect on the range of ideas. Thus, critiquing a complex response with a mix of normative and non-normative ideas may be more successful in supporting deep understanding by prompting students to reflect more holistically on their conceptual repertoire.

Methods

Participants and Study Design

The five-day *GCC* unit was completed by 94 middle school students in three intact classrooms taught by the same teacher, who had more than 10 years of experience teaching science using web-based inquiry instruction and had taught previous versions of the unit. Students had completed at least one web-based inquiry unit prior to the *GCC* unit, and had not received classroom instruction on global climate change. The teacher reported previously giving students guidance on key explanations in other web-based inquiry units and encouraging students to revise their answer. However, this study was the first time for study participants to critique and revise explanations, whether their own or another's, based on a critique activity. Students worked in pairs throughout the unit, including the pre- and post-test. The pre- and post-tests were each completed within a 50-minute classroom period. Students were randomly assigned in pairs to the *incomplete critique* condition (n=22 pairs) or to the *non-normative critique* condition (n=25 pairs). I removed a total of 20 pairs who either did not complete the pretest or posttest, or already demonstrated complex understanding in their initial explanations from the analysis.

I used a pretest/posttest experimental design with embedded assessments and two comparison conditions. Based on the design research paradigm, the study sought to investigate whether one condition is better than the other. In the *incomplete* condition, students critiqued an

explanation containing only normative ideas. In the *non-normative* condition, students critiqued a modified version of the *incomplete* explanation with a non-normative idea.

Web-based Inquiry Global Climate Change Unit

A sixth-grade technology-enhanced earth science curriculum unit, Global Climate Change (GCC, Figure 5.1), was developed in the Web-based Inquiry Science Environment (WISE, Linn, Davis, & Bell, 2004) using the KI perspective. In *GCC*, students grapple with the complex energy mechanisms driving changes in global climate through a series of interactive NetLogo simulations (Svihla & Linn, 2012). Students are provided with multiple opportunities to explain causal subsets of this complex system before generating an integrated explanation of the overall phenomenon. They investigate how factors such as greenhouse gases impact energy transformation and how that in turn impacts global temperature trends. Student explanations were coded for the sophistication of their mechanisms. I focused on an explanation targeting an energy transformation process critical to understanding the phenomenon of global climate change.

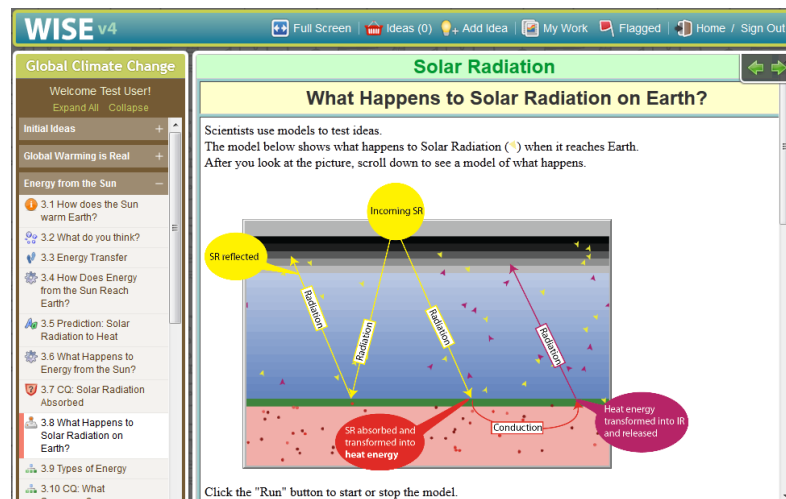


Figure 5.1. The WISE *Global Climate Change* unit.

Critique Activity Sequence Overview

The critique activity sequence consisted of two phases (Figure 5.2). After students generated an initial explanation, they critiqued and revised an assigned explanation (Phase I), received conceptual guidance on their critique, then critiqued and revised their initial explanation (Phase II). The design focused on encouraging students to discuss and negotiate alternative ideas presented through the assigned explanation and critique choices, as well as revisit evidence steps (e.g., simulations), which has been correlated with learning gains (Svihla & Linn, 2012). The unit and activity design was identical between the two conditions aside from the assigned explanation in Phase I and specific guidance associated with the assigned explanation during Phase I that carried over into Phase II, as I will explain in detail below.

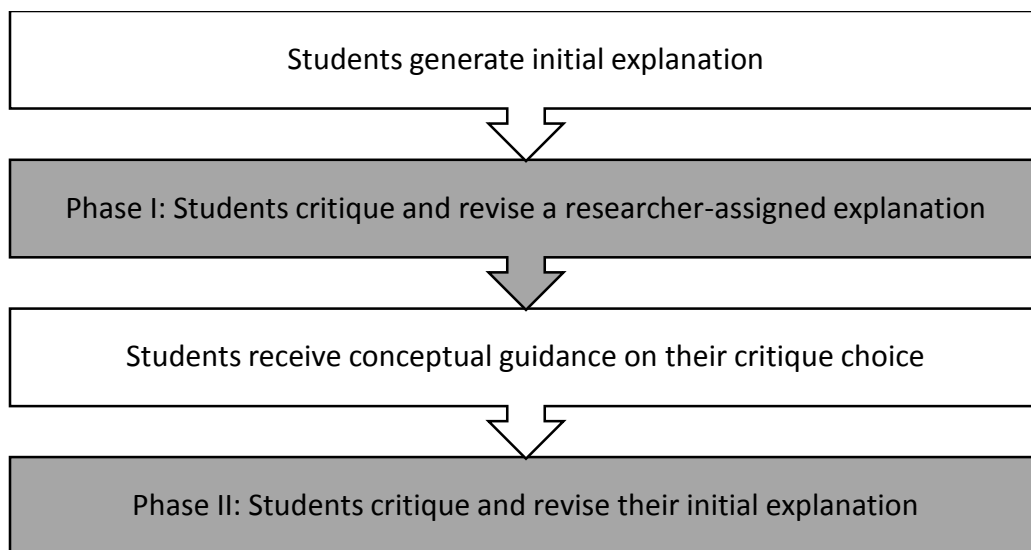


Figure 5.2. Outline of the overall activity sequence. The shaded step indicates where the curriculum design differed between the two versions.

Design and Assignment of Explanations for Critique during Phase I

For each condition, three explanations were designed by the researcher based on the analysis of responses collected during previous classroom implementations. I first developed three categories of student understanding on an increasing scale of conceptual coherence and sophistication (Table 5.1). I then designed an explanation aligned with each category that I felt would be beneficial to critique for students diagnosed with that category of understanding. I made the explanation accessible for students by designing it to express partial understanding and to be only slightly more sophisticated than the initial explanation generated by the students. I created two versions of each explanation for a given category of understanding to align with the different critique goal of each condition: find a missing idea in the *incomplete* condition versus find an incorrect idea in the *non-normative* condition. To create the two versions, I first created the *incomplete* version of the assigned explanation, then modified it to create the *non-normative* version (see Table 5.2 for example).

Table 5.1
Categories of student understanding

Category	Description	Sample Student Response
Non-Normative Energy Source	Response indicates students have non-normative idea about the type of energy coming from the Sun (heat or IR). Other relevant ideas are unelaborated.	The infrared radiation came from the sun, almost all of it came from the sun.
No Intermediate Energy Forms	Response indicates students understand initial and final forms of energy (light and IR,	Some solar radiation was reflected and some solar radiation was absorbed by the surface of the earth

	respectively), but student does not mention heat.	because of the green house gases and as its absorbed it transforms into infrared.
No Energy Transformation Conditions	Response indicates students understand energy transforms from heat into IR, but either do not mention or have incorrect ideas about energy transformation conditions.	Infrared radiation came from the heat/thermal energy that was in the Earth's surface, the energy changed by conduction into infrared radiation that went into space.

Note. The categories are in order of increasing sophistication.

Table 5.2

Sample explanation assigned to students in each condition for the same initial explanation

Condition	Incomplete	Non-Normative
Initial Explanation	The infrared radiation came from the sun, almost all of it came from the sun.	
Diagnosis	Response indicates students have non-normative idea about the type of energy coming from the Sun (heat or IR). Other relevant ideas are unelaborated.	
Assigned Explanation	Solar radiation was absorbed by earth and was released as infrared radiation	Solar radiation was reflected by earth as infrared radiation
Science Content Critique	<p>The response can be improved by...</p> <ul style="list-style-type: none"> explaining what kind of energy SR becomes when it is absorbed. (“correct” choice, adding normative) explaining that IR comes from the Sun. (“incorrect” choice, addressing non-normative) explaining that SR becomes IR when SR is reflected (“incorrect” choice, addressing non-normative) adding more evidence in general. 	<p>The response can be improved by...</p> <ul style="list-style-type: none"> explaining that IR isn't reflected SR. (“correct” choice, identifying non-normative) explaining that IR comes from the Sun. (“incorrect” choice, addressing non-normative) explaining that heat from the Sun was reflected by Earth as IR. (“incorrect” choice, addressing non-normative) adding more evidence in general.

Note. Non-normative idea in **bold**.

Design of Critique Guidance during Phase I and Phase II

The same critique guidance was provided to students during Phase I and Phase II critique. Critique involved selecting a science content critique from among several alternatives (Table 5.3), with the goal of prompting students to distinguish among alternatives. The list of alternatives were tailored to each assigned explanation and covered a range of relevant science ideas. Although the range of ideas provided was equivalent across the conditions for a given category of explanation that was assigned, as with the design of assigned explanation, the wording differed to accommodate the different critique goal of each condition. In the *incomplete* condition, the list of alternatives were worded to prompt students to consider which ideas may be missing in the explanation. In the *non-normative* condition, the list of alternatives were worded to prompt students to consider which ideas may were non-normative in the explanation (see Table 5.1 for example).

During Phase II, students were provided with the same list of alternatives as in Phase I so that they could leverage their Phase II critique experience and have a second opportunity to distinguish among the ideas presented. Students were also prevented from referencing the assigned explanation from Phase I so that they would not copy ideas from the assigned explanation when revising their own explanation.

Table 5.3
Critique guidance

Feature	Prompt
1) Assigned Explanation	The other team's response: Solar radiation was absorbed by earth and released as infrared radiation.
2) Critique of Surface Features	Score this response for spelling, grammar, and punctuation: <ul style="list-style-type: none"> • Very good: No spelling, grammar, or punctuation errors • Good: Few spelling, grammar, or punctuation errors • Not So Good: Many spelling, grammar, or punctuation errors
3) Critique of Science Content	What needs to be changed in the response to improve the scientific evidence? The response can be improved by... <ul style="list-style-type: none"> • Explaining what kind of energy SR becomes when it is absorbed. • Explaining that IR comes from the Sun. • Explaining that SR becomes IR when SR is reflected. • Explaining that SR becomes IR when SR is absorbed. • Adding more evidence in general.
4) Revision	Change and improve the other team's response based on your choice above.

Design of Guidance Checkpoint

After Phase I critique, students in both conditions were provided with an opportunity to reconsider the range of alternatives when they received automated conceptual feedback on their critique choice at the guidance checkpoint. Although each condition had its own separate goal for critique, the critique also functioned as a formative assessment opportunity if students selected the wrong alternative (Table 5.1). For example, in the *incomplete* condition, the overt goal was to identify the normative idea missing in the explanation. However, if students selected any of the alternatives, it indicated that students had the non-normative idea expressed by the alternative choice because they disagreed with the normative counterpart expressed by the explanation. In both conditions, if students selected an incorrect alternative, they received conceptual guidance in the form of a guiding question and were prompted to revisit a critical step where they could reexamine the evidence (Figure 5.3). During the guidance checkpoint, students were discouraged from mindless guessing with choices that changed order between attempts and a diminishing score structure.

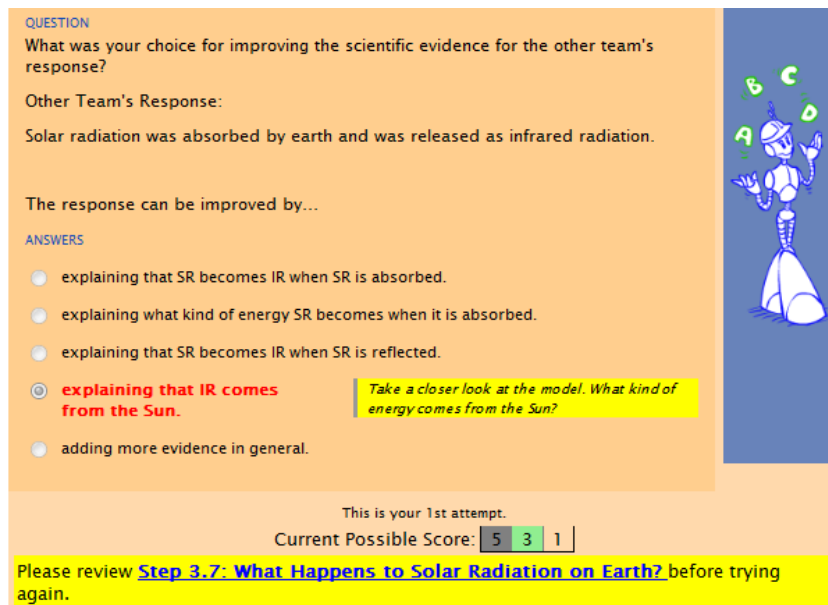


Figure 5.3. The guidance checkpoint.

Data

Student work formed the core data source in the form of the pre- and posttest, as well as the initial and revised explanations. I also collected student log data, video, and observation notes (Table 5.4). The unit of analysis was the dyad.

Table 5.4

Data sources

Data Type	Characteristics
Student Work	Pretest/Posttest results and embedded notes (original and revised explanations).

Student Log Data	Automatically generated logs of how much time dyads spent on steps and in which sequence over the course of the project, and of submitted work and of revisions to original work.
Video	Six dyads working on project and teacher instruction during project.
Observation Notes	Dyads working on project and teacher instruction during project.

Student responses were coded using a rubric based on the KI framework, which rewards coherence of ideas as represented by the number and complexity of connections students make between their ideas (see Table 5.5). Remaining data sources were analyzed to address alternative interpretations of the core data and account for additional factors that may have impacted student engagement with the writing, evaluation, and revision of explanations.

Table 5.5
Knowledge Integration rubric used to score students' original and revised explanations

Explanation Prompt: Where did infrared radiation (IR) come from in the model? Give as much detail as you can.		
Score	Description	Student Examples
1 (Irrelevant)	No answer or irrelevant answers	I don't know
2 (No Link)	Non-normative ideas or links	It came from the sun and space.
3 (Partial Link)	One relevant and normative idea	IR came from conduction, under the earths crust. The Solar Radiation transforms into heat energy that bounces off earths crust and is trapped by the greenhouse gases and unable to escape earths atmosphere.
4 (Full Link)	Scientifically valid and fully elaborated link between two relevant and normative ideas	It comes from heat energy when heat energy is released it goes into the Infrared radiation, so it becomes heat energy.
5 (Complex Link)	At least two links among three or more relevant and normative ideas	Some solar radiation is reflected back into space, and some is absorbed. The SR that is absorbed becomes heat energy, and heats up the Earth. It is in there for a while, and is eventually is released back into the atmosphere as infrared radiation.

Note. Examples are actual unedited responses by students.

Results

The GCC unit was implemented as planned. I performed ANOVA on the students' initial and revised explanations, as well as their pre- and post-test items. The data were examined for normality and homogeneity of variance. All dependent variables were normally distributed with skewness and kurtosis values in acceptable ranges. Levene's tests revealed no significant results

for all variables ($p > .05$), indicating that the homogeneity assumption is met. Overall, students benefitted from the instruction across conditions. Students in both conditions made significant gains from original to revised explanations. In-depth analyses of students' original and revised explanations revealed positive shifts toward more normative understanding, without successful revision being dependent on successful critique. Case studies illustrate the varying degrees to which the critique activity design succeeded in prompting students to distinguish among the ideas presented to them through critique choices.

Impact of the Global Climate Change Unit on Overall Learning Gains

Students made significant pretest to posttest gains across conditions (Table 5.6). There was no significant effect of condition after controlling for pretest scores ($F(1,27)=0.45$, $p>.05$). Thus all students benefitted from the unit, including the critique activities.

Table 5.6

Means and standard deviations for pre and posttest by condition

	N	<u>Pretest</u>		<u>Posttest</u>		<u>t</u>	<u>Effect Size</u> <i>d</i>	<i>p</i>
		M	SD	M	SD			
All	29 pairs	2.97	0.19	4.00	0.93	5.68	1.54	<.001
<i>Incomplete</i>	11 pairs	3.00	0.00	3.81	0.87	3.11	1.32	<.05
<i>Non-Normative</i>	18 pairs	2.94	0.24	4.11	0.96	4.75	1.67	<.01

Weighing Alternatives Effective for Supporting Revision in Both Conditions

On the embedded assessments, there was significant improvement from the students' original to revised explanation across groups (Table 5.7). The critique guidance helped students in both conditions revise their explanations, with medium effect sizes. There was a slight trend for the non-normative condition to make larger gains but no significant differences between conditions after controlling for pretest scores ($F(1,27)=0.05$, $p>.05$).

Table 5.7

Means and standard deviations for original and revised explanation scores by condition

	N	<u>Original</u>		<u>Revised</u>		<u>t</u>	<u>Effect Size</u> <i>d</i>	<i>p</i>
		M	SD	M	SD			
All	29 pairs	2.72	0.75	3.24	1.02	3.55	0.58	<.005
<i>Incomplete</i>	11 pairs	2.91	0.83	3.69	1.12	2.89	0.46	<.05
<i>Non-Normative</i>	18 pairs	2.61	0.70	3.17	0.99	2.56	0.66	<.05

Shifts in Students' Ideas Indicate Progress toward Normative Understanding

I analyzed students' initial and revised explanations for a shift in use of science ideas. Students' explanations were coded for scientifically valid ideas that were targeted by the

explanation prompt, as well as non-normative and partially normative ideas used to assign students to specific critique artifacts (Figure 5.4). Ideas were coded as partially normative when their mechanistic depth was missing details that were targeted by the explanation prompt, but were not non-normative per se. For example, if a student explanation stated that solar radiation changed into infrared radiation when energy was released back into space, it was coded as partial-normative because the explanation was missing the intervening transformation of solar radiation into thermal energy when it was absorbed into the Earth's surface.

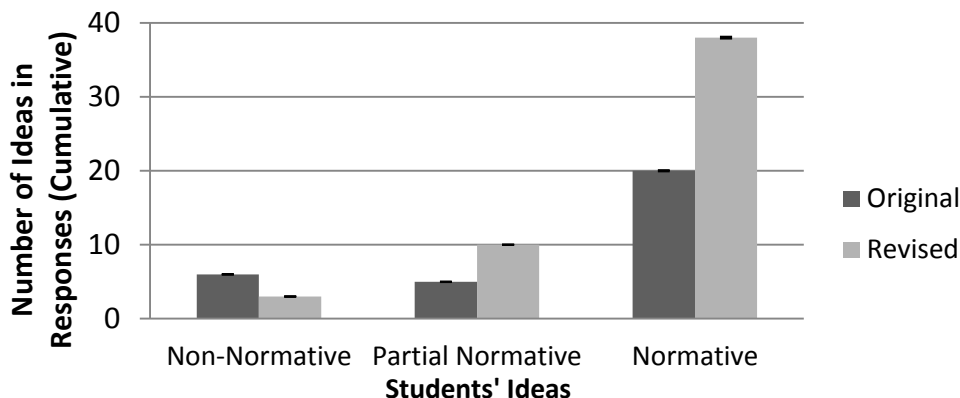


Figure 5.4. Shifts in students' ideas expressed in original and revised explanations across conditions.

Although not an exhaustive list, the ideas were selected for coding based on their prevalence in student responses collected during previous implementations of the unit. There was a significant gain across conditions for normative ideas, $t(29)=3.09$, $p<.01$, $d=.53$; the decrease in non-normative ideas approached significance $t(29)=-1.80$, $p=.083$, $d=.30$; and the increase in partial-normative ideas was not significant. There were no significant differences between conditions for each category of ideas. These results provide support for our hypothesis that critique supports students' conceptual learning of scientific phenomena by guiding them to consider a range of alternatives. Results were not influenced by the complexity of the critiqued artifact.

Successful Revision Not Dependent on Successful Critique

Because I had designed critique to support students in revision, I examined how dependent revision was on success. I analyzed students' science content critique and revision of the researcher-assigned explanation during Phase I, as well as their critique and revision of their initial explanation during Phase II after students went through the guidance checkpoint (Figure 5.5). Students' critiques were coded as a success if they selected the correct science content critique. Revisions were coded as a success if they led to gains in KI scores relative to the initial KI score.

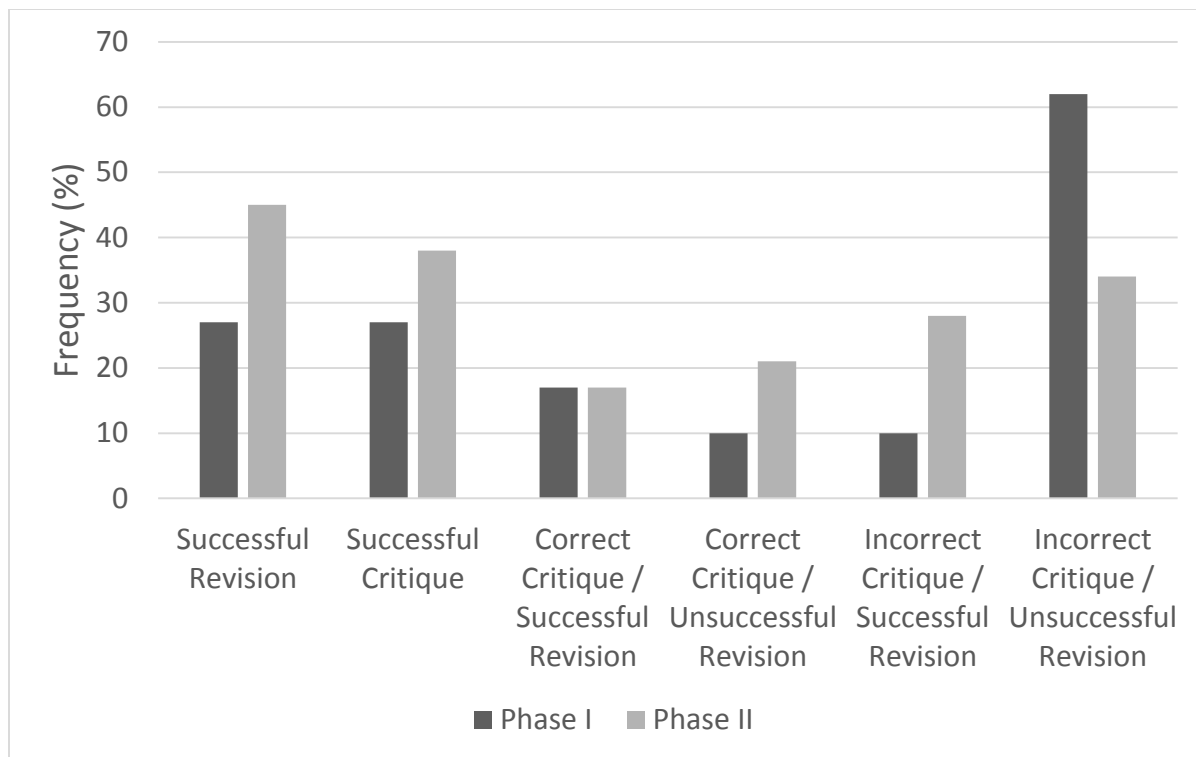


Figure 5.5. Frequency of successful and unsuccessful revision and critique by phase across conditions.

Overall, the proportion of students who successfully revised either the assigned or their own explanation increased from 27% in Phase I to 45% in Phase II. This is an encouraging finding, given that conceptual revisions are especially difficult for students, even if they receive direct feedback on the written artifact to be revised (Cho & MacArthur, 2011). In this study, students only received conceptual guidance on their critique choice. During Phase I, only 27% of all students made a successful revision of the sample explanation based on their choice. Critique was challenging for students such that 72% of them selected an incorrect critique. However, 14% of students who selected an incorrect critique were still able to improve the critiqued explanation. Even when unsuccessful, grappling with critique, which involves considering alternative ideas, may still support students in making productive revisions. Following the guidance checkpoint, more students (45%) made a successful revision of their own explanation in Phase II. Although 62% of students still struggled with critique, a greater percentage of those students—44% during Phase II as opposed to 14% during Phase I—made a successful revision of their own explanation. These positive shifts indicate that, at least for some, the guidance checkpoint was a valuable opportunity to reconsider their ideas in light of alternatives and make further progress after Phase I.

A 2x2 Chi square test suggests that there may be a significant association between critiquing and revising the target artifact (the assigned explanation) during Phase I ($\chi^2(1)=6.74$, $p<.05$). Students were 10.35 times more likely to make a successful revision of the critique artifact if they selected the correct critique. However, during Phase II, there was no significant association

between successful critique and successful revision of the students' own explanation ($\chi^2(1)=.00$, $p>.05$). The decoupling of critique and revision following the guidance checkpoint supports the idea that receiving conceptual guidance and an opportunity to revisit a key visualization allowed students to make successful revisions of their own explanation despite their continuing struggles with critique.

Student Explanation and Revision Trajectories across Phase I and Phase II

In order to characterize how individual student pairs progressed through Phase I and Phase II, I conducted an in-depth analysis of students' initial explanation, revised assigned explanation, revised initial explanation, and critique choices. Students' revisions were coded for changes in conceptual quality from the initial or assigned explanation. Because the critique choices for each assigned explanation in Phase I targeted a specific idea, and the same choices were provided when students critiqued and revised their own explanation in Phase II, I coded whether students added the targeted missing idea (*incomplete* condition) or corrected the targeted non-normative idea (*non-normative* condition). To assess whether guiding students to consider a range of ideas may enable them to distinguish among more than just the idea targeted by the critique, I also coded whether students spontaneously added other relevant ideas. Lastly, to capture limitations of the guidance, I captured other spontaneous revisions that I would consider conceptually unproductive: adding irrelevant ideas, adding non-normative ideas, or only making superficial changes (see Table 5.8 for examples).

Table 5.8
Conceptual revision categories and examples

Revision Type	Assigned Explanation	Revised Explanation
Added Targeted Missing Idea	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected. The ones that were absorbed goes through Earth and eventually come back out of the Earth and becomes infrared radiation.	you have to explain to the reader that SR comes from the sun, and when it gets absorbed into the earth it becomes heat energy the transforms into IR. if you make it clear to the reader they will be less confused and will understand global warming
Corrected Targeted Non-Normative Idea	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected by Earth. The ones that were reflected become infrared radiation and eventually goes back out to space.	the creation of infrared radiation began when the solar radiation comes from the sun. some radiation is absorbed or reflected by Earth. the ones that were absorbed become infrared radiation and eventually go back into space.
Added Relevant Idea	The creation of infrared radiation began when the solar radiation comes from the Sun. Some	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is

	radiation is absorbed or reflected by Earth. The ones that were reflected become infrared radiation and eventually goes back out to space.	absorbed or reflected by Earth. The places it is reflected is a place where it has a high albedo and vice versa. The ones that were reflected become infrared radiation and eventually goes back out to space.
Added Irrelevant Idea	Solar radiation was absorbed by earth and was released as infrared radiation	the IR comes from the sun's rays and bounces off because of its high albedo. since clouds have high albedo, the sun's UV waves bounce off them
Added Non-normative Idea	Infrared radiation came from the heat that came from the Sun, the energy changed into infrared radiation when it went into space.	Infrared radiation comes from the sun and the energy is transferred into solar radiation that reflects off of the sun.
Superficial Change	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected. The ones that were absorbed goes through Earth and eventually come back out of the Earth and becomes infrared radiation.	The creation of IR begins when the solar radiation comes from the sun. Some radiation is absorbed or reflected. The energy that is absorbed goes through earth and eventually comes back out of the earth and becomes IR .

Note. Some revised explanations demonstrated two or more categories of revision. The revision aligned with each specific category is in **bold**.

Overall, many students (13 pairs, 45%) made more than one category of change during Phase I revision, indicating the complexity of the task. Two pairs (7%) did not make any changes to the assigned explanation, and three pairs (10%) made superficial changes only. In Phase II, all pairs submitted revisions, although eight pairs (28%) simply reused their Phase I revisions as revisions of their initial explanations without revising them further. One pair used their Phase I revision, but after making additional revisions. Three pairs (10%) made superficial changes only, and nine pairs (31%) made more than one category of change. Due to the small sample size, the analysis did not reveal significant patterns in revision categories across Phase I and Phase II. I therefore present illustrative cases of student trajectories as they revised the assigned or their initial explanation in Phase I and Phase II. I will first present a case that can be construed as an optimal example of students demonstrating an incremental improvement as they progress through the two rounds of critique and revision. Then, I will present several contrasting cases where the students are less successful in integrating their insights across the activities. All names are pseudonyms.

Building on ideas and insights across revisions. Jay and Anne were assigned to the *non-normative* version of the explanation targeting transformation conditions after their initial explanation demonstrated a partial understanding of how energy transforms from solar radiation to heat, then to infrared radiation, but not of when the energy transformations occur (Table 5.9). It was hoped that the assigned critique would help them to attend more closely to the transformation

conditions for each energy type and emerge with a more coherent understanding of the transformations themselves. After selecting the correct critique choice identifying the non-normative idea in the assigned explanation, Jay and Anne rewrote the assigned explanation, contrary to most other students who revised key words or phrases and otherwise maintained the original wording. In addition to correcting the non-normative transformation condition for solar radiation, they added a normative idea from their initial explanation that heat is transformed to infrared radiation when the heat leaves the surface. Thus, their Phase I revision presents an ideal scenario where, through guided critique, they succeed not only in revising the targeted idea (transformation condition for solar radiation), but also in adding an additional idea (heat as the intermediate energy type before the energy is transformed into infrared radiation) from their initial explanation.

During Phase II, Jay and Anne also rewrote their initial explanation. Despite choosing an incorrect critique choice, their revision is a more coherent account of their initial description of the energy transformations that take place. In addition to incorporating the normative idea about the energy transformation condition from their Phase I revision, they refine their idea from Phase I revision about what energy type becomes heat energy in Earth's surface, and add another idea about how infrared radiation interacts with greenhouse gases. Thus, Jay and Anne's progression indicates incremental progress toward a more coherent understanding as they distinguish among alternatives, make revisions, and incorporate ideas from the previous activity to the next.

Table 5.9
Explanations, critiques, and revisions by Jay and Anne

Phase I	Assigned Explanation	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected by Earth. The ones that were reflected become infrared radiation and eventually goes back out to space.
	Critique	The response can be improved by... explaining that SR doesn't become IR when SR is reflected. (Correct choice for critique)
	Revision	The sun radiates SR to Earth. That radiation can reflect off clouds and be absorbed by the ground and particles. The absorbed heat in the surface will become heat energy, and move around in it. The heat will eventually reach the surface, and transform into IR, and escape to space.
Phase II	Initial Explanation	The IR comes to be when there is heat energy made from the SR. Once the heat energy gets up to the surface, it transforms into IR.
	Critique	The response can be improved by... adding more evidence in general. (Incorrect choice for critique)
	Revision	SR comes from the sun. The sun radiates SR, and it travels down to Earth where the SR is reflected and absorbed by different things. Once it reaches the surface, some will be absorbed. The absorbed SR will become heat energy inside the surface, and

		move around in the surface. Eventually, the heat will reach the top of the surface, and become IR. That IR can either escape Earth, or be reflected back by Green House gases.
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Challenges in integrating ideas from different sources. Ethan and Brittany were also assigned to the *non-normative* version of the explanation targeting transformation conditions after their initial explanation demonstrated that they had a partial understanding of infrared radiation transforming from heat (Table 5.10). It was hoped that the assigned critique would help them to attend to energy transformations preceding that of heat to infrared radiation, and to incorporate ideas about transformation conditions to their initial explanation. Ethan and Brittany selected the correct critique choice, indicating that they have identified the non-normative idea about the transformation condition for solar radiation to heat, and conduct a pinpoint revision of the assigned explanation to correct the non-normative idea (i.e., changing “reflected” to “absorbed”). However, they do not incorporate their own initial idea that infrared radiation comes from heat by adding the idea of heat as an intermediary energy form into the revision. Thus, their Phase I revision presents success at the basic level where, through guided critique, they succeeded in revising the targeted idea (transformation condition for solar radiation), but unlike Jay and Anne, they did not add an additional idea (heat as the intermediate energy type before the energy is transformed into infrared radiation) that they had in their initial explanation.

During Phase II, Ethan and Brittany chose to reuse their Phase I revision instead of revising their initial explanation. Although doing so allows them to express more ideas than with their initial explanation, it results in the loss of the valid idea in their initial explanation that infrared radiation comes from heat, which they did not incorporate into their Phase I revision. Even though they selected the correct critique choice, they did not further advance their written understanding beyond what they accomplished in Phase I revision. As I will discuss in greater detail, Ethan and Brittany’s case illustrates the challenge of supporting students in integrating ideas and insights across activities designed to support iterative refinement of ideas.

Table 5.10

Explanations, critiques, and revisions by Ethan and Brittany

Phase I	Assigned Explanation	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected by Earth. The ones that were reflected become infrared radiation and eventually goes back out to space.
	Critique	The response can be improved by... explaining that SR doesn't become IR when SR is reflected. (Correct choice for critique)
	Revision	the creation of infrared radiation began when the solar radiation comes from the sun. some radiation is absorbed or reflected by Earth. the ones that were absorbed become infrared radiation and eventually go back into space.
Phase II	Initial Explanation	The infrared radiation comes from the heat.
	Critique	The response can be improved by...

		explaining that SR doesn't become IR when SR is reflected. (Correct choice for critique)
	Revision	the creation of infrared radiation began when the solar radiation comes from the sun. some radiation is absorbed or reflected by Earth. the ones that were absorbed become infrared radiation and eventually go back into space.

Challenges in integration across revisions. Clara and Ellen were also assigned to the *non-normative* version of the explanation targeting transformation conditions after their initial explanation demonstrated a partial understanding of energy transformation, and a non-normative understanding of how energy transforms from solar radiation to heat and how infrared radiation is emitted by the Earth (Table 5.11). It was hoped that the assigned critique would help them to attend more closely to the transformation conditions for solar radiation’s transformation to heat, and to link the transformation to infrared radiation being emitted from the Earth’s surface. Although they select an incorrect critique choice indicating that they have non-normative ideas about transformation conditions, Clara and Ellen were nonetheless able to partially revise the assigned explanation to describe how “the (solar) radiation... warms the earth with thermal energy” when it is absorbed. This suggests that they were beginning to distinguish between energy transformation conditions, as their initial explanation had attributed heat energy to reflection instead of absorption. However, they did not revise the non-normative idea, “The ones that were reflected become infrared radiation and eventually goes back out to space,” and kept the idea in the revision. Instead, they duplicate the idea provided in the assigned explanation that solar radiation comes from the Sun. Thus, their Phase I revision presents some evidence that Clara and Ellen were still in the process of distinguishing among ideas. Although they were partially successful in revising the non-normative idea (transformation condition for solar radiation), they did not further revise the explanation to make it internally consistent by removing the non-normative idea and adding additional ideas about when heat transforms into infrared radiation.

During Phase II, Clara and Ellen attempt to revise their initial explanation, but the attempt is less successful than in Phase I. After choosing an incorrect critique choice, their revision consists of adding one line to the end of their initial explanation that is not relevant to the explanation prompt: “Solar Radiation have longer wave lengths than visible light and sometimes are felt as heat(Thermal Energy).” They do not incorporate or build on their insight from the Phase I revision that absorbed solar radiation is warming the earth. Clara and Ellen’s case illustrates how students may make partial progress during the critique and revision of an explanation not their own, but struggle to build on their previous success when critiquing and revising their own explanation.

Table 5.11
Explanations, critiques, and revisions by Clara and Ellen

Phase I	Assigned Explanation	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected by Earth. The ones that were reflected become infrared radiation and eventually goes back out to space.
	Critique	The response can be improved by... explaining that SR becomes IR when SR is reflected.

		(Incorrect choice for critique)
	Revision	The creation of infrared radiation begins when solar radiation comes from the Sun. Some radiation is absorbed or reflected by Earth. The radiation that is absorbed warms the earth with thermal energy. Solar Radiation comes from the sun. The ones that were reflected become infrared radiation and eventually goes back out to space.
Phase II	Initial Explanation	IR came from conduction, under the earths crust. The Solar Radiation transforms into heat energy that bounces off earths crust and is trapped by the greenhouse gases and unable to escape earths atmosphere.
	Critique	The response can be improved by... adding more evidence in general. (Incorrect choice for critique)
	Revision	IR came from conduction, under the earths crust. The Solar Radiation transforms into heat energy that bounces off earths crust and is trapped by the greenhouse gases and eventually able to escape earths atmosphere. Solar Radiation have longer wave lengths than visible light and sometimes are felt as heat(Thermal Energy).

Case Comparison

Contrasting Jay and Anne with the other two cases highlights several challenges that remain in the activity design for future refinement. Although both cases can be summarized as instances in which students did not make further conceptual progress in Phase II after Phase I, the challenge exhibited by each pair appears to be of a different nature, as I will now describe more in depth.

Ethan and Brittany's case illustrates the challenge of supporting students to keep track of their own ideas as they are exposed to other ideas in order to distinguish among them across different activity contexts. Unlike Jay and Anne, while Ethan and Brittany also met the goal of Phase I critique and revision, they were unable to continuously refine their conceptual repertoire as they progressed from their initial explanation to Phase I and Phase II. Although their initial explanation contained a productive idea that was not present in the assigned explanation, they did not incorporate that idea in their Phase I revision, and it was ultimately lost from their explanation during Phase II. Their pinpoint revision in Phase I suggests that their progress may have been hampered by what may have been a narrow focus on identifying and revising the targeted non-normative idea. Whereas Jay and Anne revised the assigned explanation in its entirety, Ethan and Brittany's pinpoint revision may indicate that the guidance did not sufficiently prompt them to more broadly reconsider the range of ideas as they progressed through Phase I and Phase II. Although they succeeded in revising the assigned explanation to meet the ostensible goal of Phase I critique and revision (i.e., identify and correct the non-normative idea for the *non-normative* condition), they may need more explicit guidance to contrast ideas across activity contexts.

Clara and Ellen's case presents a different challenge where, unlike Ethan and Brittany, they already struggled to meet the goal of Phase I critique and revision. They made partial progress by adding one sentence describing part of the process, thus beginning to revise the non-normative energy transformation condition. However, they were unable to propagate the changes across the explanation to make the explanation internally consistent. As a result, their Phase I revision ended with the explanation still containing contradictory ideas. They then proceeded to Phase II, where they stumbled during the revision of their initial explanation and did not make further progress. This may be unexpected from a KI perspective because, unlike Ethan and Brittany's pinpoint revision of the targeted non-normative idea, Clara and Ellen's attempt to add a missing idea during revision suggests that they considered a broader range of ideas. They might therefore be expected to demonstrate greater progress during Phase II revision than Ethan and Brittany. One possible explanation for their subsequent difficulty is that students need to achieve a minimum integration threshold in terms of explanatory coherence in order for students to benefit from ongoing integration as they progress through critique and revision of different explanations targeting the same concepts. Because Clara and Ellen did not consolidate their insights by fully revising the assigned explanation and removing contradictory ideas during Phase I revision, they may have been unable to further build on their insights during Phase II revision. In their case, they may need more guidance prompting them to spend more time consolidating their ideas and evaluating the assigned explanation for coherence before advancing to Phase II.

The two cases illustrating challenges students face when progressing from Phase I to Phase II highlight the importance of the guidance checkpoint, which occurred between the two phases. In this study, the guidance checkpoint provided students with conceptual guidance and prompted them to revisit an earlier step. The guidance was adaptive and was customized to the students' Phase I critique choice, which was designed to identify whether the students had non-normative ideas about key concepts in the explanation. The guidance checkpoint was intended to provide a secondary opportunity (after they had an initial opportunity to distinguish among alternatives during the initial critique and revision) to consider the alternatives before moving forward to Phase II. I therefore examined how effective the guidance checkpoint was in prompting students to reconsider their ideas through video case studies I discuss below.

Variable Student Engagement with the Guidance: Checkpoint Case Studies

To further examine how students engaged with the various steps comprising the activity sequence, I used classroom observations and video records. In this study, I characterize student engagement as the types of discussions students had with each other and their interactions with the activity guidance. During critique, I observed that some students seemingly guessed when initially selecting their science content critique and did not discuss alternatives until prompted to revise the critiqued explanation, while others discussed the critique choices during selection. During the guidance checkpoint, some were frustrated by the complexity of selecting among plausible alternatives and engaged in guessing behavior, whereas others leveraged the additional opportunity provided by feedback to reassess their understanding or to request help from the instructor or researcher.

To illustrate the kinds of engagement observed in the overall data corpus, I present descriptions and transcribed excerpts of video records. The video data suggest that the design can

provoke opportunities for students who may not otherwise engage in negotiation and reconsideration of ideas, as well as for students who are already doing so. However, how to ensure that such opportunities are leveraged by students remains an open question, as I discuss below. In this study, I focus on the guidance checkpoint, because it was intended to serve as a pivotal opportunity for students to reconsider their own ideas and their assessment of alternative ideas during critique.

Capitalizing on opportunities: collaborative sensemaking and reflection on ideas.

Janelle and Ida took turns controlling the computer and answering prompts. They were jointly engaged with the unit, discussing science content and co-constructing responses to prompts. They also asked each other for confirmation while commenting on ideas with questions such as “We’re OK, right?” and “How’s that?” before finalizing their work. Their engagement pattern persisted throughout the activity sequence, with both partners commenting on the critique choices. Their aptitude for collaborative sensemaking and deliberation raises the question of whether the activity design adds value to their learning process. The transcript below suggests that their existing orientation allowed them to capitalize on opportunities afforded by the activity design and further refine their ideas. Prior to this moment in the guidance checkpoint, they had worked their way through critique, assessing each critique choice with regard to its scientific validity, but without justifying why by referencing relevant ideas (e.g., “That’s not true.”). They made a successful critique and revision of the critique artifact (Table 5), but during the guidance checkpoint, Janelle argues for a different critique choice (“needs more evidence in general”).

- 1 Janelle: I think “adding more evidence in general” because they didn’t really explain where the energy comes from or what it transforms into. (J chooses the choice and submits; it’s wrong)
- 2 J: Oh.
- 3 Ida: Wait.
- 4 J: Sorry.
- 5 I: Oh wait I have to review it. (I goes back to simulation step and reviews text preceding the simulation while saying, “Blah, blah, blah.”)
- 6 J: OK, go back to the [guidance checkpoint] step. (I continues to and starts simulation. I and J watch it silently for 11 seconds, then I goes back to guidance checkpoint. I reads through options and evaluates each with “That’s not true,” etc. with J watching)
- 7 J: (Sighs) Wait, “Explaining that IR comes from the Sun” (.) But not directly. (.) It doesn’t come, like, directly though.
- 8 I: Yeah.

In this example, the activity design provides an opportunity for the students to further refine their understanding because the unsuccessful attempt during the guidance checkpoint prompted them to revisit and review the simulation (Line 5) and re-evaluate the choices they had previously evaluated during critique (6-7). Unlike during critique when they had evaluated the choices without justification, this time Janelle elaborated why she agreed or disagreed with the choice (7, also 1 prior to receiving guidance). Similar instances were observed elsewhere in the corpus during the activity sequence where they reassessed the content more carefully after an initial attempt to select an alternative. Although their revision of the critique artifact indicates complex

understanding of the ideas targeted by the explanation prompt (Table 5.12), they chose to elaborate on albedo's role in the process, an untargeted but relevant idea, when revising their own explanation. Their discussions and actions during the activity sequence provide evidence for how the activity's design can create opportunities for students to reconsider their ideas, which in Janelle and Ida's case enhanced their engagement with the science content and deepened their understanding.

Table 5.12
Explanations, critiques, and revisions by Janelle and Ida

Phase I	Assigned Explanation	The creation of infrared radiation began when the solar radiation comes from the Sun. Some radiation is absorbed or reflected. The ones that were absorbed goes through Earth and eventually come back out of the Earth and becomes infrared radiation. (KI Score = 4)
	Critique	The response can be improved by... explaining what kind of energy SR becomes when it is absorbed. (Correct choice for critique)
	Revision	The creation of infrared radiation begins when the solar energy radiates from the Sun. Some radiation is absorbed and/or reflected. The rays that were absorbed travel through Earth's lithosphere, transform into thermal energy, and eventually exits out of the Earth's surface as infrared radiation. (KI Score = 5)
Phase II	Initial Explanation	When solar radiation comes in contact with the Earth's surface, some of it is absorbed by the surface. When this solar radiation is absorbed by the Earth's surface, it is heated by conduction. The Earth gives off this heated solar radiation as infrared radiation as heat. (KI Score = 3)
	Critique	The response can be improved by... explaining what kind of energy SR becomes when it is absorbed. (Correct choice for critique)
	Revision	When solar radiation from the sun comes in contact with the Earth's surface, some of it is absorbed by the Earth. The amount of radiation absorbed or reflected depends on the amount of albedo, or ability to reflect solar radiation. This means that an area with high albedo would reflect more solar radiation and an area with low albedo would absorb more solar radiation. When solar radiation is absorbed by the Earth's surface, it is heated by conduction. The Earth gives off this heated solar radiation as infrared radiation or heat. (KI Score = 3)

Missed opportunities: turn-taking and guessing. Hailey and Tom took turns controlling the computers and answering prompts. Although they engaged with each other and the unit, the nature of their collaboration was primarily strategic in that they negotiated who would answer the prompt in question, which part of the step in question to focus on and so forth, but rarely discussed

the science content and their understanding of it. They both remained engaged regardless of whose turn it was, but their peer monitoring rarely ventured beyond logistics and accountability with comments such as, “It’s your turn,” “I’m not going to tell you anything,” “You just have to get it better,” “You can click there,” and so on. Upon encountering an impasse, both partners tended to ask the other to try the step. They neither asked for help nor discussed alternatives. The overall activity sequence elicited frequent turn-taking comments such as “Here, you try” that were less commonly observed elsewhere in the unit. Despite their logistics-oriented engagement, there were instances during the critique and guidance checkpoint steps that provoked moments of content discussion and negotiation. These opportunities were not fully realized or pursued.

The transcript below illustrates one example of a missed opportunity during the guidance checkpoint. Prior to this, they had engaged in numerous turn-taking while attempting revision of the critiqued explanation. However, they did not discuss the critique choices. Tom eventually typed the revision, which consisted of capitalizing one word (Table 5.13); although Hailey watched attentively, they engaged in an off-topic discussion. When Tom continued to the guidance checkpoint and paused, Hailey asked Tom if he needed help for the first time, but Tom did not take Hailey up on her offer. After multiple turn-taking and failed attempts to pass the checkpoint, they attend to the content of the critique choices for the first time in the activity sequence.

- 1 Tom: OK, remember “explain that IR comes from the Sun.” (T reading previously selected choice; T navigates back to revisit the simulation)
- 2 Hailey: It doesn’t even make sense, though. (T waits for the simulation to load)
- 3 T: I know. (T begins navigating back to guidance checkpoint without watching simulation)
- 4 T: This one, right? (T makes a selection)
- 5 H: I guess? (T scrolls down to hit submit; choice is incorrect)

I see this as an important moment because, in a departure from their usual mode of sequential collaboration, Tom asked Hailey to attend to the content of the critique choice (line 1), and Hailey commented on the content to indicate her confusion (2). However, instead of leveraging this opportunity to resolve their dilemma through discussion or by reviewing the simulation, Tom simply agreed with Hailey and navigated back to the checkpoint (3). There, Tom selected another choice without explicating why, but asked Hailey for confirmation (4), who indicated she was not sure (5), which also diverged from their turn-taking mode. However, Tom proceeded to submit his choice without comment. Following this episode, Hailey indicated her frustration and took over the computer. Tom then suggested requesting help for the first time during the activity sequence, saying, “Ask [the researcher], ‘cause that is confusing,” but neither did so. Eventually, they managed to make a correct guess without discussing the content and proceeded to the next step.

Their written artifacts (Table 5.13) suggest that activity design had no impact on Hailey and Tom’s progression through the unit. However, by examining their video records, I see moments where the design was successful in providing opportunities for the dyad to engage in collaborative sensemaking, discussion, negotiation, and reconsideration of ideas, because the guidance disrupted their turn-taking approach to collaboration. Yet, in contrast to Janelle and Ida’s case, they did not capitalize on those moments, proceeding through the activity sequence without discussing or reconsidering their ideas. Further work is necessary to refine the guidance to address these observed limitations so that more students can be supported in making progress.

Table 5.13

Explanations, critiques, and revisions by Hailey and Tom

Phase I	Assigned Explanation	Solar radiation was reflected by earth as infrared radiation. (KI Score = 2)
	Critique	The response can be improved by... explaining that IR isn't reflected SR. (Correct choice for critique)
	Revision	Solar Radiation is reflected by Earth as infrared radiation. (KI Score = 2)
Phase II	Initial Explanation	It came from the sun and space. (KI Score = 2)
	Critique	The response can be improved by... adding more evidence in general. (Incorrect choice for critique)
	Revision	It came from the sun and space. The heat came from the sun witch is in space. And it will heat the Earths atmosphere and the people. (KI Score = 2)

Summary and Design Implications

The study findings illustrate the value of encouraging students to consider a range of ideas to capitalize on critique activities, consistent with findings for desirable difficulties. Considering alternatives when formulating a critique and revising explanations prompted students to distinguish among their own and alternative ideas and led to progress in conceptual understanding of scientific phenomena through knowledge integration. Although students were assigned explanations of differing complexity in the two conditions, students in both conditions benefited equally from the critique opportunity and were able to make conceptual improvements to their initial explanations during revision. The activity sequence designed to provide students with multiple opportunities to consider a range of alternatives was equally successful for critique of explanations that were incomplete and those that included a non-normative idea. The slight trend for critique of the non-normative alternative deserves further study with a larger sample, but findings suggest that both types of critique are valuable learning opportunities. These findings build on previous studies demonstrating the value of engaging students in complex selection tasks in combination with generating explanations to support students distinguish among ideas in technology-enhanced STEM instruction (e.g., Zhang & Linn, 2013; Lee, Liu, & Linn, 2011).

Furthermore, findings point to the potential value of designing critique to serve as an opportunity to provide two rounds of formative assessment. First, students are assigned explanations to critique based on their initial explanation; second, students receive conceptual guidance based on their critique choice. Recent research has found that prompting students to engage in critique after generating an explanation can be as effective as providing conceptual guidance on students' initial explanations for supporting students in making successful revisions (Donnelly & Linn, in press). This study extends existing findings by exploring the impact of prompting students to engage in critique, then providing conceptual guidance on their critique instead of their initial explanation, on their ability to revise their explanation. Future work will

help clarify the specific value of the opportunities to reflect on alternative ideas, such as revising the critique artifact and revisiting content based on guidance, in supporting students to make progress.

By broadening the alternatives for critique and providing multiple opportunities to reconsider ideas, the current investigation showed the benefit of critique activities for enhancing students' conceptual understanding. These findings resonate with other investigations of critique activities such as providing critique guidelines (Chang & Linn, 2013). The revision case studies illustrate the limitations of this approach and point to additional factors that merit further study. Although recent research has found that adding an idea, even if it is non-normative, during revision predicts later success in conceptual understanding (Gerard & Tansomboon, accepted), the revision case studies suggest that partial integration or addition of ideas can impair the students' ability to build on their insights across different contexts. Further research may allow the development of automatically scored indicators that detect unproductive intermediary states of integration to add value to activities spanning multiple contexts. The revision case studies also revealed that while some students were sufficiently prompted by current guidance to reassess their understanding and incrementally refine their ideas across the opportunities provided, others needed additional support to draw on their cumulative experience from one step to the next. The video case studies highlight the potential for a guidance checkpoint to perform this function, but its current format as a challenge question did not necessarily prompt all students to discuss alternatives and reconsider evidence.

The generalizability of these findings is limited, given that the study was not implemented across multiple domains and grade levels. In addition, as previously mentioned, while students had prior experience revising their responses based on teacher guidance in other web-based inquiry units, they had no prior experience in critique or revision of explanations. Studies with populations having more familiarity with critique and revision practices may yield different findings. In addition, since the critique artifacts designed for the study cover a relatively narrow range of complexity, more research is also needed to identify the generalizability of these findings to other critique artifacts and to students with different levels of prior knowledge. While video case studies in the previous study found that engaging in guided peer critique can support students in making sense of criteria and detecting conceptual problems with the explanation being critiqued (Sato & Linn, 2012), students need more support and experience before they can fully benefit from the opportunity. Future work will help clarify the effects of extended training and classroom culture on guided critique and revision.

This study built on the previous study and yielded additional insights into the design of critique to better help students distinguish among ideas. Further research is needed to test the value of providing students with guided critique opportunities to revise their explanations for different grade levels and science domains. Future research should also investigate when and how providing conceptual guidance on students' initial attempts, such as revisions of assigned explanations, can help support students in further revising their own understanding. These findings extend recent studies (Ryoo & Linn, 2014; Gerard & Linn, 2013) reporting the value of prompting students to revisit critical steps and find salient information in guidance. When the prompting occurred in the form of a checkpoint, it appeared to elicit gaming behavior in some students, including those who were most likely to need additional guidance. More work is needed to refine the design of post-

critique guidance to better encourage students to build on their insights and strengthen their understanding by engaging in additional knowledge integration.

Chapter 6: Conclusion

This dissertation explores how to design guided critique to support students in distinguishing among their alternative ideas and in revising their explanations about complex phenomena in science. Extensive research on explanations and science learning shows that generating explanations can be a powerful means of improving students' conceptual understanding. In particular, generating explanations can help students connect ideas and detect gaps in their understanding (Chi, 2000). However, students struggle to disentangle their existing ideas from new ideas introduced through instruction. They may dismiss evidence that contradicts their existing beliefs (Chinn & Brewer, 1993), or gain a false sense of understanding upon generating an initial explanation (Keil, 2006). Prompting students to critique explanations in addition to generating explanations may therefore benefit students by providing a different opportunity to examine ideas in their conceptual repertoire in a different context.

Prior research shows that critique can be a powerful tool for presenting alternative ideas to students and encouraging careful consideration of the ideas (Chang, Quintana, & Krajcik, 2010). Critiquing the work of others may help students examine their own ideas from a different perspective (Cho & MacArthur, 2011). This process of evaluating a range of ideas is inherent in critique. It is synergistic with knowledge integration principles (Linn & Eylon, 2006), which seek to support student learning by building on their existing ideas and distinguishing among those and new ideas from instruction. My dissertation examines how critique designed using knowledge integration principles can benefit student learning with explanations in science. This dissertation therefore investigates the following overarching research questions:

4. How can we design guided critique in technology-enhanced science inquiry instruction to help students distinguish among their ideas and revise their explanations about scientific phenomena?
5. How can guidance on students' initial critiques or explanations help students reflect on their understanding and make progress during revision?
6. How are students' learning processes impacted when prompted to critique explanations, receive guidance, and revise their explanations?

To answer these questions, I used a combination of qualitative and quantitative methods in a series of three studies in sixth-grade earth science units, *Plate Tectonics* and *Global Climate Change*. The studies allowed me to explore the impact of iteratively refined guided critique on students' revisions of their initial explanations. In each study, I conducted quantitative analyses on conceptual learning gains demonstrated by students' written work. Pre- and post-test analyses revealed the general impact of the instructional units and examined whether the embedded critique activities impacted students' overall learning gains. Analyses on students' embedded work during the critique activities examined the impact of different critique and guidance designs on their ability to revise their initial explanations. In addition to quantitative analyses, I also conducted in-depth qualitative analyses on written work by students and instructors to characterize critiques, guidance, and revisions for further insight into the tested designs' efficacy. Lastly, I employed

video case studies to examine student engagement with the activity and investigate whether the activity designs worked as intended.

Overall, the research revealed that students consistently improved their understanding of target concepts from pretest to posttest in each study. Successfully supporting students in making productive conceptual revisions to their explanations required multiple refinements and the adaptation of a complex selection task design (Zhang & Linn, 2013; see Chapter 4) for critiquing explanations. Complex selection involves presenting students with a list of plausible alternatives and requiring them to choose a best fit choice. In my dissertation, two versions of the complex selection task were employed, one where students are prompted to choose among a list of plausible criteria about explanations in science (Chapter 4), and another among a list of plausible alternative ideas about the phenomenon being explained (Chapter 5). My case study analyses (Chapters 4 and 5) suggest that complex selection tasks can motivate students to discuss and distinguish among the range of choices presented. With regard to guidance on students' critiques and initial explanations, my findings highlight the importance of providing expert guidance that promotes knowledge integration across the multiple steps constituting the critique activity, as discussed in depth below. Lastly, analysis of log data and case studies in Chapters 4 and 5 provide insight into how students' learning processes were impacted by engaging in critique, receiving guidance, and revising their explanations. Contrary to prior studies examining the correlation between student revisiting of preceding steps and student learning outcomes (Ryoo & Linn, 2014; Gerard & Linn, 2013), no statistically significant positive correlation was found between revisiting and students' ability to improve their explanation (Chapter 4), and case studies revealed that students need more guidance in order to capitalize on opportunities to revisit previously encountered information (Chapter 5). Overall, my study findings highlight the potential of critique to serve as powerful learning opportunities for students to make progress in knowledge integration by distinguishing among their ideas and other ideas presented to them for consideration via critique.

Value of Critique in Science Instruction

This dissertation highlights the value of critique for improving student's conceptual understanding activities in science instruction. Existing literature on critique tends to focus on the value of critique in the context of supporting students develop skills in argumentation, particularly in the structural elements of argumentation (e.g., Osborne et al., 2004). My dissertation's focus is on the value of critique for supporting students in distinguishing among ideas. As seen in Chapter 5, students can benefit conceptually from critique in making revisions to their explanations, even if they are still struggling with the critique itself. While students may need more support to articulate their insights from critique in writing, the case studies in Chapter 4 show the value of critique for helping students make sense of criteria by applying them to specific examples. As seen in Chapter 3, students can readily name criteria, but stumble when asked to apply them during critique. While students may be exposed to various criteria in instruction, they have few opportunities to apply those criteria and integrate the criteria into their understanding. Students will benefit from more critique in instruction, not only to strengthen

their own understanding of the topic under study, but also to improve their understanding of criteria through practice.

Implications for Design of Critique

This dissertation demonstrates that guided critique designed with knowledge integration principles can support students in revising their explanations in science and strengthen their conceptual understanding. Students can use critiques as opportunities to reconsider their own and other alternative ideas after generating explanations. They make progress in knowledge integration by distinguishing among their ideas in a different context.

The studies in this dissertation also illustrate the various challenges and complexities of supporting students through critique and revisions of explanations in technology-enhanced science instruction. The findings suggest design principles for technology-enhanced critique.

Design Critique that Supports Distinguishing Among Ideas

Complex selection task (Zhang & Linn, 2013) is a promising approach to support distinguishing among target ideas, be they criteria about the assigned item being critiqued (Chapter 4) or specific concepts related to the phenomenon being studied (Chapter 5). Providing a range of ideas for selection may add ideas to those the student is considering. Making a selection may motivate students to distinguish among ideas they may not have considered relevant on their own. Limiting the critique to selection alone may prompt students to engage in guessing, as seen in Chapter 5 for the Challenge Question. However, as case studies suggest, when paired with a generative task requiring students to provide justification or revise the critiqued explanation based on their selection, complex selection may motivate student pairs to discuss and negotiate as they consider which of the choices should be selected.

Justification of critique is challenging for students to articulate in writing. Prompting for justification has proven effective in existing studies on argumentation as a means of motivating students to attend to evidence when engaging in face-to-face argumentation with peers (e.g., Berland & Reiser, 2009). However, as seen in Chapters 3 and 4, when prompted to articulate justification in writing, students may simply cite low-hanging fruit such as grammatical errors. While case studies in Chapter 4 revealed instances of students discussing justification with each other, it also showed instances where students had a task-oriented approach and wrote what came easily to mind in order to proceed to the next activity instead of examining the criteria in full. Whereas students are held accountable to their peers and can be asked for clarification in face-to-face argumentation contexts, students may be content to merely write a passing comment for justification when they are not required to engage with the recipients of their critiques. Thus, when prompting for justification in an activity context that does not require immediate accountability, students may not take full advantage of the opportunity to examine and distinguish among their ideas in further detail. This is a limitation of non-argumentation critique, particularly in technology-enhanced instructional settings where interactions with peers may be asynchronous. However, asking students to revise the critiqued explanation (Chapter 5) rather than to provide

justification (Chapter 4) may be an alternative means of motivating students to consider the explanation in its entirety, rather than on the specific aspect with which they found fault.

Design Knowledge Integration Guidance to Support Revision in Critique

Deciding how, when, and on what to provide guidance during critique requires careful consideration (Hattie & Timperley, 2007; Underwood & Tregigdo, 2010; Shute, 2008). Studies have shown that providing guidance to student explanations can support students in making productive conceptual revisions (e.g., Cho & MacArthur, 2010), but the guidance needs to be carefully designed to promote knowledge integration. Providing the correct response carries the risk of promoting mindless revision (Bangert-Drowns, Kulk, C., Kulik, J., & Morgan, 1991), which may result in isolated, incoherent understanding. The Chapter 4 study findings demonstrate that providing guidance with content specificity alone is not sufficient and may result in incoherent revisions when students are told which revisions to make. In comparison, expert guidance promoting knowledge integration, where students were prompted to reconsider links between ideas without being told the answer, was found to help students make productive revisions.

With regard to when to provide guidance, guidance may be immediate or delayed. Immediate guidance may be more beneficial because it improves retention of information. Delayed guidance may be more beneficial because it combats resistance to changing one's initial beliefs; the time delay has decreased the prominence of those beliefs in the students' mind (Shute, 2008). For similar reasons, providing guidance directly on the students' initial explanation may invoke their resistance to changing their initial beliefs in the explanation. Even with expert guidance on their initial explanation, many students still struggled to revise in (Chapter 4). The Chapter 5 study findings are promising in this regard. Providing guidance on students' critique of an assigned explanation, rather than on their initial explanation, was beneficial for revision. In this case, the guidance was slightly delayed, as the critique occurred after they generated their initial explanation, but not so delayed that students would have forgotten the information. In addition, providing the guidance to a different task (critiquing another explanation versus generating one's own explanation) may have helped circumvent students' resistance to changing their own beliefs and revising their explanation.

Implications for Teachers in Inquiry Instruction

This dissertation demonstrates the value of critique and guidance to support students' inquiry learning in science. Though students may struggle with critique itself, their explanation revisions indicate that they make progress in their conceptual understanding of the topic through the process of critiquing and distinguishing among ideas (Chapter 5). Students can use critique as opportunities to reconsider their own and alternative ideas after generating explanations and make progress in knowledge integration by distinguishing among their ideas in a different context. The studies in this dissertation also illustrate the various challenges and complexities of providing guidance to support students in revising their explanations, as discussed below.

Support Teachers to Strengthen Their Guidance

Providing expert guidance that follows knowledge integration principles is a challenge for teachers who are pressed for time and burdened with large class sizes. In order to provide expert guidance to a specific explanation, teachers must understand the target ideas and how they should be linked in a way that promotes coherent understanding, as well as common alternative ideas and how to prompt students to reconsider whether ideas are wrong or missing. As seen in Chapter 4, teachers may default to commenting solely on stylistic elements such as spelling and grammar, or to question the science content in a general way. Even when teachers make the effort to provide specific information, as seen in Chapter 3, specific information providing the correct response may hinder students by encouraging piecemeal revision and result in incoherent explanations. Teachers should be supported in taking advantage of available technologies and implications from research to enhance their guidance of student learning.

Take Advantage of Technology to Facilitate Teacher Guidance

Teachers can take advantage of automated guidance to add value to their own guidance. While the Chapter 4 study and other studies in the literature have made progress in identifying the characteristics of successful guidance for students, teachers are still best positioned to provide guidance to struggling students with their personalized knowledge of each individual and the instructional context (Schwartz & White, 2000; Narciss & Huth, 2004). Using natural language processing technologies to make automated analysis and guidance possible for key student explanations can free teachers by providing sufficient guidance for many students to make progress. This freedom will allow teachers to focus their efforts on students who still struggle after receiving automated guidance.

Another possibility for technology-enhanced instruction is to provide teachers with premade comments or comment templates that facilitate the composition of expert guidance. This is especially valuable when automated guidance is not available. Premade comments are guidance generated prior to instruction, and templates are incomplete comments that provide the basic structure and can be customized to the prompt. As in the Chapter 4 study, student responses in prior implementations of instructional units can be analyzed to design premade guidance or templates using knowledge integration principles. With additional support and professional development, teachers can analyze the ideas in their students' explanations and assign or generate the appropriate guidance based on their expertise and knowledge of individual students and the instructional context.

Limitations and Future Research

This dissertation investigated the impacts of several versions of guided critique on how students revise their initial explanations in technology-enhanced science instruction. Specifically, the studies in this dissertation explored the impact of different guided critique designs that were paired with additional guidance. Due to small sample sizes and the focus on sixth-grade earth science topics, there are obvious limitations regarding generalizability to other domains and grade levels that should be addressed in replication studies with larger sample sizes in different domains

and grade levels. In this section, I focus on limitations with regard to refining critique design principles and how they can be addressed through future research.

I simultaneously refined both the design of the guided critique and of the additional guidance across studies. This resulted in two major confounds with regard to extracting design principles for guided critique from these studies. First, I did not compare the impact of additional guidance on students' initial explanations (Chapter 4) to their critiques of assigned explanations (Chapter 5). Doing so will strengthen the findings of both studies and provide additional insights into how to best complement critique with additional guidance. Second, I did not fully investigate how to improve the evidence students are prompted to re-examine when they receive additional guidance. In both studies, students were specifically directed to revisit a simulation to search for and clarify key ideas. As the case studies indicate, it was challenging for students to take advantage of revisiting. Clarifying when and how students are prompted to revisit key evidence will help strengthen the overall impact of guided critique. I discuss specific studies that address these two major limitations.

Compare Guidance Provided to Students' Initial Explanation versus Critique

Following students' critiques of an assigned explanation, it may be equally beneficial to provide guidance on students' initial explanations or on their critiques. In both cases, taking advantage of the guidance presents challenges. In Chapter 4, findings demonstrated that students struggle to apply expert guidance to their explanations during revision. It may be the case that, in order to successfully incorporate ideas from guidance into their explanations during revision, students must first identify the ideas in their explanation and then determine whether ideas remain missing or are contradicted by the ideas provided in the guidance. Similar to what they did during their critique of an assigned explanation, students must now distinguish among the mix of ideas in their own explanation, the critique choices, and the guidance to determine a revision to their explanation. This may be a *desirable difficulty* if students can build on their critique experience and grapple more deeply with their ideas. However, this may be frustrating or confusing if students cannot sort out the many pieces of information. Results in Chapter 5, as well as other studies in the literature, indicate that students have difficulty evaluating their own explanations and understanding (e.g., Chinn & Brewer, 1994; Rozenblit & Keil, 2002). However, Chapter 5 findings showed that students can successfully revise their explanations after struggling with critique. This suggests that students are distinguishing ideas during the critique process and benefitting from this process to refine their conceptual understanding. Thus, providing guidance on students' critiques may be more advantageous than guidance on initial explanations because guidance on students' critiques motivates them to continue the distinguishing process initiated by the critique. Furthermore, students generally do not benefit from guidance that targets more than one idea, yet they may have multiple flaws in their explanation. Guidance targeting one idea in the student's explanation may lead students to mistakenly conclude that no further conceptual work is necessary other than to address the idea in the guidance. A study comparing these two approaches will help refine guidance design principles for critique.

Refining Prompting to Revisit Ideas

Spontaneous revisiting of evidence steps has been correlated with better learning gains in some contexts (Svihla & Linn, submitted), but results for prompting for revisiting are uneven and further research is needed to clarify when and how revisiting supports students in knowledge integration. In some studies, students benefit when they are prompted to revisit and they do revisit (Ryoo & Linn, 2014; Gerard & Linn, 2013). In other studies, prompts to revisit succeed with knowledge integration guidance but not with specific guidance (Vitale, McBride, & Linn, submitted). In Chapter 5, students were required to revisit a critical evidence step after receiving expert guidance on their critique, if their critique choice was incorrect. However, students often were observed having to have limited engagement with the revisited step. In this case, the step in question featured a complex Netlogo simulation that showed key energy transformation events infrequently. Students could re-run and scrutinize the simulation to clarify an idea, but the event necessary for clarification might not happen immediately. This meant that students were observed being frustrated or impatient with the simulation and returning to the critique step. It is possible that providing a more straightforward version of the information in the simulation (e.g., a short clip showcasing the key event; a static image with captions) will better support students in taking advantage of guidance. However, doing so may also mislead students to believe that they only need to address the idea targeted by the guidance and prevent students from reviewing their ideas in full.

Alternatively, when students were sent back to the original simulation in Chapter 5, they may have felt that they already understood the simulation due to deceptive clarity and were not motivated to re-examine the evidence in its entirety. In this case, it might be preferable to provide the information presented in the original evidence step in a new format to increase attention or interest. Thus, presenting students with the same information in a different format (e.g., an annotated static screen capture of the simulation) may allow students to reconsider the information from a new perspective without the potential pitfalls of oversimplifying the revisited evidence or assuming they already understand. Thus, comparing these approaches will help clarify how to support students in taking advantage of guided opportunities to revisit previously encountered information in instruction.

Concluding Remarks

This dissertation demonstrates that guided critique designed with knowledge integration principles can be a powerful means of supporting students in technology-enhanced inquiry science instruction. These activities help students refine their initial understanding and revise their explanations. Implications include design principles for guided critique and for supporting teachers in leveraging technology to strengthen their own practices in guiding students.

My design studies highlight the complexities of engaging students in critique in the classroom. In my work, critique is an extended activity that involves generating an explanation, receiving an explanation for critique, and receiving additional guidance before revising the initial explanation. Iteratively refining the design of such a multi-step process entailed an in-depth qualitative analysis of how students engaged with an activity so distant from their experience in

typical science classrooms. Indeed, case studies revealed the challenges of prompting students to closely examine their ideas and revise their explanations. However, examining one's beliefs with a critical eye and evaluating evidence for the purpose of revising one's thinking is a core practice in science. The Next Generation Science Standards argue that these practices are vital objectives of any science instruction. Thus increasing use of critique in the classroom will advance understanding of the science practices.

My dissertation findings provide important initial insights for teachers and instructional designers as to how students can be guided to engage in critique in the classroom. However, the small sample size and focus on a single grade level and domain limit the generalizability of my findings. Future research needs to build on these insights by conducting larger studies across grade levels and domains to extend the design principles and better support students and teachers. Conducting such design studies using technology-enhanced instruction with logging capabilities is an important means of capturing how teacher instruction, curriculum design, and student interactions combine in authentic classroom settings. In particular, employing a mixed methods approach where both quantitative and qualitative analyses are applied to closely examine student learning processes as they initially engage in critique and become more proficient in the practice over time offers valuable insights. These results characterize how students become better critics of their own and others' ideas in science.

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Appendix A

Pretest and Posttest for Global Climate Change Unit

1. On a COLD day, Akbar walks to his car, parked in the sun. When he gets into his car he is surprised by the temperature inside the car, which had NOT been driven for a week. What do you think Akbar noticed?
 - a) The temperature of the air inside the car was
 - Colder than the outside air
 - Warmer than the outside air
 - Exactly the same as the outside air
 - b) Which of the following ENERGY SOURCES affected the temperature of the air in the car the most?
 - The Sun
 - The car's engine
 - The gasoline in the gas tank
 - The Earth's core
 - No energy sources
 - c) Explain your answers.

2. Burning coal to produce electricity has increased the amount of carbon dioxide in the atmosphere.
 - a) What possible effect could the increased amount of carbon dioxide have on our planet?
 - A warmer climate
 - A cooler climate
 - Lower relative humidity
 - More ozone in the atmosphere
 - b) Explain your answer

3. Gwen is concerned about her energy use. She'd like to make changes to lower her energy use.
 - a) Which ONE of the following would help the most?
 - Walk to school instead of riding in a car
 - Turn off computer and lights when not in use
 - Eat less meat
 - Stop littering
 - b) Which ONE of the following would help the least?
 - Walk to school instead of riding in a car

- Turn off computer and lights when not in use
 - Eat less meat
 - Stop littering
- c) Explain your choices
4. Write a story to explain how the earth is warmed by energy using evidence from this project.

Be sure to include:

- Where energy comes from
- How energy moves
- Where energy goes
- How energy changes/transforms

Use scientific EVIDENCE from the Models to support your ideas.

Appendix B

Transcription Scheme

Mark	Meaning
//	overlapping utterance
(.)	very slight pause
:::	lengthened syllable
—	interruption
(description)	non-verbal gesture
<u>underline</u>	emphasis