Designing Critique to Improve Conceptual Understanding

Elissa Sato and Marcia C. Linn, University of Berkeley, California, 4523 Tolman Hall, Berkeley CA 94720
elissa.sato@berkeley.edu, mclinn@berkeley.edu

Abstract: Students become entangled in their varied scientific ideas and struggle to reconcile their understanding with ideas encountered in instruction. This design-based study with a sixth-grade technology-enhanced inquiry science unit on global climate change investigates how critique can support students in refining their conceptual understanding. Specifically, the study investigates whether students' ability to benefit from critique is impacted by the complexity of the critique artifact. Findings 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 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, 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). This study seeks to advance our understanding of critique by comparing two approaches to designing critique.

In designing critique, we 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. The first approach draws 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. 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.

However, alternative 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. From the KI perspective, conceptual critique involves distinguishing among normative and non-normative ideas. 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. Our study therefore seeks to address the following research questions:

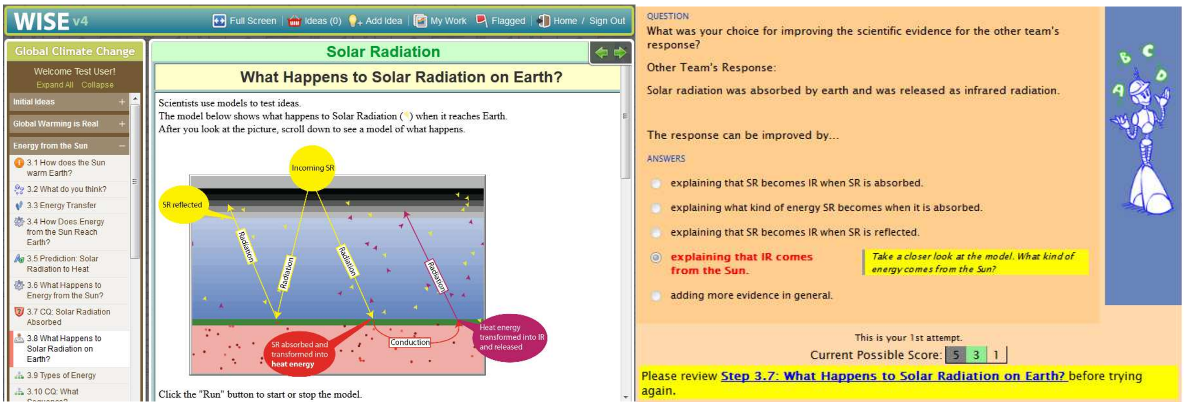
1. How do students benefit overall when they critique (a) an incomplete explanation with normative ideas to identify a missing idea (*incomplete*) or (b) an incomplete explanation combining normative and non-normative ideas to identify a non-normative idea (*non-normative*)?
2. How do students' ideas,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

We hypothesized that we would observe significant differences between conditions in students' learning gains if the potential benefit of critique depended upon carefully designing an accessible or *desirably difficult* critique artifact that was aligned to the students' prior knowledge. On the other hand, we 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.

Methods

A sixth-grade technology-enhanced earth science curriculum unit, Global Climate Change (GCC, Figure 1a), 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. We focused on an explanation targeting an energy transformation process critical to understanding the phenomenon of global climate change. The GCC unit was completed by 68 middle school students working in pairs taught by the same teacher, who had taught previous versions of the unit.

Activity sequence. Student pairs were randomly assigned to one of two promising approaches for aligning critique artifacts to students' ideas (Fig, 2). Based on the design research paradigm, the study sought to investigate whether one condition is better than the other. In the activity sequence students generated an initial explanation, critiqued and revised an assigned explanation, received conceptual guidance on their critique, then critiqued and revised their initial explanation (Figure 2). The design focused on encouraging students to revisit evidence steps (e.g., simulations), which has been correlated with learning gains (Svihla & Linn, 2012), and to discuss and negotiate alternative ideas presented through the critique artifact and critique choices.



(a) (b)

Figure 1. (a) The WISE *Global Climate Change* unit. (b) The guidance checkpoint step.

Generate
- Students generate initial explanation

Critique
- Students critique a researcher-assigned explanation
  - *Incomplete Critique*: explanation with normative ideas expressing partial understanding
  - *Non-Normative Critique*: explanation with a non-normative idea plus normative ideas expressing partial understanding
- Students revise the assigned explanation based on their critique choice

Guidance
- Students receive conceptual guidance on their critique choice and revisit the evidence step

Revise
- Students critique their initial explanation
- Students revise their initial explanation based on their critique choice

Figure 2. Outline of the overall activity sequence.
The shaded step indicates where the curriculum design differed between the two versions.

Critique artifacts. For each condition, three critique artifacts were designed by the researcher based on the analysis of responses collected during previous classroom implementations. The researcher assigned an explanation that expressed partial understanding and was slightly more sophisticated than the initial explanation generated by the students. The *incomplete* group critiqued an explanation containing only normative ideas. The *non-normative* group critiqued a modified version of the *incomplete* explanation with a non-normative idea. During critique, students in both groups selected a science content critique from among several alternatives. This entailed distinguishing among alternatives. They then revised the critiqued explanation based on their choice (Table 1).

Table 1: Critique step guidance.

Feature	Prompt
1) Critique Artifact	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: • 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… • 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 of Critique Artifact	Change and improve the other team's response based on your choice above.

Note. The design of the critique guidance was adapted from a previous study (Sato & Linn, 2011). The guidance was consistent across conditions. The conditions differed in the explanations they were assigned to critique and in the science content critique choices displayed. The same guidance was provided in the revision step.

The critiques for scientific evidence were specific to the explanation type and targeted missing ideas and connections among ideas in the *incomplete* group, or non-normative ideas and connections in the *non-normative* group. Critique choices were calibrated such that both conditions considered the same range of alternatives for a given explanation.

Guidance checkpoint. Both conditions had additional opportunities to consider the same alternatives when they received automated conceptual feedback on their critique choice at a guidance checkpoint. They received a guiding question and were prompted to revisit a critical step to reevaluate the evidence (Figure 1b). During the guidance checkpoint, students were discouraged from mindless guessing with choices that changed order between attempts and a diminishing score structure. During revision, students were also prompted to draw on their critique experience by applying the same criteria to their explanation. They were also prevented from referencing the critique step so that they would not copy ideas from the critique artifact.

Data

Student work formed the core data source; the unit of analysis was the dyad. 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 2). Ten pairs whose initial explanations already demonstrated complex understanding were removed from the analysis.

Table 2: 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.

Impact of the GCC Unit on Overall Learning Gains

Students made significant pretest to posttest gains across conditions (Table 3). 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 3: Means and standard deviations for pre and posttest by condition.

		Pretest		Posttest		t	Effect Size	*p*
	N	M	SD	M	SD		*d*	
All	29 pairs	2.97	0.19	4.00	0.93	5.68	1.54	<.001
Incomplete	11 pairs	3.00	0.00	3.81	0.87	3.11	1.32	<.05
Non-Normative	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 4). 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 4: Means and standard deviations for original and revised explanation scores by condition.

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

Shifts in Students' Ideas

We 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 3). 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.

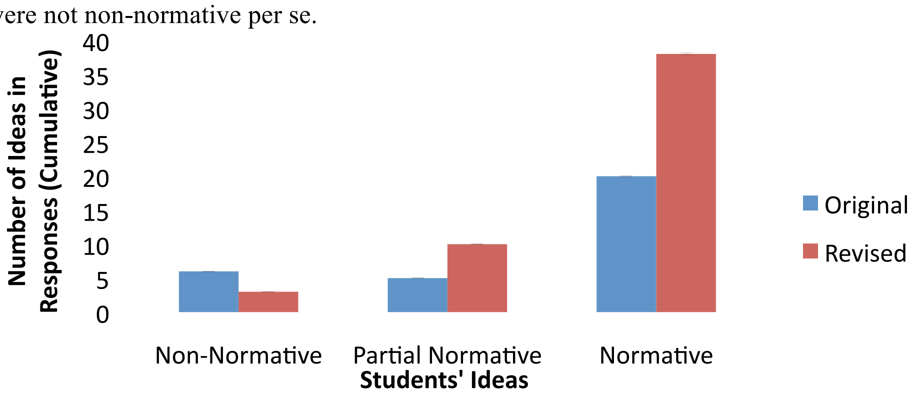


Figure 3. Shifts in students' ideas expressed in original and revised explanations across conditions.

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 then to consider a range of alternatives. Results were not influenced by the complexity of the critiqued artifact.

Value of Multiple Opportunities to Reconsider Alternatives

To investigate the general impact of the activity sequence on students' success in critique and revision of explanations, we analyzed students' science content critique and revision during the critique step prior to the guidance checkpoint and during the revision step after guidance checkpoint (Figure 4). Students' critiques were coded as a success if they selected the correct science content critique. Revisions were coded as successful if they led to a gain in KI scores relative to the initial score.

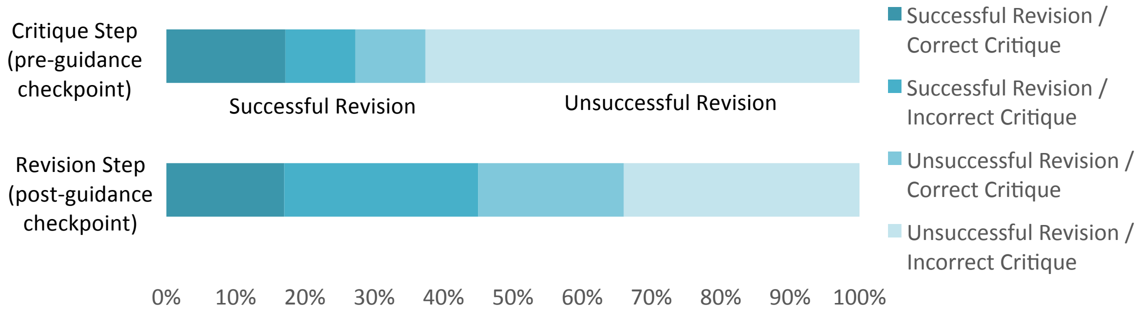


Figure 4. Frequency of Successful and Unsuccessful Revision and Critique of Assigned Explanation and Students' Explanation by Step across Conditions

Overall, the number of students who successfully revised either the assigned or their own explanation increased from the critique to the revision step. 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, 2010). In this study, students only received conceptual guidance on their critique choice. During the critique step, 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. Grappling with critique which involves considering alternative ideas, even when unsuccessful, may still support students in making productive revisions. Following the guidance checkpoint, more students (45%) made a successful revision of their own explanation. Although 62% of students still struggled with critique, a greater percentage of those students (44%) 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 the critique step.

Preliminary 2x2 Chi square tests suggest that there may be a significant association between critiquing and revising the target artifact (the assigned explanation) during the critique step ($\chi2(1)=6.74$, $p<.05$). Essentially, students were 10.35 times more likely to make a successful revision of the critique artifact if they selected the correct critique during the critique step. However, there was no significant association between successful critique and successful revision of the students' own explanation during the revision step ($\chi2(1)=.00$, $p>.05$). 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 struggles with critique.

Classroom observations. To further examine how students engaged with the various steps comprising the activity sequence, we used classroom observations and video records. In this paper, we characterize student engagement as the types of discussions students had with each other and their interactions with the activity scaffolds. During critique, we 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, we 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 we discuss below. In this paper, we 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 we 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 target ideas (Table 5), they chose to elaborate on albedo's role in the process, an untargeted but relevant idea, when revising their own explanation. Their revision was the only response in the data corpus that demonstrated increased sophistication but focused on the amount of energy transformation (using albedo) rather than on the kind of energy SR becomes. 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: Critique artifacts, critiques, and revisions by Janelle and Ida

Critique Step	Artifact (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)
Revision Step	Artifact (Original	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

	Explanation)	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 alternated responsibility for answering the prompt discussed, 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. This activity elicited more frequent turn-taking comments such as “Here, you try” that were less commonly observed in other activities. Despite their focus on turn taking, there were instances during the critique and guidance checkpoint steps that provoked moments of content discussion and negotiation. These opportunities were rarely pursued.

The transcript below illustrates one example of a missed opportunity during the guidance checkpoint. Prior to this, they had engaged in frequent 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 6); 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 instances of 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)

We see this as an important moment because, in a departure from their usual mode of turn-taking 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 6) suggest that the activity design had no impact on Hailey and Tom’s progression through the unit. However, by examining their video records, we see moments where the design was successful in provoking 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 rarely capitalized 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 6. Critique artifacts, critiques, and revisions by Hailey and Tom

Critique Step	Artifact (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)
Revision Step	Artifact (Original 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

Our findings illustrate the value of encouraging students to consider a range of ideas and to capitalize on critique activities. Considering alternatives during critique led to progress in conceptual understanding of scientific phenomena. 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, suggesting that both conditions introduced desirable difficulties. 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. 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, different domains, and to students with different levels of prior knowledge. Future work will also 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 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 case studies illustrate the limitations of this approach. While some students were sufficiently prompted by the guidance to reassess their understanding, others needed additional support. A next step is to refine the guidance design to help students such as Tom and Hailey to seriously consider the ideas of their partner.

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