Integrating Physical and Virtual Models in Biology: A Study of Students' Reasoning While Solving a Design Challenge

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Abstract: Using models to explain phenomena is important in science. Virtual and physical models have different affordances that can be integrated to foster students' learning. Integrating evidence from multiple models to justify explanations is challenging, and we know little about how students coordinate such information, especially in biology. This study investigated how students' integrated information from virtual and physical models in a design-based, biology curriculum. Some students used information from virtual simulations in written explanations of changes they would make to their physical models. However, one-third of students did not use the virtual model to justify their revisions, despite prompts from instructional materials, the teacher, and other group members. Even some students who integrated these different models did not initially do this without support from external prompts. This study provided deeper understanding of how students integrated physical and virtual models, which can help identify the kinds of support students may need.

Introduction

Constructing and using models is an important practice in science (Lehrer & Schauble, 2006; National Research Council, 2012; Windschitl, Thompson, & Braaten, 2008). Scientific models are representations of natural phenomena that are "testable, revisable, explanatory, conjectural, and generative" (Windschitl et al., 2008, p. 3). They can be generated by students (e.g., drawings, physical representations) or can be generated by others and manipulated or utilized by students (e.g., simulations). Inquiry centered around models strives to develop and defend explanations, which importantly includes using evidence to justify and inform these models (Lehrer & Schauble, 2006; Windschitl et al., 2008). Inquiry with virtual models such as simulations offers unique opportunities for students' learning, allowing students to investigate phenomena that might not otherwise be possible in a classroom. Research has investigated the affordances and learning benefits of virtual versus physical models and experiments, but this has predominately been done in physics and engineering contexts (e.g., de Jong, Linn, Zacharia, 2013; Zacharia, de Jong, 2014). Findings from research in these contexts suggest that virtual models can allow students to conduct experiments about unobservable phenomena and alter the time scale of experiments that would take a long time in the real world, whereas physical models can directly expose students to real phenomena, authentic problems, and measurement error they would not face in a virtual experiment (de Jong et al., 2013; Olympiou & Zacharia, 2012). Further, studies suggest that investigations with virtual models may better support conceptual understanding than with physical models, because investigations with virtual models allow students to more easily isolate variables, produce cleaner data to analyze, and offer more time for students to engage in experimentation (de Jong et al., 2013).

Previous research in this area has primarily explored comparing students' learning on content-based tests from participating in experiments using either physical *or* virtual models or participating in different sequences of physical and virtual experiments (e.g., Zacharia & Olympiou, 2011; Zacharia, Olympiou, & Papaevripidou, 2008). This research has produced mixed findings on the benefits of one modality over the other and ideal sequencing. Given the unique affordances of physical and virtual models, integrating or blending the usage of these models based on the particular learning objectives of an experiment has the potential to optimize these affordances for student learning (Olympiou & Zacharia, 2012). While some researchers have begun exploring such integration, there is still little research examining how students integrate and reason about information from one model to inform their experimentation with another. Further, little research has focused on how students collaborate while engaging in such tasks.

Additionally, while these findings from physics and engineering contexts are informative, it is unclear how they extend to biology, as less research has been done on physical and virtual models in biology. The complexity of biological processes offers an important context to explore the integration of these models. Many processes in biology are microscopic and take time to observe (e.g., decomposition), so virtual simulations can be valuable for quickly conducting experiments of such processes in the context of a classroom. The affordances of both physical and virtual models offer different learning opportunities that could be utilized to deepen students' understanding of biological processes. Similar to physics and engineering, virtual models in biology can let students conduct experiments that would take a long time in the real world, and physical models can let students experience real phenomena and encounter problems they would not face in a virtual experiment. Based on these affordances, both types of models can to be integrated to help foster students' learning. For example, students could use simulated experiments to gain understanding about how to improve a physical model, or the conditions of a physical model could influence how they use a virtual simulation. To successfully do this, students would need to integrate and use evidence from multiple models to appropriately justify an explanation. Previous research has shown that learning from multiple representations (e.g., Ainsworth, 2006) and using evidence to support scientific explanations (e.g., Sandoval & Millwood, 2005) are both challenging for students. Thus, utilizing information from virtual and physical models to solve a design challenge is a complex task for which students likely need support. Recent research in the context of engineering design has shown that using virtual models to plan future design decisions and to reflect on previous decisions can both help students integrate information for their designs and understand science concepts (McBride, Vitale, Applebaum, & Linn, 2016). However, we still do not know much about how students might integrate information from virtual and physical models in this way and, thus, know little about how to best support students to do this, especially in the field of biology. Our research begins to explore i. whether students integrated information from virtual and physical models; and ii. how students collaborated to try to successfully integrate this information to work towards solving a design challenge in the context of a design-based, biology curriculum.

Methods

This was an exploratory study investigating students' ability to integrate information from virtual and physical models in the context of a design-based, biology curriculum. The curriculum challenged students to work in teams to design a compost that would break down quickly and contain a lot of nutrients to reduce the amount of waste going into landfills. Students learned key concepts related to energy transformation and matter cycling in ecosystems to solve their challenge. To study decomposition and collect data to justify for their designs, students built, monitored, and refined a physical bio-reactor throughout the unit. Since it takes several weeks for compost to break down, students also used virtual compost simulations to better understand how abiotic factors influence decomposers' ability to break down matter. They conducted four virtual compost experiments related to the carbon to nitrogen ratio of materials, the amount of moisture, the size of the particles, and the combination of all these factors. Based on what they learned in the virtual experiments, students were required to revisit their physical bio-reactors and use the science ideas, data, and evidence from the virtual experiments to decide on and justify one change that would increase decomposition in their physical bio-reactors. The data for this study focused on students' written explanations in their journals and audio-recorded conversations from three groups that occurred during this activity, further described below.

Participants

The participants were twenty-six students (N=26), working in seven small groups, from an 8th grade science class at an urban middle school in a Midwestern city in the United States. This was a "talented and gifted" class taught by an experienced teacher. The composition of the small groups was determined by the teacher. We chose this class as a potential exemplar of how high-achieving students might integrate models. We further chose this class to see how an experienced teacher might facilitate this process in a student-centered way that could provide information about useful teacher supports that helped students integrate different models in a design-based curriculum.

Data sources

We identified a *Change Page* in the students' journals where they needed to provide written responses about what to change in their physical bio-reactors after conducting four virtual experiments using a compost simulation. Students were asked to work with their group to provide evidence for a current problem in their physical bio-reactors, write a potential change they could make, and then supply evidence for why the proposed change would caused improved decomposition. To do this, students needed to observe their bio-reactors to identify problems and use evidence from their virtual experiments to *explain* the change they wanted to make. The only data students had to provide evidence was from these virtual experiments, and thus they should have provided data from the simulation about the ideal conditions for decomposition in compost to support their changes. We inductively developed a coding rubric to explore how students provided evidence for the physical change from their virtual experiments (see Table 1). Twenty percent of the students' written explanations on their *Change Pages* were coded by the first and second author separately and a 90% agreement was achieved. All disagreements were resolved with discussion. The remaining written responses were coded by the second author.

To begin understanding *how* students worked together to construct the explanations recorded on their *Change Pages* and to identify if and how students talked about data from their simulations in making their decisions, we qualitatively analyzed conversations from the three groups (A, B, C) that we had audio-recorded during the unit. These groups were chosen for recording throughout the unit by the teacher as being representative groups of academically average-performing students within the class.

Table 1: Coding scheme to evaluate quality of students' written explanations to support their proposed change

Level	Example	Point Value
None / Incoherent	Blank, no explanation	0
Partial explanation without evidence from the simulation	We are adding browns like oats, leaves, newspaper, and sawdust. This will make decomposition fast.	1
General explanation without evidence from the simulation	We believe that mixing up our compost will distribute the moisture evenly. Currently the moisture is only in the middle of the compost. If we mix it up then the moisture should be distributed evenly.	2
Explanation refers to simulation	I think the C:N ratio is the most important change. We must increase nitrogen for large ratio and more moisture. If we don't have enough browns nothing will be able to break down. Our greens are living so nothing will decompose. We decided to add greens to give it more moisture.	3
Explanation refers to and uses evidence from the simulation	Our carbon to nitrogen ratio is too small. [We could] add browns to increase decomposition speed. The closer the C:N ratio is to 30:1 the better. Adding more browns 1 & 2 (63.7 grams) or more carbon. It will improve our carbon to nitrogen ratio. In turn, this will improve our smell and moisture level.	4

Results

Students' written explanations

We found that some students successfully integrated information from the virtual simulation to inform or justify the changes to their physical bio-reactors. However, the quality of students' written explanations for the proposed changes to their physical bio-reactors varied. We found that eight percent of students did not include a coherent explanation at all, while 23 percent of students gave a partial (score = 1, 11.5%) or general (score = 2, 11.5%) explanation without providing evidence (see Figure 1 below). Forty-two percent of the students referred to the simulation in their explanation, but did not include specific evidence (score = 3), and 27 percent of students offered an explanation that referred to the simulation and included evidence (score = 4). This means that 31 percent of students did not refer to the simulation in their explanation despite scaffolding in the students' journal, teacher prompting, and working with their group for support.

Some groups were more successful than others at collaborating to integrate information from the virtual simulation to provide evidence for making a change in their physical bio-reactor. We calculated an average quality of explanation score for each group and found that Groups B and C had the lowest average score ($M = 2$) and Groups D, E, and F had the highest average scores ($M = 3.3, 3.2, 3$ respectively). Groups A ($M = 2.75$) and G ($M = 2.5$) had scores in the middle. See Figure 2.

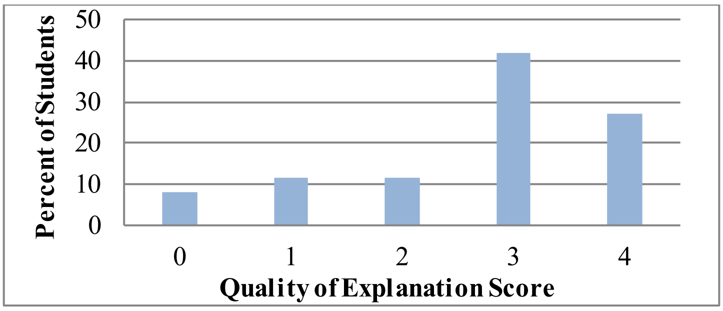

Figure 1. Percent of individual students' (N=26) responses within each quality of explanation score.

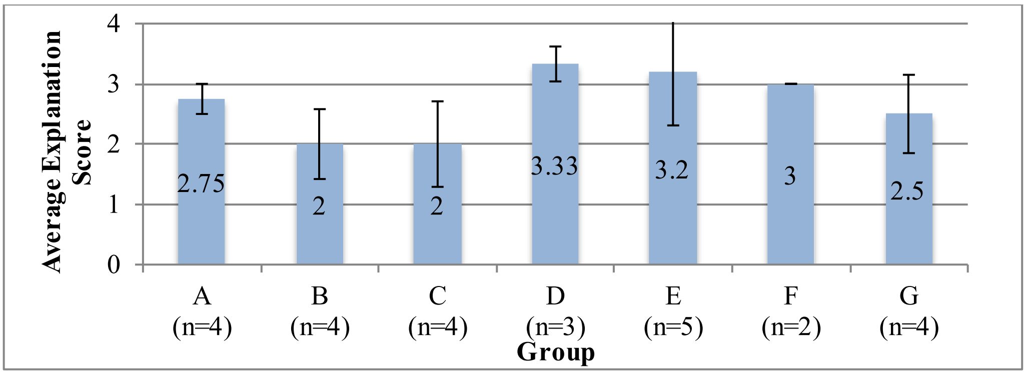

Figure 2. Groups' average quality of explanation scores, number of students per group shown below each group.

Groups' conversations

We examined groups' conversations to better understand how students collaborated to integrate information from their virtual model to make a change to their physical model. These three groups (A, B, C) were chosen by the teacher at the beginning of the unit as representative groups of academically average-performing students to be audio-recorded throughout. The analysis of Group A, B, and C's conversations revealed several differences in how these groups integrated information from their physical and virtual compost models. Group A made more use of prompts within the instructional materials and from the teacher to have richer conversations about using data from the simulation to inform the changes to their bio-reactor than Groups B and C. Groups B and C ignored, missed, or misinterpreted several prompts that Group A utilized. Vignettes of each group's interactions are presented below to illustrate interactions that were more or less successful.

Group A

Of the three audio-recorded groups, Group A's students made more references to the simulation in their explanations of changes for their bio-reactor than Groups B and C, with a group average score of 2.75. In their negotiation of changes to make in their bio-reactor, they first identified that the compost in their physical bio-reactor was too wet. Initially, they did not use any evidence from their simulation experiments to justify their decisions. However, when the group was explicitly prompted in the instructional materials to give "evidence for why this change will cause improved decomposition" on their *Change Page*, they utilized data they gathered from the virtual simulation to justify their change to their physical bio-reactor:

Student 1: Ok, so what's the evidence?

Student 2: We don't really have evidence.

Student 1: How do we know it's too moist?

Student 3: Because.

Student 1: Maybe that's the right range, how do you know that's the right range?

Student 3: Because that's not the right range.

Student 4: Because we did the simulation and the right range was 40-60% moisture.

Here, students 1 and 2 were unsure about how to justify their proposed change, or even why they thought their compost was too moist. Student 3 alluded to their moisture level not being in the "right range," but student 4 took this a step further and reminded the group of the results from their virtual experiment investigating the ideal moisture content of compost. At this point, the group decided to add oats to their bio-reactor because it was too wet, and they knew that the ideal amount of moisture should be 40-60% (by weight) based on data from the virtual simulation. The teacher then suggested to the whole class that they might want to use the virtual simulation to try their proposed change before actually making a change to their bio-reactor.

Teacher: Make sure you think out the changes that you are going to make. If that requires running through one of the simulators again, do it. Maybe run yours through the simulator.

It was not until this direction from the teacher to utilize the virtual model before making physical changes that this group began to meaningfully integrate information from both models. As a result of this prompt, Group A decided to input the conditions of their own physical bio-reactor into the virtual compost simulation and experimented with adding different amounts of oats to achieve their desired moisture content:

Student 4: What was the C to N ratio [in our bio-reactor]?

Student 3: 16.9 to 1.

…

Student 4: So try some browns [in the simulation].

…

Student 4: If it doesn't work, then we shouldn't add anything.

…

Student 4: Ok, now try it.

Student 3: 20 to 1 ratio, with 50% moisture. So add 10 grams of oats.

Student 4: Yeah just a little bit. Just to balance out the moisture.

…

Student 3: So the more, like 10 is about the same, but since ours is moister, I think we need to add a little bit more, like 15 to dry some of it up.

Student 3: So we need like 15 grams of oats or something.

Student 4: Yeah that's it.

This excerpt showed how students 3 and 4 integrated information about the conditions in their physical bio-reactors with data from the virtual simulation to refine their proposed design change. Instead of just simply "adding oats," they determined that they needed to specifically add 15 grams of oats to solve their problem. Further, student 4 insisted that they must base their final decision for the physical model on the evidence from the virtual model when he said, "If it doesn't work, then we shouldn't add anything." Through this discussion, the group was eventually able to use observations of their bio-reactor and data from both the virtual simulation to inform and justify their design change.

Group B

Group B was less successful than Group A in making reference to the simulation in both their written explanations in their journals (average group score = 2 for their quality of explanations) and during their conversations about making changes to their bio-reactor. Overall, this group of students got caught up in the "doing" of making the change, rather than thoughtfully planning and justifying their change based on data from the simulation. Unlike Group A, they did not discuss the instructional prompt in their journals that asked them to provide evidence for their change. They quickly decided on the change for their bio-reactor and left the classroom to make it outside. When they were outside, they missed the teacher's suggestion (written above) that students could use the simulation to try out their change, which prompted Group A to have a deeper discussion about how data from the simulation could inform revising their bio-reactor. Instead, Group B solely focused on discussing the state of their physical model and how the materials inside it needed to be mixed:

Student 2: Just mix it up and shake it.

Student 3: It's not evenly distributed (inaudible) and it's moist.

Student 1: Yeah but that could also cause problems if we don't do it correctly.

Student 3: Yeah cus we don't want to have the stuff growing on it.

Student 1: Because if, let's say we don't distribute everything evenly, it could cause problems. How are we gonna mix it without taking it out?

Student 2: I think if we shake it, I shook it a little bit this morning and everything moved so I think we'll be able to-

Student 1: Yeah we can only move it up and down.

Student 2: No it was-

Student 3: I think it's a little compact right here, like we pressed it down firmly, and now that area is opened, so that area is decomposed and now that area is opened, so I think it's decomposed enough so like a little bit more space. If we need to grab something to mix it with like a pencil that we're not gonna use again or something.

From this excerpt we can see that the students only focused on their physical bio-reactor when deciding to make their change. This focus on the physical model continued. They then took measurements of the temperature, pH, and moisture and made other qualitative observations of their bio-reactor. But they never connected these measurements of the current state of their bio-reactor to information they learned in the simulation to provide evidence for why their change would improve decomposition. They simply went outside and worked on mixing the materials up in their bio-reactor, and their conversation focused around how to accomplish this. This lack of using evidence from the simulation may not have been entirely the students' fault though. The *Change Page* in the students' journal had been intentionally designed to help the teacher monitor students' explanations. Since the teacher needed to approve students' proposed changes, the teacher had the opportunity to check students' supporting evidence prior to making their change. In this instance, the teacher allowed Group B to proceed with their change without providing evidence from the virtual simulation, perhaps due to the many groups needing his attention at that time.

<u>Group C</u>

Like the students in Group B, the students in Group C's average written explanation score was a 2, slightly lower than Group A's average score. We found that, unlike Group B, the students in Group C did discuss the prompt in the students' journals that asked them to provide evidence for why their change would cause increased decomposition. However, their discussion around this prompt was less focused on using data from the simulation to provide evidence than Group A's discussion, described above. Group C discussed two different potential changes: reducing the moisture in the bio-reactor because it was too wet and adding more carbon rich materials because there were not enough. Group C appeared to misinterpret the instructional prompt in their journal that asked them to provide evidence to support their change: they gave a prediction for how their change would help their bio-reactor, rather than providing evidence from their simulation experiments to *explain why* they should make the change. For example, they could have discussed what they learned about the ideal C:N ratio range to promote decomposition from doing their virtual experiments and how the ratio in their bio-reactor was not in this ideal range.

> Student 1: Evidence for why this change will cause improved decomposition.
>
> Student 2: A better smell. A more normal odor, and faster compost.
>
> Student 3: Well, no I know that, but why would this change be better? It'll create a better smell…
>
> Student 2: Faster, faster decomposition, it just makes it slow and foul odor. Um, what else?
>
> Student 3: I think that's it, right? Because we don't really need to say anything else right?
>
> Student 2: That's good.

After this exchange, Group C decided to add more carbon to their bio-reactor. When the teacher mentioned to the entire class that students could use the virtual simulation to test their proposed change before making it, the students in Group C then more specifically discussed what materials they could add to increase the carbon to their bio-reactor. However, they seemed to ignore the teacher's suggestion and never tested their ideas in the simulation or mentioned data from the previous simulation experiments they ran about the ideal C:N ratio range, like Group A did with the ideal moisture range. It was not until the teacher visited with Group C individually and prompted them to further explain what they thought would happen by adding carbon rich materials that the group specifically discussed improving the C:N ratio of their bio-reactor:

> Teacher: …it says explain why, explain specifically what you expect to happen… Don't just say something like 'we think it'll help', or 'the process will work more efficiently', explain specifically what you expect to happen.
>
> Student 2: If we say evening out the carbon to nitrogen ratio, would that be good? Ok.
>
> …
>
> Student 1: I bet, I bet if we add carbon we will be adding more materials and carbon to even out the nitrogen to carbon ratio.

Despite receiving multiple instructional prompts from the journal and the teacher, Group C never discussed data from their simulation to provide evidence for their change. These students had previously experimented with the virtual simulation to learn about the ideal C:N ratio range for decomposition, and they had previously calculated the C:N ratio in their own physical bio-reactors; however, they did not make connections between these two models to propose and support their revision to their physical model.

Conclusions and implications

We were interested in exploring whether and how students integrated information from virtual and physical models to work towards solving a design challenge in the context of a design-based, biology curriculum. This study suggested that some students in a talented and gifted class were able to integrate information from these different models to work towards solving a challenge when provided with several supports, such as prompts from instructional materials, the teacher, and other students in their group. However, even with these supports, about one third of the students' written explanations and two of the three groups' conversations showed a lack of integrating information from the virtual and physical models. The findings from our qualitative analysis of three groups additionally suggested that even the one group of students who provided information about the simulation in their explanations did not initially integrate this information from different models without the support from external prompts. These findings importantly contribute to our understanding of students' ability to reason about information from different models to inform and justify decisions. Previous research has theorized about integrating virtual and physical models and has shown enhanced conceptual learning from experimentation that blends the affordances of these models over using virtual *or* physical models (Olympiou & Zacharia, 2012). However, little is known about students' ability to reason about and coordinate these different models and the information they provide. Our findings shed light on the challenging nature of this task and suggest the need for additional support. Our findings also align with previous research that identified that students struggle to learn from multiple representations (e.g., Ainsworth, 2006) and justify explanations with evidence (e.g., Sandoval & Millwood, 2005).

Our work further extends the findings of prior research by exploring how students used evidence from different models to write explanations in biology. Students' use of multiple models in biology may be especially difficult, because the time scale between virtual and physical models in biology may add another layer of complexity. For example, many biological processes (such as decomposition) take weeks to observe whereas simulations can be run in seconds. To complicate things more, data collection in biology can be less straight forward than from a virtual simulation because many biological processes are complex systems that are hard to accurately measure. For example, the contents of a bio-reactor are varied, and temperature and moisture levels may be different depending on where students take their measurements. Therefore, the complexity of biological systems may present extra challenges for students to navigate between such diverse models (Hoskinson, Caballero, & Knight, 2013).

Additionally, we found that students seemed to pay more attention to their physical models in their written explanations and conversations about their potential revisions. We conjecture that students may focus more on physical models because they are more concrete and more familiar objects in a science classroom. Perhaps this is also due to the idea that more concrete representations have been shown to better facilitate students' understanding of scientific principles than abstract representations (Goldstone & Son, 2005). This may be because concrete representations offer information that is more salient and connected to the real world, thus better supporting students' reasoning (Goldstone & Son, 2005). Given that the students in our study were asked to make revisions to their physical bio-reactors, students may have seen these concrete physical models as providing more relevant and salient information for making their decisions. This may mean that teachers and instructional materials need to more explicitly discuss the relationships between virtual and physical models in biology to help students make useful connections between the information represented in both models.

The prompts within instructional materials and from the teacher appeared to be crucial in encouraging students to integrate data from virtual simulations to make a decision about revising their physical model. However, students did not utilize these prompts in the same way. First, explicitly pressing students for evidence in the student journal resulted in one group making a connection to the virtual simulation and utilizing that data to justify their change. This same prompt was not sufficient for supporting students in other groups to integrate information from their virtual and physical models, as either they ignored or misinterpreted the prompt. Second, the teacher's suggestion that students could use the simulation to try their proposed changes in the virtual model was instrumental for one group but ignored by another. For the group of students who decided to follow the teacher's suggestion, this facilitation was a key turning point to integrate information from their physical bio-reactors and the virtual simulation; this helped them refine their solution by utilizing the virtual model to test how their change would theoretically affect their compost. Even though this prompt was useful for one group, many students continued to focus only on their physical bio-reactors. The idea that various scaffolds are important for students when engaging in complex tasks is well known (e.g., Puntambekar & Kolodner, 2005); however, this study deepens our understanding of how particular prompts influenced students' reasoning and where students may need additional or different forms of support to successfully engage in this complex task.

While prompts from the teacher appeared to be influential, it seems that it may be difficult for teachers to support students in integrating information from multiple models. Even in a talented and gifted class, it appeared that more numerous and more explicit prompts were needed to support students to improve on such a challenging practice, given that many students did not use information from the virtual simulation in their explanations. Since this is such a difficult task for students and facilitating multiple groups of students is complex for the teacher, designing instructional materials to help students integrate virtual and physical models needs to be more intentional. Specifically, perhaps one way to better support students in making connections between different models would be to design activities that explicitly asked students to use information gathered from a virtual model to inform or revise a physical model, and vice versa. For example, students could be required to use a virtual model to test how changes might affect a physical model. Additionally, teachers likely need more professional development to better support students' work in this area (Gilbert, 2004; Gnesdilow, Smith, & Puntambekar, 2010), as even an experienced teacher who understood the nature of models could have supported students more successfully.

This study offers an important contribution because it provided a deeper look at *how* groups of students reasoned and negotiated to make connections between physical and virtual models. This information can lead to a more thorough understanding of how many students struggle to accomplish this challenging integration of information. More work needs to be done to understand the kinds of support that students may need to be successful. Given that this study took place in a class of identified talented and gifted students with an experienced science teacher, we wonder how students in a more typical context would perform on the same task. More research is necessary to understand what types of prompts and scaffolds are necessary to support students' collaboration to integrate virtual and physical models. Our future research will examine how more teachers facilitate students' coordination of information from multiple models to solve a design challenge and how different facilitation strategies may impact students' learning.

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