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Comparing Design Constraints to Support Learning in Technology-guided Inquiry Projects

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ABSTRACT

Physical design projects are a way to motivate and engage students in authentic science and engineering practices. Web-based tools can support design projects to ensure that students address and reflect upon critical science concepts during the course of the project. In addition, by specifying challenging design goals that require students to consider potential trade-offs between features, web-based tools may promote more deliberative scientific inquiry than open-ended or feature maximization goals. To study the role of web-supported projects, we developed an online curriculum that guides students through the planning, building, and analysis of self-propelled vehicles. To address content related to energy transformation we incorporated virtual models that display dynamic graphs of energy levels as a virtual scooter travels along a path. We compared two design goals for the project with different constraints. In the *target* version students are prompted to build virtual and physical scooters to reach a specific position. In the *distance* version students are prompted to maximize the distance the scooter travels. Our results indicate that students learned energy concepts from both versions; however, students with the *target* version did refer to the virtual model in their posttest responses to a greater degree than those with the *distance* version.

Keywords

Blended learning, Technology-enhanced instruction, Project-based learning, Science education

Introduction

In this study we investigate a blended, physical-virtual approach to inquiry learning projects that takes advantage of the motivational affordances of hands-on projects, as well as the guidance and scaffolding affordances of online learning. In particular, new educational standards (e.g., NGSS Lead States, 2013) recognize that hands-on projects can support mastery over disciplinary practices and understanding of core disciplinary ideas in an engaging context. The process of building a working model or artifact requires the learner to generate, integrate, and apply scientific ideas to solve real-world problems. Yet, despite this potential, open-ended design projects often draw students' attention to superficial structural or aesthetic issues, rather than underlying behaviors and functions (Hmelo, Holton, & Kolodner, 2000). On the other hand, online learning tools can structure content to make underlying mechanisms concrete (Edelson, Gordin, & Pea, 1999; Reiser, 2004). Furthermore, with adaptive mechanisms, online learning tools can provide guidance tailored to students' individual strengths and challenges (Linn et al., 2014). Bringing together physical and virtual modalities of inquiry, therefore, represents an opportunity to deliver on the enormous, but mostly untapped potential of hands-on projects in science classrooms.

Determining how to best coordinate between hands-on design and virtual tools is an open research question. We explore how a blended inquiry project may be designed so that virtual and physical components build upon each other and help students explore the underlying scientific mechanisms. In this paper, we combine a virtual and physical model in an inquiry activity to explore trade-offs between features of the design. Specifically, students build a self-propelled vehicle and use it to explore issues of energy conservation and transformation. In the *target* condition, students refine their design so that the vehicle reaches, but does not go beyond, a target. In the *distance* condition, students refine their design so that their vehicle goes as far as possible. The *distance* condition is consistent with students' typical goals for a vehicle. We discuss how both approaches take advantage of the virtual model and physical design to support learning. We hypothesize that the *target* condition will be better at helping students deliberately distinguish among their ideas.

Challenges with projects

Most students enjoy projects, but often fail to learn and apply core science principles to improve their designs (Crismond, 2011; Hmelo et al., 2000; Horn, 1922; Kanter, 2009; Karaçalli & Korur, 2014; Larmer & Mergendoller, 2010). Rather, in many cases, projects are implemented as arts and crafts activities devoid of science content (Larmer & Mergendoller, 2010). Many teachers avoid implementing hands-on projects, in favor of typical, lecture-based instruction.

Thus, engineering projects where students explore a distance goal may lead to different patterns of exploration than a project where students are encouraged to explore each variable in service of reaching a goal. For example, in the topic explored here, students are prompted to build a self-propelled vehicle using either a balloon or a wind-up device. A typical criterion for the success of their construction is the distance that the vehicle travels before stopping. We compare a typical *distance* condition to a *target* condition where students aim to get the self-propelled vehicle to stop at a target.

Supporting knowledge integration with web-based tools

While it is difficult for a single teacher to guide all students during project-based inquiry (Özel, 2013; Tal, Krajcik, & Blumenfeld, 2006), web-based tools can make projects more successful by augmenting teacher guidance. Research on adaptive guidance with digital inquiry tools (e.g., Gobert, Sao Pedro, Raziuddin, & Baker, 2013; Leelawong & Biswas, 2008; Linn et al., 2014; Roscoe & McNamara, 2013), suggests that adaptive technologies can assist students in learning scientific concepts through inquiry. Although well-defined environments, with clear expectations for learning, are the most straightforward approaches to develop adaptive guidance, new approaches for guidance and formative assessment are emerging. Designing activities to take advantage of adaptive capabilities of online systems is an important challenge for educational research.

The knowledge integration (KI) framework (Linn & Eylon, 2011) grew out of research showing that learners have multiple, often conflicting, ideas about scientific phenomena and that they benefit from building on their ideas. When new ideas are added and not distinguished from prior ideas, students often use the new idea in the situation but revert to their earlier ideas subsequently. Thus, to promote KI, guided inquiry is advantageous. The KI framework emphasizes four reasoning processes. First, instruction needs to elicit student ideas so they can be considered when new ideas are added. Second, adding new ideas using interactive virtual models can be valuable. Third, learning occurs when students distinguish new ideas from their prior knowledge and use evidence from their explorations to form a new understanding. Accordingly, in addition to exploratory activities in which students may encounter new ideas, knowledge integration activities encourage exploration of students' elicited ideas. Fourth, students benefit from reflecting on the process of comparing ideas and consolidating understanding. Guidance can help students distinguish and compare their ideas to form a coherent understanding. While knowledge integration can be supported in all forms of instruction, the Web-based Inquiry Science Environment (WISE) was designed to use logs of student activities to offer adaptive guidance and to report student ideas back to their teachers (Linn et al., 2014).

The KI approach focuses instructional design on distinguishing ideas. It calls for implementing a narrative or goal that binds activities and drives inquiry (Linn & Eylon, 2011). Furthermore, this narrative or goal must reflect inherent difficulties in the material. For example, in a KI activity addressing the question of "what makes an object float?" students are guided to generate virtual artifacts of varying masses and volumes to test their hypotheses (Vitale, Madhok, & Linn, 2016). Because students' initial ideas are often incomplete (e.g., only mass determines flotation), exploration provides surprising results, and in turn motivates further investigation of underlying mechanisms. However, developing a self-propelled vehicle to maximize distance travelled may not invoke a challenge to students' ideas. Simply through experience with related materials (e.g., toys, carts), students likely know that minimizing friction between the axle and the body of the scooter (i.e., enabling the wheel to spin freely) and maximizing initial energy will result in the best scooter. Therefore, another approach to structuring the engineering task may be required to encourage exploration of more complex relationships.

Design constraints and knowledge integration (KI)

To facilitate students distinguishing ideas, we compare two design constraints in this study. The *target* condition has the constraint of hitting a target in both physical and virtual model-testing. Students must design a scooter that lands on the target to achieve the goal. To do this, they can manipulate a number of factors, including mass, friction, and wheel size. The introduction of this design constraint, i.e., a target, may emphasize the trade-offs between mass and friction. In the *distance* condition, the design constraint is to make the scooter go as far as possible. This design might lead to fewer explorations of trade-offs. Focus on design trade-offs could support more systematic exploration of the variables by students. The *target* condition might motivate systematic investigation of underlying science issues to seek an acceptable balance between variables (Barron et al., 1998; Kanter, 2009). For example, imposing specific specifications on architectural design (i.e., specifying limitations), requires creative use of tools and materials to produce a structure (Kuhn, 2001).

In terms of knowledge integration, the target constraint could encourage learners to distinguish between the effects of the variables more than the distance constraint. We compare these constraints in the study reported here.

This study

A central science concept for middle school students is the conservation of energy – i.e., that energy in a system is never lost but transforms from one form to another (NGSS Lead States, 2013). However, this concept is challenging, particularly when energy transformation occurs between forms that are easily detectable (e.g., movement, temperature) and tacit forms (e.g., potential energy) (Edens & Potter, 2003; Linn, Songer, Lewis, & Stern, 1993; Liu & McKeough, 2005). Thus, understanding that the movement of a vehicle from start to stop is the result of transformation from potential to kinetic to thermal energy (from friction), with a constant amount of total energy, is not likely to be intuitive for most students. In this potential-kinetic-thermal ("PKT") system, losses in one form of energy result in equivalent gains across some distribution of the other two energy forms.

While functional physical models (i.e., self-propelled vehicles) inherently demonstrate mechanisms of energy transformation and conservation, these mechanisms may not be clear to students. In particular, prior to (and often after) instruction, many children believe that moving objects naturally come to a stop without any external force or source of energy transfer (McCloskey, 1983). Virtual models, depicting the transformation of energy implicit within the motion of a cart, can help illustrate these concepts and prepare students to understand their physical counterparts.

Yet, simply illustrating relationships does not take advantage of the affordances of design tasks and games to align task goals and learning objectives. While a student could analyze changes in energy after successfully achieving the goal of maximizing the distance the car travels, nothing compels him or her to do so. On the other hand, a goal that imposes constraints – i.e., make the car go a specific distance – may require analysis of energy transformation in order to complete the task successfully.

Accordingly, in the current study, students engaged in a 10-day design project where they would explore virtual and physical models of self-propelled vehicles with either a *distance* goal (i.e., maximize distance) or a *target* goal (i.e., hit a target at a specified distance). The aim of the current study is to assess the impact of these two conditions on student performance and on learning of science concepts. Therefore, we ask the following questions:
- Does the *Self-propelled Vehicles* curriculum unit support learning of energy concepts?
- How do students' exploration strategies differ by condition?
- Do learning gains in *Self-propelled Vehicles* differ by condition?
- How do students' experiences exploring and building models in each condition impact the evidence that they use to justify their responses at posttest?

Method

Participants

This study was conducted with two teachers and their 228 eighth grade (13-14 year-old) students (A: male, 10+ years teaching experience, 103 students; B: female, 2nd year teacher, 125 students) from a single school. This sample accounted for nearly the entirety of the 8th grade class (except for one additional class, taught by a third teacher, whose data is not used in this study). This school serves a diverse, but mostly mid-to-high socioeconomic status, suburban population in the western United States (38% White, 31% Asian, 17% Hispanic, 4% Black, 22% Reduced-price lunch, 12% ELL).

Materials

Assessments

A pretest consists of three sets of multi-part items addressing the relationship among different types of energies (Energy Conservation Graphs, Scooter Revision Graphs, Car Performance Comparison). A posttest consists of these three items, along with an additional item (Consultant). For each of these multi-part items, we chose to evaluate a single response component that best highlighted students' thinking about energy. The posttest may be viewed at this link: http://wise.berkeley.edu/project/18843#/vle/node1

Energy Conservation Graphs (henceforth "Conservation"). For this item, students are presented with four bar graphs that depict possible relations between potential, kinetic, and thermal energy while a scooter is moving. Only one graph correctly displays a total of 100% energy distributed among available energy types (Graph 1d). Students are prompted to choose the correct graph and explain their selection. We coded and evaluated responses to this final prompt.

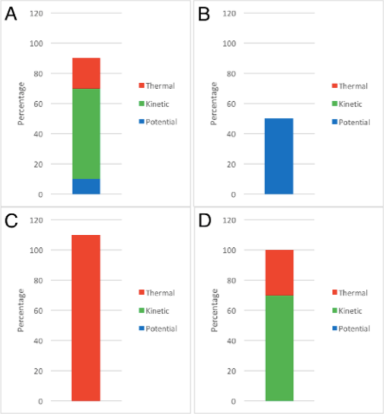


Figure 1. Response options for *Energy Conservation* item

Scooter Revision Graphs (henceforth "Revision"). In this item students are presented with a stacked bar graph depicting the distribution of energy (like Figure 1) from an arbitrary timepoint during a scooter's run. This item also presents two fictional students' plan for revising their scooter to increase kinetic energy. "Jaden" plans to reduce axle friction, while "Jordan" plans to make the wheels bigger. Students are prompted to choose whether they agree with Jaden (correct), Jordan, both, or neither. After making their selection, students are prompted to reflect upon the stacked bar graph to indicate which form(s) of energy will NOT change based upon this scooter revision. In this case, the potential energy will not change because adjusting friction only impacts the relative distribution of energy between kinetic and thermal. Students are also prompted to explain their reasoning, which we coded and evaluated.

Car Performance Comparison (henceforth "Comparison"). In this item, students are prompted with, "Liz and Destiny each built a rubber band car. Liz's car had more potential energy, but Destiny's car travelled a farther distance." Students are instructed to present reasons why Liz's car did not go as far, even though it had greater potential energy. Following this prompt, students are instructed to choose one of these reasons and explain how the selected reason affected how Liz's car transformed potential energy to kinetic and thermal energy. We coded and evaluated responses to this final prompt.

Consultant (posttest only). This item presents an image of "Lorena's" scooter and text indicating that the scooter stopped in the middle of the track. Students are prompted to list changes that can be made to the scooter to increase the distance it travels. We coded and evaluated responses to this listing prompt. Following this, students are prompted to choose one of their proposed changes and explain how the change would affect the scooter's energy.

Curriculum materials

All curricular materials are presented in the WISE unit, *Self-propelled Vehicles* (henceforth *Scooters*). During *Scooters* students are introduced to energy concepts of transformation and conservation, and then have the opportunity to apply these concepts to an engineering task. For a layout of the *Scooters* unit, see Table 1. The *target* version of the curriculum may be found at the following web address: http://wise.berkeley.edu/project/18684#/vle/node1

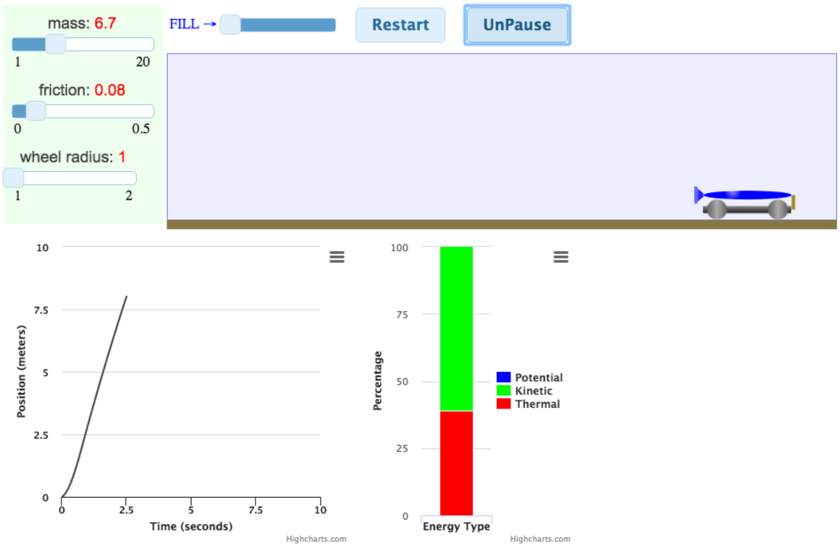
Table 1. Layout of *Scooters* lesson

Activity number	Activity	Description
1	Introduction to Scooters	Students are introduced to self-propelled “Newton Scooters” and view online examples.
2	Design Process 1	Students design, build, and test a base scooter model.
3	Energy Concepts (with virtual models)	Students engage in inquiry activities around energy types, energy transformation, and energy conservation with virtual models.
4	Design Process 2	Students improve on their base scooter model design.
5	Reflection	Students reflect on the outcomes of changes they made to their scooters.

Introduction to Scooters. Students begin the *Scooters* lesson with an introduction to what self-propelled vehicles look like and then they are prompted to describe what features might be important for a scooter to have in order for it to move. This activity does not differ by condition.

Design process 1. Following the introduction, students are presented with instructions on how to design a base scooter model. By starting the students with predefined scooter-building instructions, students can immediately have a successful experience building and testing a functioning scooter. This activity does not differ by condition.

Energy concepts (with virtual models). In this activity students are introduced to relevant energy concepts of transformation and conservation. Central to this activity, students explore a virtual model of a balloon-powered, self-propelled vehicle, whose features can be manipulated (Figures 2 and 3). Specifically, students can manipulate four of the scooter’s features: amount of air in the balloon, mass, friction, and wheel size. In this particular model, all features except for the wheel size affect how far the scooter will travel. Taking advantage of the virtual environment, the results of each model trial are depicted as graphs. On the left-hand side, the distance vs. time information is displayed in real time as the scooter moves across the screen. On the right-hand side, energy distribution is depicted as a stacked bar graph summing to 100% at all times. This graph changes dynamically as the scooter travels.


mass: 6.7

friction: 0.08

wheel radius: 1

Figure 2. Example of Distance model

Depending on experimental condition, students are presented with differing instructions and alternative versions of the virtual model. In the *distance* condition (Figure 2), students are informed that their goal when revising their physical scooters will be to “have your scooter travel the farthest distance.” Students are encouraged to explore the model in preparation for the goal.

On the other hand, in the *target* condition (Figure 3), students are informed that their goal when revising their physical scooters will be to reach a target that might be a farther or shorter distance than their initial scooter travelled. In addition, in the virtual model students are presented with a “target” feature, and asked to adjust parameters so that the scooter reaches the target. In the model, once a target is successfully landed upon (within a margin of error equivalent to half the length of the scooter), the target is automatically moved to a new, random location along the track.

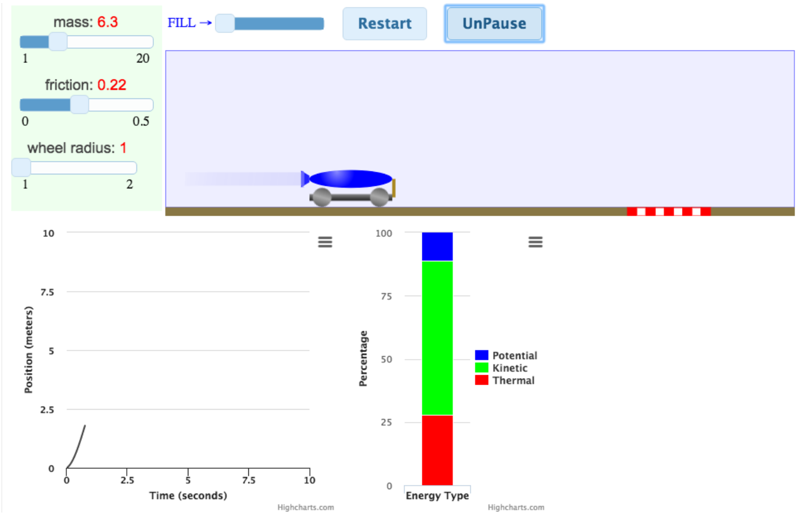


Figure 3. Example of Target model

During the course of this activity, students interact with three different virtual versions of either the *target* or *distance* model. In all versions, the model input parameters remain constant; however, the right-hand stacked-bar energy graph is updated to reflect the introduction of new concepts. In particular, in the first model (Figure 4) only the potential energy is displayed and labelled, while all remaining energy (summing kinetic and thermal) is labelled as "other". In the second model, once the concept of kinetic energy is introduced, the energy graph distinguishes between potential and kinetic energy (blue and green, respectively), while the remaining energy is labelled as "other". Finally, in the last model all three forms of energy are displayed and labelled. By limiting the forms of energy displayed in the first two models, we aim to focus students' attention on a single form of energy at a time, while also motivating the introduction of new forms of energy with the "other" bar.

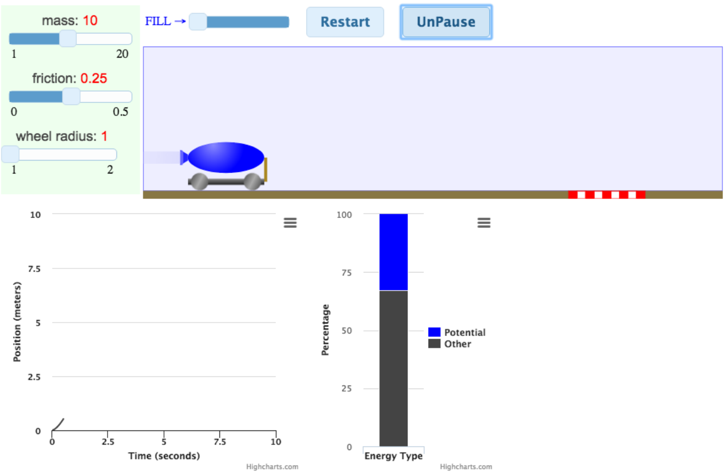


*Figure 4***.** Example of the first target model

Design Process 2. After exploring the computer models, students in both conditions are guided to re-design, re-build, and re-test their original scooters. Unlike the first design, the goal of this engineering process differed by condition. For students in the *target* condition, their goal was to reach a specific distance. This distance was determined uniquely in each class by calculating the median distance of all initial scooter designs (see Figure 5). This ensured that half of the class would need to travel farther, but half of the class would need to make their scooter travel less distance. On the other hand, for students in the *distance* condition, their goal was to produce a scooter that would travel the farthest in their class.

Prior to revising their scooters, students are guided through a group collaboration activity. Specifically, students are instructed to meet in groups of 4 (i.e., two pairs) to discuss how to improve their scooters. Pairs are chosen by the experimenter (in collaboration with the teacher) to ensure that one pair's initial scooter travelled under the median distance, while the other pair's scooter travelled further than the median distance. For instance, if the median class distance was 75 cm, one group whose scooter travelled 50 cm could be paired with another group whose scooter travelled 125 cm. In the *distance* condition this establishes a peer-mentoring situation in which one group with a better initial design can advise the other pair on how to increase distance. In the *target* condition, neither group would necessarily have a "better" design for the median target goal, because even the group whose initial scooter traveled further would need to revise in order to limit distance.

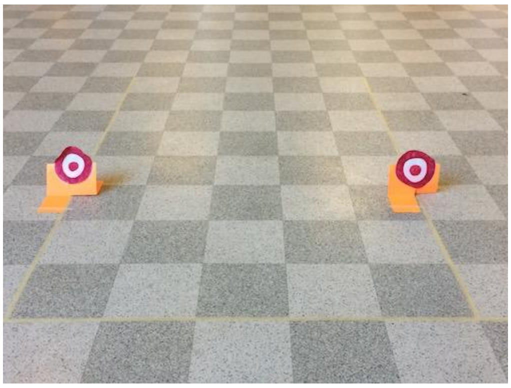


Figure 5. Testing "lanes" set up for *target* condition

Reflection. Finally, after completing the redesign and testing, students reflect on the process of revising the scooter and their outcomes. Students are prompted to reflect on the role of energy in their designs and integrate energy concepts with practical issues of design, as well as make final suggestions for future models.

Procedure

We administered a pretest to all students before they began the lesson. Students performed the pretest individually on a set of classroom laptops for approximately 30 minutes. Following the pretest, students were assigned to workgroup pairs based upon teacher discretion (i.e., the teacher assigned partners based on previous classroom projects). Whole classes were assigned randomly to experimental condition. Teacher A had two *target* condition classes and two *distance* condition classes, while teacher B had three *target* condition classes and two *distance* condition classes. After the students completed the *Scooters* activity they performed the posttest individually. The posttest took approximately 30 minutes. The entire length of the study from pretest through posttest was 10 days.

Coding and analysis

Pretest and posttest items were scored according to a knowledge integration rubric (scores 1 – 5), which rewards linking ideas into a coherent narrative (Liu, Lee, & Linn, 2011). Lower scores represent incomplete or nonormative ideas (e.g., I don't know (1), "everything on the graph changed because if you change one thing on the car it will change everything on the graph" (2)), while higher scores indicate normative ideas that are linked together (e.g., "The *potential energy didn't change* because *less friction doesn't have more energy stored*" (4, representing one complete link between two ideas). This approach has been used in previous graphing applications (Vitale et al., 2016) to emphasize links between narrative elements of the item (e.g., the "speed") and spatial elements (i.e., relative height of kinetic energy in a stacked bar graph).

Log data during virtual model exploration was collected with the WISE system. Each time a student clicked on a virtual model, the action was recorded. The "click events" were processed and analysed.

Results

We began this study with three research questions focusing on overall learning gains, learning differences by condition, and qualitative differences in evidence supplied in each condition. We address each in turn.

Learning of energy concepts

To determine whether the *Scooters* unit effectively teaches energy concepts, we compared scores on all three repeated pre- and posttest items. Using paired, two-tailed t-tests, we found significant increases from pretest to posttest on all three items, *Conservation* [pretest: $M = 2.10$, $SD = 0.46$; posttest: $M = 2.32$, $SD = 0.77$; $t(224) = 5.1$, $p < .001$, $d = 0.35$], *Revision* [pretest: $M = 2.32$, $SD = 0.70$; posttest: $M = 2.64$, $SD = 0.84$; $t(193) = 5.0$, $p < .001$, $d = 0.41$], and *Comparison* [pretest: $M = 2.66$, $SD = 1.03$; posttest: $M = 3.22$, $SD = 1.03$; $t(162) = 6.4$, $p < .001$, $d = 0.51$].

Differences in exploration strategies by condition

The logged data from the virtual model further suggests the *target* condition better supported students to distinguish relevant variables. Students had the opportunity to interact with the virtual model at three different time points. The following results reflect the students' first virtual model experience. Students viewed one of two versions of the model: *distance* or *target* (Figures 2 and 3). In the *distance* model, students are told to explore the model. In the *target* model, students are told to try to hit the target that appears along the scooter's track. Once students hit the target, the target moves randomly to another position. On average, students ran the model 10.99 ($SD = 8.79$) times, suggesting that students were actively engaged. Students in the *target* condition conducted significantly more trials in the model than students in the *distance* condition (mean target = 14.38, mean distance = 7.55, $t(95) = 4.91$, $p < .001$). Further, students in the *target* condition conducted more efficient trials. In our model, wheel radius did not affect how far the scooter travelled. Therefore, if students understood this, there would be little reason to continue to alter this feature. Students in the *target* condition altered the wheel radius significantly less than students in the *distance* condition (target: 24% of runs; distance: 49% of runs; $t(133) = 3.77$, $p < .001$), suggesting that more students in the *target* condition distinguished the impact of wheel radius relative to the other variables on motion. Adjustments to mass and friction did not vary between conditions.

Learning differences by condition

To address which condition generated stronger learning outcomes, we conducted a mixed effects regression with random effects for student and fixed effects for condition, teacher, and pretest total score. A mixed effects model allows us to utilize results from each of the three assessment items to determine the overall impact of each of our predictors (pretest, teacher, condition). Results from the mixed effects regression can be found in Table 2. The results show that, controlling for teacher and pretest score, there is only a trend for condition, suggesting that the *target* condition was positively related to students' performance at posttest ($\beta = 0.11$, $p = .14$).

Table 2. Regression data for the effect of condition on posttest scores, controlling for teacher and pretest score

	Estimate	Std. error	*t*-value	*p*-value
Target Condition	0.11	0.07	1.47	0.14
Teacher 1	0.07	0.07	0.96	0.34
Pretest Score	0.55	0.07	8.35	< .001

Differences in evidence supplied by condition

Our last research question asks if condition affects how students relate the information from the computer model to building a physical scooter. We begin by looking at the posttest item *Consultant*, because it provided an appropriate opportunity for students to supply evidence from their instructional experience to justify their responses. (This item appeared at posttest only, and is not included in the analyses above.) This question required students to list as many changes as they could to help improve Lorena's car, which had stopped in the middle of the track. There was no difference between conditions for the number of changes students suggested (*target*: $M = 2.44$; *distance:* $M = 2.36$; $t(227) = 0.55$, $p > .1$). However, students did differ in terms of the types of changes offered (see Table 3 for examples). Students in the *target* condition consistently suggested improvements to Lorena's car that were based on the model. For example, students were more likely to suggest that Lorena increase the air in the balloon (*target*: 75% of 244 students; *distance:* 61%; $\chi^2(1) = 4.80$, $p = .03$), reduce the mass of the scooter (*target*: 45%; *distance:* 32%; $\chi^2(1) = 3.77$, $p = .05$), and marginally more likely to suggest decreasing friction (*target*: 59%; *distance:* 46%; $\chi^2(1) = 3.22$, $p = .07$). Students suggested adjustments to the car's wheels (an incorrect answer based on the model) at equal rates (*target:* 31%, *distance:* 30%; $\chi^2(1) = 0$, $p > .1$).

While students in the *target* condition appeared to focus on the virtual model more often, students in the *distance* condition were more likely to suggest practical changes to the car that were based on their own building experiences. For example, students in the *distance* condition more frequently suggested that Lorena makes sure her wheels are straight, uses a straw over her axle (a practical solution for decreasing friction that was not shown in the model), or adjusts the amount of tape on her scooter. On average, 28% of *target* students and 44% of *distance* students offered suggestions related to practical issues, as opposed to the mechanistic variables influencing energy transformation. The difference between the two conditions was significant ($\chi^2(1) = 5.38$, $p = .02$). This suggests that the *target* condition may be more effective in helping students to distinguish variables and their relationship to both the underlying science principles and the physical design than the *distance* condition.

Table 3. Illustrative examples of student responses to posttest *Consultant* item

	Target condition	*Distance* condition
1	I would recommend that she make the wheels of the car larger, reduce friction between that axle of the wheels and the body of the car, and inflate the balloon more.	You could change it from a balloon to a ruber band or you could add a straw
2	To increase the distance of a Newton´s scooter, Lorena can: Blow up the balloon more, decrease the friction, decrease the mass, or decrease the wheel size.	She can fill up her balloon with more air in the beginning so it can move farther, she can choose a stretchier balloon, and she can find a way to make the air come out slower(she could use a straw).
3	I think she could blow up the ballon more so there is more potential energy that can later on be turned to kinetic and she could make the wheels slightly bigger.	Change the placement of the balloon. Make the tires more straight.
4	1. You could reduce friction 2. Put less mass 3. Fill the balloon up more 4. The wheels are bigger	To make it go further maybe add more friction on to the wheels by taping the sides around the wheel. You can tape more with the cd on to the skewer.

Discussion

Designing engaging, rigorous, and hands-on inquiry projects requires trial and refinement (Edelson et al., 1999). Designing multi-faceted inquiry projects that address both core disciplinary concepts and scientific practices is particularly challenging. However, such activities can integrate science practices and content knowledge, as well as engage students in ways that are likely to make a lasting impact. Thus, developing approaches to support student design projects is an essential goal of educational research.

In this study we found some evidence for engaging students in exploring trade-offs by focusing students on using their scooter to hit a target. The target design constraint led to more exploration of trade-offs than did the distance design constraint. This is consistent with findings of Schauble, Klopfer, and Raghavan (1991). They found that when an activity prompts students to control variables, students explore variables carefully and deliberately. On the other hand, when the activity prompts students to make a boat go as far or as fast as possible, they chose experiments focused on the goal, rather than systematically controlling variables that are not essential to the solution. In the present study, the opportunity to integrate experimentation with the virtual model appears to have engaged both the target and the *distance* condition in exploring the variables, suggesting that the specific design features of the activity involving distance are important.

Combining a virtual model and a physical design activity requires careful design and analysis of conditions to ensure that the students succeed. This study highlights both the unique affordances of physical models and virtual models, and the challenges of combining the two formats (de Jong, Linn, & Zacharia, 2013). For example, Zacharia, Olympiou, and Papaevripidou (2008) found that students who learned about heat and temperature through a combination of a physical activity and a virtual model made greater gains than students who learned using physical activities only.

One of the successes of combining physical activities and virtual models can be seen in the use of the virtual model in the *Consultant* question. Both groups engaged with the virtual activity. Students in the *target* condition were more likely than those in the *distance* condition to draw on the virtual model when providing ideas to the *Consultant* question. In previous pilot iterations of the study, without the *target* condition, students infrequently used the model as evidence when discussing their ideas about how scooters work. Students appeared to think only of the hands-on activity and did not view the virtual-physical activities as integrated. By providing suggestions from the virtual model, students in the *target* condition showed that they are beginning to consider the virtual model as providing evidence that can be applied outside the model context. This suggests that students in the *target* condition recognized the value of the virtual model for distinguishing among variables to hit a target. More research is needed to validate this conjecture.

The use of both virtual and physical approaches generates challenges for teachers who may worry that building physical models could distract from learning science principles. Many teachers prefer to limit hands-on projects to extracurricular activities. To make physical model building effective, we clearly specified the materials and procedures for building scooters, enabling teachers to prepare for construction. Furthermore, by guiding students' initial designs in WISE, we ensured that students had similar experiences. Using WISE, students could make plans, describe their designs, interpret evidence, and link their results to energy principles. Teachers could use the dashboard to evaluate student thinking as it developed. These supports enabled efficient implementation of the activities, consistent with the finding that all students made clear learning gains on each of the posttest items focused on energy.

This study also illustrates the importance of determining constraints carefully when designing engineering projects. Similar issues emerge in research on games. Games impose design constraints to lengthen the experience, induce creativity, and add competition. Games can improve learning by focusing constraints on science-related phenomena and providing appropriate feedback. Recognizing the relevancy for education, a number of researchers have suggested that more game-like features should be introduced into educational applications while also cautioning designers to explore the addition of these features carefully to avoid unintended consequences (see Clark, Tanner-Smith, & Killingsworth, 2016, for overview and meta-analysis). For example, in a learning activity with a game-like simulation, Miller, Lehman, and Koedinger (1999) found that students learned relevant physics concepts (related to electromagnetism) better when their actions in the simulation were limited to specific options than when they could engage in more open-ended exploration. In this case, specifying the options compelled learners to engage challenging problems that could be avoided in open-ended navigation. This illustrates how successful designs for constraints can direct student attention to key inquiry activities.

Even with the support of online tools, there is potential for students to focus on superficial elements of their engineering designs and overlook critical features. Ensuring that the design elicits scientific thinking is an important task in instructional design. In this study, we hypothesized that the *target* condition (compared to the *distance* condition) would encourage linking the virtual model exploration and physical building tasks and result in more careful attention to the relations between scooter features and underlying energy concepts. We found evidence in the *Consultant* item that students in the *target* condition drew more on the virtual model than students in the *distance* condition (i.e., they were more likely to refer to the model in their responses). Nevertheless, the impact on learning energy concepts was similar. Although the *target* condition did increase emphasis on trade-offs, students may not have fully analyzed the model to recognize relationships such as between adding friction and its impact on transfer of kinetic energy to thermal energy. In future research we will explore ways to encourage students to focus and make predictions directly from information on the energy graphs.

Despite a lack of clear evidence to differentiate learning of energy concepts by condition, the results suggest that the design constraint approach helps clarify the interactions that arise when students combine virtual and physical designs. Determining how best to design activities with constraints remains a process of trial and refinement.

Implications for teaching and instructional design

While many teachers feel pressure to cover a wide range of topics within a short time-span, educational standards highlighting scientific practices (e.g., NGSS Lead States, 2013) offer an opportunity to engage students in exploring complex science concepts. Ensuring that hands-on projects meet content requirements requires critical analysis of the design activity. In designing effective activities, it is essential to link activities to science principles. Although web-based systems are one tool for addressing this question, teachers may supplement hands-on inquiry with a diverse array of activities, such as journal writing, drawing, diagramming, graph construction, etc. Each of these activities could reinforce the scientific mechanisms and build upon students' ideas (Linn & Eylon, 2011). This study suggests the value of studying design constraints and refining them to help students think creatively and engage in knowledge integration.

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