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Can Tinkering Prepare Students to Learn Physics Concepts?

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> "Tinkering is the essential art of composing and decomposing physical things to suit a variety of purposes – from practical to whimsical…[it is] both a manual and mental labor, perhaps even a labor of love."
> -Dale Dougherty, Editor and Publisher of *Make Magazine*, in *The Art of Tinkering*[1]

Introduction

Tinkering is creation and open-ended exploration with materials; its openness aligns well with learning in informal settings such as maker spaces and museums, where learning is driven by visitors' choices to pursue their own interests and passions. Tinkering, and making activities more broadly, have been gaining traction in school curriculum as teachers and administrators recognize their value in engaging students in STEM content and disciplinary practices. However, the very diversity in learning trajectories fostered by these activities can create tension with science instruction in K-12 classrooms, where the emphasis is often on the investigation of specific phenomena and the learning of particular concepts. Here we present research which aims to blend the goals of schools and tinkering in museums in a complementary fashion. Rather than directly assessing whether students learned a particular concept through tinkering, we examine whether students who have tinkered on a museum field trip are better prepared to learn from a presentation on related science content once they return to their classrooms. We expected that tinkering activities, which have engaged students in "manual and mental labor," would provide students with compelling experiences, questions, and unsolved problems that would lead naturally to a "time for telling"[2].

The theoretical basis of the study resides under the assessment framework known as Preparation-for-Future-Learning (PFL), which examines performance when a new learning resource becomes available[3]. Typical assessments measure static learning outcomes, say, by asking whether students can recall a concept or if they can apply a procedure they have previously mastered to a new situation. But the benefits of some learning experiences are more nascent and may not be apparent until students are given an opportunity to learn new information. For instance, students can be better prepared to learn a concept by first actively comparing across contrasting cases[2] or by trying to invent their own solution[4] before being formally "told" the answer. It is critical to test for PFL dynamically, by providing learning resources *during the assessment* and after active engagement with examples. Schwartz, Chase, Oppezzo, & Chin compared instructional methods for learning density[5]. The *tell-and-practice* approach involved presenting students with the formula for density and having them practice applying the density equation to examples of boxes with varying levels of "crowdedness". The *inventing* condition had students compare across the very same examples to invent their own numerical index for how crowded each box was. All students then received a lecture on the density formula and its importance. Students who had first tried to invent their own index were better prepared to learn the ratio structure of density, as evidenced by reconstructing the crowdedness examples as well as transferring to new ratio problems.

In many science classrooms, a common approach is to teach scientific principles through engineering and design projects. For example, by designing balloon cars, students are supposed to learn Newton's 3rd law. Despite the popularity of this approach, there is surprisingly little evidence of its effectiveness, as nonexperts rarely draw connections between their designs and target science ideas[6,7]. One thing these approaches have in common is a static assessment of physics principles after the project is completed. This adherence to static assessments may help explain why so little evidence of science learning has resulted from engineering and design projects.

We hypothesize that some benefits of engineering design projects may not manifest until the students are given the chance to learn new information. A PFL perspective may thus be better suited to find the ways in which tinkering and engineering projects aid in the learning of science concepts. By tinkering with materials, students may spontaneously make comparisons across contrasting cases they have set up on their own, and may be inventing their own solutions to the problems they encounter while tinkering. By allowing students opportunities to generate their own ideas and solutions first, tinkering may provide a "time for telling"[2] in which they are prepared to learn science principles from a new learning resource.

In what follows, we present the design and analysis of a preliminary study with 76 sixth-graders on the impact of tinkering for learning. In a research design blending both informal and formal learning, students participated in one of two tinkering activities on a museum field trip, Marble Machines or Wind Tubes, for approximately 45 minutes. Back at school, two weeks later, both groups had the opportunity to learn from a 20-minute instructional video, which contained segments that explained scientific concepts relevant to both activities. We seek to answer the question of whether a relatively short experience with tinkering prepares students to better learn science content from an instructional video related to their tinkering experience.

Methods

Participants

The participants were sixth-graders (N=76) from a diverse urban public middle school (30% Black, 29% Asian, 21% Hispanic, 12% White; 10% English Language Learners). The teachers signed up for a field trip and agreed to participate in a follow-up lesson in their classroom.

Design

The study involved two phases. In Phase 1, students went on a field trip to the tinkering space of a local museum, where they participated in one of two activities, Marble Machines (N=46) or Wind Tubes (N=30). Due to administrative constraints, students were not randomly assigned to tinkering activity, but teachers were instructed to assign students such that the groups were balanced on class performance and gender. Phase 2 occurred two weeks later back at the school, where the PFL assessment was administered. All students first answered two pre-video science questions, one related to each of the tinkering experiences, then watched a 20-minute instructional video related to both tinkering activities. Finally, all students were given a posttest on the relevant science concepts presented in the video. Our prediction was that students in each condition would learn more about the science related to their specific tinkering activity when compared with the other group. A schematic of the experimental design is shown in Figure 1.

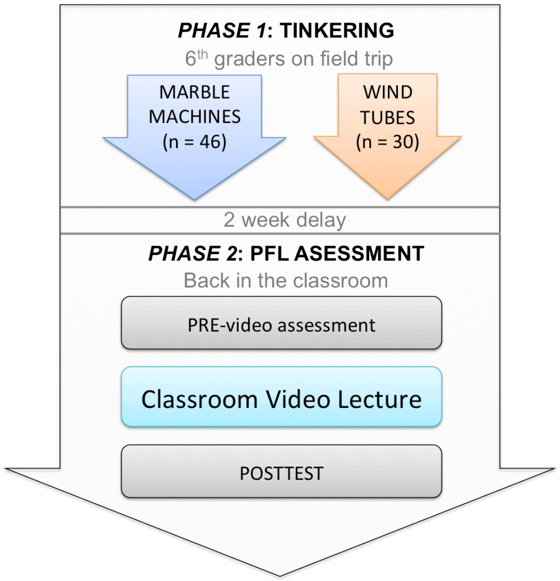


Figure 1. Study design. Phase 1: Students tinkered in one of two activities while on a field trip to the museum**.** Phase 2: Two weeks later in their regular classrooms, all students watched the same video and took the same assessments.

Phase 1: Tinkering Activities

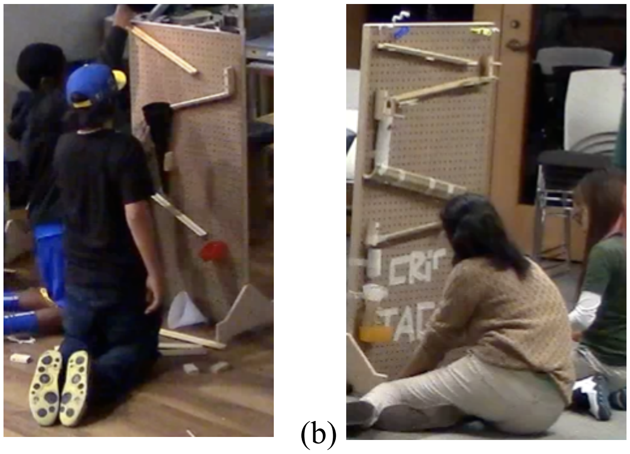
To study the learning impact of tinkering activities, we had to anticipate what challenges the students would encounter during their creation process, which is difficult given their open-endedness. In consultation with museum staff, we picked two activities that seemed to have challenges that most kids would encounter.

Wind Tubes (WT)

Figure 2. (a) Examples of students' contraptions from the Wind Tubes tinkering activity, and (b) one contraption in action in the wind tube.

Wind Tubes involved constructing objects out of paper cups, strawberry baskets, strips of paper, masking tape, etc. to place in a vertical wind tunnel and observe the behavior (Figure 2). The goal presented to students, deliberately vague on the part of facilitators, was to "make something float." A common student-adopted goal was to see if they could build an object that started at the bottom of the tube and flew up and out the top. Sometimes kids would build objects that would float in the middle of the tube, or that spun really fast, or that could lift several washers.

Marble Machines (MM)



(a) (b)

Figure 3. Two examples of students' ramps (a) and (b) from the Marble Machines (MM) tinkering activity.

Marble Machines involved pairs of kids attaching ramps and tubes and other assorted parts to a pegboard wall, building a track on which they roll marbles (Figure 3). The challenge presented to students was to build a track which would make the marble go as slow as possible during its journey from top to bottom. However, the challenge was quickly forgotten in the heat of the moment, and students adopted their own, relatively ill-defined goals of creating "cool" or "fun" tracks.

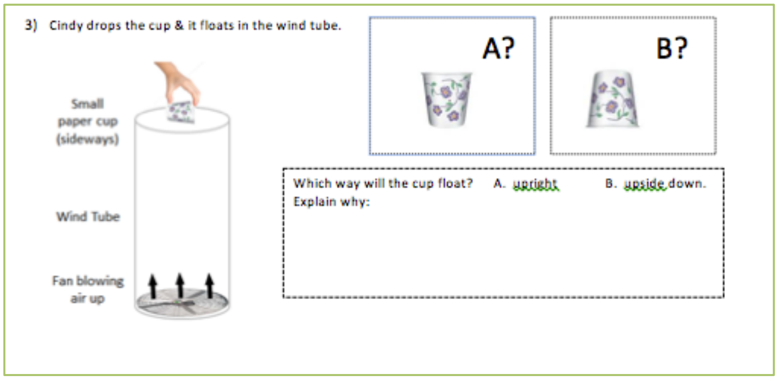
One problem that most students encountered is the marble's tendency to bounce off the track once it picked up too much speed. Sometimes the museum facilitators would offer advice to adjust the track to make the marble roll as slowly as possible. In response, at times students would make the ramps less steep to keep the marble from speeding up too much. At other times, facilitators noted, instead of slowing the marbles down many kids built walls and ceilings at the junctures of the track to keep the marbles contained (Figure 3b).

Phase 2: PFL Assessment

The usual approach to learning science concepts through engineering/design/tinkering projects would be to explain the principle before or during the activity, then give a test on the concepts after the activity. In the PFL paradigm, we do not expect that the kids will have learned the relevant physics principles by the time they have completed the activity. Instead, we expect that they have bumped into enough aspects of the phenomenon such that they will be primed to learn when the opportunity arises. Assessments for PFL are different than typical assessments in that they explicitly include an opportunity to learn. In this study, the learning resource was an instructional video on science topics related to both tinkering experiences.

Learning Measures: Pre-video questions

Before watching the video, the students were asked two questions as a check of whether they ran into the problems that we anticipated. The WT question showed a paper cup being held sideways above the wind tube. The question asked which way the cup would float in the tube, open-side up or open-side down (Figure 4). Most students responded that the cup would float open side down, like a parachute. In practice, the cup is more stable in the tube when it is closed-side down, since that places the center of pressure below the center of mass. We coded open-side up responses as evidence that they experienced this counter-intuitive behavior of the cup in the wind tubes.

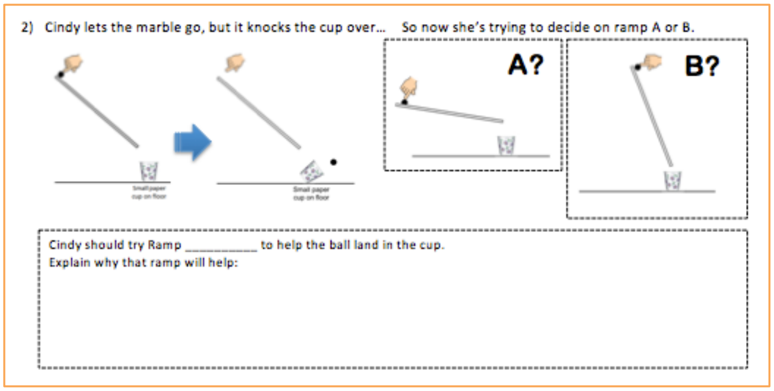


3) Cindy drops the cup & it floats in the wind tube.

Which way will the cup float? A. upright B. upside down.
Explain why:

Figure 4. Pre-video question related to Wind Tubes.

The MM question showed a marble rolling down a ramp and knocking over a paper cup that was supposed to catch the marble. The question asked whether the ramp should be made more or less steep in order for the cup to catch the marble, and asked them to explain their choice (Figure 5). We coded responses that mentioned momentum, speed, or energy being built up as the marble rolls down the ramp.



2) Cindy lets the marble go, but it knocks the cup over... So now she's trying to decide on ramp A or B.

Cindy should try Ramp __________ to help the ball land in the cup.
Explain why that ramp will help:

Figure 5. Pre-video question related to Marble Machines.

Classroom Video Lecture

Immediately after answering the two questions above, students watched a 20-minute video created by researchers. The video consisted of a series of clips explaining physics concepts that were relevant to both tinkering activities. The first segment of the video targeted Wind Tubes and discussed how to float stably by increasing surface area and utilizing curved surfaces. A series of clips explained how a ping-pong ball can float stably in a column of wind because the airflow curves around it, and how an indoor skydiver or a flying snake can increase surface area to produce lift. The video used specific vocabulary and displayed abstract visual representations for invisible quantities such as curved airflow around a ping-pong ball (Fig 6a), as well as the balanced forces of lift and weight on an indoor skydiver.

The second segment of the video targets Marble Machines and discussed how to "fall softly" by decreasing momentum more gradually. A series of clips explained how as you fall, you build up momentum, and showed parkour artists, a pebble toad, and the blue aliens from *Avatar* all falling safely from large heights by breaking up big falls into many small falls, as well as rolling out of falls to decrease momentum more gradually. The video used specific vocabulary and displayed abstract visual representations for invisible quantities, including arrows of increasing size to convey a person's increasing momentum along a water slide (Fig 6b).

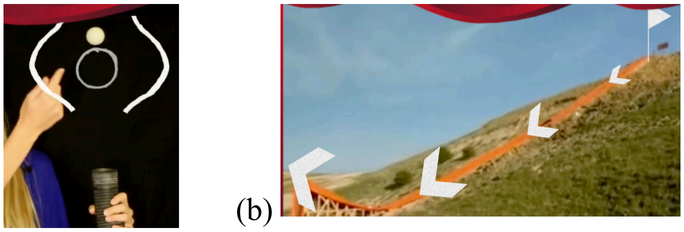
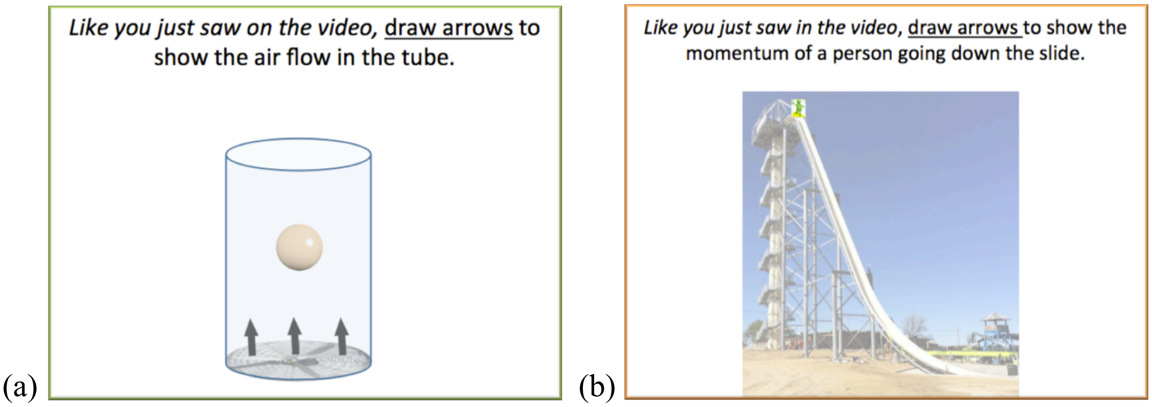

(a) (b)

Figure 6. Abstract representations used in the video to convey (a) curved airflow around a ping-pong ball, and (b) increasing momentum of a person on a water slide.

Learning measures: Posttest questions

After the video, we asked a variety of questions related to the content of the instructional video as well as the tinkering activities. Two questions asked students to recall abstract representations from the video and apply it to a new example. One question presented students with a picture of a ball in a wind tube, and asked them to draw arrows to indicate airflow in the tube (Figure 7a). We coded responses that included arrows that curved around the ball. Another question presented students with a picture of a water slide and asked students to draw arrows to represent a person's momentum as they go down the slide (Figure 7b). We coded for whether the students put arrows that got bigger and/or further apart towards the bottom of the slide.



Like you just saw on the video, draw arrows to show the air flow in the tube.

Like you just saw in the video, draw arrows to show the momentum of a person going down the slide.

Figure 7. Posttest questions related to (a) WT and (b) MM video segments.

There were also a series of six fill-in-the-blank, multiple-choice questions targeting the vocabulary introduced in the video (Table 1). Three questions (#1, 3, 5) asked about vocabulary specific to the WT activity (lift, stability, balanced forces), and the other three questions assessed vocabulary specific to the MM activity (momentum, soften, absorb).

Table 1. Multiple-choice vocabulary questions in posttest.

1. When flying, more surface area gives more ___________.
(a) stability (b) lift (c) speed (d) support (e) momentum
2. When dropping an object, starting higher produces more ___________.
(a) gravity (b) resistance (c) lift (d) momentum (e) crashes
3. A curved surface increases a floating object's ___________.
(a) momentum (b) stability (c) lift (d) resistance (e) pressure
4. Breaking a frog's fall into pieces helps ___________ its landing.
(a) absorb (b) stabilize (c) resistant (d) increase (e) soften
5. To keep an object floating in the same place, there needs to be ___________ forces.
(a) balanced (b) curved (c) lift (d) absorbed (e) stable
6. When a big bug falls on a leaf, the leaf bends a little because it is ___________ the momentum of the bug.
(a) lifting (b) absorbing (c) folding (d) increasing (e) crashing

Results

We combine the performance on the abstract visualization items and the vocabulary questions to obtain a combined posttest score. To determine if the posttest was fair to both conditions, we compare the mean combined posttest score for each condition. An independent-samples t-test reveals no significant difference between the scores for the Wind Tubes (M=4.63, SD=2.03) and Marble Machines (M=4.47, SD=1.90) conditions; t(74)=0.362, p=0.718.

Next we separate out the performance on posttest material relevant to each condition, to test the predicted target effects. Our prediction was that WT students would perform better on questions specific to the wind-related segments of the video, while MM tinkerers would perform better on questions targeting the marble-related clips. For the wind-related posttest material, an independent-samples t-test shows no significant difference for WT (M=1.93, SD=1.21) and MM

(M=1.99, SD=1.27) conditions; t(74)=0.19, p=0.85. Likewise for the marble-related posttest material, there was no significant difference in performance for the WT (M=2.70, SD=1.24) and MM (M=2.48, SD=1.03) conditions; t(74) 0.85, p=0.40.

The lack of significant difference on material relevant to the tinkering activity could be due to the variability in students' experiences of the open-ended activities. As a result, they may not have encountered the anticipated challenges and experiences that we geared the instructional material toward. To test whether this is the case, we include an analysis of performance on the pre-video questions, to take into account whether they encountered the experiences we had anticipated.

Factoring in students' performance on the pre-video questions, our prediction becomes about the interaction of condition with pre-video question: Students who tinkered in a particular activity *and* answered the activity-related pre-video question correctly should perform better on the related posttest material. This turned out to be the case for both conditions.

Looking first at the wind specific posttest scores, ANOVA reveals a significant interaction between condition and performance on the WT pre-video question, *F*(2, 72)=2.73, p=0.05. Figure 8 shows that students who tinkered with Wind Tubes *and* got the WT pre-video question correct performed better on the wind specific posttest items.

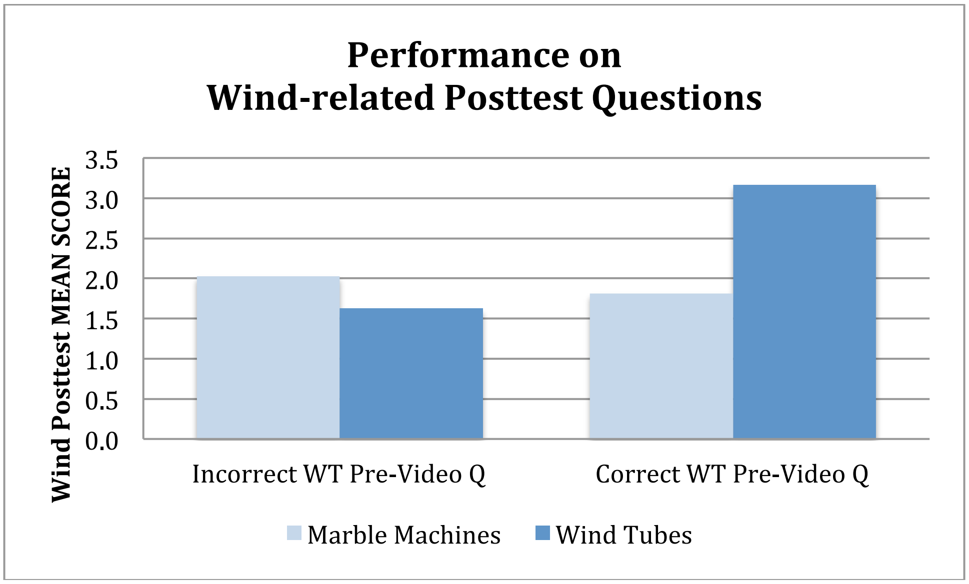


Figure 8. Performance on Wind Tubes related posttest items, clustered by condition and performance on WT pre-video question. Wind Tubes tinkerers performed the best, if they got the pre-video question correct.

Data analyses on the marble-related posttest questions showed a similar trend, but were less clear-cut (see Fig 9). ANOVA revealed a marginally significant interaction between condition and MM pre-video question, *F*(2, 72)=3.61, p=0.078. This was because the performance on the pre-video MM question alone was a better predictor of the combined Marble posttest score, *F*(2, 72)=5.30, p=0.024. Students who got the Marble Machines pre-video question correct (by mentioning the problem of the marble gaining too much speed) performed better on the marble-related posttest items. The conditions were less important for this one most likely because the pre-video and posttest questions were quite similar. If students mentioned increasing momentum/speed before the video, they were more likely to attend to this in the video as well.

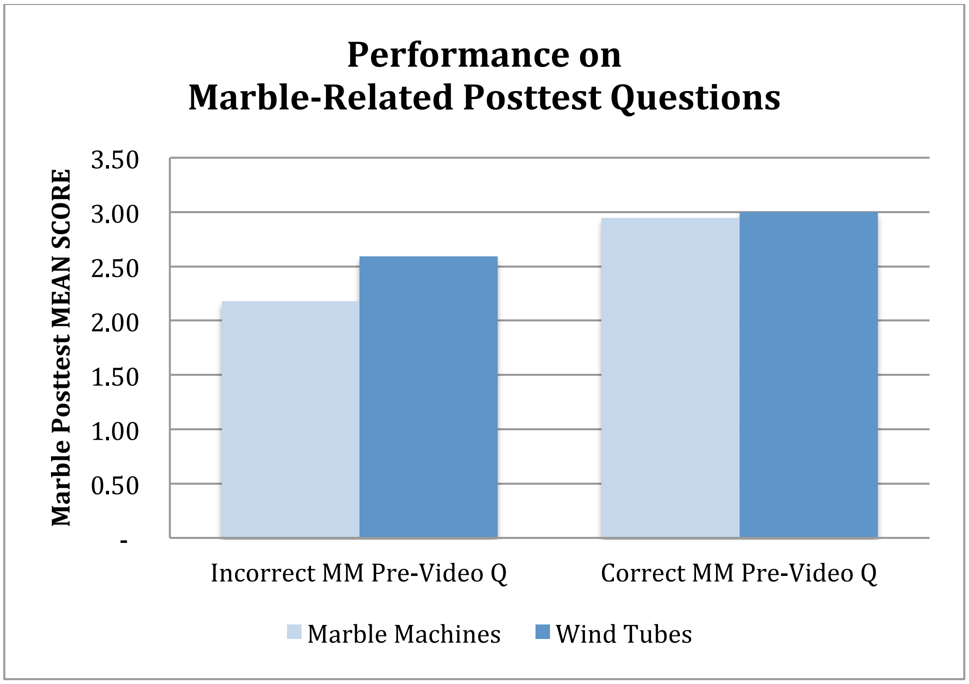


Figure 9. Performance on Marble Machines related posttest items, clustered by condition and MM pre-vid question. MM tinkerers performed the best, if they got the pre-vid Q.

While there was no overall condition effect, the interactions on pre-video and posttest questions by condition suggest that tinkering activities can prepare students to learn science content. The interaction was strong for the Wind Tubes condition, but only marginal for Marble Machines. To gain more insight into the nature of this learning, including the marginal interaction for Marble Machines, in the next sections we conduct separate analyses on both the abstract visualization tasks and the vocabulary questions.

Visual Representation Questions

Analyses of the interaction effect between condition and pre-video performance on just the visual representation questions indicate that if students correctly answered the pre-video question relevant to their tinkering activity, then they drew their respective visual representations correctly on the posttest (significant for both MM & WT).

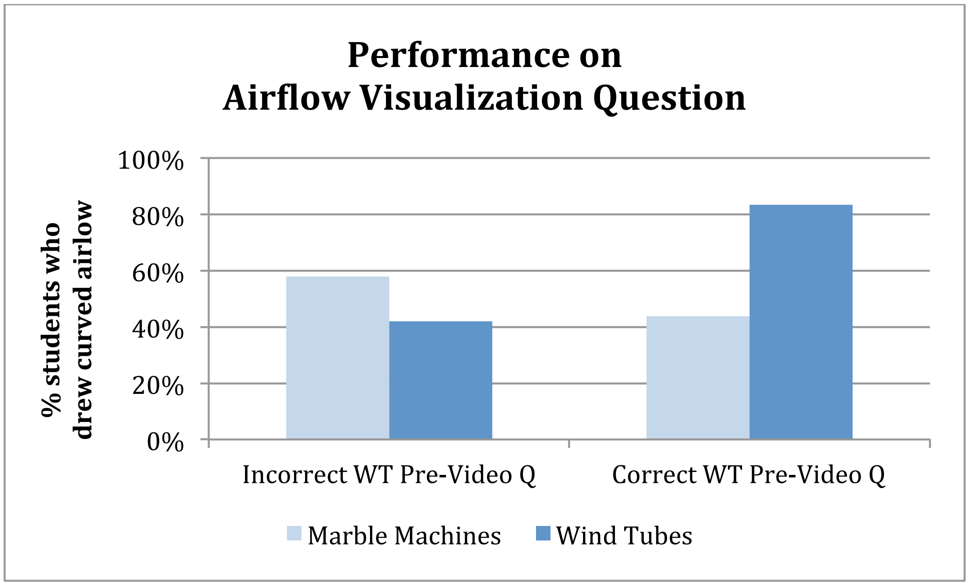


Figure 10. Performance on WT-related posttest question about curved airflow. Students in the WT condition performed best, but only if they got the WT pre-video question correct.

Figure 10 shows that students who tinkered in the Wind Tubes were most likely to correctly draw the airflow around a ping pong ball in the posttest, but only if they answered the WT-related pre-video question correctly (e.g., by choosing the correct orientation of a floating cup). On the other hand, Marble Machines students performed about the same on the airflow visualization question, regardless of their performance on the WT-related pre-video question. Thus it is not prior knowledge alone, but an interaction of relevant tinkering experience with knowledge prior to the video that predicts who is most likely to draw the airflow correctly. An ANOVA revealed that the interaction of condition with performance on the wind tubes pre-video question was significantly associated with performance on the posttest question about drawing airflow, $F(2,72)=3.21$, $p<.05$.

The corresponding interaction for the Marble Machines relevant question was also significant (Figure 11). Students were more likely to correctly draw the abstract representation of increasing momentum if they had done the Marble Machines tinkering activity *and* got the Marbles-related pre-video question correct. As we saw before, the conditions were less important than for the corresponding Wind Tubes posttest question, possibly because the pre-video and posttest questions were quite similar (increasing momentum/speed), but in this case the interaction was significant. An ANOVA reveals that the interaction with condition and pre-video question performance was significantly associated with successfully recreating the abstract representation of increasing momentum in the posttest question, $F(2,72)=3.23$, $p<.05$.

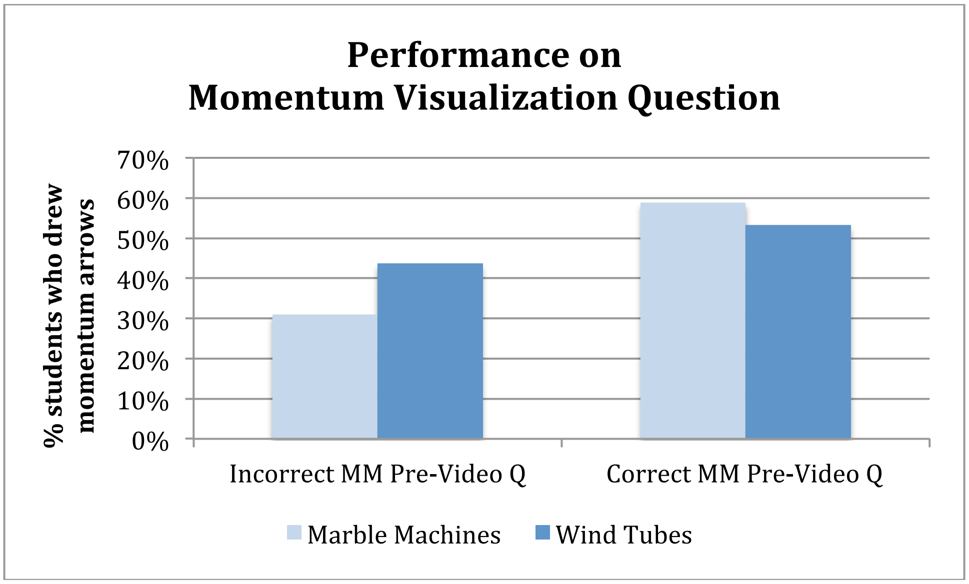


Figure 11. Performance on MM-related item on abstract visual representation of momentum. Students in the MM condition were most likely to recreate the representation, but only if they also got the MM pre-video question correct.

In summary, we found significant interactions in the expected directions between condition and pre-video score, which predicted performance on a posttest abstract representation task. For students in each condition, their respective tinkering activity prepared them to learn a relevant abstract representation from an instructional video. This provides a proof of concept that tinkering activities can prepare students to learn abstract visual representations.

Vocabulary Posttest Items

The vocabulary questions show a similar trend of interactions with condition & pre-video question (Figure 12), although these trends do not quite rise to significance.

For the Wind Tubes related vocabulary performance, an ANOVA shows that the interaction of condition and WT pre-video question is not quite significant, $F(3,72)=1.91$, $p=0.14$. The corresponding interaction for Marble Machines is also not significant, $F(3, 72)=0.79$, $p=0.50$.

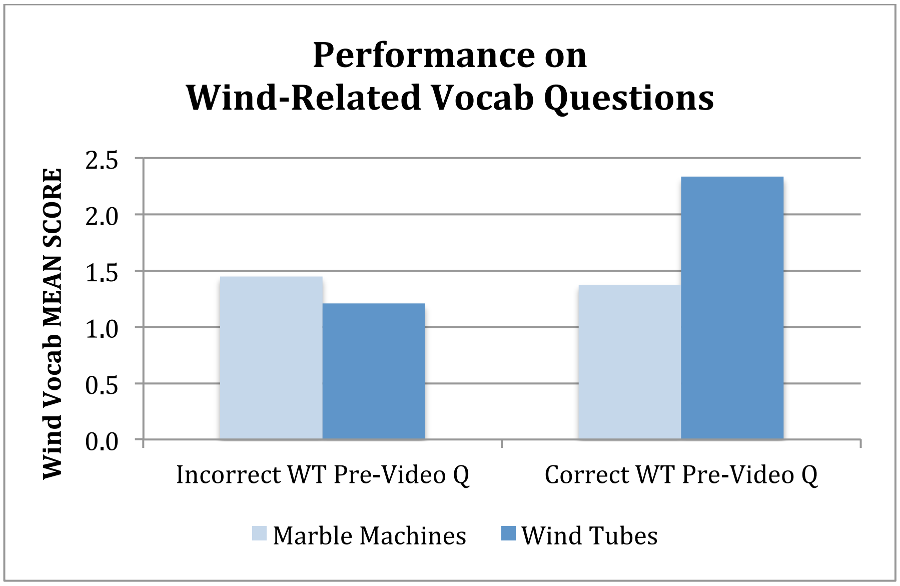


Figure 12 Performance on Wind Tubes related vocabulary questions, by condition and pre-video question performance. The same trend is there, but not quite significant.

Although these trends are not significant, they offer hints at future avenues for investigation of tinkering as PFL. The fact that they are not significant suggests that the interactions effects for MM- and WT-Posttest scores were driven by students' performance on the abstract visual representation tasks.

Discussion

While there were no overall condition effects on posttest performance, interactions on pre- and post-video questions by treatment condition provide evidence of preparation for future learning. Students who first tinkered with making things float in wind tubes accurately recreated an instructional video's abstract representation of wind flowing around a curved shape, but only if they correctly answered the wind-relevant pre-video question. Likewise, students who had tinkered with Marble Machines were more likely to accurately recreate the video's abstract representation of increasing momentum, but only if they had answered the marble-relevant pre-video question correctly. The significance of the corresponding interactions in each condition suggest that students' prior knowledge was not the driving factor for posttest performance, but rather that the tinkering experience prepared students to learn science content relevant to their experiences, as long as they encountered the problems we anticipated during tinkering.

As national policy shifts toward integrating science learning with engineering practices, as reflected in the Next Generation Science Standards, the need for evidence of the effectiveness of this approach is mounting. Yet, most studies have failed to demonstrate the reliable learning of science concepts through engineering and design projects. We suggest that part of the problem is the method of assessment. By using static assessments of science content, most approaches might be missing the way students can learn science through designing and tinkering with materials, the benefit of which may not show up until a later opportunity for learning. In this preliminary study we have demonstrated evidence of the preparation for future science learning afforded by tinkering activities.

A symbiosis of formal & informal learning environments

A central goal of informal learning environments such as museums is to offer their visitors rich and compelling experiences, driven by the learners' own choices and interests. Tinkering and making spaces, for instance, can give visitors compelling experiences with physical phenomena through open-ended exploration with materials. Meanwhile a central goal of science classrooms is to offer explanations of phenomena in terms of scientific concepts and terminology. This difference can be a source of tension, or synergy. One source of tension that has been previously unexamined arises from the common approach of assessing understanding of science concepts immediately after a visit to the museum. Instead, we look for evidence that students' experiences on a museum field trip can prepare them to learn from later instruction on science concepts once they return to their classrooms. This design leveraged the goals of formal and informal contexts to help students learn more than they would have from either environment alone, highlighting the synergy between these contexts rather than the tension.

At a broader level, there is a potential tension between museum experiences, which are based on free-choice and open-ended activities (including tinkering), and conducting quasi-experimental research on learning, which necessitates randomly assigned conditions and specific learning targets. We have found ways to alleviate this tension, but not take it away completely. As a result, some limitations arose which could limit the amount of signal we picked up in this preliminary study, and which we will attempt to address in follow-up studies. For instance, we were not able to truly randomize the assignment to conditions, although we were able to check that the posttest was fair for both conditions. Also, due to time constraints at the school, we could not administer a pre-tinkering assessment, and could not administer the PFL assessments until two weeks after the tinkering experience. We were able to account for prior knowledge for some extent without a pretest, by administering pre-video questions relevant to the tinkering experience before having both conditions watch the same video, but we only had time to include one pre-video question per condition.

Overall, the results presented here provide an existence proof that tinkering activities can prepare students to learn relevant science content at a later date. Specifically, the results suggest that students who tinkered were prepared to learn an abstract representation of the phenomenon, but only if they experienced the anticipated challenges during tinkering. Due to the open-ended nature of tinkering, students may be working towards a different goal from the anticipated one (e.g., building an object that spins, rather than flies out of the wind tube), making it harder to anticipate which concepts tinkerers are prepared to learn, a challenge for future studies to address.

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