Comparing Students' Performance with Physical and Virtual Manipulatives in a Simple Machines Curriculum

Jacquelyn J. Chini, Adrian Carmichael, N. Sanjay Rebello and Elizabeth Gire
Kansas State University
Sadhana Puntambekar
University of Wisconsin, Madison

Please address all correspondence to:
Jacquelyn J. Chini
Kansas State University
Physics Department
116 Cardwell Hall, Manhattan, KS 66506
785-532-7167 - Phone
785-532-6806 - Fax
haynicz@phys.ksu.edu

Paper presented at the
Annual Meeting of the American Educational Research Association
Denver, April 30-May 4, 2010

Comparing Students' Performance with Physical and Virtual Manipulatives in a Simple Machines Curriculum

Jacquelyn J. Chini, Adrian Carmichael, N. Sanjay Rebello and Elizabeth Gire
Kansas State University
Sadhana Puntambekar
University of Wisconsin, Madison

We compare the effects of physical versus virtual manipulatives in an inclined plane curriculum for students enrolled in a conceptual-based introductory physics laboratory. ANCOVA with pre-test score as a covariate showed that post-test scores for students who completed activities about length and height with virtual manipulatives (M=.775, SD=.026) were significantly higher than those of students who performed the same activities with physical manipulatives (M=.662, SD=.019), F(1,63)=13.5, p<.001, r=.43. Individual post-test questions that attributed to performance spread are identified and analyzed. We then analyze the manipulatives through the lens of dynamic transfer in an effort to explain the difference in students' performance.

Background and Introduction

This study contributes to the ongoing research in physics education of how student learning is supported by interaction with physical and virtual manipulatives. This question has been the focus of several studies where students used traditional physical equipment or a computer simulation to perform analogous experiments. The literature has shown mixed results about the relative effectiveness of the physical and virtual manipulatives.

In some studies, researchers have found students who performed virtual experiments did better on the assessment than students who performed an analogous physical experiment. For example, Finkelstein *et al.* (2005) compared how students enrolled in an algebra-based introductory physics course learned about circuits while performing physical or virtual experiments. Researchers found that students who used the simulation could build a physical circuit quicker, had better explanations of circuit behavior, and performed better on related exam questions than students who used physical equipment. Zacharia and colleagues (Zacharia, 2007; Zacharia, Olympiou, & Papaevripidou, 2008) studied how pre-service teachers' ideas and understanding changed after performing physical and virtual experiments on the topics of circuits and heat and temperature. Researchers found that students who performed virtual experiments had higher post-test scores and a higher prevalence of scientifically correct conceptions than students who performed physical experiments.

In other studies, however, researchers have found no difference between students who performed experiments with physical equipment or simulations. In these studies, researchers tried to control for some of the potential advantages of the virtual manipulatives by controlling the time on task. For example, Zacharia and Constantinou (2008) repeated their study of students' learning about heat and temperature and gave the students in the physical condition preset equipment. In this case, they found no difference between students' post-test scores or the prevalence of conceptions between the two groups. Klahr, Triona and Williams (2007) compared how students learned about mousetrap cars after performing design experiments with physical equipment or a computer simulation. Students were limited to either a certain length of time or a certain number of trials. The researchers found no difference in the students' conceptual change, their ability to design cars, or their confidence in their knowledge.

Even when some potential advantages of the virtual manipulatives were controlled, experiments performed by computer simulation appear to promote student learning as effectively as experiments performed with traditional physical equipment. Zacharia and Constantinou (2008) have called for more research to understand how physical and virtual manipulatives should be integrated in physics curricula.

This study provides another step toward increasing the knowledge base in this area. In this study, we compared the effect of physical and virtual experimentation on student learning about inclined planes. We ask, how does the pre/post-test performance of students using physical manipulatives compare to that of students using virtual manipulatives?

Theoretical Perspective

We hold a constructivist view of learning (Piaget, 1964; Vygotsky, 1978), which posits that students construct their own understanding. Triona and Klahr (2003) have pointed out that while constructivist theory suggests students must be actively involved in the process of learning, active involvement does not require physical manipulation.

We also believe students may engage in dynamic transfer during the learning process. Schwartz, Varma, and Martin (2008) distinguish between similarity transfer, involving application of well-formed concepts to a new situation, and dynamic transfer, involving application of component competencies in an environment to yield new concepts. In similarity transfer the environment cues the retrieval of intact prior knowledge, while in dynamic transfer the environment coordinates different components of prior knowledge. An environment supporting dynamic transfer allows for distributed memory, affords alternative interpretations and feedback, offers candidate structures by constraining and structuring actions, and provides a focal point for coordination.

Reviewing the literature on the use of computers in physics experiments, we have built a "master list" of the reasons why computers can potentially be effective learning tools. Thornton and Sokoloff (1990), who successfully used microcomputer-based labs (MBLs) in a kinematics curriculum, suggested five important characteristics. Students focused on the physical world, immediate feedback was available, collaboration was encouraged, tools reduced drudgery, and students moved from the specific and familiar to the more general and abstract. Redish, Saul, and Steinberg (1997), who successfully used MBLs in mechanics, agreed and added to the above list the conjecture that students were actively involved in exploring and constructing their own understanding. Finkelstein *et al.* (2005) successfully used a simulation to replace a physical circuits lab. They noted that the simulation was successful because it made visible models that were useful for forming concepts and constrained students in productive ways.

The characteristics for successful simulations and dynamic transfer are summarized in Table 1. We find significant overlap between the properties of successful computer use and the characteristics of an environment supportive of dynamic transfer, as shown in Table 2. The remaining three properties for successful computer use are more general views of learning. For example, C6 relates to a constructivist view of learning.

TABLE 1

Characteristics identified for successful simulations (C) and dynamic transfer (DT).

Properties of Successful Computer Use	**Characteristics of Environment for Dynamic Transfer**
C1. Focus on the physical world.	DT1. Allows for distributed memory.
C2. Immediate feedback is available.	DT2. Offers alternative interpretations and feedback.
C3. Collaboration is encouraged.	DT3. Offers candidate structures by constraining and structuring actions.
C4. Powerful tools reduce drudgery.	DT4. Provides a focal point for coordination of different knowledge pockets.
C5. Understand the specific and familiar before moving to the more general and abstract.	
C6. Students are actively engaged in exploring and constructing their own understanding.	
C7. Useful models for forming concepts are made visible.	
C8. Students are constrained in productive ways.	

TABLE 2

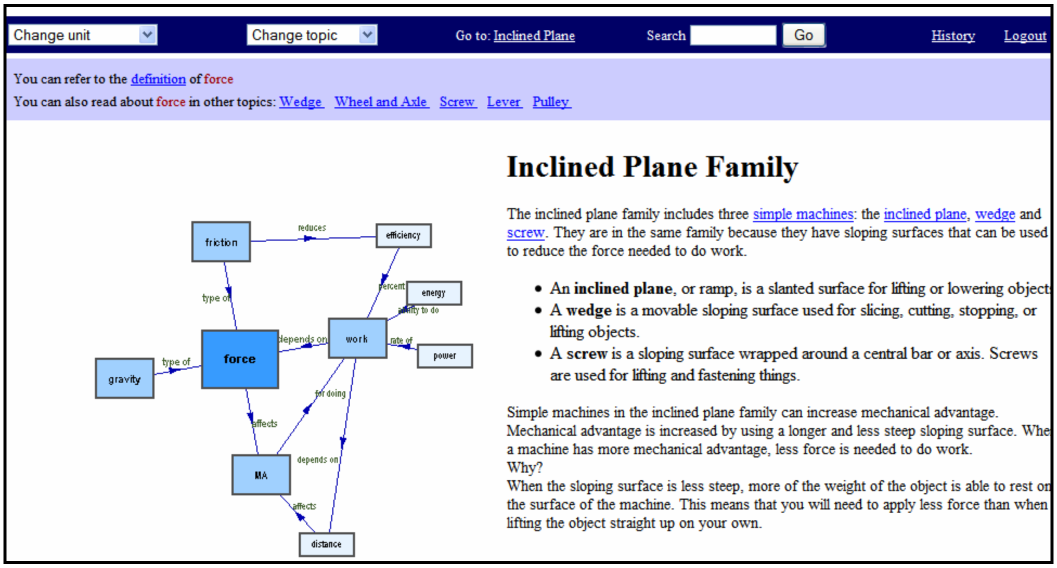
Alignment between dynamic transfer and computer use characteristics.

Dynamic Transfer Characteristic	**Aligned Computer Use Property**
DT1	C4
DT2	C2
DT3	C8
DT4	C5, C7

Methods

The CoMPASS (Concept Map Project-based Activity Scaffolding System) curriculum for inclined planes was used in the laboratory of a conceptual-based physics course (Puntambekar & Stylianou 2005). The CoMPASS curriculum combines design-based and project-based activities with an interactive hypertext system. Students used the hypertext system, shown in Figure 1 below, to explore the science concepts related to simple machines.

The inclined planes curriculum includes activities where students explore the effects of changing the length, height, and surface of the plane using physical or virtual manipulatives. The physical manipulatives included boards of different lengths, bricks to create different heights, and sandpaper to change the board's surface. Students measured distances with a meter stick, measured forces with a spring scale, and calculated work, mechanical advantage, and change in potential energy. The virtual manipulatives were web-based simulations. An example of the simulation for the length activity is shown in Figure 2 below. Students could use the sliders to vary the ramp length, ramp height, load and friction. The simulation allowed them to input up to the minimum force to lift the load.



You can refer to the definition of force

You can also read about force in other topics: Wedge Wheel and Axle Screw Lever Pulley

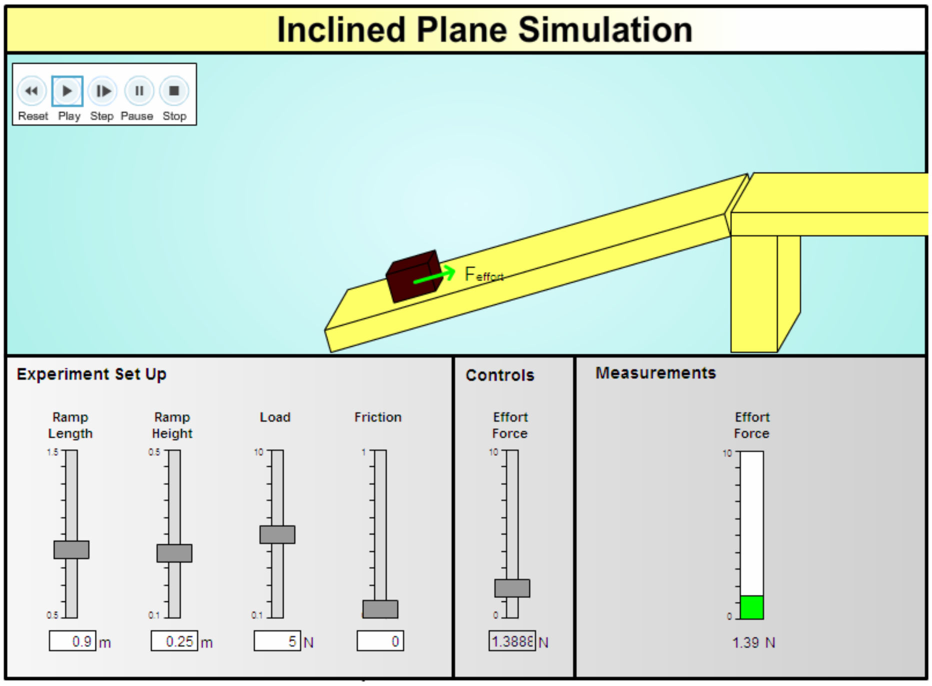
Inclined Plane Family

The inclined plane family includes three simple machines: the inclined plane, wedge and screw. They are in the same family because they have sloping surfaces that can be used to reduce the force needed to do work.

- An **inclined plane**, or ramp, is a slanted surface for lifting or lowering object
- A **wedge** is a movable sloping surface used for slicing, cutting, stopping, or lifting objects.
- A **screw** is a sloping surface wrapped around a central bar or axis. Screws are used for lifting and fastening things.

Simple machines in the inclined plane family can increase mechanical advantage. Mechanical advantage is increased by using a longer and less steep sloping surface. Whe a machine has more mechanical advantage, less force is needed to do work.
Why?
When the sloping surface is less steep, more of the weight of the object is able to rest on the surface of the machine. This means that you will need to apply less force than when lifting the object straight up on your own.

FIGURE 1. *CoMPASS online hypertext system.*



Ramp Length 0.9 m
Ramp Height 0.25 m
Load 5 N
Friction 0
Effort Force 1.3888 N
Effort Force 1.39 N

FIGURE 2. *Inclined plane simulation for length experiment.*

The CoMPASS inclined planes curriculum was used in an in-class implementation in a conceptual-based physics laboratory. The laboratory had five sections, ranging in size from 23 to 37 students on the day of the implementation, and each section met for two hours. The sections were assigned to the physical or virtual condition in order to make the total number of students in each condition as close as possible. Thus, three sections used physical manipulatives for the activities and two sections used virtual manipulatives. Due to time constraints, the students were only able to complete two of the three activities, either length and height experiments or length and friction experiments. The experimental design is summarized in Table 3. Students worked through worksheets in groups of two to four students, and a teaching assistant and researcher were available to answer students' questions.

TABLE 3
Experimental design.

Manipulative Type	Activities	N
Physical	Length/Height	29
Virtual	Length/Height	37
Physical	Length/Friction	23
Physical	Length/Friction	31
Virtual	Length/Friction	30

Because the same curriculum was used with only the activities changed, we were able to control for confounding factors such as curriculum and method of instruction. Students in the physical and virtual treatments spent similar amounts of time on task. There were some variations in the resource capabilities, as the simulation calculated work and potential energy for the students and displayed them as bar graphs.

In this paper, we will focus specifically on students' performance on a conceptual test about the science concepts related to inclined planes. The test had 16 multiple-choice questions covering concepts such as force, work, mechanical advantage and potential energy. Six questions focused on force, four questions on work, three questions on mechanical advantage, and three questions on potential energy.

Results

The mean and standard deviation (S.D.) for the pre-test and post-test from each section are shown in Table 4 below.

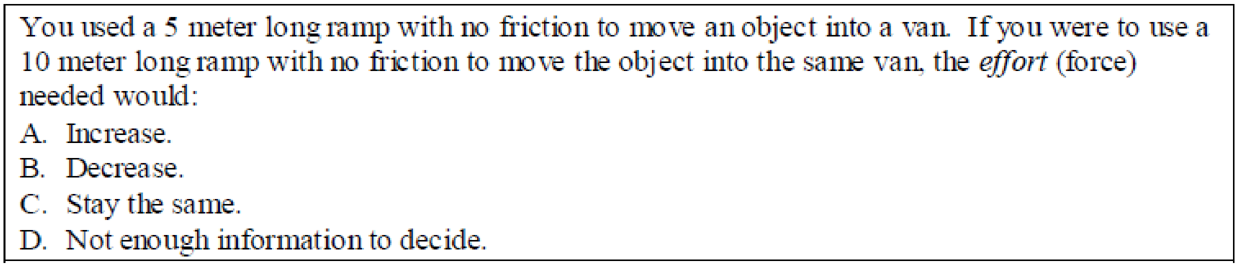
TABLE 4
Pre-test and post-test performance by section.

Section	Pre-test Mean	Pre-test S.D.	Post-test Mean	Post-test S.D.
Length/Height Physical	59.9%	13.8%	66.2%	10.2%
Length/Height Virtual	60.0%	13.7%	77.5%	15.8%
Length/Friction Physical	59.2%	17.8%	66.0%	12.2%
Length/Friction Physical	60.1%	13.6%	65.9%	10.7%
Length/Friction Virtual	56.7%	15.5%	67.1%	13.6%

Because students could only perform two of the three activities, we separately compared post-test scores of students who performed the length and height activities and students who performed the length and friction activities. We compared the post-test scores of students who used physical or virtual manipulatives to perform the same activities with their pre-test score as a covariate. For students who performed the length and height activities, pre-test score was significantly related to post-test score, $F(1, 63)=15.2$, $p<.001$, $r=.44$. After controlling for the pre-test score, there was a significant effect of manipulative (physical or virtual), $F(1, 63)=13.5$, $p<.001$, $r=.42$. For students who performed the length and friction activities, pre-test score was significantly related to post-test score, $F(1, 78)=17.5$, $p<.001$, $r=.43$. However, after controlling for the pre-test score, there was no significant effect of manipulative (physical or virtual), $F(1, 78)=.735$, $p=.394$. In summary, post-test score was affected by the type of manipulative used for students who completed the length and height activities but not for students who completed the length and friction activities. Comparing the post-test scores of the physical and virtual treatments for the length and height activities, we see students who performed the activities with virtual manipulatives had significantly higher scores than students who used physical manipulatives.

We examined the post-test questions to see which led to the difference in performance between the physical and virtual length and height students. We identified four questions for which the difference between percentages of students responding correctly from the two groups was 20% or more. We describe these questions and analyze students' performance on the post-test using Pearson's chi-square below.

Question 6 is shown in Figure 3 below. Students were asked what would happen to the work needed to move a pool table into a van if a 5 meter long frictionless ramp were changed to a 10 meter long frictionless ramp. The choices and percentage of students choosing each are shown in Table 5. The majority of students who used the virtual manipulatives correctly selected "stay the same." However, the majority of students who used the physical manipulatives incorrectly selected that the work would increase. Pearson's chi-square test showed a significant association between the type of manipulative and whether students got Question 6 correct, $\chi^2(1)=21.1$, $p<.001$. Students who used the simulation were 13.9 times more likely to get this question correct than students who used the physical equipment.



You used a 5 meter long ramp with no friction to move an object into a van. If you were to use a 10 meter long ramp with no friction to move the object into the same van, the *effort* (force) needed would:

A. Increase.
B. Decrease.
C. Stay the same.
D. Not enough information to decide.

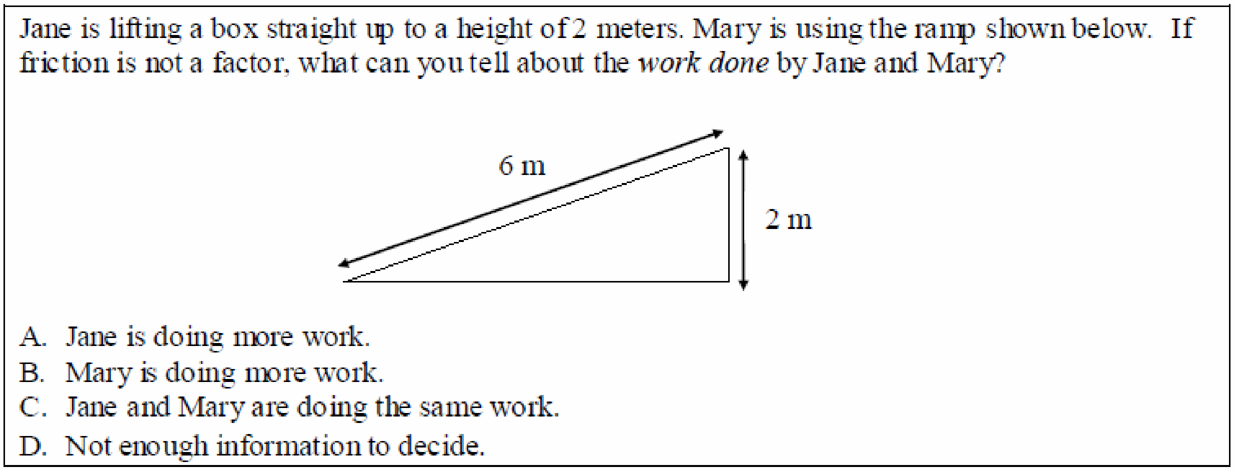
FIGURE 3. *Question 6.*

TABLE 5

Responses to question 6 (correct response in bold).

Answers to Q6	Length/Height Physical	Length/Height Virtual
A. Increase	55%	11%
B. Decrease	24%	11%
C. Stay the same	**21%**	**78%**
D. Not enough information	0%	0%

Question 7 is shown in Figure 4 below. Students were asked to compare the work required to lift a box to a certain height using a ramp with that of the work required to lift the same box to the same height without a ramp. The results are shown in Table 6. This question seems to have been difficult for both groups. More students who used the virtual manipulatives correctly selected “both require same work,” but an equal number selected “no ramp requires more work.” The students who used physical manipulatives were spread out among most of the choices. Pearson’s chi-square test showed a significant association between the manipulative and whether students got Question 7 correct, $\chi^2(1)=5.5$, $p=.019$. Students who used the simulation were 3.6 times more likely to get this question correct than students who used the physical equipment.



Jane is lifting a box straight up to a height of 2 meters. Mary is using the ramp shown below. If friction is not a factor, what can you tell about the *work done* by Jane and Mary?

A. Jane is doing more work.
B. Mary is doing more work.
C. Jane and Mary are doing the same work.
D. Not enough information to decide.

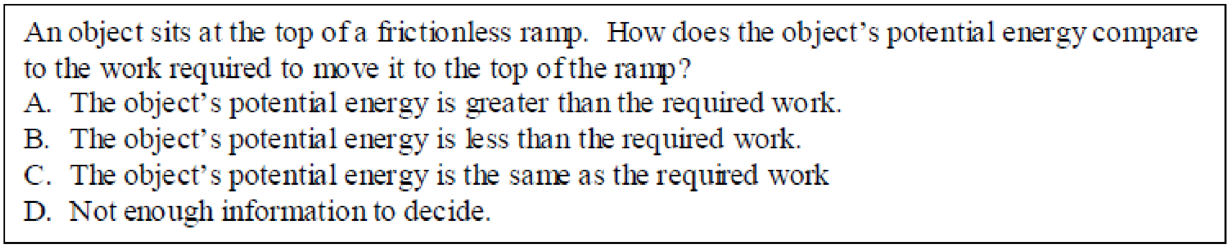
FIGURE 4. *Question 7.*

TABLE 6

Responses to question 7 (correct response in bold).

Answers to Q7	Length/Height Physical	Length/Height Virtual
A. No ramp requires more work	38%	49%
B. Ramp requires more work	38%	3%
C. Both require same work	**21%**	**49%**
D. Not enough information	3%	0%

Question 14 is shown in Figure 5 below. Students were asked to compare the work required to lift an object using a frictionless ramp to the object’s potential energy once lifted (assuming the group as the zero point of potential energy). The results are shown in Table 7. The majority of students who used virtual manipulatives correctly selected “potential energy is the same as the required work.” However, the majority of students who used physical manipulatives selected “potential energy is less than the required work.” Pearson’s chi-square test showed a significant association between the manipulative and whether students got Question 14 correct, $\chi^2(1)=44.8$, $p<.001$. Students who used the simulation were 177.8 times more likely to get this question correct than students who used the physical equipment.



An object sits at the top of a frictionless ramp. How does the object’s potential energy compare to the work required to move it to the top of the ramp?

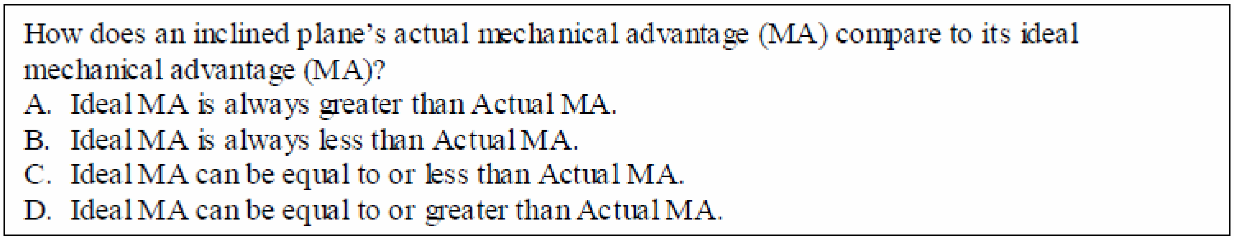
A. The object’s potential energy is greater than the required work.
B. The object’s potential energy is less than the required work.
C. The object’s potential energy is the same as the required work
D. Not enough information to decide.

FIGURE 5. *Question 14.*

TABLE 7
Responses to question 14 (correct in bold).

Answers to Q14	Length/Height Physical	Length/Height Virtual
A. Potential energy > Work	28%	8%
B. Potential energy < Work	69%	0%
C. Potential energy = Work	**3%**	**86%**
D. Not enough information	0%	5%

Question 15 is shown in Figure 6 below. Students were asked to compare an inclined plane’s actual and ideal mechanical advantages. The results are shown in Table 8. The majority of students who used virtual manipulatives correctly selected “ideal MA can be equal or greater than actual MA.” However, the majority of students who used physical manipulatives selected “ideal MA is always greater than actual MA.” Pearson’s chi-square test showed no significant association (at the level p=.05) between the type of manipulative and whether students got Question 15 correct, $\chi^2(1)=3.02$, $p=.082$. However, students who used the simulation were 2.5 times more likely to get this question correct than students who used the physical equipment.



How does an inclined plane’s actual mechanical advantage (MA) compare to its ideal mechanical advantage (MA)?

A. Ideal MA is always greater than Actual MA.
B. Ideal MA is always less than Actual MA.
C. Ideal MA can be equal to or less than Actual MA.
D. Ideal MA can be equal to or greater than Actual MA.

FIGURE 6. *Question 15.*

TABLE 8

Responses to question 15 (correct in bold).

Answers to Q15	Length/Height Physical	Length/Height Virtual
A. Ideal MA > Actual MA	48%	22%
B. Ideal MA < Actual MA	14%	8%
C. Ideal MA ≤ Actual MA	10%	22%
D. Ideal MA ≥ Actual MA	**28%**	**49%**

Discussion

Students' performances on Q6, Q14, and Q15 can be linked to the type of manipulatives they used. Students who performed the length and height activities with virtual manipulatives only saw a frictionless environment, while students who performed the same experiments with physical manipulatives always had friction present. Thus, the choices selected by the majority of students in both groups make sense. Students who had performed the physical experiments tended to answer the questions according to their data from the physical experiment, which is not specialized to a frictionless environment. These students did have the opportunity to read about how work, potential energy, and mechanical advantage would be affected by a frictionless environment in the CoMPASS hypertext system. However, from students' answers, it appears they relied more heavily on their experiences in the experiments when responding to the test questions.

As stated previously, Q7 seems to have been difficult for both groups. The responses chosen are not explained by the presence or absence of friction. We compared the physical experiment with the simulation to determine whether there might have been additional reasons the students who used virtual manipulatives outperformed the students who used physical manipulatives. We focused specifically on how each set of manipulatives met the characteristics of an environment for dynamic transfer (Schwartz, *et. al.*, 2008) discussed in the theoretical perspective above. Thus, we have assessed the extent to which the manipulatives allow for distributed memory, offer feedback and alternative interpretations, constrain and structure possible actions, and provide a focal point for coordination. The length simulation is displayed in Figure 2 above and the height simulation is shown in Figure 7.

In Figure 3 we see that the simulation calculated work and potential energy for the students and displayed them as bar charts, thus allowing for distributed memory. In the physical experiment, students calculated these values themselves and recorded them in a data table. Perhaps the additional scaffolding provided by the bar graphs benefited the virtual manipulative students. Additionally, the bar charts in the simulation offer feedback and alternative interpretations more quickly than the data tables used in the physical experiment.

The simulation also constrains and structures possible actions more than the physical experiment. In the simulation, students change the length and height of the inclined plane simply by moving the associated slider. In the physical experiment, students have to set up and measure the inclined plane themselves and have a limited number of variations to explore. They sometimes have difficulty determining where along the inclined plane to measure the height. Also, in the simulation the load is moved at a constant velocity to assure an accurate force reading while in the physical experiment students move the load themselves. They may accelerate the load and cause an inaccurate force reading.

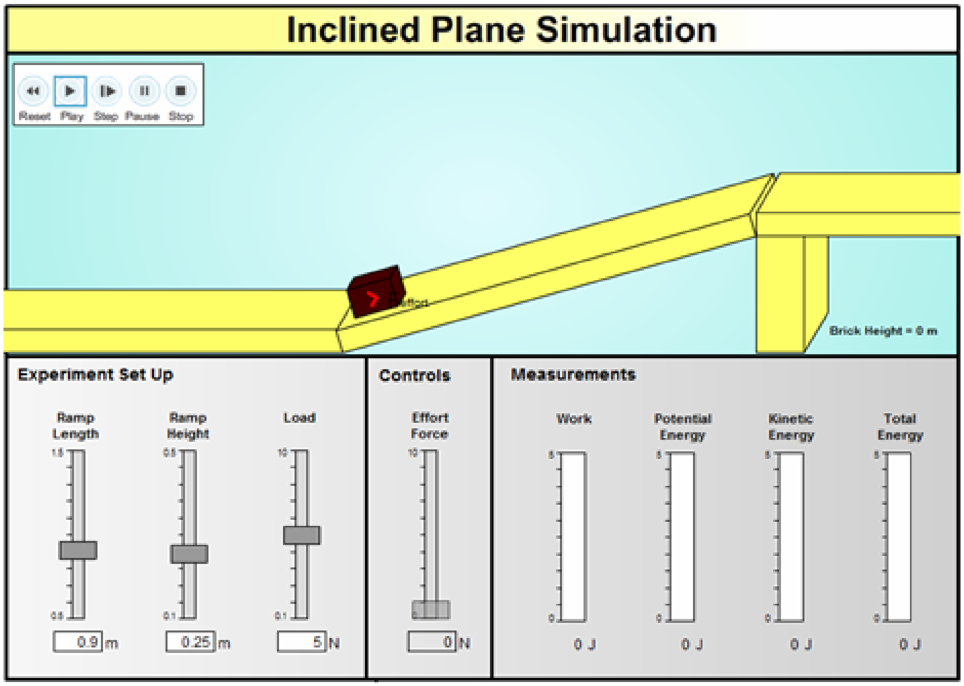


FIGURE 7. *Inclined plane simulation for height activity.*

The simulation also constrains and structures possible actions more than the physical experiment. In the simulation, students change the length and height of the inclined plane simply by moving the associated slider. In the physical experiment, students have to set up and measure the inclined plane themselves and have a limited number of variations to explore. They sometimes have difficulty determining where along the inclined plane to measure the height. Also, in the simulation the load is moved at a constant velocity to assure an accurate force reading while in the physical experiment students move the load themselves. They may accelerate the load and cause an inaccurate force reading.

Finally, the inclined plane simulation provides a focal point for coordination by displaying the relevant physics concepts all in one place. Because concepts such as force, work, and potential energy are pictured together, the students can more easily see how they relate. Students can quickly see how changing the plane's length affects the work required to move the load. While students who performed the physical experiment were also asked to think about how these concepts were related, they were not provided the same visual comparison as in the simulation.

Summary and Future Work

This study compared how students' learning about the science concepts related to inclined planes was supported by experimentation with physical and virtual manipulatives. Due to time constraints, students either performed activities about how length and height or length and friction related to the inclined plane. Analysis of students' performance on a multiple-choice conceptual test about the science concepts related to inclined planes revealed no significant difference in performance between the scores of students who completed the length and friction activities using either the physical equipment or the computer simulation. However, when students performed length and height activities, students who used the computer simulation had significantly better post-test scores than students who used the physical equipment.

Further analysis of students' performance on specific questions revealed four main questions that led to the performance difference between the students who completed the length and height activities. For three of these questions, the answers students selected can be tied to the manipulatives they used, with students who had used physical equipment answering as though friction were present. For the remaining question, the type of manipulative used cannot explain students' answers.

We presented the theory of an environment supportive of dynamic transfer (Schwartz, *et. al.*, 2008) as a possible framework for comparing the support offered by the physical equipment and computer simulation. As described above, the criteria specified for an environment to support dynamic transfer align closely with properties of successful computer use outlined in the physics education research literature. When we analyzed the physical and virtual manipulatives through this lens, we found the virtual equipment offered better support by allowing for distributed memory, providing alternative interpretations and feedback, offering candidate structures by constraining and structuring actions, and providing a focal point for coordination. Thus, the framework of dynamic transfer may be helpful for explaining how physical and virtual manipulatives differently support students' learning.

More research is needed to investigate whether there are added benefits from performing physical and virtual experiments for the same activity. For example, if students performed the length experiment with physical equipment and then repeated it with the computer simulation, would their learning be enhanced beyond using the computer simulation alone? In addition, it would be useful to analyze students' actual interaction with the manipulatives through the lens of dynamic transfer.

REFERENCE LIST

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Kohl, K. K., Podolefskey, N.S., et al. (2005). When Learning about the Real World is Better Done Virtually: A Study of Substituting Simulations for Laboratory Equipment. *Physical Review Special Topics-Physics Education Research*, *1,* 010103-1--010103-8.

Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on What? The Relative Effectiveness of Physical Versus Virtual Materials in an Engineering Design Project by Middle School Children. *Journal of Research in Science Teaching, 44*(1), 183-203.

Piaget, J. (1964). Part I: Cognitive Development in Children: Piaget Development and Learning. *Journal of Science Education and Technology, 2*(3), 176-186.

Puntambekar, S. & Stylianou, A. (2005). Designing Navigation Support in Hypertext Systems Based on Navigation Patterns. *Instructional Science*, *33*, 451-481.

Redish, E. F, Saul, J. M., & Steinberg, R. N. (1997). On the Effectiveness of Active-engagement in Microcomputer-based Laboratories. *American Journal of Physics, 65*(1), 45-54.

Schwartz, D.L., Varma, S., & Martin, L. (2008). Dynamic Transfer and Innovation. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 497-506). New York: Routledge.

Thornton, R. K., & Sokoloff, D. R. (1990). Learning Motion Concepts Using Real-time Microcomputer-based Laboratory Tools. *American Journal of Physics, 58*(9), 858-867.

Triona, L. M. & Klahr, D. (2003). Point and Click or Grab and Heft: Comparing the Influence of Physical and Virtual Instructional Materials on Elementary School Students' Ability to Design Experiments. *Cognition and Instruction 21*(2), 149-173.

Vygotsky, L. S. (1978). *Mind in Society: Development of Psychological Processes* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Cambridge: Harvard University Press.

Zacharia, Z. C. (2007). Comparing and Combining Real and Virtual Experimentation: An Effort to Enhance Students' Conceptual Understanding of Electric Circuits. *Journal of Computer Assisted Learning*, *23*(2), 120-132.

Zacharia, Z. C. & Constantinou, C. P. (2008). Comparing the Influence of Physical and Virtual Manipulatives in the Context of the Physics by Inquiry Curriculum: The Case of Undergraduate Students' Conceptual Understanding of Heat and Temperature. *American Journal of Physics, 76*(4&5), 425-430.

Zacharia, Z. C., Olympiou, G., & Papaevripidou, M. (2008). Effects of Experimenting with Physical and Virtual Manipulatives on Students' Conceptual Understanding in Heat and Temperature. *Journal of Research in Science Teaching, 45*(9), 1021-1035.