Comparing Students' Performance and Reasoning with Physical and Virtual Manipulatives to Learn about Pulleys

Jacquelyn J. Chini[1], Amy Rouinfar[2], Adrian Carmichael[1], N. Sanjay Rebello[1,] and Sadhana Puntambekar[3]

[1]Kansas State University

[2]Florida State University

[3]University of Wisconsin

Abstract

Approximately 130 students performed experiments with physical (PM) and virtual pulley manipulatives (VM) as part of an introductory conceptual-based physics laboratory ("in-class study"). These students completed a pre-test before instruction, a mid-test after performing one set of experiments (physical or virtual), and a post-test after all instruction. In a separate study, we interviewed 13 introductory physics students about questions related to the tests used in the in-class study ("interview study"). We have used the results of the in-class study mid-test to identify questions for further analysis in the interview study. We present the analysis of one question where students who used PM outperformed students who used VM, one question where VM students outperformed PM students, and one question where there was no performance difference. Our results suggest the PM and VM may offer different support for learning different concepts by activating and deactivating different conceptual resources.

Background and Introduction

In this study, we examine the benefits of physical and virtual manipulatives in assisting student learning about pulleys. Previous studies have shown mixed results about the comparative effectiveness of physical and virtual manipulatives. Many studies (e.g. Zacharia, Olympiou, & Papaevripidou, 2008 ; Finkelstein, et al., 2005) have found simulations outperform analogous physical experiments. However, when the speed of manipulation was controlled, other studies (e.g. Klahr, Triona, & Williams, 2007; Zacharia & Constantinou, 2008) have shown no difference in learning using physical or virtual manipulatives. Klahr, Triona and Williams (2007) have suggested that when no learning difference is observed as a result of using physical or virtual manipulatives, other characteristics of the materials, such as the ease of development and implementation, should be the basis for which to use. Still, no definitive characteristics have been identified to assist educators in determining which type of manipulative will be the most effective in a particular learning situation. Zacharia and Constantinou (2008) have called for more research on how physical and virtual manipulatives should be integrated in a physics curriculum.

We aim to add to the existing knowledge base by investigating whether there is a difference in students' understanding of the physics concepts related to pulleys when they perform experiments with physical or virtual pulley manipulatives. We will address this question in two ways:

1) Is there a difference in understanding as measured by students' performance on a multiple choice test?

2) Is there a difference in understanding as measured by students' verbal explanations and reasoning?

Theoretical Underpinnings

We hold a constructivist view of learning which posits that students construct their own understanding. Triona & 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 the context plays an important role in activating the ideas students use in a learning situation. Hammer's (2000) model of conceptual resources asserts that students bring many potentially useful ideas, or resources, to each learning situation. The context will activate particular resources, which the students then use to construct their understanding. For example, the context of the physical manipulatives may activate resources for explaining the kinesthetic sensations of the experiment. On the other hand, the context of the virtual manipulatives may activate resources for explaining the data as presented in graphs. Rebello, et al., (2005) has suggested a model of transfer in which students actively construct associations between prior knowledge in their memory and new information acquired through external inputs. Since different external inputs are provided by different contexts, the context will affect the associations that students construct. Both Hammer's model of conceptual resources and Rebello's model of transfer suggest the context, here physical or virtual manipulatives, directly affects student learning.

Curriculum

All students in this study used the CoMPASS (Concept Mapped Project-based Activity Scaffolding System) curriculum to learn about pulleys. Students begin by reviewing what they already know about pulleys by describing the factors they think will affect the force and work needed to lift an object using a pulley setup. Next they develop a list of questions about pulleys that they would like to explore and search for the answers in the CoMPASS online hypertext system as shown in Figure 1. The hypertext system allows students to use concept maps or in-text links to navigate through the science concepts related to pulleys. Students then performed a series of experiments to test how different pulley setups affect the force and work needed to lift an object, as well as the distance pulled to lift the object, the mechanical advantage of the setup, and the object's potential energy. After performing the experiments, students answered analysis questions about the science concepts they had investigated in the experiments.

Students used physical and/or virtual manipulatives to perform the experiments. The physical manipulatives included real pulleys, string, a mass, a spring scale and a meter stick, as shown in the right side of Figure 2. Using the physical manipulatives, students had to build their own pulley setups (single fixed, single movable, single compound and double compound) and make their own measurements of the length of string pulled and force required to lift the mass. They also had to calculate the work required to lift the object, the mechanical advantage of the setup, and the change in the object's potential energy. The virtual manipulative was a computer simulation of pulleys, shown on the left side of Figure 2. Using the simulation, students selected the type of pulley setup they wanted to investigate and set the load of the object and the distance the object was to be lifted. They then adjusted the input (effort) force until the object moved. The computer provided the data related to length of string pulled, the force, and the work required to lift the object. Students had to calculate the mechanical advantage of the setup and the change in the object's potential energy.

Methodology

Studies

This analysis will draw from two studies we have done with the CoMPASS pulley curriculum. The students in these studies completed different activities in different settings, so each study will be discussed in detail below.

The first study involved undergraduates enrolled in a conceptual-based introductory physics laboratory. All students performed activities to learn about pulleys with both physical and virtual manipulatives as part of their normal laboratory. They answered the same questions on their worksheets and took the same conceptual tests. However, the order in which the manipulatives were used was varied. Three sections (N=71) performed experiments with physical pulleys first, while two sections (N=61) performed the same experiments using virtual pulleys first. Pre-, mid- and post-tests were given. Students completed the pre-test before any instruction, the mid-test after performing experiments with the first type of manipulative and answering the analysis questions, and the post-test after using the second type of manipulative. The mid-test allows us to compare the effects of physical manipulatives (PM) with the effects of virtual manipulatives (VM) only, while the post-test allows us to compare the effects of order of PM and VM.

The second study involved undergraduates enrolled in an algebra-based introductory physics course. Thirteen students participated in in-depth interviews. The students performed the same activities as the conceptual physics students, but used only PM (N=7) or VM (N=6). The students also completed the same written pre-test and post-test as the students in the class study. Since the students in the interview study only performed experiments with one type of manipulative, their post-test is equivalent to the mid-test in the in-class study. After each written test, the students were verbally re-asked the test questions in a new context so their reasoning could be probed. Each student was interviewed about half of the questions after the pre-test and the other half of the questions after the post-test. Each question was asked pre- and post- to three VM students and three or four PM students.

Conceptual Test

The conceptual test consisted of 13 questions related to the physics of pulleys. There were four questions related to force, four questions related to work, two questions related to mechanical advantage, two questions related to potential energy, and one question related to distance. Two questions (one related to work and one related to potential energy) required the students to perform calculations. All but one question (the work calculation) were multiple choice.

Analysis

Statistical analysis was used on the pre- and mid-tests from the in-class study. Analysis of the in-class post-test scores is not included here as we are focusing on the differences between students' learning from the physical and virtual manipulatives. We used the test scores from the in-class study to identify questions for further investigation in the interview study. Interview transcripts of the questions of interest were qualitatively analyzed using a phenomenographic approach (Marton, 1986). In order to reduce potential bias in the analysis, the qualitative analysis was done blind to the type of manipulatives students had used.

Results

We compared the mid-test scores of the two treatments in the in-class study. Students who had used PM to perform the experiments had an average score of 58% on the mid-test compared to 60% for students who had used VM. This difference in students' test scores between physical (M=58%, SD=19%) and virtual manipulatives (M=60%, SD=24%) is not statistically significant (U=2084, p=.708). Thus, it appears that overall the physical and virtual manipulatives were equally effective.

However, if we look at the test data question-by-question, we find some interesting differences between the two groups. As will be reported (Gire, et al., in press), PM students in the class study were more successful on questions related to effort force, distance of rope pulled, and mechanical advantage than VM students. On the other hand, VM students were more successful on questions related to work.

The interview data allows us to probe these differences more deeply. We used the in-class study data to identify questions on which PM students outperformed VM students, questions on which VM students outperformed PM students, and questions on which there was no difference in performance. We then matched these questions with the written test data from the interview study to identify questions that had the same pattern. Since the interview study included a small number of participants, we did not always see the same magnitude of performance spread between PM and VM students. Below we will analyze the interview study participants' responses to the verbal questions matched to a test question that exhibited: 1) PM students outperform VM students, 2) VM students outperform PM students, and 3) no performance difference between PM and VM students. The results of these questions on the pre- and mid- or post-test are summarized in Table 1.

Physical Outperforms Virtual

In Question 1, students were asked which of two pulley systems (a single fixed pulley or a single movable pulley, as shown in Figure 3, left) would require less effort force to lift an object. On the pre-test, there was no statistically significant difference between the performance of the PM (M=11%, SD=32%) and VM students (M=11%, SD=32%), $t(130)=.037$, $p=.970$. However, on the mid-test there was a statistically significant difference between the PM students (M=83%, SD=38%) and the VM students (M=62%, SD=49%), in favor of the PM students, $t(112)=2.7$, $p=.008$.

In the interview, students were asked a similar question. They were shown a diagram of two pulley systems (Figure 3, right) and asked which they would choose to use less effort force to lift the mattress. Half of the students were asked this question in the interview after the pre-test and the other half were asked after the post-test. Students' responses and the reasoning they provided are displayed in Table 2.

As shown in Table 2, all students who answered Question 1 after the pre-test selected Pulley B, the single fixed pulley, to reduce the effort force. Before instruction, we see students mainly used intuition-based resources to arrive at this answer. For example, they reasoned it would be easier to pull down than up and it would be easier to pull with gravity than against gravity. The students who answered this question after the post-test chose a wider variety of answers. All three PM students correctly chose Pulley A to reduce the effort force, while the VM students spread across all possible answers. This matches the trend observed in the test data. After instruction, we do not see a pattern in the students' reasoning. Only one student (VM) uses the common sense reasoning observed in the pre-test responses. However, only one student (PM) provides a scientifically correct explanation that Pulley A (the single moveable) increases the distance pulled, which reduces the required effort force.

Students in the interview were also asked to explain the definition of effort force they used to answer this question. Students' responses are shown in Table 3. There is no difference between the PM students' and VM students' responses at the pre-test. Several students described effort force in terms of the effort or force physically exerted to lift the mattress. Other students had definitions that referred to work either explicitly or implicitly, by including a role for distance. At the post-test, we do observe a difference among the PM students' and VM students' responses. All the PM students refer to the effort or force physically exerted to move the object. However, the VM students' responses showed evidence of confusing effort force with work, as observed at the pre-test.

Virtual Outperforms Physical

In Question 6.2, students were asked what would happen to the work needed to lift a watermelon to a certain height if the pulley system were changed (from a single fixed to a single movable) (Figure 3, left). No statistically significant difference between the PM (M=32%, SD=47%) and VM students (M=42%, SD=50%), t(125)=1.2, p=.230 was found on the pre-test. However, on the mid-test there was a statistically significant difference between the PM students (M=28%, SD=45%) and VM students (M=80%, SD=40%), in favor of the VM students t(130)=7.0, p=.000.

In the interview, students were asked to compare the work needed to lift a futon to their balcony using Pulley B (single fixed) versus Pulley A (single movable) (Figure 3, right). Half of the students were asked this question in the interview after the pre-test, and the other half were asked after the post-test. Students' responses and the reasoning they provided are displayed in Table 4.

As shown in Table 4, the majority of students who answered this question after the pre-test thought Pulley A (single movable) would require more work to lift the futon than Pulley B (single fixed). At the pre-test, we see an initial difference in reasoning between the PM and VM students. All VM students reasoned the work would be more for Pulley A since the force would be more for Pulley A. While one PM student shared this reasoning, the others provided a variety of explanations for their choices. At the post-test, we see a difference in both responses and reasoning between the PM and VM students. All VM students correctly stated that the work would be the same with either pulley system and provided scientifically correct reasoning as shown in Table 4. However, we see one PM student using the idea observed in the pre-test responses that more force would indicate more work and another using the idea that pulling a longer distance indicates more work done. While these students have correctly identified some of the factors related to work, they are not able to apply them appropriately in this context to arrive at the correct answer. The third PM student used common sense reasoning, as observed in the pre-test responses to Question 1.

Most students in the interview were also asked to explain the definition of work they used to answer this question. At the pre-test, students provided a wide variety of explanations of varying scientific correctness as shown in Table 5. Interestingly, we do not observe a difference in the definitions provided by the PM and VM students at the post-test. Both PM students who were asked to provide definitions gave responses that should have led them to the correct response to Question 6.2. Their definitions contain the proper combinations of the object's weight and the distance it moved or the effort force and the distance pulled. The VM students' responses do not appear more scientifically correct than those of the PM students.

Similar Performance for Physical and Virtual

In Question 8, students were asked how the work required to lift a board 20 meters would compare to the work needed to lift the same board 10 meters. No diagram was provided. No statistically significant difference between PM ($M=83\%$, $SD=38\%$) and VM students ($M=85\%$, $SD=36\%$), $t(130)=.33$, $p=.739$, was found on the pre-test. On the mid-test there was still no significant difference between the performance of PM (M=72%, SD=45%) and VM students (M=64%, SD=48%), t(130)=.97, p=.335.

In the interview, students were asked to compare the work done by two people who used the same pulley to lift identical mattresses to their dorm rooms – one on the third floor and the other on the sixth floor. Half of the students were asked this question in the interview after the pre-test, and the other half were asked after the post-test. Students' responses and the reasoning they provided are displayed in Table 6.

As shown in Table 6, most students correctly stated that it would take more work to lift the mattress to the sixth floor than to lift it to the third floor. Returning to Table 1, we see there is actually a decrease from pre-test to post-test in the number of students answering this question correctly for all groups. In other words, students were more likely to answer this question correctly on the pre-test than on the post-test. However, we do not see the same decrease from pre-test to post-test on the interview question, likely due to the small number of participants. There is some difference between the PM and VM responses at the pre-test. We see most PM students stating that the work increased because the distance increased while the VM students provided a wider variety of answers. At the post-test, we see the PM students are more likely to refer to the distance of rope pulled, while the VM students referred to a general increase in distance.

Some of the students were again asked to explain the definition of work they used to arrive at their answer. Their responses are shown in Table 7. In general, we see an equivalent increase in the scientific correctness of explanations from the pre-test to the post-test for both PM and VM students. At the post-test, the VM students provided more specific definitions, specifying the distance (either distance of rope pulled or distance the object lifted).

Conclusions and Implications

Our work (Gire, et al., in press) has suggested that physical manipulatives may offer better support for student learning about distance of rope pulled, force, and mechanical advantage while virtual manipulatives may offer better support for student learning about work. We have investigated this phenomenon more deeply by exploring the conceptions students develop from experiments with PM and VM and how they use those conceptions to reason about force and work in pulley systems. Due to the limited number of participants and questions analyzed at present, we cannot make any broad generalizations. However, our data does suggest a potential avenue for further study.

On Question 1, we saw a higher prevalence of "common sense" reasoning on the pre-test than on the post-test for both PM and VM students. This type of reasoning did not reappear among the PM post-test responses but did reappear in the VM post-test responses. Hammer's (2000) model of conceptual resources explains that the context activates and deactivates the resources students use to build understanding. It is possible that the context of the physical manipulatives better supports deactivation of a resource related to the idea "downward movement is easier" than do the virtual manipulatives.

On Question 6.2, we found that PM and VM students provided equally useful definitions of work at the post-test. However, the VM students were more likely to use their definitions to arrive at the correct answer. This seems to indicate that the PM students are having more trouble applying their definition of work in context. A common resource is the idea that "more input means more output". On the pre-test, many students may have used this resource to build the idea that "more force means more work." On the post-test, we see PM students continuing to apply this resource as "more force means more work" or "more distance pulled means more work." This resource needs to be deactivated in favor of a resource for proportional reasoning, as is exhibited by the VM student who stated "force and distance change proportionally".

On Question 8, we see a decrease in students' performance from pre-test to post-test for the in-class study and for the written test in the interview study. Students are initially quite likely to get this question correct, which we would expect because it can be answered with the resource "more input means for output" in the form "more distance lifted means more work". During the experiments, the students repeatedly lift an object to the same height and should observe that different pulley systems require the same work for this task. It is possible that repeatedly seeing the same work deactivates the use of this resource in the context of work.

Returning to our research questions, the multiple choice pulley test does reveal differences in students' understanding of pulleys after performing experiments with physical or virtual manipulatives. While students' overall performance on the test was similar, specific questions have been identified that exhibit a performance difference between the PM and VM students. Analyzing students' verbal responses and reasoning about these questions uncovered a possible underlying factor for the performance difference on the test.

In general, our results support the idea that physical and virtual manipulatives may offer different support for student learning on different topics. We suggest a possible avenue through which the manipulatives affect student learning may be that PM and VM activate and deactivate different resources, which is consistent with the idea that resource activation is context dependent (Hammer, 2000).

References

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefskey, N., 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.

Gire, E., Carmichael, A., Chini, J. J., Rouinfar, A., Rebello, S., & Puntambekar, S. (in press). The Effects of Physical and Virtual Manipulatives on Students' Conceptual Learning About Pulleys. *International Conference of the Learning Sciences.* Chicago.

Hammer, D. (2000). Student Resources for Learning Introductory Physics. *American Journal of Physics , 68* (S1), S59-S59.

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.

Marton, F. (1986). Phenomenography—A Research Approach to Investigating Different Understandings of Reality. *Journal of Thought , 21*, 28-49.

Rebello, N., Zollman, D., Allbaugh, A., Engelhardt, P., Gray, K., Hrepic, Z., et al. (2005). Dynamic Transfer: A Perspective from Physics Education Research. In H. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective* (pp. 217-250). Greenwich, CT: Information Age.

Triona, L., & Klhar, 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.

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), 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.

Table 1

Percentage of Students Responding Correctly on Specific Questions

	N	Q1 Pre	Q1 In-Class Mid/ Interview Post	Q6.2 Pre	Q6.2 In-Class Mid/ Interview Post	Q8 Pre	Q8 In-Class Mid/ Interview Post
Class Physical	71	11%	83%	32%	28%	83%	72%
Class Virtual	61	11%	62%	42%	80%	85%	64%
Interview Physical	7	0%	71%	29%	14%	100%	71%
Interview Virtual	6	0%	17%	33%	67%	83%	67%

Table 2

Students' Responses (in italics) and Reasoning in Question 1

	Pre-Answer	Reasoning		Post-Answer	Reasoning
PM 2	*Pulley B*	Easier to pull down than to pull up	**PM 4**	*Pulley A*	For Pulley A, distance increases, so effort force is less
PM 8	*Pulley B*	Pulley B spreads out weight between two ropes	**PM 6**	*Pulley A*	Direction of the force for Pulley A is the same, but for Pulley B the direction of the force is switched
PM 10	*Pulley B*	Easier to pull down than to pull up; Working against gravity to pull up; Can use body weight to pull down	**PM 12**	*Pulley A*	Less force for Pulley A, so less work done
PM 14	*Pulley B*	With Pulley A you have to lift the pulley and the mattress; Pulley B doesn't move			
VM 3	*Pulley B*	Easier to pull down than to pull up	**VM 1**	*Pulley A*	Pulley A moves with the object
VM 5	*Pulley B*	Easier to pull down than to pull up	**VM 7**	*Pulley B*	Working against gravity to pull up; Pull more distance with Pulley A
VM 9	*Pulley B*	Easier to pull down than to pull up; Working against gravity to pull up	**VM 11**	*Pulley B; Both equal*	If pulleys are massless, force is divided by two for each pulley

Table 3

Students' Definitions of Effort Force in Question 1

	Description at Pre-test		Description at Post-test
PM 2	How much effort you put out	**PM 4**	Force required to pull up
PM 8	How much force it takes to lift something a certain distance, a certain way	**PM 6**	How much force you put in to move object
PM 10	What would be more difficult to do just effort as far as work you need to lift the object	**PM 12**	Amount of effort it takes to move an object
PM 14	Amount of force you physically put into it		
VM 3	Amount of effort you have to use	**VM 1**	Amount of effort it takes to lift object from point A to point B
VM 5	How hard you have to work	**VM 7**	Amount of energy required to move an object a certain distance
VM 9	Force you put out trying to move an object	**VM 11**	Does not provide a definition

Table 4

Students' Responses (in italics) and Reasoning in Question 6.2

	Pre-Answer	**Reasoning**		**Post-Answer**	**Reasoning**
PM 4	*Work Same*	Same task accomplished	**PM 2**	$W_B > W_A$	Pulley B requires more effort force
PM 8	$W_B < W_A$	Lift more weight with Pulley A than Pulley B	**PM 6**	$W_B < W_A$	With Pulley A you pull a longer distance
PM 12	$W_B < W_A$	Pulley A requires more effort force; Put more energy into Pulley B than Pulley A	**PM 10**	$W_B < W_A$	Pull upwards with Pulley A; Gravity helps with Pulley B; They have different mechanical advantages
PM 14	$W_B < W_A$	Pulley A requires the puller to do more work, whereas Pulley B shares more of the load			
VM 3	$W_B < W_A$	Pulley A requires more effort force; More force leads to more work	**VM 1**	*Work Same*	Object weighs the same & moves the same distance
VM 7	$W_B < W_A$	Pulley A requires more effort force	**VM 5**	*Work Same*	Force and distance change proportionally to keep work the same; Work stayed the same in the project
VM 9	$W_B < W_A$	Pulley A requires more effort force	**VM 11**	*Work Same*	Object weighs the same & moves the same distance

Table 5

Students' Definitions of Work in Question 6.2

	Description at Pre-test		**Description at Post-test**
PM 4	What it takes to get the thing from point A to point B	**PM 2**	How much object weighs and distance you travel with it
PM 8	Spending energy	**PM 6**	Amount of effort you put in over the distance pulled
PM 12	When you do something and it causes you to sweat; Amount of force put into it times the distance it was moved	**PM 10**	(Not asked to give definition)
PM 14	Distance times mass		
VM 3	Amount of force in relation to the mass of the object or force you're pulling with	**VM 1**	Distance you move the object times weight of object
VM 7	Amount of effort and duration	**VM 5**	Distance pulled divided by effort force
VM 9	Change in kinetic energy	**VM 11**	Work is equal to force times distance

Table 6

Students' Responses (in italics) and Reasoning in Question 8

	Pre-Answer	Reasoning		Post-Answer	Reasoning
PM 2	*Not same work*	Work is a constant; Same amount of work needed to keep mattress lifting	**PM 4**	*More work*	More rope distance pulled
PM 8	*More work*	Since distance increased, work increases	**PM 6**	*More work*	More rope distance pulled; distance further
PM 12	*More work*	Distance increased	**PM 10**	*Same work*	Takes longer to move mattress higher; Just as easy to pull
PM 14	*More work*	Since distance increased, work increases			
VM 1	*Same work*	Takes longer to move mattress higher	**VM 3**	*Less work*	Work spread over greater distance
VM 5	*More work*	Common sense	**VM 7**	*More work*	Distance increased
VM 11	*Same work*	Work= force x distance, and at some points force > work, at others force <work; Same rope and pulley used	**VM 9**	*More work*	Distance increased

Table 7

Students' Definitions of Work in Question 8

	Description at Pre-test		**Description at Post-test**
PM 2	Amount of energy person uses to move the object	**PM 4**	(Not asked to give definition)
PM 8	(Not asked to give definition)	**PM 6**	Effort force times distance
PM 12	(Not asked to give definition)	**PM 10**	Effort you have to put in factoring in mass and height
PM 14	Work is distance times mass		
VM 1	Not sure how to define work	**VM 3**	Force times distance pulled to get the object up
VM 5	Amount of energy you expend over a period of time	**VM 7**	(Not asked to give definition)
VM 11	A mass moving at a certain acceleration over a distance; Work is equal to a force times a distance	**VM 9**	The effort force times the distance pulled

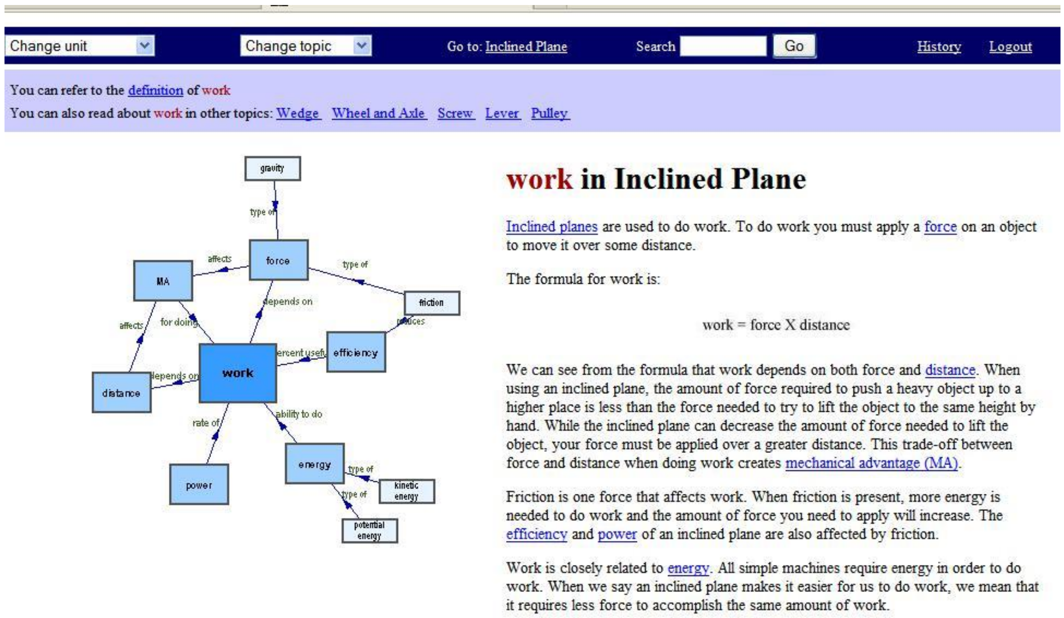

Figure 1. The CoMPASS hypertext system.

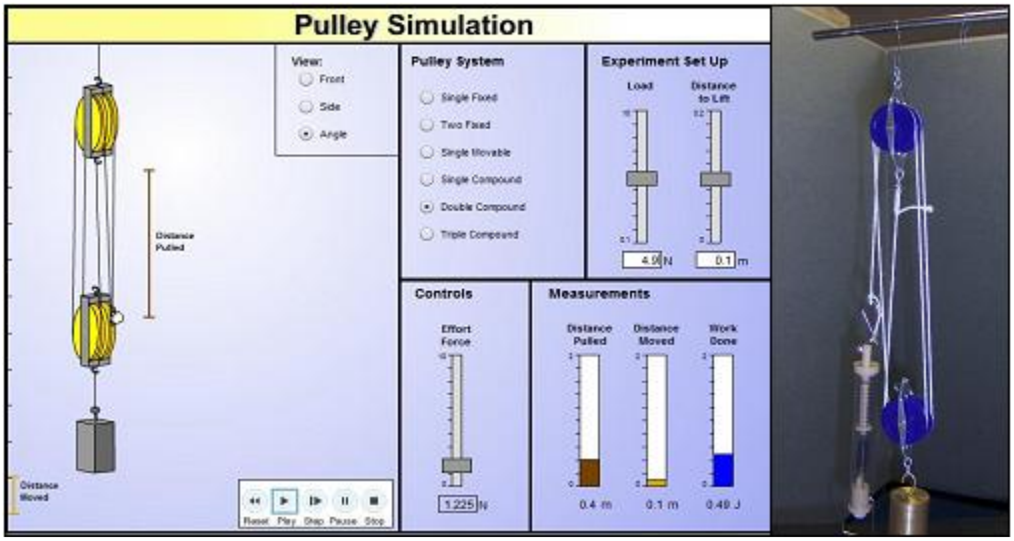

Figure 2. Virtual (left) and physical (right) manipulatives.

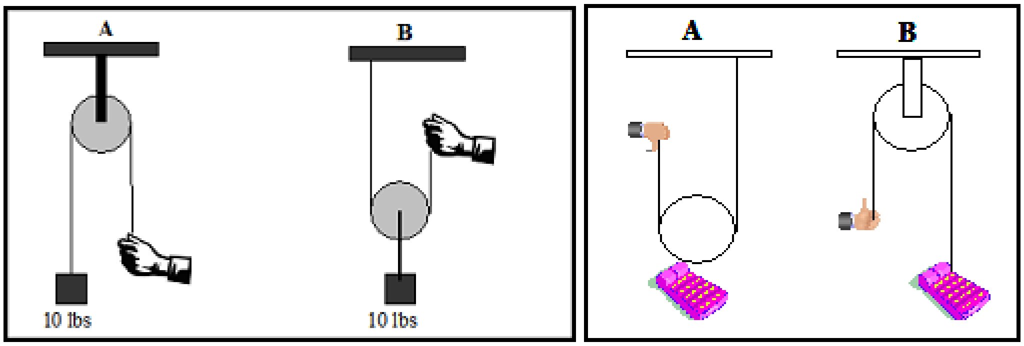

Figure 3. Diagram for written test (left) and interview (right).