EXAMINING THE COMBINATION OF PHYSICAL AND VIRTUAL EXPERIMENTS IN AN INQUIRY SCIENCE CLASSROOM

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ABSTRACT
Physical investigations and computer simulations have often been used independently in inquiry science classrooms. This study investigates the benefits of combining physical and virtual experiments when learning about pulleys in a middle school science classroom and whether the sequence of activities impacts student conceptual understanding. Students conducted either a physical experiment followed by a virtual experiment, or a virtual experiment followed by a physical experiment. The students who conducted the physical experiment followed by the virtual experiment outperformed those who conducted the experiments in the reverse order. Furthermore, these results were driven largely by particular concepts and situations related to the designed affordances of the physical and virtual experiments. The results suggest that combining physical and virtual experiments can improve conceptual understanding and that the sequence of physical and virtual activities can have important effects on learning.

KEYWORDS
Simulations, Virtual Experiments, Physical Experiments, Science Inquiry, Pulley Systems

INTRODUCTION

Physical investigations and computer simulations have each been used extensively in science classrooms to enable students to engage in science inquiry processes – such as designing experiments, collecting data, analyzing data and using evidence to justify claims – all of which are emphasized in the National Science Standards (1996). This paper will discuss the potential advantages of incorporating both hands-on activities and computer simulations in inquiry science classrooms and present a study that explores the roles of physical and virtual investigations in supporting student learning.

Several authors have identified advantages and disadvantages of both hands-on activities and computer simulations in science classrooms. Hands-on investigations allow students to experience science phenomena directly through experimentation with physical materials and by designing and engineering physical artifacts. Through these processes, students can gain experience in planning investigations, using appropriate scientific instruments, and collecting, recording and analyzing real-world data. Such investigations can include laboratory experiments (Hodson, 1996; Kirschner & Huisman, 1998) and engineering-type challenges, including project-based learning (e.g., Krajcik et al., 1998) and design-based learning (e.g., Kolodner et al., 2003) approaches. Although hands-on activities can be helpful for students, there have been several concerns noted about the focus on such activities in classrooms. For example, students can build working solutions by trial and error (Kolodner et al., 2003; Hmelo, Holton, & Kolodner, 2000; Baumgartner & Reiser, 1998; Hennessy, Deaney & Ruthven, 2006) or can become entangled in practical details (Kirschner & Huisman, 1998) without understanding the underlying deep science principles and phenomena. Problems with the difficulty level of the activities (Kirschner & Huisman, 1998) as well as with the sometimes substandard equipment in science classrooms (Hodson, 1996) can also be disadvantages of physical investigations.

Computer simulations have shown promise in supporting student understanding of science, particularly in inquiry-based classrooms (de Jong, 2006). Simulations, as dynamic, interactive representations of a system, phenomena or set of processes, allow students to act as investigators, developing and testing working models of their own understanding of the system (Gredler, 2004). Simulations can provide a different set of advantages in science classrooms than physical investigations. Sadler, Whitney, Shore & Deutsch (1999) argue that computer simulations can "focus attention on formal variables, parameters, and frames of reference." They provide opportunities for exploration that would be impractical or impossible with physical materials (Zacharia & Anderson, 2003; Hofstein & Lunetta, 2004), such as trying out experiments in ideal situations. Setting up simulations is less time consuming than preparing hands-on investigations, thereby allowing students more time for reflection (Hofstein & Lunetta, 2004). They can also combine multiple representations – verbal, numerical, pictorial, conceptual and graphical – and allow students to perceive variables that are not directly observable in the physical environment (Snir, Smith, & Grosslight, 1993). As computer-based learning environments, they can provide immediate feedback to learners (Ronen & Eliahu, 2000) and integrate various forms of support for scientific inquiry (de Jong, 2006).

Despite several advantages of including simulations in science classrooms, such advantages do not always lead to increases in student learning, largely due to problems students have with scientific inquiry (de Jong & van Joolingen, 1998). Computer simulations provide students with de-contextualized representations of real-world phenomena (Hofstein & Lunetta, 2004) in which the causal variables must be pre-programmed into the system, preventing students from testing alternative models that were not planned for in advance (Chinn & Malhotra, 2002).

Physical experimentation and computer simulations have traditionally been considered competing methods in science classrooms (Jaakola & Nurmi, 2008), with research finding that students performing virtual investigations learn as much (e.g., Klahr, Triona & Willams, 2007) or more than (e.g., Finkelstein, et al., 2005) those performing physical investigations. However, research has begun to explore the potential benefits of combining physical and virtual experimentation rather than comparing them against each other. The use of computer simulations in conjunction with hands-on activities has been shown to improve learning of abstract physical phenomena, helping students construct mental models that explain observable results of hands-on experiments (Zollman, Rebello & Hogg, 2002). Researchers have found that simulations help bridge the gap between formal representations and concrete artifacts (Ronen & Eliahu, 2000), and between verbal and mathematical representations of physics problems (Van Heuvelen & Zou, 2001). Zacharia and Anderson (2003) found that simulations improved students' ability to make predictions and explanations of the phenomena observed in hands-on experiments, and claim that simulations can serve as a cognitive framework for enhancing subsequent learning from hands-on experiments.

Further research has recently been conducted to directly compare combined virtual/physical investigations with either form individually. Zacharia (2007) compared one group of students learning about electronic circuits from real experiments with another group learning from a combination of real and virtual experiments. The author found that the students who learned from the combination of real and virtual experiments had better conceptual understanding of the material than those who encountered the material only through real experiments. This result held true for the domain of heat and temperature as well (Zacharia, Olympiou, & Papaevripidou, 2008). Jaakkola & Nurmi (2008) went a step further, comparing three learning environments in teaching electricity to elementary school students: a laboratory exercise, a computer simulation, and a simulation-laboratory combination. They found that, while there were no significant differences in conceptual gains between the laboratory and simulation groups, the simulation-laboratory combination led to significantly greater learning gains than either the laboratory or simulation alone. The authors suggest that simulations can be used first to help students understand the underlying theoretical principles, and that laboratory exercises can then be used to demonstrate that those principles apply in the real world. Although these results show promise for combining physical and virtual science investigations, physical-virtual experiment combinations do not always lead to improved learning outcomes over each form individually (e.g., Zacharia & Olympiou, 2010).

In at least some cases, integrating hands-on investigations with computer simulations can improve student conceptual understanding more than either activity alone. However, there is still much to learn. From the body of research outlined above, it is still unclear why and under what conditions combining physical and virtual experiments can be helpful for students. Furthermore, there are also several remaining questions pertaining to how integrating physical and virtual investigations can affect learning. In addition to exploring the overall impact of combining physical and virtual experiments in a middle school inquiry science classroom, the following study was conducted to answer the following specific research questions: (1) When combining physical and virtual experiments, is the sequence of activities important for student conceptual learning? (2) Are particular concepts learned better with physical or virtual investigations?

METHODS

Participants

To begin addressing these questions, we performed a study examining student learning from physical and virtual experiments with pulley systems, as part of a simple machines curriculum. The study took place in a classroom setting at a private Midwestern middle school with three 6th grade classes (N=60) with the same teacher. The classes were assigned to two conditions: one in which students performed a physical experiment followed by a virtual experiment (Physical-Virtual condition), and one in which students completed the virtual experiment followed by the physical experiment (Virtual-Physical condition). Two classes (N=43) were assigned to the Physical-Virtual condition and one class to the Virtual-Physical condition (N=17). During the physical experiment, students set up and tested pulley systems to determine which system most reduced the amount of force required to lift an object. For the virtual experiment, a computer simulation was used to allow students to select a pulley system and run an equivalent experiment while viewing dynamic representations of the related variables.

Context: Simulations and Physical Experiments

The unit was part of the CoMPASS simple machines curriculum (Puntambekar, Stylianou & Goldstein, 2007), which integrates a digital hypertext environment, hands-on science experiments, and design challenges within cycles of inquiry. This curriculum has been shown to help students gain a deeper understanding of underlying physics concepts – such as force, work, energy, and mechanical advantage – and the connections between them (Puntambekar, 2006; Puntambekar, Stylianou, & Hübscher, 2003; Puntambekar, Stylianou & Goldstein, 2007). For the pulley unit, students first encountered the hypertext environment, allowing them to become familiar with the concepts they would be encountering in their experiments. Students then encountered their first experiment (physical or virtual) followed by their second experiment (virtual or physical). The teacher – who was the same teacher for all classes – conducted a whole class discussion between each of the activities. Students worked in groups of 3 to 4 for all activities.

The simulation was designed to take advantage of particular affordances and of a virtual versus a physical environment. In the physical experiment (see Figure 1), students gain practice in setting up pulleys in the real world, receive haptic feedback in feeling how much force is needed to lift the object with different pulley systems and gain experience in measuring, recording and analyzing real-world data. However, in previous implementations of the pulley unit, the pulleys tended to take time to set up properly, restricting the number of different configurations students could test. Additionally, because of friction and measurement error, students were unable to observe important phenomena, including the fact that when lifting an object to the same height using different pulley systems, the amount of force required changes but the amount of work done does not.

To overcome these limitations of the physical experiment, the pulley simulation was designed to allow students to observe the intended phenomena in an idealized environment. Since the pulleys in the simulation environment take far less time to set up, students have time to test additional pulley configurations that they would not have time to explore in the physical experiment. The simulation also displays underlying variables in real time and provides multiple representations of data, including numerical values, and dynamic graphs (see Figure 2).

Figure 1. Equipment for physical pulley experiment.

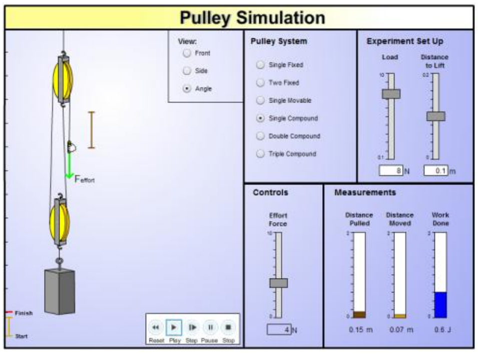

Figure 2. Screenshot of pulley simulation environment.

Data Sources

Student learning was assessed through a 10-item multiple choice test of physics concepts in the domain of pulleys, which was administered at three different points (pre, mid and post) during the pulley unit (see Figure 1). The pre-test was given before the pulley unit, the mid-test was given after the first experiment (physical or virtual) and the associated class discussion, and the post-test was given at the end of the unit, after the second experiment (virtual or physical) and the associated class discussion. Of the ten questions, four of these questions compared single fixed with single movable pulleys for their effects on force (2), mechanical advantage (1), and the distance pulled (1) to lift an object; one question compared the amount of work done when lifting an object to the same height while using three different pulley systems; two questions comparing the effects of a single fixed pulley with two fixed pulleys on force and mechanical advantage; two questions comparing four different pulley configurations (single fixed, two fixed, single movable, double compound) on force and mechanical advantage; and one question concerned the amount of work needed to use a pulley to lift an object to different heights. Missing data (from student absence on the day of a test) were considered missing completely at random and were handled through pairwise deletion.

RESULTS

Sequence of Physical and Virtual Experiments

To compare the two conditions (Physical-Virtual and Virtual-Physical), a set of analysis of covariance (ANCOVA) tests were conducted (see Table 1). These consisted of: a pre-mid comparison, where the mid-test score was used as the dependent variable with the pre-test score as the covariate; a mid-post comparison, with the post-test score as the dependent variable and the mid-test score as the covariate;

and a pre-post comparison, where the post-test score was used as the dependent variable with the pre-test score as the covariate. We used Holm's sequential Bonferroni approach to control for family-wise error rate across these comparisons, with the family-wise alpha set at .05. ANCOVAs were used for these comparisons, since there was a statistically significant difference on pre-test scores between the two conditions ($t = 2.20$, $p = .032$). For the ANCOVA tests, preliminary analyses evaluating the homogeneity-of-slopes assumption indicated that the relationship between the covariate and the dependent variable did not differ significantly as a function of the independent variable. The ANCOVA tests were computed through a general linear model approach to allow for the unbalanced design (Keppel & Wickens, 2004).

The results of the ANCOVAs indicate that the Physical-Virtual condition significantly outperformed the Virtual-Physical condition from pre-test to mid-test, from mid-test to post-test, and from the pre-test to post-test (see Table 1). This suggests that students the physical experiment was more effective as the first learning environment encountered, the virtual experiment was more effective as the second learning environment encountered, and that the sequence of the learning environments was important. Students learned more when conducting the physical experiment followed by virtual experiment (see Figure 2).

Table 1. Results of analysis of covariance (ANCOVA) tests comparing across conditions. *p<.05

	Pre-Mid	**Mid-Post**	**Pre-Post**
	adjusted mean (SE)	**adjusted mean (SE)**	**adjusted mean (SE)**
Physical-Virtual condition	6.40 (.361)	6.97 (.325)	7.10 (.354)
Virtual-Physical condition	4.52 (.544)	5.07 (.498)	4.00 (.599)
ANCOVA	$F_{1,45}$= 8.044 p =.007* η^2 = .152	$F_{1,45}$= 9.42 p =.004* η^2 = .173	$F_{1,53}$= 19.13 p< .001* η^2 = .265

To analyze the improvement between the pre-test and mid-test and between mid-test and post-test within each condition, we conducted planned contrasts using Holm's sequential Bonferroni approach to control for family-wise error rate (at $\alpha = .05$) across the comparisons (see Table 2). Within the Physical-Virtual condition, students improved significantly on the overall test from pre-test to mid-test and from mid-test to post-test. This indicates that students learned a significant amount during both the physical and virtual experiments. Within the Virtual-Physical condition, students improved significantly from the pre-test to the mid-test but not from the mid-test to the post-test, indicating that they learned a significant amount during the virtual experiment but not the physical experiment.

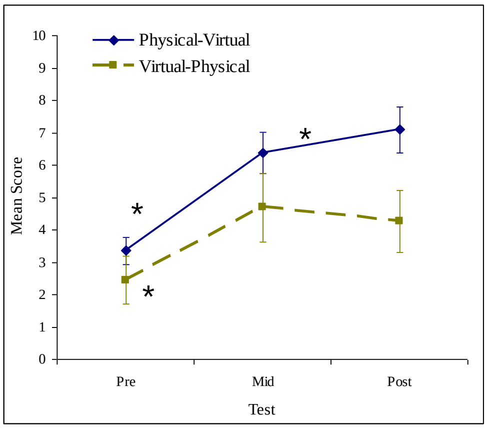

Figure 3. Overall pre, mid and post-test results by condition, with bars representing 95% confidence intervals. *p < .05

Table 2. Results of planned contrasts to determine pre-mid and mid-post improvements within each condition *p<.05

	Pre-Mid					Mid-Post				
	Pre mean (SD)	Mid mean (SD)	F (df)	p	η^2	Mid mean (SD)	Post mean (SD)	F (df)	p	η^2
Physical-Virtual	3.41 (1.37)	6.41 (1.97)	46.50 (1,31)	<.001*	.600	6.41 (1.97)	7.28 (2.32)	5.78 (1,31)	.022*	.157
Virtual-Physical	2.36 (1.60)	4.43 (2.17)	6.80 (1,13)	.022*	.343	4.43 (2.17)	4.14 (2.07)	4.81 (1,13)	.500	.136

Individual Test Questions

To analyze the impact of individual test questions on the above results, difference scores from pre to mid tests and from mid to post tests were calculated for each individual test question, resulting in four mean difference scores for each test question: pre-mid and mid-post for each of the Physical-Virtual and Virtual-Physical conditions. The results were then grouped by the pattern of these four difference scores, resulting in three separate groups of questions. For two questions (comparing force and mechanical advantage in fixed and movable pulleys), the physical experiment was more helpful than the virtual experiment, especially when the physical experiment was conducted first (see Figure 4). (A 2x2 mixed ANOVA indicated that there was a significant interaction between the test and the condition, $F(1, 46) = 14.61$, $p < .001$; a significant main effect of condition, $F(1, 46) = 14.61$, $p < .001$; and a significant main effect of test, $F(1,46 = 8.06$, $p = .007$). For three other questions (two questions comparing one fixed pulley with two fixed pulleys and one question concerning the amount of work done while using three different pulley configurations under equivalent circumstances), students learned more from the virtual experiment than the physical experiment, but only when the virtual experiment was conducted after the physical experiment (see Figure 5). (A 2x2 mixed ANOVA indicated that there was an interaction nearing significance between the test and the condition, $F(1, 46) = 2.95$, $p = .093$; a significant main effect of condition, $F(1, 46) = 9.59$, $p = .003$; but no significant main effect of test, $F(1, 46) = 2.04$, $p = .160$). For the remaining five test questions, students on average learned more from the experiment they conducted first than the experiment they conducted second, independent of the condition (see Figure 6). (A 2x2 mixed ANOVA indicated that there was no interaction between the test and the condition, $F(1, 46) = .732$, $p = .397$, and no significant main effect of condition, $F(1, 46) = 1.36$, $p = .205$, but there was a significant main effect of test, $F(1, 46) = 15.16$, $p < .001$).

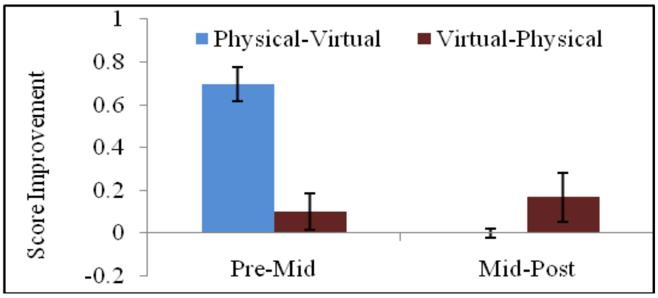

Figure 4. Mean improvement on test questions where students learned more from the physical experiment than the virtual experiment when physical experiment was conducted first.

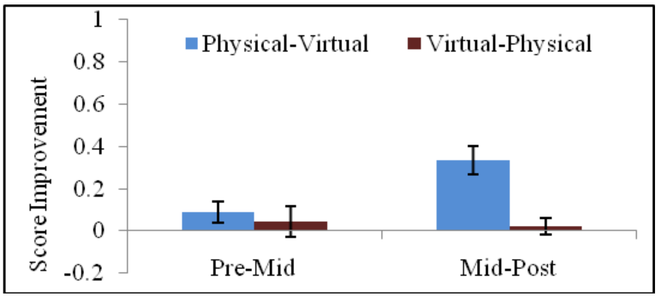

Figure 5. Mean improvement on test questions where students learned more from the virtual experiment than the physical experiment when the virtual experiment was conducted second.

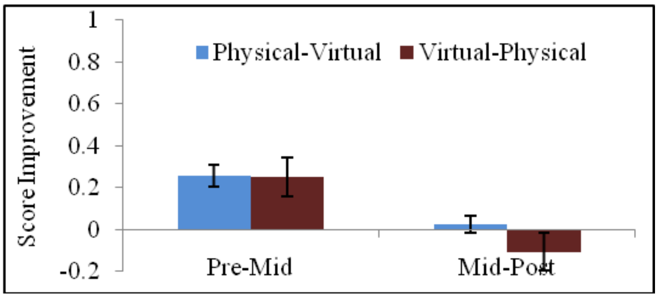

Figure 6. Mean improvement on test questions where students learned more from the first experiment encountered, regardless of condition.

DISCUSSION

The results concerning the sequence of physical and virtual experiments show that conducting the physical experiment followed by the virtual experiment was more beneficial for student learning than conducting the virtual experiment followed by the physical experiment. Furthermore, students learned more from the physical-virtual combination than the physical experiment alone (as evidenced by the mid-test to post-test gain under the physical-virtual condition). These results suggest that having students conduct virtual experiments through computer simulations after conducting physical experiments can lead to enhanced student conceptual understanding.

Why would the physical-then-virtual sequence be more beneficial for students under these circumstances? Examining student responses to specific test questions helps us to understand this result. Two test questions in particular (those comparing force and mechanical advantage in fixed and movable pulleys) largely drove the overall result that students learned more from the physical experiment than the virtual experiment as the first experiment encountered. For three other questions (two questions comparing one fixed pulley with two fixed pulleys and one question concerning the amount of work done while using three different pulley configurations under equivalent circumstances), students gained more from the virtual experiment than the physical experiment, but only when the simulation was used after the physical experiment. For the remaining questions, the form of experiment had little effect; students learned these concepts more during the first experiment, regardless of whether the physical or virtual experiment was conducted first.

These results are important in explaining the overall effect of sequence for two reasons. First, the fact that there were specific questions that largely drove the overall effect of sequence shows us that there were particular reasons why the physical experiment was more beneficial in the first position and the virtual experiment was more beneficial in the second position. Second, the fact that these three groups of test questions did not correspond strictly to particular physics concepts (e.g. force), nor to particular situations pulley configurations presented (e.g. fixed vs. movable pulleys) shows us that the types of learning that each form of investigation supported did not simply fall along lines of physics concepts or configuration, but to an interplay of physics concepts, pulley configurations, and the complexity of each.

Digging deeper into the individual test questions reveals that, as might be expected, the three questions that showed the most student improvement after performing the virtual experiment corresponded to the designed affordances of the computer simulation, helping students engage with phenomena that were either impossible (due to friction) or impractical (due to time constraints) for students to observe in their physical experiments. Interestingly, though, the simulation only helped students improve on these questions when they had performed the physical investigation first. The physical experiment, when conducted first, was most helpful in supporting students' understanding that using a movable pulley versus a fixed pulley increases your mechanical advantage and decreases the amount of force you need to apply to lift an object, a basic and fundamental concept in understanding the physics of pulleys. Although both the physical and virtual experiments were intended to address this idea, the physical act of using a movable pulley and comparing the force needed to lift an object to using a fixed pulley may have been important for learning this fundamental concept. One explanation of the overall results, then, is that students first learned the basic concepts of pulleys through grounded, physical experience with real-world pulleys and were then able to test and refine their conceptions in situations that were either impossible or impractical in their physical experiment.

Although students learned more from the physical-then-virtual sequence of investigations in this study, some other studies exploring the combination of physical and virtual experiments (e.g., Zacharia & Anderson, 2003; Jaakkola & Nurmi, 2008) have had students explore a simulation environment prior to performing a physical investigation. The theoretical rationale for this is that the computer simulation serves as a "cognitive framework" (Zacharia & Anderson, 2003), allowing students to first understand theoretical principles (Jaakkola & Nurmi, 2008) and later apply them to real-world inquiry. From the results of our study, we provide a different model that motivates a physical-then-virtual sequence of scientific inquiry in the classroom. We posit that, in some cases, conducting real-world experiments first provides important grounded, physical experience with the phenomena of interest. Exploring a simulation environment then provides students with opportunities to build upon this grounded experience and knowledge, both by expanding and testing this knowledge in situations that would be impossible or impractical in the real world and by connecting this grounded knowledge with multiple, formal representations. This model would follow closely with theories of grounded or embodied cognition (see Barsalou, 2008 for a review), which emphasize (among other things) the importance of perception and action in cognition. This model can also align with the concept of "concreteness fading" (Goldstone & Son, 2005), where grounded, concrete representations, which support initial learning, are then faded into more idealized representations, which allow for more transferable knowledge.

Based on our results and previous studies, we believe that the success of using a combination of physical and virtual experiments likely depends on many factors. Perhaps most importantly, the success of a particular sequence in supporting student learning is influenced by the goals and designed affordances of the individual physical and virtual activities; with physical and virtual activities designed with different goals in mind, the benefit of a particular sequence of activities may differ. This may also be a factor in explaining differences in the overall effectiveness of combining physical and virtual experiments; the more each form of activity takes advantage of the different affordances of physical and virtual artifacts for learning, the more likely we are to see benefits in combining them.

Other factors are likely to be important as well in understanding why and how combining physical and virtual science investigations can be beneficial, including the physical basis of the content to be learned. The haptic feedback acquired in using pulleys may be more important for understanding force in pulley systems than other concepts in other scientific domains, such as electrical circuits. This would agree with Zacharia, Olympiou, & Papaevripidou (2008) who claim that physical experimentation is likely to have more advantages in domains requiring "physical manipulation and tactile sensation". In addition to aspects of content, the impact of combining physical and virtual investigations and the sequence in which students conduct them may depend on student factors such as prior knowledge and conceptions, age and developmental level. The roles that these factors may play should be explored in future research.

CONCLUSIONS

The goal of this study was to investigate whether combining a simulation with a laboratory activity would be beneficial in an inquiry science classroom, and which sequence of activities would be most favorable. The results of the overall test indicated that combining the two activities was beneficial for student conceptual learning on the subject of pulleys, but only for students who used the simulation after the physical experiments. Students who encountered the laboratory activity first, followed by the computer simulation learned significantly more concepts than the students who encountered the activities in the reverse order. Further, this effect of the sequence of activities was largely driven by the particular goals and designed affordances of the physical and virtual experiments.

Overall, from the results of this study, we would agree with previous authors in that computer simulations and laboratory activities should not be considered as competing methods of science instruction. Both forms of activity have unique properties that are needed to promote deeper conceptual understanding (Jaakkola & Nurmi, 2008), and provide something that the other cannot offer (Winn et al., 2006). This study builds upon previous research by showing that there are cases where physical experiments can give students opportunities to gain grounded, physical experience to develop a basic understanding of the phenomena of interest, while the simulations can allow students to test their understanding in situations that are impractical or impossible in the real world. When designing an inquiry science curriculum, the sequence of activities can significantly impact learning and the sequence chosen should be based on the carefully considered roles that the physical and virtual activities are intended to play.

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REFERENCES

Barsalou, L. (2008). Grounded cognition. *Annual review of psychology, 59*, 617.

Baumgartner, E., & Reiser, B. (1998). Strategies for supporting student inquiry in design tasks. *Annual Meeting of the American Educational Research Association, San Diego, California*.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*(2), 175-218.

de Jong, T. (2006). Computer Simulations: Technological Advances in Inquiry Learning, *Science* (Vol. 312, pp. 532-533).

de Jong, T., & van Joolingen, W. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68*(2), 179-201.

Finkelstein, N., Adams, W., Keller, C., Kohl, P., Perkins, K., Podolefsky, N. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. Physical Review Special Topics-Physics Education Research, 1(1), 10103.

Goldstone, R., & Son, J. (2005). The Transfer of Scientific Principles Using Concrete and Idealized Simulations. *Journal of the Learning Sciences, 14*(1), 69-110.

Gredler, M. (2004). Games and simulations and their relationships to learning. *Handbook of research on educational communications and technology*, 571-581.

Hennessy, S., Deaney, R., & Ruthven, K. (2006). Situated expertise in integrating use of multimedia simulation into secondary science teaching. *International Journal of Science Education, 28*(7), 701-732.

Hmelo, C., Holton, D., & Kolodner, J. (2000). Designing to Learn About Complex Systems. *The Journal of the Learning Sciences, 9*(3), 247-298.

Hodson, D. (1996). Laboratory work as scientific method: three decades of confusion and distortion. *Journal of Curriculum Studies, 28*(2), 115-135.

Hofstein, A., & Lunetta, V. (2004). The laboratory in science education: Foundations for the twenty-first century. *Science Education, 88*(1), 28-54.

Jaakkola, T., & Nurmi, S. (2008). Fostering elementary school students' understanding of simple electricity by combining simulation and laboratory activities. *Journal of Computer Assisted Learning, 24*(4), 271-283.

Keppel, G., & Wickens, T. (2004). *Design and analysis: A researcher's handbook*: Prentice-Hall Englewood Cliffs, NJ.

Kirschner, P., & Huisman, W. (1998). 'Dry laboratories' in science education; computer-based practical work. *International Journal of Science Education, 20*(6), 665-682.

Klahr, D., Triona, L., & 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.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., et al. (2003). Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design(tm) Into Practice. *Journal of the Learning Sciences, 12*(4), 495-547.

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredericks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. Journal of the Learning Sciences, 7(3 & 4), 313-350.

National Research Council (1996). National Science Education Standards. Washington, DC: National Academy Press.

Puntambekar, S. (2006). Analyzing collaborative interactions: divergence, shared understanding and construction of knowledge. *Computers & Education, 47*(3), 332-351.

Puntambekar, S., Stylianou, A., & Goldstein, J. (2007). Comparing Classroom Enactments of an Inquiry Curriculum: Lessons Learned From Two Teachers. *The Journal of the Learning Sciences, 16*(1), 81-130.

Puntambekar, S., Stylianou, A., & Hübscher, R. (2003). Improving Navigation and Learning in Hypertext Environments With Navigable Concept Maps. *Human-Computer Interaction, 18*(4), 395-428.

Ronen, M., & Eliahu, M. (2000). Simulation a bridge between theory and reality: the case of electric circuits. *Journal of Computer Assisted Learning, 16*, 14-26.

Sadler, P., Whitney, C., Shore, L., & Deutsch, F. (1999). Visualization and Representation of Physical Systems: Wavemaker as an Aid to Conceptualizing Wave Phenomena. *Journal of Science Education and Technology, 8*(3), 197-209.

Snir, J., Smith, C., & Grosslight, L. (1993). Conceptually enhanced simulations: A computer tool for science teaching. *Journal of Science Education and Technology*, *2*(2), 373-388.

Van Heuvelen, A., & Zou, X. (2001). Multiple representations of work–energy processes. *American Journal of Physics, 69*, 184.

Winn, F. S., Sarason, R. Fruland, P.O. & Lee, Y-L. (2006). Learning oceanography from a computer simulation compared with direct experience at sea. Journal of Research in Science Teaching, 43(1), 25-42.

Zacharia, Z., & Anderson, O. (2003). The effects of an interactive computer-based simulation prior to performing a laboratory inquiry-based experiment on students' conceptual understanding of physics. *American Journal of Physics, 71*, 618.

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, 120-132.

Zacharia, Z., & Olympiou, G. (2010). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction*. doi:10.1026/j.learninstruc.2010.03.001

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.

Zollman, D. A., Rebello, N. S., & Hogg, K. (2002). Quantum mechanics for everyone: Hands-on activities integrated with technology. *American Journal of Physics, 70*, 252.

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