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

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We compare the effect of experimenting with physical or virtual manipulatives on undergraduate students’ conceptual understanding of heat and temperature. A pre–post comparison study design was used to replicate all aspects of a guided inquiry classroom except the mode in which students performed their experiments. This study is the first on physical and virtual manipulative experimentation in physics in which the curriculum, method of instruction, and resource capabilities were explicitly controlled. The participants were 68 undergraduates in an introductory course and were randomly assigned to an experimental or a control group. Conceptual tests were administered to both groups to assess students’ understanding before, during, and after instruction. The result indicates that both modes of experimentation are equally effective in enhancing students’ conceptual understanding. This result is discussed in the context of an ongoing debate on the relative importance of virtual and real laboratory work in physics education. © 2008 American Association of Physics Teachers.

I. INTRODUCTION

The current literature on reform in science education has reopened the debate on the role and practice of laboratory experimentation in science teaching and learning.1–4 One reason is the rapid growth of computer-based virtual manipulatives5 and their implications for teaching, learning, and research.6 During the past decade empirical studies have revealed the potential of virtual manipulatives to enhance students’ skills,7,8 attitudes,9 and conceptual understanding.10–12 In some of these studies the method of instruction, curriculum materials, and resources were not completely controlled. For example, Finkelstein et al.13 describe results from a conceptual survey on simple electric circuits that show that students who had used virtual manipulatives outperformed peers who had used physical manipulatives. However, the results could be attributed to the fact that only the use of a computer simulation (a virtual manipulative) allowed students to explicitly model electron flow. Nevertheless, such a result suggests that laboratory experimentation, as commonly experienced by the use of physical manipulatives,14 can be redefined and restructured to include virtual manipulatives.7,12,13

Some researchers argue that the use of virtual manipulatives deprives students of hands-on manipulation of physical materials, which are essential for learning.15,16 According to these researchers, virtual manipulatives should be used for experimentation only when a real laboratory is unavailable, too expensive, or too intricate, the experiment is dangerous, the experimental techniques are too complex, or there are severe time constraints. This perspective implies that experimenting with virtual manipulatives should be regarded at best as a surrogate for experimenting with physical manipulatives,17 and is counter to virtual manipulative proponents who claim that it is the process of manipulation, rather than the physical or virtual nature of the manipulatives, that is the important aspect of instruction.7,12,18

Given this disagreement, there are several questions that have important implications for physics education. Are the two modes of experimentation equally conducive to conceptual understanding in physics? Is manipulation, rather than physicality, the important contributor to learning?

II. THE STUDY

The purpose of this study was to investigate whether the two modes of experimentation are equally conducive to physics learning, while controlling for the method of instruction, curricular materials, and the resource capabilities of the two modes. We made an explicit effort to design a study that controls for all variables that might affect learning outcomes, which according to Ref. 18, is an important limitation of prior studies. The manipulatives were selected so that both could offer participants the same capabilities for experimentation.

We investigated how using physical or virtual manipulatives affected undergraduate students’ conceptual understanding of heat and temperature in the context of the Physics by Inquiry curriculum.19 This study involved quantifying students’ conceptual understanding into conceptual knowledge gains11 and the identification of students’ concepts about temperature and changes in temperature. The aim of the latter identification was to examine whether the type and nature of student conceptions differed between experimentation with physical and virtual manipulatives.

The study was done in the context of the Physics by Inquiry curriculum to compare the effect of two instructional conditions that differ only in the medium of experimentation. The guidance provided by the activity sequence of this curriculum enabled us to control for the manipulation aspects of both physical and virtual experimentation.

We selected the Physics by Inquiry curriculum because it appears to enhance undergraduate students’ conceptual understanding across physics subject domains,12,20–22 including
heat and temperature. The success of this curriculum is based on three components that facilitate conceptual understanding, namely, inquiry, socioconstructivism, and strategies such as the predict-observe-explain cycle.

III. METHODS

A. Sample

The participants of the study were 68 undergraduate students (15 male, 53 female) in an introductory physics course for preservice elementary school teachers. The course took place at a university in Cyprus. The participants were randomly separated into a control group (CG, 34 students) and the experimental group (EG, 34 students). None of the participants had taken college physics prior to the study.

The students in both groups were randomly assigned to subgroups (three per subgroup whenever possible). Such an organizational structure, in association with the curriculum materials, is consistent with a social constructivist framework, which entails the construction of knowledge within a community of learners in the classroom.

B. Curriculum materials

The first two sections of the module Heat and Temperature of the Physics by Inquiry curriculum were used for the purposes of this study. The first section focuses on constructing an operational definition of temperature, and the second section is on investigating temperature changes when samples with varying amounts of hot and cold water are mixed. The students are guided through the process of constructing a conceptual model for how temperature changes, starting from direct hands-on experience. Students perform experiments and draw inferences from their observations to construct the basic concepts of room temperature, thermal interaction, and thermal equilibrium. The ultimate goal is for the students to synthesize their own conceptual frameworks, which will enable them to predict and explain how temperatures change when objects interact thermally.

C. Manipulatives

The physical manipulatives involved the use of real instruments (thermometers), objects (beakers, styrofoam cups, and heaters) and materials (wood, aluminum, and water) in a conventional physics laboratory. During the experiments feedback is available to students through the behavior of the actual system (for example, water boils or not) and through the instruments that are used to monitor the experimental setup (for example, thermometers).

The virtual manipulatives involved the use of the corresponding virtual instruments, objects, and materials. The virtual lab THERMOLAB was used for this purpose because of its fidelity and the fact that it retains the features and interactions of Heat and Temperature as the physical manipulatives. In this open-ended environment students in the experimental group can design and conduct any experiment discussed in the module of Heat and Temperature by employing the “same” material as the ones used by the control group where real instruments were used.

In THERMOLAB, students are provided with a virtual workbench on which experiments can be performed, virtual objects for the experimental setup, virtual materials whose thermal properties are to be investigated, and virtual instruments and displays. Experiments are set up by clicking on icons representing the objects or materials needed for each experiment and moving them to the desired position on the workbench.

D. Experimental design

A pre–post comparison study design was used. The two control groups worked in the same laboratory environment, which has both conventional equipment and a computer network at the periphery. The duration of the study was about two months. Students met once a week for 90 minutes. The time on task was the same for both groups. In particular, both groups spent the same amount of time on a brief introduction that familiarized the students before engaging in the study’s conditions. We controlled for the time on task required for students using both kinds of manipulatives. For example, because the process of bringing a sample of water to a desired temperature takes more time with physical manipulatives than with virtual manipulatives, the control group was provided with preset material (for example, preheated samples of water) to avoid any time spent on such routine procedural tasks. In this way the participants of the experimental group did not have the convenience that the virtual experiments would otherwise have provided. It has been
found that the time on task is one of the variables that influences the learning process and outcomes of a learning activity in favor of virtual manipulatives, because a virtual manipulative activity can be experienced by students more times in a given time period than a physical manipulative activity.24,29 All other important variables (for example, instructors, method of instruction, curriculum materials, and procedures) were identical for the two student groups.

E. Data collection

Conceptual tests were administered to assess the students’ understanding of concepts related to temperature and changes in temperature. A temperature and change in temperature (T&CT) test was administered before and after instruction. In addition, before and after completing each section two more tests were administered: a temperature test (test 1) and a change in temperature test (test 2). An example is given in Fig. 2. The questions on the tests were developed and used in previous research studies by the Physics Education Group of the University of Washington.33

Tests 1 and 2 contained four open-ended conceptual questions that require explanations of reasoning (see the Appendix for a sample of questions of test 2). The T&CT test included eight open-ended questions assessing both sections of the study’s curriculum; tests 1 and 2 were used for the assessment of sections 1 and 2, respectively. There were no identical questions on the T&CT test and tests 1 and 2. Each question of each test was scored separately; a total correct score was derived from each test and used in the analysis. All tests were scored and coded blind to the group in which the student was placed. A table was used that specified different criteria for the responses to each question. Each response was scored on each criterion. The total maximum score for all criteria of all items on each test was 100.

F. Data analysis

The data analysis involved both quantitative and qualitative procedures. The quantitative analysis involved paired-samples t-tests for the comparison of the pretest to the posttest scores on the three tests for each group separately, and one-way ANCOVA for the comparison of the posttest scores of the two groups on each test. For the latter procedure, the students’ scores in the corresponding pretests were used as the covariate. The aim of the first procedure was to investigate whether the use of physical and virtual manipulatives within the context of the Physics by Inquiry curriculum improved students’ conceptual understanding, both after introducing each section of the study’s curriculum and after the completion of the study. The aim of the second procedure was to investigate whether physical and virtual manipulatives had a different effect on the students’ overall conceptual understanding of the whole of the study’s curriculum and of each section of the study’s curriculum separately.

The qualitative data analysis focused on identifying and classifying students’ scientifically accepted and nonscientifically accepted conceptions. For the purposes of this paper, only the analysis of the conceptions of changes in temperature is included. The analysis followed the procedures of phenomenography,30,31 which is used to identify students’ qualitatively different, hierarchically related conceptions of learning.24 In this case the purpose of the phenomenographic analysis was to reveal the categories of the qualitatively different perspectives in which conceptions concerning changes in temperature were conceptualized by the students of each group. In addition, the prevalence of each one of the resulting categories for each test (T&CT pre and posttests, and pre and posttests 2) was calculated. The purpose of the latter was to examine whether the prevalence of each category of the students’ conceptions differed prior to and after the study.

To ensure objective assessment, the tests were coded and scored anonymously. Internal reliability data were also collected for both research questions. Two independent coders reviewed about 25% of the data. The reliability measures (Cohen’s kappa) for scoring of the T&CT test (pre and post) and tests 1 and 2 (pre and post), were 0.89, 0.88, and 0.9, respectively. The reliability measure (proportion of agreement) for the qualitative analysis calculated as the agreement coefficient for the categories of students’ conceptions was 0.88. Disagreements were discussed after the reliability analysis and were resolved by consensus.

IV. RESULTS

The paired-samples t-test procedure indicated that the mean scores for both groups on each of the posttests (see Table I) were statistically higher, at the $p < 0.001$ level, than
the corresponding mean scores on the pretests $[\text{EG, Test1}(33) = 32, \text{EG, Test2}(33) = 40.2, \text{CG, Test1}(33) = 35.2, \text{CG, Test2}(33) = 37.9]$. These scores show that both conditions improved undergraduate students’ conceptual understanding of temperature and changes in temperature.

The one way ANCOVA procedure did not reveal any significant differences between the posttest scores of the two groups for the tests of the study $F(1,65)_{\text{EG vs CG, Test1 posttest}} = 1.94, p = 0.17$, $F(1,65)_{\text{EG vs CG, Test2 posttest}} = 0.98, p = 0.32$, $F(1,65)_{\text{EG vs CG, T&CT posttest2}} = 0.68, p = 0.41$. This finding suggests that the use of physical and virtual manipulatives were equally effective in promoting the students’ understanding of concepts concerning temperature and changes in temperature.

The phenomenographic analysis revealed that the two groups shared mostly the same conceptions concerning changes in temperature, either scientifically accepted or not, both before and after the teaching intervention (see Table II).

Additionally, most of the participants of both groups shifted from nonscientifically accepted to scientifically accepted conceptions after the study. Both groups were found to have the highest prevalence for scientifically accepted and lower prevalence for nonscientifically accepted, with similar shifts in their frequency. Moreover, the two groups shared the same most prevalent nonscientifically accepted conceptions. These findings indicate that the use of physical and virtual manipulatives had the same effect on the students’ understanding of concepts concerning changes in temperature, namely, on the transition from nonscientifically accepted to scientifically accepted as well as on the nature of conceptions concerning changes in temperature after the study.

V. DISCUSSION

The goal of this study was to investigate the relative value of physical and virtual manipulatives on changes in students’ conceptual understanding. The findings indicate that the use of physical and virtual manipulatives, when used in the framework of the Physics by Inquiry curriculum and when controlling as completely as possible the range of variables that influence the learning process and outcomes, can provide equally interactive experiences that enhance students understanding of concepts related to temperature and changes in temperature. Both the quantitative and qualitative analysis showed that the nature of learning and the learning outcomes do not change substantially when physical manipulatives are substituted by virtual manipulatives, which has been disputed as a viable means for experimentation. The qualitative analysis revealed that the vast majority of the students in both groups appeared to share similar distributions of nonscientifically accepted conceptions both before and after instruction.

These findings challenge the assumption that the physicality of manipulation is an essential aspect of effective laboratory experiments. The more significant influences on teaching and learning outcomes derive from the design of the activity sequences and the extent to which students are intellectually engaged with the process of developing meaning. According to Triona and Klahr, the assumption that only the use of physical manipulatives enhances learning is not well grounded in either constructivist or cognitive learning theory. Constructivist theory emphasizes the importance of learners taking an active role in their own learning, but it does not specifically require physical manipulation. Cognitive theory focuses on the need for learners to actively process information and practice the target skill. Neither a theoretical nor an empirical justification exists that portrays physical manipulation of materials as a requirement for active processing and practice, unless the target skill is perceptual-motor.

This study leaves open the question about the conditions under which the use of physical or virtual manipulatives in science experimentation may be preferable. Findings of recent empirical studies that involved comparisons between virtual and physical manipulatives, although limited, have revealed instances where the use of virtual manipulatives would appear to be more beneficial to physics learning than the use of physical manipulatives and vice versa. If the use of one type of manipulative brings expanded or improved opportunities for student learning in the course of conducting experiments, that manipulative should be preferred over the other. For example, only the “messy” interactions with physical manipulatives teach students about the underlying complexity of collecting scientific evidence (for example, measurement errors) and give them a more grounded perspective on the limitations of specific virtual environments. In contrast, virtual manipulative interactions are the only ones that provide students with opportunities to manipulate conceptual objects (objects that have no perceptual fidelity) or depict and study phenomena of very large or very small temporal and physical dimensions (for example, astronomy and molecular dynamics). Clements has argued that virtual manipulatives can provide representations that are just as meaningful to students as physical manipulatives and may even be more “manageable, ‘clean,’ flexible, and extensible than their physical counterparts.” Much promise lies in efforts to combine physical and virtual manipulatives so as to optimize the effectiveness of individual activities in a sequence.

VI. CONCLUSION

We have described a pre–post study in which the objective was to replicate all aspects of a guided inquiry classroom except the manner in which students performed the experiments. This study revealed that both virtual and physical manipulatives can be effective in developing conceptual understanding. This finding challenges commonly held assumptions about laboratory work in the physics classroom and calls for a redefinition and restructuring of experimentation to include both physical and virtual manipulatives. This call for change creates the need for understanding how both modes of experimentation should be integrated in activity sequences for physics teaching and learning. It is essential to expand the empirical base through similar research to test further these perspectives as well as to ground theoretical conjectures regarding a framework for integrating physical and virtual manipulatives within physics learning environments.
Table II. Students’ conceptions about changes in temperature as they emerged from the phenomenographic analysis.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Conceptions</th>
<th>Control group (N=34)</th>
<th>Experimental group (N=34)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pretests % (n)</td>
<td>Posttests % (n)</td>
</tr>
<tr>
<td>Thermal interaction and equilibrium</td>
<td>When hot and cold water are mixed, both the hot and cold water change temperature (because heat, not temperature, is transferred from the hot water to the cold water). The temperature of the hot water decreases and the temperature of the cold water increases until they both reach the same intermediate temperature (scientifically accepted).</td>
<td>8.8 (3) b</td>
<td>73.5 (25)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, both the hot and cold water change temperature because temperature is “provided” from the hot water to the cold water: The temperature of the hot water decreases and the temperature of the cold water increases until they both reach the same intermediate temperature (nonscientifically accepted).</td>
<td>61.7 (21)</td>
<td>26.4 (9)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, both the hot and cold water change temperature because temperature is “provided” from the hot water to the cold water: The temperature of the hot water decreases and the temperature of the cold water increases without reaching the same intermediate temperature (nonscientifically accepted).</td>
<td>23.5 (8)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, their temperature does not necessarily change (nonscientifically accepted).</td>
<td>20.6 (7)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Thermal interaction: Quantifying changes in temperature</td>
<td>When hot and cold water are mixed, the product of the mass and the temperature change of the hot water is equal to the product of the mass and the temperature change of the cold water; in other words, the change in temperature of the hot water depends upon the masses of both the cold and hot water as well as the change in temperature of the cold water and vice versa, or the change in temperature is larger for the sample of water, cold or hot, that has the lower mass (scientifically accepted).</td>
<td>0 (0)</td>
<td>100 (34)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, the mass of either the hot or the cold water does not affect the change in temperature of both the hot and cold water (nonscientifically accepted).</td>
<td>64.7 (22)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, the change in temperature is always the same for both the hot and the cold water regardless of their mass (nonscientifically accepted).</td>
<td>26.4 (9)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>When hot and cold water are mixed, the initial temperature of either the hot or the cold water does not affect the change in temperature of both the hot and cold water (nonscientifically accepted).</td>
<td>23.5 (8)</td>
<td>0 (0)</td>
</tr>
<tr>
<td></td>
<td>When two samples of water of the same temperature are mixed, the temperature of both samples changes according to their mass. The higher the mass the less the temperature change (nonscientifically accepted).</td>
<td>29.4 (10)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Students were not required to refer to the concept of heat because the concepts of heat and heat transfer (Sec. III of the Heat and Temperature module of the Physics by Inquiry curriculum) are introduced right after the section on Changes in Temperature (Sec. II of the Heat and Temperature module of the Physics by Inquiry curriculum). Despite the fact that it was not a prerequisite to explain why the temperature of cold and hot water changed, students did provide such explanations in their attempt to explain their reasoning while answering the questions of pre and posttest 2.

The percentage and number (included in the parenthesis) refer to students who explicitly mentioned the particular conception referred to, which does not mean that other students might not also share these conceptions. In other words, it is very possible that certain conceptions are more widespread than the numbers suggest. In addition, the response of one individual student may appear in more than one category, depending on the conceptions that were evident in the response.

APPENDIX: SAMPLE OF QUESTIONS OF TEST 2

Test 2: Problem 1 (adapted from Ref. 19)
A. Suppose that 500 g of hot water at 60 °C is mixed with 500 g of cold water at 40 °C.

(1) The temperature of the hot water increases, decreases, or remains the same? Explain your reasoning.
(2) The temperature of the cold water increases, decreases, or remains the same? Explain your reasoning.
(3) The temperature of the mixture will be higher than 50 °C, lower than 50 °C, or exactly at 50 °C?

B. Suppose that 250 g of hot water at 60 °C is mixed with 250 g of cold water at 20 °C.

(1) The temperature of the hot water increases, decreases, or remains the same? Explain your reasoning.
(2) The temperature of the cold water increases, decreases, or remains the same? Explain your reasoning.
(3) The temperature of the mixture will be higher than 50 °C, lower than 50 °C, or exactly at 50 °C?
500 g of cold water at 40 °C.

(1) The temperature of the hot water increases, decreases, or remains the same? Explain your reasoning.

(2) The temperature of the cold water increases, decreases, or remains the same? Explain your reasoning.

(3) The temperature of the mixture will be higher than 50 °C, lower than 50 °C, or exactly at 50 °C? Explain your reasoning.


4Experiments with virtual manipulatives is defined as the use of a simulation environment that includes virtual apparatus and material to conduct an experiment on a computer. Virtual manipulative activities are defined as learning experiences that involve a process in which students interact with materials or models to observe and understand the natural or material or world, and which lead to asking questions, making discoveries, and rigorously testing those discoveries in the search for new understanding.


6L. Triona and D. Klahr, “Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students’ ability to design experiments,” Cogn. Instruct. 21, 149–175 (2003).


13Experimenting with physical manipulatives is defined as the use of real apparatus and material to conduct an experiment in a laboratory. Physical manipulative activities are defined in the same way as virtual manipulative activities (Ref. 5).


23For more details see Z. Zacharia, G. Olympiou, and M. Papaevripidou, “Effects of experimenting with physical and virtual manipulatives on students’ conceptual understanding in heat and temperature,” J. Res. Sci. Teach. (in press).


26The wording of the curriculum used by the experimental group was slightly modified to refer to the features of the virtual manipulatives.


30F. Marton and S. Booth, Learning and Awareness (Lawrence Erlbaum, Maywah, NJ, 1997).


