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COMPARING THE EFFECTS OF PHYSICAL, VIRTUAL, AND HYBRID LABS ON PRIMARY SCHOOL STUDENTS' CONCEPTUAL LEARNING OF HEAT AND TEMPERATURE

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Abstract. *Physical and virtual labs have unique capabilities that can influence how students learn from them. The purpose of this study was to examine the effect of physical and virtual manipulatives on students' learning of heat and temperature and to examine the influence of various combinations of physical and virtual manipulatives. A total of 205 participants were divided into four groups: only physical manipulatives, only virtual manipulatives, physical-virtual manipulatives, and virtual-physical manipulatives. Students' knowledge acquisition was tested using Pre-test–Post-test design. The results showed that physical and virtual manipulatives are as effective in facilitating students' learning of state changes, but virtual manipulatives are more beneficial to students' learning of thermal expansion and contraction than physical manipulatives are. Physical-virtual manipulatives are more effective than virtual-physical manipulatives or physical manipulatives alone are to promote students' learning of heat and temperature, but this effect is similar to that of virtual manipulatives alone. The results suggest that virtual laboratories can effectively model abstract concepts. The better effect of the physical-virtual operation sequence on learning does not depend on whether the two types of experiments are combined or on the sequence of operations but on the type of experiment when its advantages actually contribute to learning.*

Keywords: *experimental design, heat and temperature, physical manipulative, virtual manipulative*

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Introduction

Students come to classes with preconceived ideas that are sometimes different from accepted scientific views, called *misconceptions*. Students' misconceptions are ingrained and resistant to change. Misconceptions are one of the major obstacles students face when learning proper scientific concepts. Students' learning is heavily influenced by misconceptions. Science curricula contain many abstract and complex concepts, but heat and temperature are important subjects to learn at all educational levels (Gönen & Kocakaya, 2010). Children learn the science of heat and temperature, including heat transfer, states of matter, changes of state, and thermal expansion and contraction. Heat and temperature are definitely among the most difficult concepts in science curricula. Numerous studies have indicated that children understand heat and temperature differently from scientists. Children gain understanding from their everyday experiences and even from incorrect explanations at school (Sözbilir, 2003). Studies have pointed out that children have many misconceptions of heat and temperature. The following are examples of misconceptions some students might have: When a substance is transformed into another state, it will become another substance (Lee et al., 1993). The solid state of matter is heavier than the liquid state. The mass of matter changes with the change of state; for instance, when we heat a substance, its mass will decrease (Çakir, 2005). When matter is heated, atoms will expand, and when matter freezes, atoms will freeze as well. In the process of changing the state of matter, the atoms' size, shape, and weight change; when matter changes from liquid to gas, its mass decreases (Griffiths & Preston, 1992). When a gas is cooled, the particles can shrink, condense, sink, or settle down (Novick & Nussbaum, 1981). The reduction in gas volume during cooling is due not to a decrease in particle motion, but rather to an increase in attractive force (Novick & Nussbaum, 1981). As the temperature rises, the particles

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absorb heat and begin to expand (Brook et al., 1984). In an object with holes, when the object is heated, the holes' diameter decreases (McHugh & McCauley, 2016). Traditional teaching cannot change students' misconceptions, so researchers have turned their attention to finding effective teaching methods to overcome these misconceptions. Physical and virtual laboratory experiments are among these methods (Agyei et al., 2019; Hung & Tsai, 2020; Kibirige & Bodirwa, 2021; Pyatt & Sims, 2012).

In a number of comparative studies, researchers have attempted to examine the effects of physical and virtual laboratory experiments with respect to science learning, yet their results are inconsistent (Klahr et al., 2007; Renken & Nunez, 2013; Zacharia & de Jong, 2014). Zacharia et al. (2008) stated that the studies' inconsistent results were caused by each of these two teaching methods' unique advantages. For example, physical laboratory experiments can provide real and concrete experiences (Gire et al., 2010), and virtual laboratory experiments can reify abstract concepts (Zacharia & de Jong, 2014). In the literature, many researchers have advocated combining the advantages of these two types of laboratories to enhance students' learning outcomes (Jaakkola et al., 2011; Olympiou & Zacharia, 2012). A strand of research has emerged comparing the relative effectiveness of physical manipulatives (PMs), virtual manipulatives (VMs), and a combination of both for teaching students science. The results of most studies indicated that the combination of the two types of experimental manipulatives is better than either only PMs or only VMs is (Jaakkola et al., 2011; Olympiou & Zacharia, 2012; Zacharia et al., 2008; Wang & Tseng, 2018). Another strand of research has also emerged comparing the effects of various sequences of two types of experimental manipulatives (e.g., PMs before VMs or VMs before PMs) on students' science learning. However, researchers have not reached any consensus conclusion. The results of some studies have shown that using physical before virtual manipulatives can result in similar effects for students' conceptual understanding as using VMs before PMs does (Zacharia & Olympiou, 2011). Some study results have shown that using VMs before PMs leads to better learning outcomes (Akpan & Andre, 2000); others have shown that using PMs before VMs leads to better learning outcomes (Gire et al., 2010). Some studies have pointed out that it is not clear how to combine virtual laboratory activities with physical laboratory activities in different ways to produce optimal learning outcomes; therefore, more research is needed to focus on this direction (Jaakkola et al., 2011; Olympiou & Zacharia, 2012; Olympiou & Zacharia, 2014).

Research Focus

Each virtual lab activity developed in this study corresponds to each physical lab activity. The topic of heat and temperature explored in this study includes two learning activities: (a) state changes and (b) thermal expansion and contraction. In particular, the concept of state changes is a relatively macroscopic or concrete concept, whereas the concept of thermal expansion and contraction is a relatively microscopic or abstract concept. The focus of this study was to examine the effects of different forms of experimental manipulation (physical and virtual manipulatives) on different content characteristics (macro/concrete and micro/abstract) and to examine the influence of different combinations of physical and virtual manipulatives to find the optimal teaching effect.

Research Aim and Research Questions

This study aimed to examine the effect of using physical and virtual manipulatives separately in specific physics concepts as well as the outcomes of using various combinations of physical and virtual manipulatives in teaching the topic of heat and temperature. The idea behind using various combinations was to explore possible ways of combining physical and virtual manipulatives in an effort to optimize their educational effect. The questions of this study were as follows:

1. Does a significant difference exist between the effects of using PMs and PMs on students' learning of the concept of state changes?
2. Does a significant difference exist between the effects of using PMs and VMs on students' learning of the concept of thermal expansion and contraction?
3. What is the relative effectiveness of using PMs alone, VMs alone, PMs first then VMs, and VMs first then PMs on students' learning physics concepts of heat and temperature?

This study addressed three hypotheses: (a) PMs can help students develop knowledge of state changes more than VMs; (b) VMs can help students develop knowledge of thermal expansion and contraction more than PMs can; and (c) the combination of PMs first then VMs can be more conducive to students learning the physics concepts involved in heat and temperature than the other three experimental conditions could.

Research Methodology

General Background

The courses of the four experimental groups— PMs alone, VMs alone, PMs first then VMs (PMs–VMs), and VMs first then PMs (VMs–PMs)—were based on a sixth-grade science and technology textbook (Science and Technology, 2011) and the Taiwanese science curriculum guide (Ministry of Education, 2010). The same course topic, heat and temperature, was taught in the four learning environments, focusing on the concepts of state changes and thermal expansion and contraction. The study was conducted in October and November of the 2017-2018 school year. For each group, the study was conducted over 2 weeks, and it included two activities, each with two and four periods. Each period was 40 min, and the entire study consisted of six periods for a total of 240 min. Students' knowledge acquisition was tested through a Pre-test, Post-test 1 (state changes), and Post-test 2 (thermal expansion and contraction) design as shown in Table 1. Students completed the Pre-test before the two activities, Post-test 1 after the first activity, and Post-test 2 after the second activity. The Post-test 1 and Post-test 2 scores allowed comparisons between the effects of physical and virtual manipulatives on students' knowledge acquisition of state changes and thermal expansion and contraction, respectively, and the total scores from adding the Post-test 1 and Post-test 2 scores indicated the combination effects.

Table 1
Design of the Experiment

Group		First activity			Second activity				
		State changes			Thermal expansion and contraction				
		Period 1	Period 2		Period 3	Period 4	Period 5	Period 6	
PMs	Pre-test	PMs	PMs	Post-test 1	PMs	PMs	PMs	PMs	Post-test 2
VMs	Pre-test	VMs	VMs	Post-test 1	VMs	VMs	VMs	VMs	Post-test 2
PMs–VMs	Pre-test	PMs	PMs	Post-test 1	VMs	VMs	VMs	VMs	Post-test 2
VMs–PMs	Pre-test	VMs	VMs	Post-test 1	PMs	PMs	PMs	PMs	Post-test 2

Participants

Participants included 205 sixth-grade students (11–12 years old; 101 boys and 104 girls) from eight science classes taught by two science teachers in a primary school in Taiwan. The eight science classes were assigned to one of the four experimental groups (PMs, VMs, PMs–VMs, or VMs–PMs). Each of the two science teachers taught in each of the four learning conditions. Prior to the study, both science teachers had participated in a 10-week professional development program designed by two instructional experts and two science teacher educators. The 30-hr program trains science teachers to integrate real laboratories and virtual laboratories effectively into their teaching practices for specific subject domains (e.g., heat and temperature). The Taiwan Ministry of Science and Technology granted permission to carry out this study. Before the implementation, all students were informed about the study and their right to leave the study at any time. Students' participation was voluntary and anonymous. The confidentiality and privacy of participants were ensured and protected throughout the entire study.

Research Instrument

Science Achievement Test

Based on the learning objectives of the topic of heat and temperature in Taiwan's sixth-grade science curriculum, a science achievement test was developed to assess students' knowledge acquisition. The test questions include the concepts of state change and thermal expansion and contraction, including 22 multiple choice questions, four state change questions, and 18 thermal expansion and contraction questions (see Appendix for sample

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questions). Each question has one correct answer and three distractors. The maximum score on the test is 22 points (4 points for state changes and 18 points for thermal expansion and contraction). The higher the score, the more scientific knowledge was obtained. An expert panel consisting of two teacher educators and three experienced primary school science teachers established the content validity of this instrument.

Before completing the two activities, students answered a set of questions related to concepts in the domain of heat and temperature (Pre-test), a subset of questions related to state changes after the first activity (Post-test 1), and another subset of questions related to thermal expansion and contraction after the second activity (Post-test 2). The Kuder–Richardson Formula 20 reliability coefficient was calculated based on data collected from 205 sixth-grade students in Taiwan. The Pre-test, Post-test 1, and Post-test 2 coefficients were .76, .77, and .78, respectively.

Curriculum Materials

For the purposes of this study, two activities were carried out on the topic of heat and temperature. The first activity focused on concepts related to state changes, and the second activity explored concepts related to thermal expansion and contraction. In particular, the learning objectives in each activity were as follows: The first activity enabled students to understand changes in the state of matter through heating or cooling. The details of the activities are described as the following. Butter and chocolate can change state from solid to liquid when they are heated. Keep cooling the liquids, and they eventually turn back into solids. When a shrimp is heated, not only does the color turn bright red; it also curls up. When an egg is heated, the albumen turns from clear to white, and the egg white and yolk solidify. The second activity allowed students to understand the thermal expansion and contraction of solids, liquids, and gases when they are heated and cooled. For example, a metal ball passes through a metal ring when both are at room temperature. If the ball is heated, then it will no longer pass through the ring because the ball will expand. However, when cooled, the ball will pass through the ring because it shrinks. If both the ring and the ball are heated to the same temperature, the ball will pass through the ring again. An Erlenmeyer flask containing red water is placed in an acrylic water tank containing hot water. The red water will expand when heated by hot water. The students can see the water level rise in the glass tube. Take a balloon and stretch the opening over the mouth of an Erlenmeyer flask. Put the Erlenmeyer flask in an acrylic water tank filled with hot water. The air in the Erlenmeyer flask expands when heated, causing the balloon to expand. To reverse the results, when the Erlenmeyer flask is placed in an ice water tank, the ice water cools the air in the Erlenmeyer flask. The air then moves out of the balloon and returns to the Erlenmeyer flask, causing the balloon to deflate.

Laboratory Materials

Materials in the Physical Laboratory

Physical lab activities involve manipulating experiments in a traditional science laboratory using actual instruments (e.g., thermometers) and objects (e.g., butter, chocolate, eggs, shrimp, beakers, alcohol lamps, silver paper plates, metal balls, metal rings, Erlenmeyer flasks, red water, glass tubes, cork, balloon, hot water, ice water, acrylic water tank, and an alcohol burner bracket).

Materials in the Virtual Laboratory

Virtual lab activities involve manipulating experiments on tablets using virtual instruments and objects. In this study, the research team at National Tsinghua University in Taiwan used virtual reality technology to develop a virtual laboratory on the topic of heat and temperature. The virtual laboratory, *Heat & Temperature Lab*, was chosen for its high fidelity and preservation of the characteristics and interactions of the physical laboratory in terms of heat and temperature. Moreover, a corresponding virtual experiment activity was developed for each physical experiment activity in this topic. In this 3D virtual lab, students who use virtual manipulatives can perform any experiment using the same instruments and objects that students use under physical laboratory conditions. In the Heat & Temperature Lab, the students were given a virtual workbench, where they were able to perform simple and direct manipulations on virtual materials. They set up the experiment by clicking on the icons representing the instruments and objects required for each experiment and moving them to the desired virtual location on the workbench. For example, they heated a shrimp on a silver paper plate on an alcohol burner bracket and a spirit

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lamp (see Figure 1), heated a metal ball placed on a spirit lamp (see Figure 2), put the Erlenmeyer flask with red water and glass tube into the acrylic tank with hot water (ice water) on the workbench to heat (cool) the red water (see Figure 3), and put the balloon over the mouth of the conical flask and put it into the acrylic water tank filled with hot water (ice water) on the workbench to heat (cool) the balloon (see Figure 4). The Heat & Temperature Lab allows students not only to visualize and manipulate concepts and phenomena but also to view the experiments from multiple perspectives.

Data Analysis

The comparison of students' science achievement scores between groups was analyzed through one-way analysis of covariance (ANCOVA). The experimental group (type of experiment) and the Post-test scores played the part of the explanatory and response variables, and to control the error variability, the Pre-test scores played the role of a covariate. According to the guideline in Kutner et al. (2005), high *p* values (> .05) of the tests of normal distribution, homogeneity, and linearity suggest the adequacy of using ANCOVA for the analyzed data.

Research Results

The Pre-test and two Post-test research design was conducted to compare the degrees to which students' performance was supported by PMs or VMs as well as the combinations of PMs and VMs (only PMs, only VMs, PMs–VMs, and VMs–PMs). The results will be discussed below according to each single concept and overall concepts (state change score, thermal expansion and contraction score, and total score).

State Change Score

A one-way ANCOVA was applied in this study to assess the difference between PM and VM groups in facilitating students' knowledge acquisition of state changes. The independent variable was the type of experiment (PMs or VMs). The dependent variable was the state change score of Post-test 1. The covariate was the state change score of the Pre-test to control for group differences.

The ANCOVA results are presented in Table 2. The comparison of adjusted and unadjusted means is presented in Table 3. The ANCOVA revealed an insignificant effect for type of experiment, *F*(1, 202) = .808, *p* = .370 > .05. The adjusted means were 3.37 (*SD* = .08) and 3.27 (*SD* = .07) for the PM and VM groups, respectively. The results showed that the two types of manipulatives seem to be equivalent in facilitating students' knowledge acquisition of state changes.

Table 2
ANCOVA Summary Table for Post-test 1 Achievement Scores

Source	*df*	*F*	Partial η^2	*p*
Pre-test	1	9.198*	.044	.003
Group	1	.808	.004	.370
Error	202			
Total	205			

* *p*<.05

Table 3
Adjusted and Unadjusted Group Means for Post-test 1 Achievement Scores

Source	Adjusted mean	Unadjusted mean
PMs (n = 103)	3.37	3.35
VMs (n = 102)	3.27	3.29

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Thermal Expansion and Contraction Score

A one-way ANCOVA was performed to evaluate the relative effectiveness of PM and VM groups in facilitating students' knowledge acquisition of thermal expansion and contraction. The independent variable was the type of experiment (PMs or VMs). The dependent variable was the thermal expansion and contraction score of Post-test 2. The covariate was the thermal expansion and contraction score of the Pre-test to reduce error variability.

The ANCOVA results are presented in Table 4. The comparison of adjusted and unadjusted means is presented in Table 5. The ANCOVA revealed a significant effect for type of experiment, $F(1, 202) = 15.807$, $p < .001$, partial $\eta^2 = .073$ with a moderate effect size. The adjusted means were 12.29 ($SD = 0.26$) and 13.81 ($SD = 0.27$) for the PM and VM groups, respectively. The results showed that the implementation of VMs was more effective than PMs in promoting students' knowledge of thermal expansion and contraction.

Table 4
ANCOVA Summary Table for Post-test 2 Achievement Scores

Source	*df*	*F*	Partial η^2	*p*
Pre-test	1	60.123***	.229	< .001
Group	1	15.807***	.073	< .001
Error	202			
Total	205			

* *p*<.05, ** *p*<.01, *** *p*<.001

Table 5
Adjusted and Unadjusted Group Means for Post-test 2 Achievement Scores

Source	Adjusted mean	Unadjusted mean
PMs (n = 103)	12.29	12.15
VMs (n = 102)	13.81	13.96

Total Score

A one-way ANCOVA was conducted to find the difference between the effect of PMs alone, VMs alone, PMs–VMs, and VMs–PMs in facilitating students' knowledge acquisition of the concepts of heat and temperature. The independent variable was the experimental group (only PMs, only VMs, PMs–VMs, or VMs–PMs). The dependent variable was the total score obtained by adding the two Post-test scores. The covariate was the Pre-test score to control for group differences.

Table 6 shows the results of the one-way ANCOVA, Table 7 shows the comparison of adjusted and unadjusted means, and Table 8 shows Bonferroni post hoc test for pairwise comparisons of groups. The ANCOVA indicated a significant effect of group, $F(3, 200) = 4.381$, $p = .005 < .01$, partial $\eta^2 = .062$, which corresponded to a moderate effect size. The adjusted means from high to low were PMs–VMs ($M = 17.54$, $SD = 0.41$), VMs alone ($M = 16.43$, $SD = 0.42$), VMs–PMs ($M = 15.94$, $SD = 0.41$), and PMs alone ($M = 15.57$, $SD = 0.40$). Bonferroni-adjusted pairwise comparisons revealed that the use of PMs–VMs enhanced students' gains in knowledge related to heat and temperature more than the use of VMs–PMs or the use of PMs alone did. Moreover, the pairwise comparisons revealed that using PMs–VMs and using VMs alone had equal effect in increasing students' knowledge in all of the concepts of heat and temperature. Although PMs and VMs have similar efficiency for learning about state changes, PMs is more highly recommended because of its unique real-world learning experiences.

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Table 6
ANCOVA Summary Table for Total Achievement Scores from Post-test 1 and Post-test 2

Source	*df*	*F*	Partial η^2	*p*
Pre-test	1	71.334***	.263	< .001
Group	3	4.381**	.062	.005
Error	200			
Total	205			

* $p<05$, ** $p<.01$, *** $p<.001$

Table 7
Adjusted and Unadjusted Group Means for Total Achievement Scores from Post-test 1 and Post-test 2

Source	Adjusted mean	Unadjusted mean
PMs (n=52)	15.57	14.87
VMs (n=51)	16.43	17.02
PMs-VMs (n=51)	17.54	17.51
VMs-PMs (n=51)	15.94	16.12

Table 8
Bonferroni Post Hoc Test for Pairwise Comparisons of Groups

Group Compared	*p*	95%	confidence interval
		Lower bound	Upper bound
PMs vs. VMs	.900	−2.450	.727
PMs vs. PMs–VMs	.005**	−3.526	−.426
PMs vs. VMs–PMs	1.000	−1.933	1.187
VMs vs. PMs–VMs	.346	−2.670	.441
VMs vs. VMs–PMs	1.000	−1.060	2.037
PMs-VMs vs. VMs–PMs	.037*	.059	3.147

* $p <.05$, ** $p<.01$

Discussion

Comparison of Learning Gains by Type of Experiment

One of the purposes of this study was to examine how individual physical and virtual manipulatives support students in learning certain physics concepts related to heat and temperature. When exploring how different manipulatives affected students' learning of specific physics concepts, some differences were found. Regarding the concept of state changes, regardless of the type of experiment, physical and virtual manipulatives affected students' knowledge acquisition similarly. However, for the concept of thermal expansion and contraction, VMs improved students' knowledge gains more than PMs did. The results did not confirm Hypothesis 1 but confirmed Hypothesis 2.

Not as expected, using VMs was as effective as PMs in supporting students in learning the concept of state changes. According to the literature, some proponents of physical laboratory activities emphasized the importance of real experiences. For example, physical laboratory activities provided students directly experiencing scientific phenomena through experiments with concrete materials and instruments in the real world, allowing them to

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observe and understand the natural or material world (Gire et al., 2010; Zacharia & Olympiou, 2011). Han and Black (2011) stated that this effect could even be further improved when combined with other human senses, especially visual and auditory. In this study, students were able to see and feel these changes in color, shape and hardness through physical manipulatives. Therefore, one might speculate that PMs might be more important for the concept of state changes involving visual and tactile progressions. However, the results of this study showed that when PMs were replaced by VMs, the learning results did not change substantially. Concerning the concept of state changes, this alleged advantage regarding physical experiments could now also be afforded by virtual experiments. In this study, whether students virtually witnessed the state of matter change or directly saw and felt these changes in physical experiments, there was no difference in the learning results. In short, this study findings indicated that tactile feedback might not be so beneficial for students' learning of state changes, which seemed to be a "visual" concept. One possible explanation for why virtual experiments could effectively replace physical experiments is the proposition of Dalgarno et al. (2002), which showed that the perception in a 3D virtual environment was equivalent to the real world. A virtual laboratory provided a realistic 3D environment that could simulate macroscopic natural phenomena in the real world. Therefore, in this study, students were able to observe similar natural phenomena in physical experiments and virtual experiments so that both experimental modes provided similar learning effects. In other words, the concept of state changes was easy to understand regardless of the type of experiment.

On the other hand, as expected, virtual laboratory activities led to better learning benefits in terms of thermal expansion and contraction compared to physical laboratory activities. After participating in the second activity, students should have been capable of understanding that a substance's release or absorption of heat energy affects the movement of its particles and changes its volume. Obviously, unlike state changes, thermal expansion and contraction is a more abstract concept. Hennessy et al. (2006) argued that in a real laboratory environment, students might encounter problems when learning the theoretical principles of complex scientific topics (such as electricity) because, in many cases, they could only see what happens on the surface. Comprehending the underlying mechanisms and processes when not visible in natural phenomena (such as an electric current) was impossible. Compared with physical laboratories, only virtual laboratories could provide students with representations of concrete objects and allow them to observe abstract/conceptual objects and processes not observable in real life, such as electron flow or light (Jaakkola et al., 2010; Olympiou et al., 2013). The findings of the study highlighted the advantages of using virtual experiments to facilitate students' learning of thermal expansion and contraction. The reason virtual experiments were more effective than physical experiments might be that virtual experiments allowed students to observe heat increases and see that as atoms moved faster, the distance between them increased. Perhaps these findings could be explained by the particle model, which allowed students to view unobservable to the naked eye, underlying processes and mechanisms in natural phenomena, thereby helping them construct appropriate mental models to understand abstract and complex concepts. The results of this study provided evidence for the idea that the particle model of matter helped students understand abstract concepts. The findings of the study were consistent with those of previous studies (Papageorgiou & Johnson, 2005; Tytler et al., 2007; Wang & Tseng, 2018) showing that the particle model could help primary school students understand abstract natural phenomena such as condensation and evaporation, as well as thermal expansion and contraction. In addition, this study and others (Chini et al., 2012; Sullivan et al., 2017; Zacharia, 2007; Zacharia & de Jong, 2014; Wang & Tseng, 2018) have verified that virtual laboratory activities were more conducive to understanding abstract concepts than physical laboratory activities. The benefit of this study is to extend this verification from pulleys, circuits, evaporation, and condensation to thermal expansion and contraction.

Comparison of Learning Gains Between Groups

The second purpose of this study was to examine how various ways of combining physical and virtual experiments affected students' understanding of the specific physics concepts of heat and temperature. The findings of the study demonstrated that students who first conducted physical experiments and then virtual experiments learned more effectively than students who first conducted virtual experiments and then physical experiments or conducted physical experiments alone. However, the learning effect was the same as that of students who conducted virtual experiments alone. Hypothesis 3 cannot be verified.

The results showed that the differentiation between the four learning environments could be attributed to the existence of virtual experiments in the second activity of the course. In the study, replacing physical experiments with virtual experiments at a key point (the second activity) seemed to have had a significant positive effect on students' learning outcomes. A possible reason was that, unlike in a real laboratory, a virtual laboratory could provide unique affordances such as manipulating reified objects (e.g., a view of the vibration of atoms and molecules speeding up and increasing in distance from each other so that students could observe the microscopic changes of thermal expansion and contraction of matter not observable in real life). The virtual laboratory allowed students to model thermal expansion and contraction of matter explicitly at the micro level, which was conducive to understanding these abstract and complex physics concepts. The findings of the study were inconsistent with those of Olympiou and Zacharia (2012). In that study, they found that using a blended combination of a physical experiment with a virtual experiment was more beneficial to students' learning than using physical experiments alone or virtual experiments alone. One aspect of this study that differed from the aforementioned study was that this study results showed that performing physical experiments first and then virtual experiments was as effective as performing virtual experiments alone. The students in this study were equally effective in learning the concept of state changes whether they conducted a physical experiment or a virtual experiment as their first activity. It is reasonable to believe that under certain conditions, a virtual laboratory could provide an experience not essentially different from a real laboratory, and therefore applying Olympiou and Zacharia's framework led to different results in both studies. More research is needed to test the reliability of this framework in different subject areas. In addition, more frameworks that concentrate on blending physical and virtual capabilities should be developed and tested so that students can experience the best method of learning.

Another interesting finding was that not all combinations of physical and virtual experiments were more beneficial to learning than either form alone. This did not support the results of most previous studies, indicating that combining physical and virtual experiments could promote students' learning concepts more effectively than using physical or virtual experiments alone (Farrokhnia & Esmailpour, 2010; Jaakkola & Nurmi, 2008; Jaakkola et al., 2011; Olympiou & Zacharia, 2012; Ünlü & Dökme, 2011; Wang & Tseng, 2018; Zacharia, 2007; Zacharia et al., 2008). In view of the inconsistent research results, the combination of physical and virtual experiments did not always have an additive effect. Further research is still needed to find the best way for students to learn.

In addition, studying the impact of different operation sequences (physical–virtual, virtual–physical) on students' learning of the concepts of heat and temperature, it was found that the physical–virtual operation sequence promoted students' knowledge development more effectively than the virtual–physical operation sequence. Thus, the order of operations did seem to affect students' learning performance. The findings of the study were in accordance with findings from previous studies on pulleys (Gire et al., 2010; Smith, & Puntambekar, 2010), and all showed that the physical–virtual operation sequence was better than the virtual–physical operation sequence. Nevertheless, the findings of the study were not consistent with some other studies. For example, some studies on frog anatomy and circuits have shown that the virtual–physical operation sequence was better than the reverse, whereas other studies on pulleys, DNA gel electrophoresis, and heat and temperature (Chini et al., 2012; Sullivan et al., 2017; Toth et al., 2009; Zacharia & Olympiou, 2011) have shown that the effects of the two operation sequences were similar. In short, the results of these studies were contradictory. The inconsistent results might be due to the materials and methods used in these studies or the various affordances of physical and virtual experiments in each study. According to the results of this study, it is reasonable to argue that the greater effects of the physical–virtual operation sequence resulted from the virtual experiment having an advantage over the physical experiment in the second activity to convey the concept of thermal expansion and contraction. A virtual laboratory could visually provide students with microscopic phenomena of the thermal expansion and contraction of matter, such as a view of the distance between particles changing due to temperature changes. It implied that a properly designed virtual laboratory could benefit students' learning when applied to abstract concepts.

The present study had two research limitations. First, the research experiment lasted only 240 min; thus, studies with longer study duration are needed for results that are more reliable. Another limitation of this study was that the virtual laboratory of this study only focused on heat and temperature, and more research is needed for wider ranges of subject domains to reach definite conclusions.

Conclusions and Implications

The first purpose of this study was to examine the effect of physical and virtual experiments on students' knowledge acquisition of specific physics concepts with different levels of abstraction. The results showed that physical and virtual experiments were as effective for learning the concept of state changes; however, for learning the concept of thermal expansion and contraction, virtual experiments were significantly better than physical

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experiments. Results from this study suggested that virtual labs could replace real labs under the right conditions. Moreover, they suggested that virtual labs were beneficial for learning abstract concepts such as thermal expansion and contraction. Notably, other characteristics of content, such as dynamic and static materials, were not explored in this study. Many science domains require dynamic descriptions of phenomena (e.g., the movement of stars throughout the year, magnetic effects of currents, cell division). The unique capabilities of virtual labs may be more effective in describing dynamic changes and processes than physical labs. However, more research comparing the influence of virtual and physical labs in dynamic materials of different science domains is necessary to support this hypothesis.

The second purpose of this study was to gain insight into when and how virtual labs should be used to optimize learning. This study examined the effectiveness of four combinations of physical and virtual experiments for students to learn heat and temperature. The results showed that physical–virtual experiments were more effective than virtual–physical experiments and physical experiments alone in enhancing students' learning outcomes in the topic of heat and temperature, but physical–virtual experiments were as effective as virtual experiments alone. Taken together, the differences among the four learning conditions might be mainly due to the unique advantages of the virtual lab, which provided students with a microscopic view of volume changes as matter expanded and contracted, thereby helping students understand the theories and principles of abstract concepts. Furthermore, this study highlighted that students operating in a specific sequence of physical–virtual experiments could produce better learning outcomes. This greater learning effect did not appear to be related to the order of physical and virtual experimental manipulations or whether physical and virtual experiments were combined but it did seem related to whether the advantages of virtual experiments matched the characteristics of the learning content. It is worth noting that although there was no significant difference between physical–virtual experiments and virtual experiments alone, the score of physical–virtual experiments was slightly higher than that of virtual experiments alone. It is speculated that, although the concept of state changes is more inclined to visual learning, changes in color, hardness, shape, weight, and texture of matter, including visual cues and tactile feedback, still need to be observed and experienced during the learning process. Because the virtual laboratory used in this study only provides visual scenes, haptic technology can be added to design visuohaptic simulations in the future so that students can vividly experience concepts and phenomena. A future study could also compare the learning outcomes of physical labs, visuohaptic labs, and virtual labs.

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Declaration of Interest

The authors declare no competing interest.

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Appendix

Sample items for state changes and thermal expansion and contraction

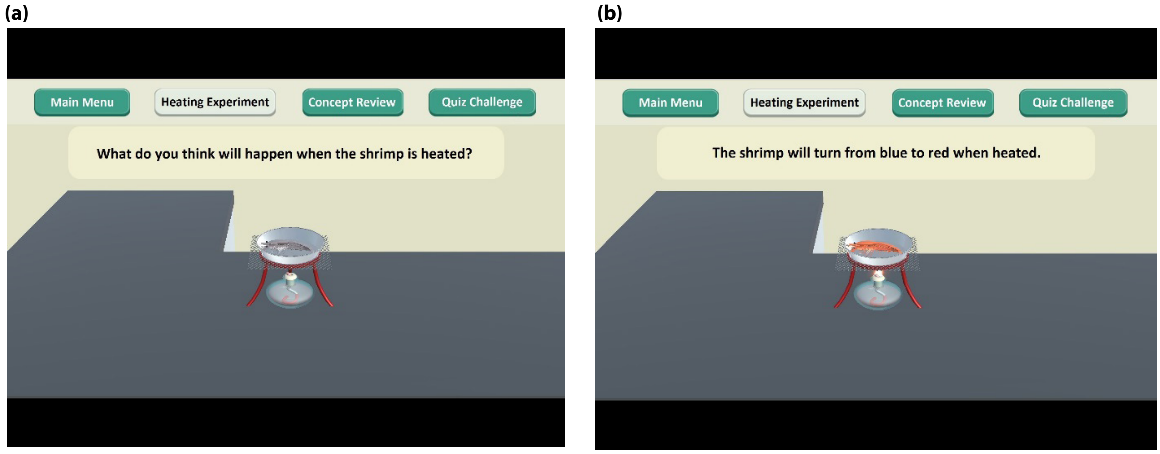
Sample item for state changes

( ) Which of the following substances can only change in shape after heating and can return to its original state?
(A) After water-barrier heating chocolate
(B) Mung beans in cooked mung bean soup
(C) Cooked clams
(D) Grains cooked into rice

Sample item for thermal expansion and contraction

( ) Why does a metal ball's volume increase when it is heated?
(A) The distance between the particles in the metal ball increases.
(B) The particles in the metal ball expand.
(C) The density of particles in the metal ball increases.
(D) The number of particles in the metal ball increases.

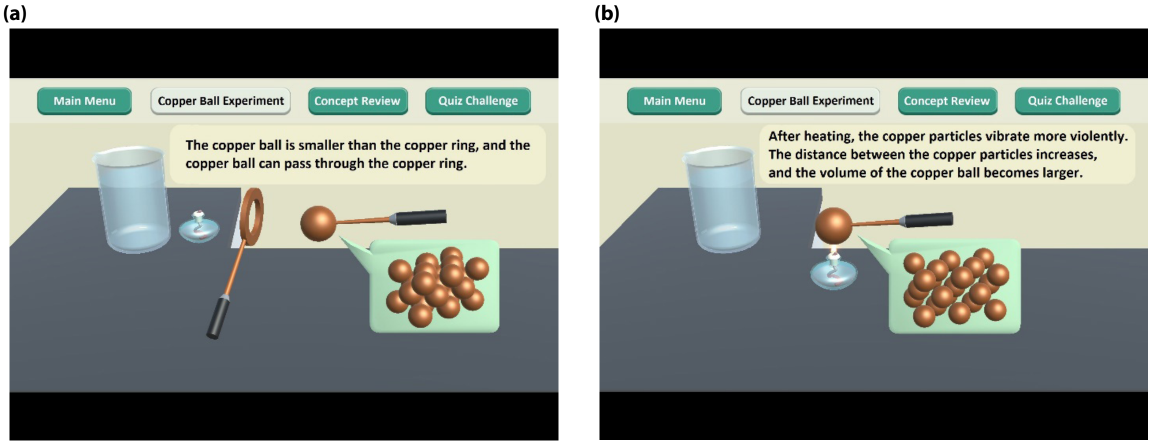
Figure 1
Shrimp State-Change Experiment When Heated



What do you think will happen when the shrimp is heated?

The shrimp will turn from blue to red when heated.

Figure 2
Solids Expand When Heated



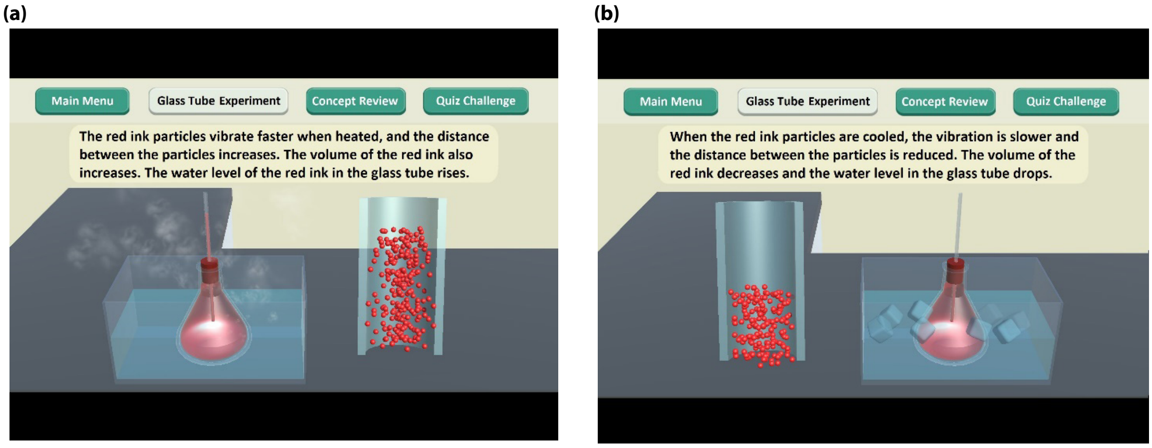
(a)

The copper ball is smaller than the copper ring, and the copper ball can pass through the copper ring.

(b)

After heating, the copper particles vibrate more violently. The distance between the copper particles increases, and the volume of the copper ball becomes larger.

Figure 3
Liquids Expand and Contract When Heated and Cooled



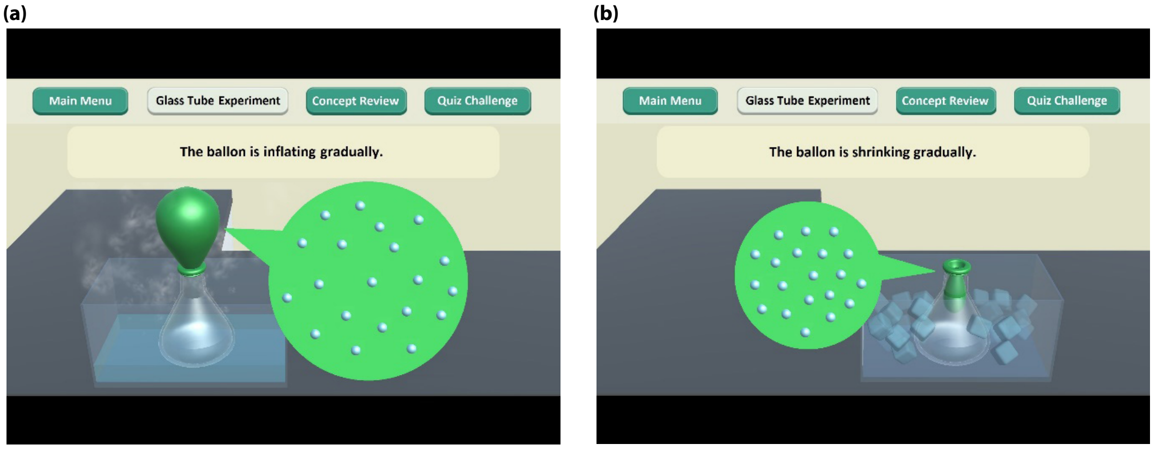
(a)

The red ink particles vibrate faster when heated, and the distance between the particles increases. The volume of the red ink also increases. The water level of the red ink in the glass tube rises.

(b)

When the red ink particles are cooled, the vibration is slower and the distance between the particles is reduced. The volume of the red ink decreases and the water level in the glass tube drops.

Figure 4
Gases Expand and Contract When Heated and Cooled



(a)

The ballon is inflating gradually.

(b)

The ballon is shrinking gradually.

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