Computer Simulations vs.Physical Experiments: A Gender Comparison of Implementation Methods for Inquiry-Based Heat Transfer Activities

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Abstract

Fundamental concepts in chemical engineering such as rate versus the amount of heat transferred and thermal radiation, can be difficult for students to understand. While prior research has found that one way to facilitate conceptual understanding and alter misconceptions is with inquiry-based activities, there may be differing outcomes based on their method of implementation. This quasi-experimental study compared two implementation methods for inquiry-based activities to address misconceptions about thermal radiation and rate versus amount of heat transferred with undergraduate engineering majors. One group of participants used computer simulations while the other group primarily did physical experiments. Changes in conceptual understanding were assessed using the Heat and Energy Concept Inventory (HECI; [21], [22]) and two of its sub-tests: Rate versus Amount and Radiation. Both implementation groups sampled were predominantly composed of white males with self-reported GPAs of 3.0 and higher. Findings showed that participants who used physical experiments to learn the concepts had significantly higher mean post-test scores on the total HECI and their respective sub-tests than those who used computer simulations. This same pattern was seen with concept area and gender.

Introduction and Background

Heat and temperature concepts are found at all levels in the science curricula [9] and are well-known for creating conceptual difficulties for learners [28]. Carlton [1] found many students described temperature as "…a measure of how hot or cold something feels" (p. 102). Others found students believed there is no difference between heat and temperature or that heat is a form of energy [6], [7], [25], [29]. While it could be hypothesized that the more coursework taken, the greater the conceptual understanding, Jasen and Oberem [9] found that the number of courses/semesters of physical science taken had "minimal influence" (p. 892) on students' abilities to correctly answer questions on thermal equilibrium and heat transfer.

Conceptual issues are not limited to the pre-college grades. Engineering undergraduates have also been found to have difficulty understanding the concepts of heat and temperature [16], [20], [24]. For example, Prince and Vigeant [20] discovered that many engineering undergraduates considered heat and temperature equal entities. Self and others [24] found that almost 30% of chemical and mechanical engineering seniors could not, "…logically distinguish between temperature and energy in simple engineering systems and processes" (p. S2G-1). This can be due to preconceived beliefs built on what have been labeled misconceptions [26]. Misconceptions about circumstances affecting the rate and amount of heat transferred have been observed in engineering undergraduates [18], [19]. Misconceptions about thermal radiation have also been documented [8], [18], [19].

Typical methods of teaching generally fail to alter misconceptions [11], [24]. "It is very difficult to repair many of these robust misconceptions through simple lecturing…" [24, p. S2G-6]. Previous research has found that inquiry-based physical experiments can increase students' understanding of difficult engineering concepts [31]. Despite the positive outcomes from hands-on inquiry-based activities, there may be obstacles to their implementation. Some engineering programs are unable to implement inquiry-based experiments due to time or financial constraints [12]. Wright and Sundal [32] found multiple barriers to the use of more innovative pedagogies in their survey of faculty from math, science, and technology faculty at 30 institutions. Among those were the lack of curriculum modification to encourage innovative methodologies and lack of money to support training and assessment of new methods. More recently, data collected by the AIChE Concept Warehouse [10] on five versions of inquiry-based activities to teach radiation and rate versus amount concepts, found that faculty preferred the simulations over physical experiments by a ratio of two to one.

While prior research has found that one way to alter these misconceptions is with inquiry-based activities, there may be differing outcomes based on their method of implementation. For example, some research has indicated computer simulations may be able to more clearly demonstrate a concept than a physical experiment [4] because simulations highlight important evidence and delete confusing information [30]. Other research has found no significant differences in the conceptual understanding of undergraduate preservice teachers learning about temperature or changes in temperature with either physical or virtual manipulatives [33]. Both computer simulations and physical experiments have been shown to be effective when used in science courses [3]. Additionally, when physical and virtual labs were used together to learn about heat and temperature, students outperformed those doing just a physical lab [34].

Other factors may influence the effectiveness of instructional methods, including lab group composition and gender. Even with effective implementation methods, there can also be differences in learning based on the composition of lab groups. For example, Ding, Bosker, and Harskamp [5] found that females in single-gender dyads significantly outperformed females in mixed-gender dyads. For males, this pattern was not evident. One factor that could impact females' performances in lab groups is self-efficacy. MacPhee, Farro, and Canetto [13] discovered that when starting college, females tended to regard themselves as academically weaker than males. However, by graduation their self-efficacy increased and was comparable to that of males. Another factor that could influence females' performance is their prior knowledge, specifically differences in the foundational science courses they have taken prior to college [17].

Purpose of the Study

Students have difficulty understanding concepts related to heat, temperature, and thermal radiation. Inquiry-based pedagogies that can foster the learning of these difficult concepts are needed. Physical experiments and computer simulations are two alternatives with the potential to increase students' conceptual understanding. While physical experiments develop authentic

laboratory skills and highlight the challenges involved in scientific research, computer simulations can emphasize key information, control outside variables, and reduce distracting aspects [3]. But, are both equally effective in promoting undergraduate engineering students' conceptual learning?

Therefore, the purpose of this study was to compare the effectiveness of computer simulations with primarily physical experiments on undergraduate engineering students' understanding of rate versus amount and thermal radiation concepts. While some previous research has found that students using computer simulations outperformed those doing physical experiments (e.g., [4]), other research has discovered no significant differences in the conceptual understanding of students using the two different pedagogies [33]. Given these findings, more research is warranted.

A secondary purpose of this study was to determine whether computer simulations and physical experiments would be equally effective with different heat transfer concepts and by gender. Is there a difference in the students' level of understanding of rate versus amount of heat transferred and thermal radiation by method of instruction? Does one pedagogy work better for one concept? Does the effectiveness of the modes of instruction vary by gender?

Methodology

Design

This quasi-experimental study compared two implementation methods for inquiry-based activities. One group of participants used computer simulations while the other group primarily did physical experiments. Pre- and post-test comparisons were made. Descriptive statistics were used to determine means for each of the comparison conditions. Analysis of variance (ANOVA) was done to determine if differences seen were statistically significant. Effect sizes were determined by partial eta-squared and interpreted according to Cohen [2], Miles and Shevlin [15], and Salkind [23].

Participants

Intact groups of engineering undergraduates from two different universities across multiple semesters participated in research to see whether their understanding of those concepts would alter and differ after instruction based on instructional method (physical experiment vs. computer simulation), concept area, and gender. Both implementation groups were predominantly composed of white males with self-reported GPAs of 3.0 and higher.

Table #1 provides the demographic characteristics of each group. As can be seen, key differences between the two groups were major and year in school, with undergraduates in the student simulation group being primarily Mechanical Engineering majors who were predominantly sophomores and juniors, while learners in the physical experiment group were mainly junior, Chemical Engineering majors.

Table 1: Demographic Characteristics of Student Experiment and Computer Groups

Demographic Characteristics	**Student Simulations n = 161**	**Student Physical Experiments n = 88**
Gender	72.7% Male 26.1% Female 1.2% Other	58% Male 42% Female
Race/Ethnicity[a]	72.1% White 10% Asian/Pacific Islander	79.6% White 11.4% Asian/Pacific Islander
Major	66.5% Mechanical Engineering 25.5% Chemical Engineering	98.9% Chemical Engineering Remainder "Other"
Year in Undergraduate Education	47.2% Sophomore 44.1% Junior	98.9% Junior 1.1% First Year

[a] Only top two provided for Race/Ethnicity, Major, and Year in School.

Materials

Inquiry-Based Activities

Two inquiry-based activities in each concept area were done by participants. One group of students did all simulations while the other group did primarily physical experiments. The inquiry-based activities were designed to address previously identified misconceptions in rate versus the amount of heat transferred and thermal radiation. For Radiation, one activity involved a Steam Pipe while the other used a Sun Lamp. For Rate versus Amount of Heat Transferred, one test involved cooling a beverage with either a snowball or chipped ice, while the other involved melting ice with heated metal blocks. The latter was only available as a simulation. Table 2, adapted from Vigeant, Prince, Nottis, Koretsky, and Ekstedt [31], details the experimental situation at the heart of the four activities.

Table 2: Inquiry-Based Activity Overview (after Vigeant and others [31])

Concept Area	**Description of Experimental Situation**
Radiation	**Steam Pipe**: Steam condenses in a polished metal pipe where there are pipes painted black and white. Students predict, then observe the rate of liquid water accumulation, which is proportional to energy loss through radiation.
Radiation	**Sun Lamp**: Students predict and observe heating and cooling curves for bare copper tubing and white and black painted tubing, heated by a lamp or allowed to cool on a lab bench.
Rate vs. Amount	**Cooling Beverage**: Students predict and observe both the rate of cooling and final

	temperature of cups of water chilled by either a "snowball" or chipped ice of equal mass.
Rate vs. Amount	**Melting Ice**: Students predict and observe how much ice can be melted by heated metal blocks when they control the number, size, and thermal properties of those blocks. This is only presented as a simulation.

Both the computer simulations and physical experiments began with a description of a physical situation and asked students to predict what would happen in that circumstance. Students then either used the computer simulations or engaged in physical experiments. Each involved discrepant events, something participants holding certain misconceptions would not have expected. Finally, learners were asked to answer a group of reflection questions that had them reconsider their original ideas and revise them based on what had occurred.

Assessment

Changes in conceptual understanding were assessed using the Heat and Energy Concept Inventory (HECI) [21], [22] and two of its sub-tests: Rate versus Amount (8 questions) and Radiation (11 questions). Previous research (e.g., [22]) determined that these two subscales have high enough estimates of internal consistency reliability as measured by the Kuder-Richardson Formula 20 (KR20) to be used as separate instruments. Estimates of internal consistency reliability were 0.76 for Rate versus Amount and 0.75 for Thermal Radiation [22].

Each conceptual area was evaluated separately to determine whether one method of implementation facilitated conceptual understanding better than the other and whether there were differences by content area and gender.

Procedure

Within the first two weeks of the semester, students completed an electronic version of the HECI [21], [22]. During the semester, students used either physical experiments or computer simulations to learn either one or both concepts. At the end of the term, students once more completed the HECI [21], [22]. Students who did primarily physical experiments did them with both concept areas. In the simulation condition, one concept area was taught with students using a computer simulation. One year it was rate versus amount, the other year it was thermal radiation.

Results and Discussion

Simulations versus Physical Experiments

Descriptive statistics showed that while students' scores on the pre-test were very close, there was a difference between them on the post-test favoring those taught by doing a physical experiment. Table #3 shows the pre- and post-test scores by instructional method.

Table 3: Mean Scores on the HECI [21], [22] by Instructional Method

Teaching Method	**Mean Pre-Test Score**	**Mean Post-test Score**
Student Using Computer Simulation	16.73 (SD = 5.73) n = 157	20.61 (SD = 6.12) n = 145
Student Doing Physical Experiment	17.00 (SD = 5.13) n = 88	26.35 (SD = 5.19) n = 84

A one-way analysis of variance (ANOVA) revealed no significant differences between instructional groups on the entire pre-test, $p > .05$. However, a one-way analysis of variance (ANOVA) showed there was a significant difference with a large effect size on the post-test. The mean post-test score for the students doing physical experiments was significantly higher than for the students using the computer simulation; $F(1, 227) = 52.08$, p. < .01, *partial* $\eta^2 = .19$. This was also the group that used primarily physical experiments for both rate versus amount and thermal radiation. This may have been a factor in the higher mean scores for this group.

Simulations versus Physical Experiments by Gender

Gender was first examined by instructional method using the entire HECI [21], [22] as a measure of overall understanding. As can be seen in Table 4, there were differences in the mean scores of males and females in each instructional category on the pre- and post-tests. However, both males and females doing physical experiments scored higher on the post-test than those using the computer simulation.

Table 4: Mean Pre- and Post-Test Scores on the Entire HECI [21], [22] by Gender[b] and Instructional Group

Instructional Method	**Gender**			
	Male		Female	
	Pre-Test	Post-Test	Pre-Test	Post-Test
Student Simulation	17.47	20.94	14.39	19.74
Student Physical Experiment	18.55	27.98	14.86	24.37

[b] "Prefer Not to Answer" data for gender removed for analyses as n = 2 and both were in simulation category.

One pattern seen in the descriptive statistics is that females had lower pre-test scores than males. This has previously been observed in the broader STEM research literature and has implications for gender differences in post-test scores as well. Noack, Antimirova and Milner-Bolotin [17] found that in an introductory physics course, gender had the largest influence on pre-test scores of undergraduate science majors, with women scoring approximately 14% lower than males. This discrepancy has been attributed to a variety of factors, among them prior foundational knowledge, including previous coursework in high school. For example, Noack and others [17] found that 9 out of 10 males had taken higher-level physics in high school while only 6 out of 10 females had done so.

The differences in mean pre-test scores between males and females warranted a statistical examination. A two-way analysis of variance (ANOVA) with gender and instructional method as independent variables and mean pre-test scores on the entire HECI [21], [22] as the dependent variable was done. It revealed there was a significant difference by gender with a medium effect size. Males scored significantly higher than females on the pre-test: $F(1, 239) = 20.62$, $p < .01$, *partial* $\eta^2 = .08$. There were no significant differences by instructional method nor was there a significant interaction between instructional method and gender. Because of this significant difference on the pre-test, an analysis of covariance (ANCOVA) was done when examining post-test results. "Analysis of covariance is an extension of analysis of variance where the main effects and interactions are assessed after the effects of some other concomitant variable have been removed" [14, pp. 93-94). In this case, the pre-test score differences were removed.

A 2 x 2 analysis of covariance (ANCOVA) was conducted on post-test scores on the entire HECI [21], [22]. Independent variables consisted of gender and instructional method (physical experiment versus computer simulation) and the covariate was pre-test scores. After significant adjustment by the covariate of pre-test scores, post-test scores varied significantly by instructional method with a large effect size; $F(1, 214) = 48.80$, $p < .01$, *partial* $\eta^2 = .19$. However, there were no significant gender differences ($p > .05$). This finding supports previous literature that has found that post-test scores did not seem to be impacted by gender, despite variations in pre-test results [17], [19].

Simulations versus Physical Experiments by Concept Area

Instructional method was also examined for each concept area to determine whether there was a difference in students' levels of understanding of rate versus amount of heat transferred and thermal radiation. Would one instructional method operate better with one concept area or work equally well with both?

As can be seen in Table #5, students' post-test scores on the respective sub-tests were higher for physical experiment than computer simulation.

Table 5: Mean Post Sub-Test Scores for Instructional Method

Concept Area	**Student Simulation**	**Student Physical Experiment**
Thermal Radiation (11 questions)	5.62 (51.1%) SD = 2.35 n = 83	7.96 (72.4%) SD = 2.26 n = 82
Rate versus Amount (8 questions)	4.57 (57.1%) SD = 1.86 n = 62	5.71 (72.3%) SD = 1.97 n = 83

To determine whether the post-test difference between instructional methods was significant for thermal radiation, a one-way analysis of variance (ANOVA) with instructional method as the independent variable and the radiation sub-test from the HECI [21], [22] as the

dependent variable was done. This test showed that the difference was significant, favoring physical experiment with a large effect size; $F(1, 163) = 42.81$, $p < .01$, *partial* $\eta^2 = .21$.

A one-way analysis of variance (ANOVA) was also done to determine whether the post-test difference between instructional methods was significant for rate versus amount of heat transferred. This analysis showed there was a significant difference with a medium effect size. Students doing primarily physical experiments had higher mean scores on the rate versus amount sub-test from the HECI [21], [22] than those doing computer simulations; $F(1, 143) = 14.24$, $p < .01$, *partial* $\eta^2 = .09$.

Simulations versus Physical Experiments by Gender and Concept Area

Descriptive statistics for gender and implementation method by each concept area continued to show a pattern of higher mean post-test scores when students did physical experiments rather than computer simulations. The mean scores also showed a pattern of females' scores being lower than males' except when using the computer simulation to learn about rate versus amount of heat transferred.

Table 6: Mean Post Sub-Test Scores[c] by Instructional Method and Gender

	Computer Simulation		**Primarily Physical Experiment**	
	Male[d]	**Female**	**Male**	**Female**
Thermal Radiation (11 questions)	5.85 (53.2%)	5.09 (46.3%)	8.31 (75.6%)	7.41 (67.4%)
Rate vs. Amount (8 questions)	4.49 (56.1%)	4.75 (59.4%)	6.11 (76.4%)	5.34 (66.8%)

[c] For Radiation, the Radiation Sub-test was used while for Rate vs. Amount, the Rate versus Amount Sub-test was used.
[d] "Other" or "Prefer not to Answer" were not included as n = 1, only in the simulation group.

A 2 x 2 analysis of variance (ANOVA) was conducted on each respective post sub-test from the HECI [21], [22] to determine if there were any significant differences based on gender and instructional method with each concept area. Independent variables consisted of gender and instructional method (physical experiment versus computer simulation). For radiation, the radiation post sub-test was the dependent variable and for rate versus amount, the rate versus amount post sub-test was the dependent variable.

With thermal radiation, a significant difference was found for instructional method but not gender. Males and females who did primarily physical experiments scored significantly higher than students who used the computer simulations; $F(1, 157) = 39.11$, $p < .01$, *partial* $\eta^2 = .20$. When rate versus amount was examined, a significant difference was also revealed for instructional method but not gender. Both males and females who did physical experiments

scored significantly higher, with a small effect size, than their counterparts who used computer simulations; $F(1, 137) = 8.54$, $p < .01$, *partial* $\eta^2 = .06$.

Conclusions

Students using each instructional method showed improvement after instruction. However, those doing primarily physical experiments consistently had higher mean scores than those using computer simulations. This pattern was found regardless of concept area and gender.

Despite the positive findings, there are several limitations in this study. Only two different schools participated and one school used one method (physical experiments) to teach both rate versus amount and thermal radiation each semester. The other school taught one concept with one method one semester and the other concept with the other method another semester. Further, there was a greater percentage of juniors in the physical experiment group, which could mean those students had more prior knowledge to connect to new conceptual understandings. Also, the school doing primarily physical experiments had one activity that was always a computer simulation. It could be that the combination of methodologies is what made this instructional method so effective, supporting previous research that found that when physical and virtual labs were used together, students scored higher than those doing only a physical lab [34]. In order to more definitively determine which instructional method is better, future research needs to use more schools with greater diversity.

One other factor that could have impacted students' learning is their generation. Participants in the study were all part of what has been labeled the Millennial Generation or Generation Y. Previous research [27], focused on Millennials at six colleges at a midwestern state university, found that almost 60% of respondents indicated a preference for "hands-on," "interactive labs," or "experiential learning" (p. 55). The researchers also revealed, "…60% of students said that hands-on experiential activities get them more engaged and act as a pivotal aid to their learning" [27, p. 59]. It is possible that students involved with physical experiments were more actively engaged than those watching a computer simulation, and this increased their learning. Future research should include a survey of preferred learning strategies or a qualitative component where students indicate how a specific pedagogy facilitates or hinders their learning.

Finally, future research needs to investigate more thoroughly each methodology, especially the physical experiment. It could be that there are aspects of the physical experiment methodology that made it more effective for both males and females. Conversely, there may be parts of the simulations that worked better for women, resulting in the higher mean score for females with rate versus amount, and other parts that need to be improved. While the physical lab was done in a designated lab period, the simulation could have been done outside of class as homework. Information about the conditions under which students used the simulations was not collected. Future research should gather data about how the simulation was done and presented to determine if method of use was a factor. The simulations should also be examined to see whether there are areas in need of improvement. Heat and temperature concepts are important to understand and require the best pedagogies to eliminate misconceptions.

This work was generously supported by the National Science Foundation (NSF) through #1225031.

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