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Using or Viewing a Demonstration of Inquiry-Based Computer Simulations: The Effectiveness of Both in Learning Difficult Concepts in Heat Transfer

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Abstract

Major chemical engineering concepts such as rate versus the amount of heat transferred and thermal radiation, can be difficult for undergraduates to understand. This can be due to prior knowledge built on what have been characterized as misconceptions [1]. Misconceptions about circumstances affecting the rate and amount of heat transferred have been observed in engineering students [2], [3]. Misconceptions about thermal radiation have also been documented [4], [2], [3]. Previous research has found that one way to facilitate conceptual understanding and alter misconceptions is with inquiry-based activities. However, there can be differing outcomes based on their method of implementation. This quasi-experimental study compared the learning that occurred when rate of heat transfer versus amount of heat transferred and thermal radiation were taught by two different computer simulation methods, students individually using simulations versus faculty demonstration of simulations. A secondary purpose of this study was to determine whether background information on concepts through previous coursework would impact students' conceptual understanding by each instructional method. Changes in conceptual understanding were assessed using the Heat and Energy Concept Inventory (HECI; [5], [6]) and two of its sub-tests: Rate versus Amount and Radiation. The majority of participants were White, male sophomores and juniors who were either chemical or mechanical engineering majors. Students using each instructional method showed improvement in understanding from pre- to post-test with each concept. However, the effectiveness of each approach varied by concept being taught. With rate versus amount, descriptive statistics showed greater improvement with the Student Simulation method. However, there were no significant differences between the two methods on the post-tests. With thermal radiation, there was greater improvement with Faculty Demonstration. Post-test results showed that those taught with the Instructor Demonstration method had significantly higher mean scores with a medium/moderate effect size, than those taught with the Student Simulation method. An examination of prior engineering coursework showed some variations that could possibly account for the findings. The differences found for concepts with simulation pedagogies raise questions about whether certain concepts require more scaffolding than others, especially if students are being introduced to a concept.

Introduction and Background

Heat and temperature concepts are experienced in everyday life [7] and found throughout the science curricula from elementary school to college. These concepts are also considered difficult to learn [8]. For example, Jasien and Oberem [9] found that the number of courses or semesters of physical science had a "minimal influence" (p. 892) on students' ability to correctly answer questions about thermal equilibrium and heat transfer.

Difficulty understanding heat and temperature concepts has also been found in undergraduate engineering programs. Self and others [10] 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 prior knowledge built on what have been characterized as misconceptions [1]. Misconceptions about circumstances affecting the rate and amount of heat transferred have been observed in engineering students [2], [3]. Research has also found that engineering students recurrently confound factors that affect the rate of heat transfer with factors that determine the total amount of energy transferred in a specified physical situation [11]. Misconceptions about thermal radiation have also been documented [4], [2], [3]. Students are often confused about the effect of surface properties on the rate of radiative heat transfer.

More traditional pedagogies have been found to leave misconceptions, even after instruction [8]. "It is very difficult to repair many of these robust misconceptions through simple lecturing…" [10, p. S2G-6]. One way to facilitate conceptual understanding and alter misconceptions is with hands-on, inquiry-based activities [12]. Despite the positive outcomes from these activities, there may be obstacles to their implementation [13]. Some engineering programs are unable to implement inquiry-based experiments and even traditional laboratory courses due to time or financial constraints [13]. Also at work is pedagogical preference. Data collected by the AIChE Concept Warehouse [14] on five versions of inquiry-based activities to teach radiation and rate versus amount concepts, found that faculty chose the simulations over physical experiments by a ratio of two to one.

However, there can be differing outcomes from inquiry-based activities, based on their method of implementation. For example, prior research has found that inquiry-based physical experiments can increase students' understanding of difficult engineering concepts [10], [12]. Other research has shown that computer simulations may be able to more clearly demonstrate a concept than an experiment [15] because they emphasize important data and delete confusing information [16]. While Nottis and others [17] determined that students doing physical experiments outperformed students using computer simulations, Jong, Linn, and Zacharia [18] found that, "Virtual investigations can equal or exceed the impact of physical investigations on measures of conceptual understanding…" (p. 308). The conflicting findings could be due to students' levels of participation when doing experiments and how they are using computer simulations. Weisner and Lan [19] found no difference between the learning of mass transfer and heat exchange by chemical engineering students in virtual and physical labs.

In a literature review done by Ma and Nickerson [13], it was noted that there were no standard definitions for simulated or even remote labs in the research. Some of the more positive results found in the literature could have occurred because of other conditions not indicated in specific studies. In addition, when discussing methodologies, they also noted that, "…most laboratory environments may already involve an amalgam of hands-on, computer-mediated, and simulated tools" [13, p. 10]. Other methods could be confounding the results from one specific methodology. Given the multiple ways simulations have been defined, it is not surprising that results among studies would vary.

Purpose of the Study

Inquiry-based activities can increase students' conceptual understanding of heat and temperature concepts in engineering [12]. These activities can be implemented as physical experiments or computer simulations. The method used may impact learning outcomes. In most studies, when comparing computer simulations with hands-on experiments, the simulation method has been primarily students using computer simulations with instructor assistance, although the definition of simulation has been found to vary in the research [13]. There is a need to know whether varying ways of using computer simulations are equally helpful in increasing engineering students' conceptual understanding of difficult concepts. Does having an instructor demonstration of a simulation result in the same amount of learning as when students individually use simulations? How does the efficacy of each method vary by concept addressed and its difficulty level? What is the role of students' prior course knowledge on the effectiveness of each method?

Therefore, the purpose of this study was to compare the learning that occurred when two difficult concepts, rate of heat transfer versus amount of heat transferred and thermal radiation, were taught by two different computer simulation methods, students individually using simulations versus faculty demonstration of simulations. The key research question focused on the following: how does participants' understanding of those concepts alter and/or differ after instruction using a specific simulation method? Demographic information was collected on all participants including whether they had taken or were taking courses in Fluid Mechanics, Heat Transfer, and Thermodynamics. This provided information for a secondary purpose of this study, determining whether background information on concepts through previous coursework would impact students' conceptual understanding by each instructional method. What is the effect of previous coursework on the effectiveness of each method?

Methodology

Design

This quasi-experimental study compared two implementation methods for inquiry-based activities to address misconceptions about thermal radiation and rate of heat transfer versus amount of heat transferred. The learning of participants in each concept area was compared by instructional method, students using computer simulations or faculty demonstrating computer simulations.

Descriptive statistics examined changes in participants' understanding of each concept area, as measured by mean scores on the entire concept inventory as well as relevant sub-tests. Paired samples t-tests were used to determine whether there was a significant change in scores from pre- to post-test in each concept area using each method. Analysis of variance (ANOVA) was calculated to determine if differences between instructional methodologies in each concept area were statistically significant.

Effect size measures "the magnitude of the treatment" [20, p. 207]. The larger the effect size, the more meaningful the difference is between the means of the two groups. In this study, Cohen's d was used to measure the effect size for t-tests. According to Fraenkel, Wallen, and Hyun [21, p. 248], any effect size of .50 or larger for Cohen's d, "is an important finding." Partial eta-squared was used to determine the effect size of significant differences for analysis of variance (ANOVA). The results were interpreted according to Cohen [22], Miles and Shevlin [23], and Salkind [20].

Participants

Intact groups of engineering undergraduates from two different universities across multiple semesters participated in this study. For each concept, one group of students individually used computer simulations (designated Student Simulation) and the other saw a faculty demonstration of computer simulations (labelled Faculty Demonstration) as part of instruction. One institution used both methods for each concept area in and across semesters. The other university only used faculty demonstration of radiation activities for one semester.

Since each concept area was examined separately the demographic information is divided by concept area. Table 1 shows the demographic characteristics of participants who were taught Rate vs. Amount using the two different simulation methods. As can be seen in this table, the majority of participants were White males who were Mechanical Engineering majors at the sophomore and junior levels.

Table 1: Demographic Characteristics of Rate vs. Amount Participants by Instructional Method

Demographic Characteristics	**Student Simulation**	**Faculty Demonstration**
Gender[a]	76.5% Male, 22.1% Female	70.7% Male, 28.3% Female

Race/Ethnicity	77.9% White, 8.8% Asian/Pacific Islander	68.5% White, 10.9% Asian/Pacific Islander
Major	66.2 Mechanical Engineering, 26.5% Chemical Engineering	68.5% Mechanical Engineering, 22.8% Chemical Engineering
Year in Undergraduate Education	51.5% Sophomores, 39.7% Juniors	48.9% Juniors, 43.5% Sophomores

[a] Only top two provided for each demographic category.

In both groups, the majority had previously taken Fluid Mechanics and Thermodynamics and almost all of the students were taking Heat Transfer at the time of the study (Student Simulation group – 95.6% and Faculty Demonstration group – 91.3%).

The demographic characteristics of participants who were taught Thermal Radiation using the two different simulation methods can be seen in Table 2. In both, the majority were White males who were primarily Juniors and Sophomores. In the Student Simulation group, the majority were Mechanical Engineering majors while in the Faculty Demonstration group, the majority were Chemical Engineering majors.

Table 2: Demographic Characteristics of Thermal Radiation Participants by Instructional Method

Demographic Characteristics	**Student Simulation**	**Faculty Demonstration**
Gender[a]	70.7% Male, 28.3% Female	73.8% Male, 24.6% Female
Race/Ethnicity	68.5% White, 10.9% Asian/Pacific Islander	54.1% White, 17.2% African American
Major	68.5% Mechanical Engineering, 22.8% Chemical Engineering	57.4% Chemical Engineering, 36.9% Mechanical Engineering
Year in Undergraduate Education	48.9% Juniors, 43.5% Sophomores	56.6% Juniors, 28.7% Sophomores

[a] Only top two provided for each demographic category.

In terms of prior coursework, the majority in the Student Simulation group had previously taken courses in Thermodynamics and Fluid Mechanics and were taking a Heat Transfer course at the time of the study. By contrast, the majority of the Faculty Demonstration group had not taken courses in Thermodynamics or Fluid Dynamics but were taking a Heat Transfer course when the study was conducted.

Materials

Inquiry-Based Activities

Two inquiry-based computer-simulation activities in each concept area were the focus of this study. These activities were designed to address previously identified misconceptions in rate of heat transfer versus amount of heat transferred and thermal radiation, following what Vosniadou [24] has labelled as the "classical approach" to conceptual change. Each involved discrepant events, something participants holding certain misconceptions would not have expected. This was meant to provide students with a sense of dissatisfaction with their existing conceptions.

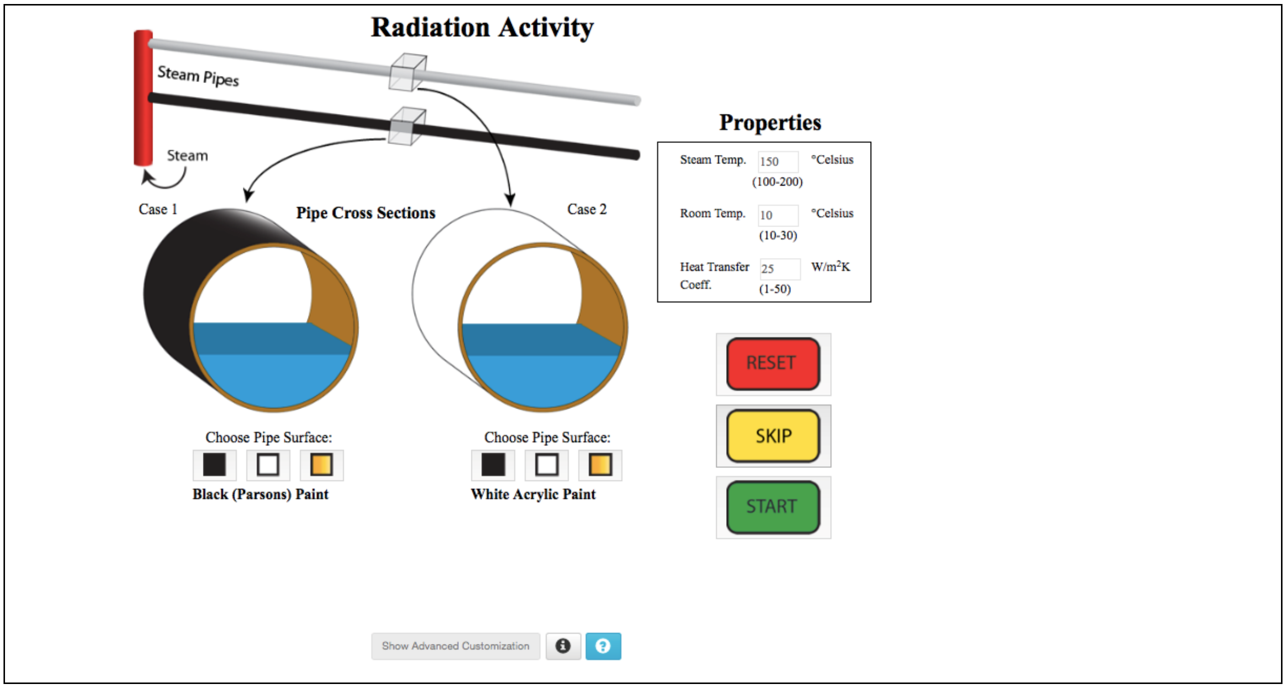
With Thermal Radiation, one activity contained a Steam Pipe while the other used a Sun Lamp. For Rate of Heat Transfer versus Amount of Heat Transferred, one test involved cooling a beverage with either a snowball or chipped ice, while the other involved melting ice with heated metal blocks. Table 3, adapted from Vigeant, Prince, Nottis, Koretsky, and Ekstedt [12] summarizes the four inquiry-based activities.

Table 3: Inquiry-Based Activity Overview [12]

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.

Figure 1 shows the graphics used for the Steam Pipe inquiry-based activity.

Figure 1: Graphic for Radiation Steam Pipe Simulation



Since an inquiry-based instructional approach was used, students did more than view or use the computer simulations. Both simulation methods began with a description of a physical situation and asked learners to predict what would happen in that circumstance. Students then either individually used the computer simulations or had an instructor demonstration of the computer simulation. After the simulation, 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; [5], [6]) and two of its sub-tests: Rate versus Amount (8 questions) and Radiation (11 Questions). Previous research [6] 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 [6].

Procedure

Within the first two weeks of the semester, students completed an electronic version of the HECI [5], [6] and an appropriate sub-test, either Rate versus Amount or Radiation, depending upon the concept of focus. During the semester, students either used the computer simulations or were shown the computer simulation as part of their instruction. At the end of the term, students once more completed the HECI [5], [6] and the appropriate sub-test.

Results and Discussion

Student Simulations versus Instructor Demonstration – Rate versus Amount

Descriptive statistics for Rate versus Amount by simulation method showed that both instructional groups had similar pre-test scores on the HECI [5], [6]. However, as can be seen in Table 4, there was a mean score percentage increase from pre- to post-test of 12.4% for the Student Simulation group while there was an increase of 9.1% for the Faculty Demonstration group. The median scores for each methodology also show a pre- to post-test difference between the two groups, favoring Student Simulation. For Student Simulation, the median pre-test score was 16 and increased to 22 on the post-test. By contrast, the median pre-test score for Faculty Demonstration was 15 and increased to 19 on the post-test.

Table 4: Mean Scores on the total HECI [5], [6] for Rate vs. Amount Inquiry-Based Activities by Instructional Method

Teaching Method	**Mean Pre-Test Score 36 Questions**	**Mean Post-Test Score 36 Questions**
Student Using Computer Simulations	17.16 (47.7%) SD = 5.89 n = 67	21.62 (60.1%) SD = 6.54 n = 60
Faculty Demonstrating Computer Simulations	16.39 (45.5%) SD = 5.64 n = 89	19.64 (54.6%) SD = 5.62 n = 81

Paired samples t-tests showed that students significantly improved from pre- to post-test with each simulation method on the total HECI [5], [6]. The Student Simulation group significantly improved from pre- to post-test with a very large effect size; $t(58) = -7.62$, $p < .01$, $d = .99$. Instructor Demonstration participants also significantly improved from pre- to post-test with a large effect size; $t(79) = -7.36$, $p < .01$, $d = .82$.

A One-way Analysis of Variance (ANOVA) with instructional method as the independent variable, and the HECI [5], [6] post-test scores as the dependent variable revealed a difference approaching significance between the two instructional methodologies, $F(1, 139) = 3.70$, $p = .056$, with the Student Simulation group having a higher mean score than the Instructor Demonstration group. It is possible that with a larger sample size a significant difference between the two groups might have been found.

A more targeted examination of the impact of the simulation methods on students' conceptual understanding can be found in an inspection of the mean scores of participants on the Rate vs. Amount Pre-Sub-test [5], [6]. As can be seen in Table 5, there were minimal differences between the mean scores of the two groups on the pre-test. However, the mean scores of the Student Simulation group were higher on the post-test than the Faculty Demonstration group.

Table 5: Mean Scores on Rate vs. Amount Sub-Test [5], [6] for Rate vs Amount Inquiry-Based Activities by Instructional Method

Teaching Method	**Mean Pre- Sub-Test Score 8 Questions**	**Mean Post Sub-Test Score 8 Questions**
Student Using Computer Simulations	3.00 (37.5%) SD = 2.10 n = 67	4.55 (56.9%) SD = 1.88 n = 60
Faculty Demonstrating Computer Simulations	3.03 (37.9%) SD = 2.24 n = 88	4.31 (53.9%) SD = 1.87 n = 81

Dependent t-tests showed that students significantly improved their understanding of Rate vs. Amount concepts from pre- to post-test with each simulation method on the Rate vs. Amount Sub-test. The Student Simulation group significantly improved with a very large effect size; $t(58) = -7.08$, $p < .01$, $d = .92$. The Faculty Demonstration group showed significant improvement with a moderate to large effect size; $t(78) = -5.06$, $p < .01$, $d = .57$. Both implementation methods increased students' understanding of rate versus amount of heat transferred.

A One-way Analysis of Variance (ANOVA) with instructional method as the independent variable and the Rate vs. Amount post-sub-test as the dependent variable showed there was no significant difference between the two groups.

While no significant differences were found between the different instructional groups for rate versus amount, the mean scores showed a pattern favoring Student Simulation. It may be that students' background knowledge of that concept, due to previous coursework in Thermodynamics, resulted in their being less reliant on the instructor to point out key points in the post-activity processing activities. With the stronger background, they were less likely to miss crucial points. It is also possible that the Student Simulation group had repeated access to the simulations. Zacharia, Olympia, and Papaevripidou [25] found that students using computer programs had more time to experience experiments in heat and temperature. If the Student Simulation group had repeated access to the simulation or used it a number of times in one sitting, their understanding could have been increased. If the Faculty Demonstration group was shown the simulations only once as part of class instruction, the participants would not have had the benefit of recurring contact.

Student Simulations versus Instructor Demonstration – Radiation

Descriptive statistics for Radiation by simulation method showed that students' scores on the pre-test in each group were comparable; the median score for each group was the same, 15. However, as seen in Table 6, post-test scores were higher for the Instructor Demonstration group than the Student Simulation group. Median scores for each instructional method also illustrated the post-test differences between the two groups; Student Simulation = 19, Faculty Demonstration = 22.

Table 6: Mean Scores on the total HECI [5], [6] for Radiation Inquiry-Based Activities by Instructional Method

Teaching Method	**Mean Pre-Test Score 36 Questions**	**Mean Post-test Score 36 Questions**
Student Using Computer Simulations	16.39 (45.5%) SD = 5.64 n = 89	19.64 (54.6%) SD = 5.62 n = 81
Faculty Demonstrating Computer Simulations	16.79 (46.6%) SD = 5.59 n = 121	21.98 (61.1%) SD = 6.36 n = 111

Dependent t-tests showed that students significantly improved their understanding of Thermal Radiation from pre- to post-test with each simulation method on the HECI [5], [6]. The Student Simulation group significantly improved with a large effect size; $t(79) = -7.36$, $p < .01$, $d = .82$. Instructor Demonstration participants also significantly improved from pre- to post-test with a very large effect size; $t(109) = -11.84$, $p < .01$, $d = 1.13$. The magnitude of the difference from pre- to post-test was greater for the Instructor Demonstration group.

A one-way analysis of variance (ANOVA) with the HECI post-test [5], [6] as the dependent variable and instructional method as the independent variable showed a significant difference between the two simulation methods with a small effect size; $F(1, 190) = 6.98$, $p < .01$, partial $\eta^2 = .04$. The Faculty Demonstration group had higher mean post-test scores on the entire concept inventory than the Student Simulation group.

In addition to instructional method used, year in school could account for the differences seen. There was a greater percentage of sophomores in the Student Simulation group and they might have needed more scaffolding because they would not have previously had courses that could have given them some background on this topic. The needed scaffolding could have come with the Instructor Demonstration.

Table 7 shows the descriptive statistics for the Radiation Sub-test by simulation method. Both groups began with approximately the same mean score. However, on the post-test, the mean score for the Faculty Demonstration group was greater than that of the Student Simulation group. The mean score percentage of the Student Simulation group increased from pre- to post-test by 8.2%, while the mean score percentage of the Faculty Demonstration group increased by 19.9%. Median scores for each instructional group also illustrate the difference. The Student Simulation group had a median pre- and post-test score of 5 (out of 11 questions) while the Faculty Demonstration group had a median pre-test score of 4 and a median post-test score of 7.

Table 7: Mean Scores on Radiation Sub-Test [5], [6] for Radiation Simulation Activities by Instructional Method

Teaching Method	**Mean Pre- Sub-Test Score 11 Questions**	**Mean Post Sub-Test Score 11 Questions**
Student Using Computer Simulations	4.68 (42.6%) SD = 2.02 n = 88	5.59 (50.8%) SD = 2.34 n = 81
Faculty Demonstrating Computer Simulations	4.79 (43.6%) SD = 2.18 n = 121	6.98 (63.5%) SD = 2.63 n = 111

Paired samples t-tests showed that students significantly improved from pre- to post-test with each instructional method on the Radiation Sub-Test [5], [6]. The Student Simulation group significantly improved with a medium effect size; $t(78) = -3.51$, $p < .01$, $d = .40$. The Instructor Demonstration group also significantly improved from pre- to post-test with a large effect size; $t(109) = -8.36$, $p < .01$, $d = .80$. Once again, the magnitude of the difference from pre- to post-test was greater for the Instructor Demonstration group.

A one-way analysis of variance (ANOVA) with instructional method as the independent variable, and the Radiation post-sub-test as the dependent variable revealed a significant difference with a moderate/medium effect size; $F(1, 190) = 14.37$, $p < .01$, partial $\eta^2 = .07$. Those taught by Faculty Demonstration scored significantly higher than students who did the Simulation themselves.

With thermal radiation, the use of Faculty Demonstration of simulations resulted in more conceptual learning than students individually using the simulations. A lack of prior knowledge about this concept area may have resulted in students being less likely to make important connections on their own when introduced to it in a Heat Transfer course. The Faculty Demonstration method would have allowed the instructor to provide explanations to the students about what was seen and why, and given him/her an opportunity to walk the class through relevant equations and parameters. This type of scaffolding would be more needed when students are first introduced to a concept, something not necessarily considered in the "classical approach" to conceptual change [24].

Conclusions

Students using each instructional method showed improvement in understanding from pre- to post-test with each concept. However, the effectiveness of each approach seemed to vary by concept being taught, which may have been influenced by students' prior coursework. With rate versus amount, descriptive statistics showed greater improvement in both the mean and median scores on the entire HECI [5], [6] and the Rate versus Amount sub-test with the Student Simulation method. However, there were no significant differences between the two methods on the post-tests, although the difference on the HECI was approaching significance, $p = .056$. The majority of students in both groups had taken Thermodynamics previously where they were exposed to this concept. With that exposure, they may have been better equipped to benefit from using the simulations by themselves.

With radiation, descriptive statistics indicated greater improvement in mean and median scores on both the entire HECI and the Radiation sub-test with Faculty Demonstration. Post-test results showed that those taught with the Instructor Demonstration method had significantly higher mean scores with a medium/moderate effect size, than those taught with the Student Simulation method. The majority of the Faculty Demonstration group had not taken courses in Thermodynamics or Fluid Mechanics but were taking a Heat Transfer course. Without some relevant prior coursework, participants may have needed the extra scaffolding that Faculty Demonstration method could provide. Also, demonstrating a simulation keeps the class together and affords an opportunity for timely explanation of the experiment by faculty in a way that the individual timing of students' use of the simulation on their own does not.

Despite these intriguing findings, there are several limitations in this study, which need to be acknowledged. Only two different schools participated and one school used both methods, one to teach one concept and the other to teach the other concept, in the same semester. This may have confounded the results. The other school taught one concept, radiation, with one method, Faculty Demonstration, one semester. A larger, more representative sample from multiple universities is needed.

Finally, future research needs to continue to investigate each methodology, taking care to thoroughly define what is meant by simulation. Although the researchers attempted to provide more explicit definitions of the two simulation methods by having specific agents (either student or instructor) be active, there is still a lack of information about what else might have been done, especially with the Faculty Demonstration, that could have facilitated conceptual understanding. The differences found for concepts with simulation pedagogies raise questions about whether certain concepts require more scaffolding than others, especially if students are being introduced to a concept. There may be times when a demonstration of a simulation is a better instructional strategy than having students independently use a computer simulation.

Heat and temperature concepts are important to understand and require the best teaching methodologies. Studies such as this one need to be replicated and expanded to more definitively determine the best instructional strategies for challenging concepts.

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