Investigating simulation use on student learning outcomes in introductory physics

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The use of computer simulations in physics education is a growing and evolving practice. In this paper, we report the results of a two-year study on the development and analysis of computer simulations and supporting instructional materials for the topic of momentum conservation. In an algebra-based, studio physics course for life science students at a large, private, R1 institution, the designed simulation was implemented into a traditional, two-cart collision lab activity in place of hands-on equipment using a quasi-experimental design. Learning outcomes were measured over two years by comparing student performance on written post-lab exercises, midterm and final exam scores, and pre- and post-test scores of the Energy and Momentum Conceptual Survey (EMCS). In assessing student mastery of the subject matter, we found no significant differences on written assessments for momentum-related learning outcomes between students using only the simulation in the experimental group, and students using only hands-on lab equipment in the control group. Our results continue to add to the growing body of evidence for better understanding the use of computer simulations in place of hands-on equipment for lab activities in physics.

I. INTRODUCTION

Increased subject matter mastery and content knowledge gain are some of the primary goals of laboratory instruction in science [1, 2]. Using technology supported laboratory experiments is an established practice in science courses to help achieve these goals [3]. Well-designed simulations, for example, have been shown to produce significant gains in student learning in physics on written conceptual assessments and hands-on exercises [4 – 6].

Compared to computer-based labs, where students use computer-interfaced probes with hands-on lab equipment, simulations may provide greater learning benefits for students. In comparison to hands-on equipment, simulations can provide greater focus on key variables [7], are self-paced, inexpensive, require less time for investigation, and provide greater flexibility and accessibility for students [1, 3, 8 – 10]. When used in place of hands-on lab equipment, studies have shown that simulations are more or equally effective in supporting student learning for topics in physics [4, 11 – 17]. Furthermore, simulations have been shown to support student modeling skills by providing a platform for multiple visual representations in the classroom [18, 19], and boost active-learning environments by encouraging student interaction and engagement [20 – 23].

Despite evidence of simulation-supported student learning in laboratories, questions still remain regarding the use of computer simulations compared to hands-on equipment [24]. One of the primary arguments against their use for lab experiments is that simulations may provide over-simplified environments, hindering student understanding of authentic science practices [25]. As such, continued investigation into student learning outcomes between simulation and hands-on equipment is needed.

This study adds to the growing body of evidence investigating the impact of computer simulations in place of hands-on experimental equipment on student learning outcomes, and addresses the following research question: *Does the use of a computer simulation, compared to hands-on lab equipment, impact student scores on written assessments?* Specifically, the lab activity investigated in this study demonstrated the concept of momentum conservation through the context of one-dimensional collisions for a two-cart system.

II. METHODS

In this paper, we report the results of a quasi-experimental design study carried out in an undergraduate, algebra-based introductory physics course. The investigated lab activity on conservation of momentum of two carts colliding in one dimension was conducted half way through the course. During two years of study, individual sections acted as either the control group, completing the collision lab using the traditional, hands-on equipment, or as the experimental group, completing a similar lab using a computer simulation of our own design.

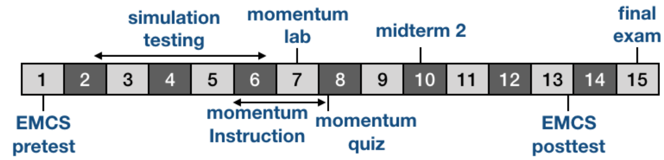

FIG. 1. A timeline of the intervention implementation, showing when different activities were done during the 15-week semester. Each numbered box represents one week.

The development and evaluation of the intervention, which included our computer simulation and accompanying instructional materials, included several stages of data collection, analysis, and revision. The implementation of the intervention and administration of assessments over the course of one semester is shown in Fig. 1.

A. Development of simulations and written lab materials

The simulation used in the study was written in HTML5 (Javascript) by one of the researchers (AD), who has over 20 years experience writing and using simulations in physics classrooms [26]. The benefit of using our own simulation was the ability to modify it throughout the development phase of research, moving toward a user-centered design [27]. The simulation provides dynamic visual representations for the traditional hands-on lab activity on momentum conservation for two carts colliding in one dimension, investigating three types of collisions (completely elastic, inelastic, and completely inelastic) (see Fig. 2) [28]. The simulation shows an animation of a two-cart system along with momentum bar graphs, and graphs of momentum vs. time, energy vs. time, velocity vs. time, and position vs. time. Students can change the elasticity of the collision, the mass ratio of the two carts, and the initial velocities of the two carts in the simulation, and the animation can be paused, stepped forward, or stepped backward in time.

Care was taken to ensure that the written lab materials students completed while using the simulation were as identical as possible to the original hands-on lab, with the exception of necessary instructional differences. The lab packets are available on our web site [29].

Refinement and review of the simulation and written lab materials were done through interviews with course Learning Assistants (LAs). LAs are talented undergraduate students who return to a course as part of the instructional team [30]. With their experience having taken the course, coupled with pedagogical training in how to help students learn effectively, LAs provided unique classroom insight while aiding in the refinement of the intervention. Think-aloud interviews were conducted with pairs of LAs, where they worked through the simulations and accompanying worksheets [31]. At the end of each interview, LAs were asked about the difficulty of the concepts and the activity,

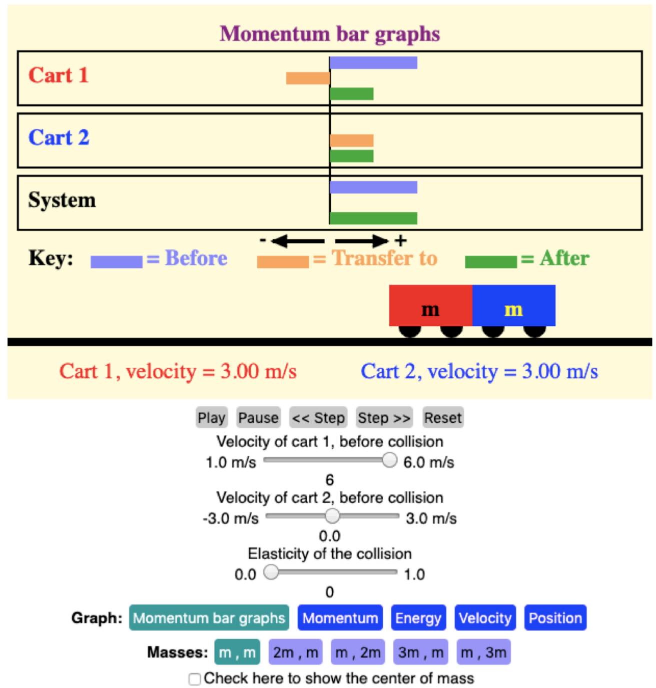

FIG. 2. Screenshot of the momentum conservation simulation for two carts colliding in one dimension.

and they gave suggestions for changes to the materials. Interviews were both video- and audio-recorded, and screen capture software was used to record their use of simulations. Interviews were transcribed and coded based on the types of feedback provided during both parts of the interviews. Revisions of the simulation and accompanying worksheet were made based on the analysis of interview feedback.

B. Description of the target population

The study was conducted during two fall semesters in a studio-style algebra-based undergraduate physics course focused on introductory mechanics at a large, private, R1 university. The course ran a total of 15 weeks each year, and the momentum lab activity took place halfway through the semester (week 7). Approximately 80 students in each section of the course worked in groups of three at round tables of nine students, enabling a teaching staff of one faculty instructor, two graduate student teaching assistants, and two undergraduate LAs to circulate around the room. To minimize possible instructor effects, a single faculty member, with over 20 years teaching experience of this specific course, taught all four sections included in this study (two sections in the fall of the first year and two in the fall of the second year). The students in the course were primarily life science and pre-medical upperclassmen, with students identifying as approximately 70% female and 30% male, with approximately 5% URM (under-represented minority).

C. Description of the intervention

Instruction in momentum concepts and the momentum collisions lab activity were given at the same point of the year for all students in this study (week 7). Prior to the lab, students received approximately three hours of interactive instruction on impulse, momentum, collisions, and an introduction to the concept of kinetic energy.

For the lab activity, all students worked through the 8-page lab packet described previously, in groups of three. Each year, one section of the course acted as the experimental group and received the intervention of the developed computer simulation in place of the traditional hands-on equipment. The second section acted as the control group and only used the traditional hands-on lab equipment, using a track with two low-friction carts, and two ultrasonic motion sensors to measure the cart positions. Sensor data is fed into a computer, and the students see graphs of the cart positions as a function of time, as well as their velocities as a function of time. The lab for both groups took place during a 105-minute session, and all students completed the activity without the need for additional time.

D. Assessment instruments

Investigation of student learning outcomes in this study was done through the statistical analysis of written assessments including a pre- and post-test concept survey, course-specific assessments, and summative assessments for the course.

Pre- and Post-test Conceptual Survey: To assess student baseline knowledge for each group, the Energy and Momentum Conceptual Survey (EMCS), a research-supported and validated instrument, was administered to all students in the first week of the semester [32]. As a measure of content knowledge gain throughout the course, the EMCS was administered again in the 13th week of the semester (Fig. 1). Overall scores on the EMCS pre- and post-tests were compared between groups (matched pairs only), as well as normalized gains [33]. Of the 25 total questions, pre- and post-test scores on the subset of 10 questions related specifically to momentum were also compared [32].

Momentum-Specific Assessments: While the EMCS pre- and post-tests were given at the beginning and end of the semester, and not directly before and after instruction, additional assessments (course-specific quizzes and exams) were given closer to the intervention. The benefit of these assessments was that they targeted specific learning goals related directly to the lab activity used in the intervention and not taught in other areas of instruction.

Identical assessments were given to the experimental and control groups around the time of instruction. These included a momentum quiz, administered less than a week after completion of the lab activity, and a multi-part problem on momentum conservation and collisions on the second of two midterm exams ("midterm 2") that was administered two to three weeks after completion of the lab activity. Scores on these assessments were collected and analyzed to compare groups.

Direct comparison of the momentum lab scores was not possible because of differences in questions and grading rubrics between the simulation and hands-on groups. As a result, lab write-up scores are not included in the analysis reported here.

Overall Course Performance: The final exam for the course predominately assessed student knowledge of the content covered in the final third of the course and did not include any momentum-specific questions. As a result, the final exam scores and course grades were analyzed to compare overall student achievement in the course.

E. Data analysis

Two-tailed Pearson correlations and Cohen's d effect sizes were calculated between the experimental and control groups for all written assessment scores. Pearson chi-squared tests were also calculated for student responses to the ten momentum questions of the EMCS to assess student responses and possible misconceptions as indicated by incorrect, distractor answer selections [32]. Only matched scores for all assessments were included in this study.

III. FINDINGS AND DISCUSSION

The results of this study, through statistical analysis of written assessments including a pre- and post-test concept survey, course-specific assessments, and summative assessments for the course, provide insight to address the research question. Of the students who started the course over the two years, 275 completed all assessments in this study, with 140 students in the first year (N_{exp} = 71 and N_{control} = 69) and 135 in the second year (N_{exp} = 72 and N_{control} = 63). This excluded 17% of students who initially enrolled in the course but did not complete all assessments.

Pre- and Post-test Conceptual Survey: Statistical analysis of the EMCS pre-test, post-test, normalized gain scores, and the subset of momentum questions, showed no statistically significant differences between experimental (*i.e.,* with simulations) and control (*i.e.,* without simulations) groups for the two years of data (Table I). Pearson chi-squared test calculations also showed no statistically significant differences between groups on how students answered each of the ten momentum questions of the EMCS ($N = 275$, $p > 0.05$).

Momentum-Specific Assessments: Analysis of scores on course-specific assessments showed satisfactory performance on the topic of momentum conservation and collisions, but no statistically significant differences between groups (Table I).

Overall Course Performance: Comparison of groups for both years of data on overall course performance showed a positive correlation between those students who received the simulation in the experimental group with the overall course grades ($r = 0.119$, $p < 0.05$), with a small effect size between group means ($d = 0.239$, $t = 1.984$). However, no statistically significant difference was found between groups for scores on the final exam (Table I). Analysis of summative assessments in the course was done to compare the two groups based on their overall performance in the course, and it is not expected that the simulation intervention would result in significantly higher course grades without also affecting momentum-specific assessments. As a result, the positive correlation between the experimental group and final course grades is likely due to something other than the simulation intervention.

Further analysis was conducted on each year of the study to better understand the correlations shown in Table I.

Year 1 Data Analysis: During the first year of data collection, no statistically significant differences were found between the experimental and control groups for the EMCS pre-test, post-test, normalized gain scores, and subset of momentum questions, nor were differences seen for scores on course-specific assessments or summative assessments ($N = 140$, $p > 0.05$).

Year 2 Data Analysis: During the second year of this study, no statistically significant differences were found between the two groups and the EMCS pre-test, post-test, gains, or the subset of momentum-specific questions ($N = 135$, $p > 0.05$). Positive correlations were found between the experimental group and scores on major course-specific assessments, including the momentum quiz ($N = 135$, $r = 0.182$, $p < 0.05$, $d = 0.369$, $t = 2.140$), final exam ($N = 135$, $r = 0.205$, $p < 0.05$, $d = 0.413$, $t = 2.394$), and the final course grades ($N = 135$, $r = 0.206$, $p < 0.05$, $d = 0.420$, $t = 2.434$). However, no statistically significant correlations were found between the two groups on the momentum-specific questions on midterm 2.

Consideration of the individual years of data suggests that the experimental group in year 2 had students who performed better overall, resulting in higher quiz and exam scores, as well as overall course grades. However, the lack of correlations between groups and the EMCS and momentum-specific questions on the midterm 2 exam suggests that the group's achievement was not a result of the simulation intervention.

To check whether excluding students who did not complete all assessments affected our results, correlation and effect sizes were calculated for all students who completed each specific assessment listed in Table I. As seen with the matched data, only the final course grade showed a statistically significant correlation with those students in the experimental group ($N = 303$, $r = 0.116$, $p < 0.05$, $d = 0.232$, $t = 2.018$).

These results suggest that the use of computer simulations had an equal effect overall on assessment scores compared to the use of traditional, hands-on equipment for the momentum and collisions lab activity for this sample.

TABLE I. Statistical analysis of assessment scores for experimental (simulation) and control (hands-on equipment) groups (N = 275)

Assessment	Descriptive Statistics		Correlation (Pearson's r)	Effect Size (Cohen's d)
	Experimental Group (N = 143)	Control Group (N = 132)		
EMCS Pre-test	$Mean$ = 6.04 (out of 25) SD = 2.57	$Mean$ = 6.34 (out of 25) SD = 2.60	---	---
EMCS Post-test	$Mean$ = 9.71 (out of 25) SD = 3.85	$Mean$ = 10.0 (out of 25) SD = 3.71	---	---
EMCS Gain	$Mean$ = 0.189 (out of 1) SD = 0.196	$Mean$ = 0.192 (out of 1) SD = 0.189	---	---
EMCS Pre-test Momentum Questions	$Mean$ = 3.14 (out of 10) SD = 1.50	$Mean$ = 3.16 (out of 10) SD = 1.45	---	---
EMCS Post-test Momentum Questions	$Mean$ = 4.27 (out of 10) SD = 2.03	$Mean$ = 4.12 (out of 10) SD = 1.94	---	---
Momentum Quiz	$Mean$ = 3.50 (out of 5) SD = 1.02	$Mean$ = 3.40 (out of 5) SD = 1.20	---	---
Midterm 2 Momentum Questions	$Mean$ = 8.88 (out of 10) SD = 1.77	$Mean$ = 8.59 (out of 10) SD = 1.81	---	---
Final Exam	$Mean$ = 44.0 (out of 60) SD = 8.40	$Mean$ = 42.4 (out of 60) SD = 9.84	---	---
Course Grade	$Mean$ = 82.7 (out of 100) SD = 8.61	$Mean$ = 80.6 (out of 100) SD = 9.66	r = 0.119 $p < 0.05$	d = 0.239 t = 1.984

"---" Indicates no statistically significant correlation ($p > 0.05$)

IV. CONCLUSIONS

The conclusion we draw from the results is that there is no overall difference in written assessment performance between students who used simulations and those who used hands-on equipment for the momentum collisions lab. These findings suggest that simulations can be a beneficial means to support student mastery of subject matter for a lab activity on conservation of momentum of two carts colliding in one dimension.

More generally, our results contribute to the growing research literature comparing simulations with hands-on labs in terms of student learning outcomes. As long as students are actively engaged in learning, our results suggest that the delivery medium may be less important than providing students' opportunities to investigate.

V. LIMITATIONS AND FUTURE WORK

The limitations of this research include the study of only one topic, in only one context, and measuring only learning outcomes. In future work, we plan to investigate the use of simulations on other topics such as energy, rotational dynamics, and simple harmonic motion. By increasing the number of simulations tested throughout the course, we hope to gain a broader understanding of their overall impact beyond just the topic of momentum conservation. In addition, we would like to look at the use of simulation interventions in additional contexts, such as supplementing discussion-based activities. Finally, we aim to expand our scope by investigating other outcomes such as self-efficacy and student attitudes toward learning.

Regarding generalizability, our research study is also limited to the set of students in one course in one select institution, albeit repeated in a second year. Students in this course are generally upperclassmen, having persisted through a rigorous pre-health science and math curriculum to their junior year, and are not representative of the broad diversity of students taking introductory physics nationwide [35]. Students in this particular course may also be more adept at using both simulations and hand-on lab equipment, since everyone completed the momentum activity in the time allotted. We have published our simulations and accompanying materials online [29] and encourage instructors with different student populations to test the efficacy of our simulations at their institutions.

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