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THE IMPACT OF DIGITAL SIMULATIONS IN PHYSICS TEACHING ON ACADEMIC ACHIEVEMENT AND LEARNING MOTIVATION

O IMPACTO DAS SIMULAÇÕES DIGITAIS NO ENSINO DE FÍSICA SOBRE O DESEMPENHO ACADÊMICO E A MOTIVAÇÃO PARA A APRENDIZAGEM

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Abstract

Physics Educators using Digital Simulation Tools in Physics Education. This study examines the impact of physics simulations on first year undergraduate students academic performance and motivation to learn. A quasi-experimental design was used with an experimental group (i.e. digital simulations in physics coursework) and genetic control (i.e. traditional instruction). Conceptual understanding and problem-solving performance in some domain of physics was measured through pre- and post-intervention tests; and in some studies motivation and attitudes of students in regard to moving from conceptual learning into problem solving were measured through surveys and interviews. Results showed that the experimental group had a significant improvement in their mean post-test scores and traditional approaches gave lower scores in physics post test, with the experimental group obtaining significantly higher mean scores than the control group, and there was also a significant difference towards students' enthusiasm and interest compared to a traditional approach in learning physics. Further qualitative feedback uncovered that simulations were effective in providing concrete illustrations of abstract phenomena, making students more enthusiastic about the subject, and enhancing their confidence in solving physics problems. The results in this study highlight that interactive simulations can hold promise for both learning and motivational outcomes in the context of physics education. The implications of accompanied curriculum design and teacher training are discussed, and proposed directions for future studies, including the utilization of virtual reality, and the long-lasting effects of simulation-based learning on students' retention of physics principles are suggested.

Resumo

Professores de Física que utilizam ferramentas de simulação digital no ensino da Física. Este estudo examina o impacto das simulações de Física no desempenho acadêmico e na motivação para aprender de alunos do primeiro ano de graduação. Foi utilizado um desenho quase-experimental com um grupo experimental (ou seja, simulações digitais nas aulas de Física) e um grupo de controle (ou seja, ensino tradicional). A compreensão conceitual e o desempenho na resolução de problemas em alguns domínios da física foram medidos por meio de testes pré e pós-intervenção; e, em alguns estudos, a motivação e as atitudes dos alunos em relação à transição da aprendizagem conceitual para a resolução de problemas foram avaliadas por meio de questionários e entrevistas. Os resultados mostraram que o grupo experimental apresentou uma melhora significativa em suas notas médias no pós-teste, enquanto as abordagens tradicionais obtiveram notas mais baixas no pós-teste de física; o grupo experimental obteve notas médias significativamente mais altas do que o grupo de controle, e também houve uma diferença significativa no entusiasmo e interesse dos alunos em comparação com a abordagem tradicional no aprendizado da física. Outros comentários qualitativos revelaram que as simulações foram eficazes em fornecer ilustrações concretas de fenômenos abstratos, tornando os alunos mais entusiasmados com a matéria e aumentando sua confiança na resolução de problemas de física. Os resultados deste estudo destacam que simulações interativas podem ser promissoras tanto para os resultados de aprendizagem quanto para os resultados motivacionais no contexto do ensino de física. São discutidas as implicações para o desenho do currículo e a formação de professores, e são sugeridas direções para estudos futuros, incluindo a utilização da

Keywords: Digital Simulations. Physics Education. Academic Achievement. Learning Motivation. Active Learning.

realidade virtual e os efeitos duradouros da aprendizagem baseada em simulação na retenção dos princípios da física pelos alunos.

Palavras-chave: *Simulações Digitais. Ensino de Física. Desempenho Acadêmico. Motivação para a Aprendizagem. Aprendizagem Ativa*

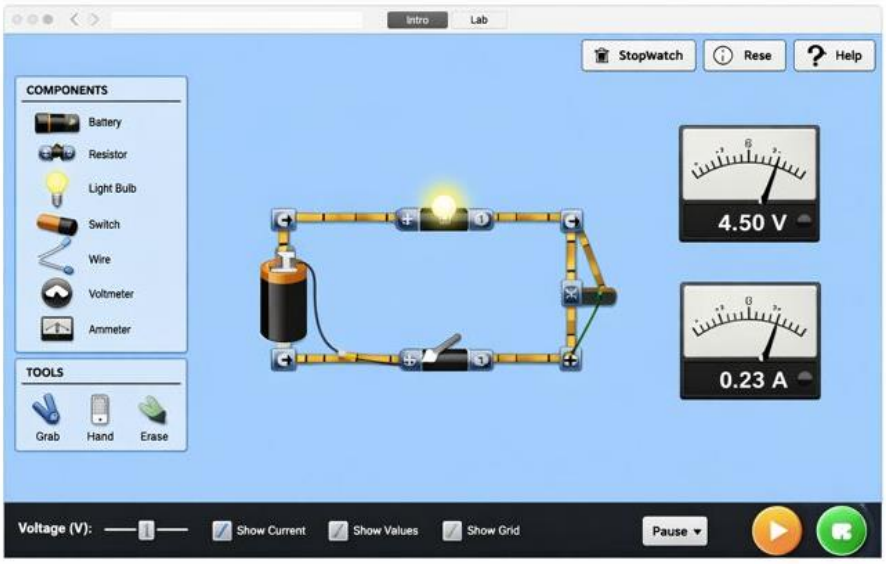
1 INTRODUCTION

1.1 Research background

For decades, physics education has prioritized lectures, textbooks, and physical experiments to illustrate and explain complex scientific phenomena. Over the last few decades, though, educators have made more use of digital simulations to create interactive learning activities. Digital simulations are computer programs used to replicate real-life phenomena, whereby students can manipulate variables and conduct ‘experiments’ in a digital space. The use of such simulations have basis in both education theory and the growth of technology in education, as they provide dynamic, visual representations of abstract topics (similar to electric fields or quantum states) that may be hard, or impossible, to directly visualize in the classroom. Students discover learnings with the help of exploration and hands-on experience thus this fits to constructivist learning where constructivist learning states when students explore and create for their own knowledge that means they learn best. There was a significant movement in this direction in the early 2000s: in 2002, Nobel Laureate Carl Wineman initiated the PhET Interactive Simulations project at the University of Colorado Boulder, making live access physics simulations available to educators around the globe. Since then, an increasing body of research has underscored the pedagogical benefits of simulation-based learning in STEM. Research indicates that interactive simulations improve conceptual understanding, promotes exploratory behavior and lead to a higher adoption of students active learning strategies. They are essentially online laboratories where students can perform what-if experiments as frequently as they wish, receive prompt feedback on the result, and consequently develop a better intuition regarding physical laws. Because of the benefits mentioned above, an increasing number of physics teachers are using simulations in addition to, or

in place of, traditional demonstrations and laboratory experiments. Technology in learning (as opposed to passive content delivery)—is bridging many gaps in physics and relevant disciplines—between formulae and practice, between virtual and safety/cost concerns of physical labs (as dangerous and costly experiments can literally be done in a Virtual Lab now!), between various learning styles (visual, kinesthetic etc. through multimodal content) Something that was a significant challenge for physics education: those things are not so easy with physics education as physical laws/software based implementations/other experiential scenario based modalities are there to divergent needs. Therefore, this is the background of research, digital simulations are potentially a way to improve physics learning. The current study, however, aims to examine the real impact of simulations on students learning outcomes and motivation — which does require a more controlled analytic leveraging. (see Figure 1).

Figure 1. PhET Interactive Simulation Interface Used for Undergraduate Physics Learning.



Sources: Authors.

1.2 Research problem

However/ Nonetheless, while the theory behind digital simulation use in education makes sense, there are questions and practicalities about their effectiveness in real classrooms. The main research question we sought to address in this study is: What are the effects of digital physics simulations on students' learning achievement and

motivation in their learning of physics as compared to traditional methods? There are multiple sub-issues inside this problem. While advances in simulation-based instruction have been documented, some studies have associated improved performance on summative skills tests with simulation, others have shown mixed or minimal effects and that the influence of technology on outcomes is greatly dependent upon the alignment of knowledge and skills with learning objectives. However, the incorporation of simulations in the pedagogical process does not always lead to better academic performance – factors like the implementation (if replaces supplementary to hands-on experiments), the realism of the simulation environment and the level of scaffolding provided can affect the learning process. Second, the impact of it on motivation to learn is a complex one. Simulations will combine all the above (learning) to make the learning process more interesting and entertaining, or even to increase the students motivation with physics play In contrast, if these simulations are not just a frivolous gimmicks, they will build distraction or shallow learning outcomes which will lead to a negative atmosphere for student learning. Also, not all learners may respond to motivation in the same way, so it could be that high-performing students might be more excited by simulations than students who do poorly in more traditional types of learning. Second, we also need to explore the representational power of simulations—that is, whether or not simulation differentially benefits subgroups of students who enter the classroom both with low initial interest in science or between males compared to females or students from various cultural backgrounds. This entails that the research problem is not whether simulations work or fail to work, but rather: how and for whom do simulations work best? Faculty in general are conservative and resistant to anything new unless some proof of effectiveness is already established, and especially so at the undergraduate level. This is also looking into potential barriers: are there barriers to using simulations (such as instructor training or subpar computing power) that might inhibit their effectiveness? But how do students feel about simulations compared to other forms of instruction? In this study we attempt to answer the aforementioned questions and fill up the gap in literature, and to provide some data driven insights for digital simulations impact on physics teaching.

1.3 Research objectives

The study is guided by several specific objectives, which are outlined as follows:

- Objective 1: To evaluate the effect of interactive physics simulations on students' academic achievement, as measured by their performance on concept tests and problem-solving exercises;
- Objective 2: To assess the impact of simulation-based instruction on students' learning motivation and attitudes toward physics, including their interest, engagement, and self-efficacy in the subject;
- Objective 3: To compare the outcomes of simulation-enhanced teaching with those of traditional teaching methods (lectures and physical labs), thereby determining any significant differences in learning gains and motivational changes between the two approaches;
- Objective 4: To explore students' qualitative experiences with using digital simulations – capturing feedback on what aspects of the simulations aided their learning or motivation, and identifying any challenges or drawbacks from the student perspective;
- Objective 5: Based on the findings, to derive practical recommendations for educators on effectively integrating digital simulations into physics curricula and to suggest areas for future research (such as long-term retention effects or the use of emerging technologies like virtual reality in physics education).

By addressing these objectives, the research aims to paint a comprehensive picture of the educational value of digital simulations in physics. The focus is not only on quantifiable outcomes (scores and survey ratings) but also on understanding the learning process and student experience in a simulation-based environment.

1.4 Research significance

There are actually several reasons that this study is important. If students exhibit better academic persistence and performance shown through simulations, this may translate to a higher likelihood of having a positive and successful learning process for physics, a notoriously dry and abstract topic for many students. Increasing motivational

levels is especially essential since students who are more engaged and interested in a subject are more likely to exert effort, persevere through barriers, and pursue additional education or careers in science and engineering. By making the underlying physics more accessible, digital simulations could increase the number of students participating in physics by engaging those who might otherwise disengage out of boredom or intimidation. For instructors and institutions alike, with research-based insights on whether contemporary instructional modalities are effective. Of course, there are always new teaching strategies out there, and physics teachers want to know what works, which is why we need studies like ours — Does using simulations actually help students learn better? If so, then you should use simulations to teach your subject, if not then you should rethink how you teach (potentially). If the findings are favorable, it would support high school and university physics instructors using such simulations in their teaching and help inform principles of effective practice for doing so (e.g., complementary use with guided inquiry worksheets, and/or integration into curricula with real-world experiments). Ultimately, the research might identify specific risks to avoid (e.g., over-reliance on simulations without necessary conceptual framing, or when teacher support is required and absent), giving educators a better chance to make the most out of the potential of these tool. This is for the digital simulations that are tested for better learning outcomes will influence the curriculum and resource allocation decisions of education policymakers and curriculum developers. More businesses may invest in simulation-based or engineer teachers in education technology for schools and universities. But this broader scale is also poked by digital literacy and innovation in education that need education to complement fast changing technology. Finally, this study addresses additional relevant, though less explored gaps in the scholarly literature on the interplay between the use of technologies and user motivations. Even more importantly, earlier studies focused primarily on either cognitive or affective outcomes in isolation whereas this study investigates both simultaneously enhancing simulation-based learning literature completeness. Finally, introducing a qualitative measure (student feedback) makes logics not just about whether the simulations work but why and how. These types of findings might also help spur new areas for research (for example, are the observed benefits long-term benefits, and/or how might simulations be combined with other instructional methods (for example, combine with flipped classrooms and/or gamification for more

work)? This study, therefore, can transform physics education by developing practices and results that facilitate effective, engaging and inclusive science teaching.

2 LITERATURE REVIEW

While the history of research in science education and computer simulations spans 30 years or more, the 21st century has seen a growing intensity in the volume of research as personal computers that are powerful enough to run simulations and interactive software become widely available. Several literature reviews and meta-analyses have determined that appropriately designed simulations can augment and enhance traditional instruction in meaningful ways. As an example, a systematic review of higher education studies reported positive results of educational games and simulations for student learning outcomes and engagement. Simulations give students the ability to manipulate parameters and see what happens, over and over again under different conditions, thus they represent a virtual laboratory for physics teaching. Such dynamic interactions are thought to enhance understanding by allowing students to see the unobservable (such as fields, waves, or atomic interactions) and to connect formal theory with experiential learning. Physical and virtual labs each possess their own merits, and previous work by De Jong, Linn, and Zacharia stresses that a combinationwill achieve the best of both worlds with the hands-on realism of actual experiments and the flexibility and enriched visualization that simulation affords. So their work in Science education shows that virtual labs can prepare students for physical labs or even replace them without loss of learning gains, if there are resource constraints.

These results are supportive of a key aspect highlighted in the literature regarding the function of simulations in enhancing conceptual understanding. Physics tends to work with abstractions that students are unable to understand (Quantum Mechanics, electromagnetism, or Newtonian mechanics in non-intuitive situations, etc.). If students do not build an internal mental model of the underlying physics, traditional problem-solving can become rote. Pointing interactive simulations is an answer to this issue, where students are in a position to change some parameters and witness the results right away cementing the the concept of cause-and-effect. One illustration is an interactive simulation linked to projectile motion in which students can change the launch angle and speed and

instantly see the impact on the projectile's trajectory. Such exploration can sometimes lead to an aha-moment in which students realize that equations relate to real behavior. Multiple studies have reported that students who use simulations demonstrate significant improvements in their conceptual understanding compared to students who experience traditional lecture-based instruction in the same course. In one quasi-experimental investigation involving middle school and high school students, users of PhET simulations scored higher on some conceptual questions and progressed to better reasoning about the explanations of phenomena, denoting a deeper internalization of concepts. Simulations have also been successfully used to recreate topics that would be extremely difficult to recreate in a school lab — such as cosmic events, subatomic particles, or very slow/fast processes — expanding the amount of process that students can act upon in an active Investigate experience.

A further repeated discovery in the literature is that simulations can prompt active learning and inquiry. While teacher demonstrations might be passively observed, simulations frequently put students behind the wheel. In addition to using group activities, many educators have developed guided inquiry worksheets based around simulations, asking their students to predict indications, run the simulation, and then analyze the comparisons between their predictions and the results of the simulation. This process helps science and creativity go hand in hand. Pedagogical research suggests that simulations, on their own, are rarely effective. Instead, the most effective use of simulations includes structured learning tasks with prediction, experimentation, and reflection phases. This use of simulations can foster development of science processes like hypothesis testing, interpreting data, and transferring learning to novel contexts. For instance, in a study by Moore and colleagues using PhET simulations to teach various chemistry concepts, students showed increased understanding of molecular interactions and were able to transfer their knowledge from the situated context of the simulation to different problems. The various interactive/game-like elements that are incorporated into simulations (real-time feedback, visual cues, sometimes scoring, or challenge tasks) further maintain students' interest throughout the learning journey.

While cognitive outcomes are the most widely studied, an emerging area of research is the influence of simulations on affective outcomes, such as motivation, interest, and self-efficacy. Physics has a history of being a difficult subject that, at times, drives

students who may be otherwise interested in the subject away, because some of their problems cannot be solved with formulas or equations, but by visualizing the world around them — which many students may find hard to do. Physics becomes more accessible and fun by using simulations. Students have consistently favored such classes over comparable non-simulated classes over a number of studies, giving various reasons that include the ability to learn at their own pace, the instantaneous feedback of the simulation, and the enjoyment of "playing" with parameters. For example, Kirmizigül (2021) researched a 5th grade science classroom using an interactive simulation software called Algodoo, and found far beyond statistical significance, not only higher gains on assessments but also inmcreased engagement and motivation in the experimental grou. In a study that you can read more about here, students stated the simulation made the learning experience more enjoyable, less threatening, and they were more likely to work with the learning task. Likewise, studies based on introductory undergraduate physics courses have seen shifts toward positive attitudes toward learning physics when simulations were included. Another study of college-level introductory physics reported that students indicated greater confidence in the material and in solving homework problems when simulations were used as supplemental tools, implying an increase in self-efficacy. Sometimes though, the effect on motivation has been more modest - such as a recent study from high school where motivation survey items showed no overall significant change after a short simulation intervention (though students reported positive feedback about the simulation experience). This means that motivation can be contextual to how integrated the simulation is (brief use may not budge the needle on surveys, but continued throughout a course may add up).

Not every study tells a uniformly happy tale, however, which offers a more subtle picture. Other research suggests that simulations yields outcomes that are comparable or even equal to those from more traditional methods (for certain subjects or student populations). In these cases, researchers will study the context − the simulation use may have been limited, for example, or the students became confused and lost as they were unguided, or the novelty wore off. For example, a study that trained Grade 12 physics students in Canada with PhET for one topic measured motivation pre- and post-simulation yet found no statistically significant difference. In focus group interviews conducted for that study, students reported enjoying the simulation but also noted that it did not eliminate

the need for explanation from the teacher. It reinforces the idea that simulations are not a magic bullet in and of themselves; the role of the teacher to situate what is happening and orient the exercise is still fundamental. Indeed, studies found that the most effective — and sometimes even innovative — use of simulations occur when educators use simulations in a deliberate manner, that is by linking them to a learning goal and providing students with scaffolding (e.g., guiding questions or prompts) to enable them to learn what was intended from participating in the exploration. (918).

A second aspect addressed in the literature is the impact of student attributes on the success of simulations. Some headed simulations have suggested that, perhaps because of the needed concrete, interactive support locations situation, low-achieving students or students with poor background knowledge can benefit more than high-achieving students who may have been able to abstract the concepts reasonably well. As an example, from their own work, an interactive simulation on electricity led to better understanding for all students, but the students who had the most initial misconceptions benefitted the most — indicating that simulation can be an effective tool for remediation. Some researchers have also considered gender — for example, whether male and female students respond differently to simulation-based learning. In sum, the evidence suggests that both genders achieve similarly well when simulations are used inclusively, with only small, generally insignificant differences between male and female outcomes that are more attributable to extralaid experience (e.g., prior interest in gaming or computing). In this context, we will also consider such differences, although we are primarily interested in overall patterns.

To sum up, the literature provides a strong rationale for the use of digital simulations in physics teaching: they have been demonstrated to facilitate conceptual understanding, support inquiry-based learning and will frequently stimulate motivation and engagement for students. However, pedagogical implementation is always going to determine the extent to which they used to their full potential. Simulations should be seen not as a gimmick or a teaching aid, but as one component of a comprehensive approach to instruction, the report suggests to educators. The literature review also explores some of challenges. Another aspect is the requirement of teacher professional development – not all physics teachers are familiar with simulations and they would need training to use the simulations appropriately in lesson plans. Also, there is the need for equal access to tech; simulations generally require the use of computers or tablets, so classrooms will need the

required hardware and stable electricity/internet. Questionnaires which included teachers (Stinken-Rösner, 2020) have shown that the majority of teachers are approaching simulators in lessons, they are at least occasionally using the tools available, but the method of choice is often not suitable, and the tools interactive potential is not always used. This underlines the need to investigate both teacher preparation and support with resources before making an argument for simulation-based curricula.

We relied on this state of knowledge in our study. Our study design integrates both academic achievement and motivation, which have typically been investigated separately in the literature to explore the impact of simulations. Much of the research cited has either focused on testing or motivation; here we capture data on both as well as qualitative student data. We will use this method to confirm (or disconfirm) the patterns observed in the literature with new data and in the specific context of undergraduate physics education, which is less represented in simulation studies relative to K-12 contexts. The results will inform the ongoing conversations on how to best use ed tech in the name of improved learning in physics, and possibly in other areas of science as well.

3 METHODOLOGY

This study used quasi-experimental designs accompanied by qualitative methods to study the effects of digital simulations on student learning outcomes in physics together with their motivation. Participants were undergraduate students at a public university, enrolled in an introductory physics course (Mechanics and Waves) generally taken during the first year of a science or engineering program. The following subsections describe the participants, materials (simulations), procedure, and data collection methods.

Methods Time spent in study was examined in this 2 × 2 experiment involving the manipulation of the format of a traditional physics course (lecture vs. small-group format) and type of cue (discovered vs. warned) using a sample of 60 undergraduate students (aged approximately 18–20) enrolled in two sections of the same course, which were assigned to the four conditions. So, one section (30 students) was the experimental group and one section (30 students) was the control group. Assignment of the various groups was based on the class sections taught by the same instructor in order to minimize the variability attributed to the instructor. A pre-study analysis established that both groups were similar

in background knowledge of physics as well as demographics. At the beginning of the semester, their average scores on a diagnostic physics quiz did not differ significantly (the experimental groups mean was 50.3% versus 49.8% for the control; $p>0.8$ - equivalence). The 30 subjects in the experimental group were composed of 12 females and 18 males; the 30 subjects in the control group consisted of 10 females and 20 males, approximately the gender ratio for students enrolled in the course at the time. Participation in the study was voluntary, and all students in both sections consented to participate (in the case that a student would have opted out, then that student would still undergo the same instructional treatments as all of the other students, however their data would not be included; in the current case no students opted out). Students were informed that the study was assessing different methods of teaching rather than individual performance, and that their group assignment designee would not impact their course grade.

Intervention: The experimental group received at least half of their instruction via digital simulations, while the control group received instruction via traditional methods (textbook readings, lectures, and hands-on lab activities) on the same topics. In the 6 week curriculum we covered four of the major topics in physics: Kinematics of motion, Newtons Laws and forces, Energy conservation, and Simple harmonic motion (oscillations). The experimental group used interactive simulations in the classroom or lab time in a portion of the time for each topic. Most of our simulation use came from the PhET Interactive Simulations library, specifically: “Moving Man” (kinematics), “Forces and Motion” (Newtonian mechanics), “Energy Skate Park” (energy), and “Masses&Springs” (harmonic motion). We selected these simulations based on how closely their hands-on activities aligned with our curriculum topics and how easily our students could use the interface. In a common simulation session, students in the experimental group worked in dyads, using a computer. These researchers provided a guided activity worksheet that prompted them to investigate certain situations within the simulation (for example, in the Energy Skate Park sim, they might have to explore how the potential and kinetic energy the skater has changes with different heights of track, and then answer conceptual questions about energy transformation). A pair of facilitators were on-hand to answer any questions, and an instructional assistant complemented the video as the students discussed their observations. In addition, the experimental group engaged in short didactic

lectures/problem-solving sessions (to reinforce theory), but more class time was spent in interactive exploration than in the control group.

The control group received the standard curriculum that did not include computer simulations. They were present in conventional lectures with identical content (delivered by the same instructor to ensure consistency of explanation and emphasis) and engaged in equivalent duration laboratory sessions every week. Instead, the control group completed physical experiments in the lab (where possible) pertaining to the topics (e.g., measuring motion using ticker tape timers, investigating oscillations using spring-mass systems, etc.) rather than virtual labs. The experimenter performed some complex experiments (frictionless energy conservation) or presented them via video for the control group, rather than allowing students to interactively perform the experiments (the experimental group could "do" them virtually). Both groups received the same weekly homework assignments as well as identical content in the recitation problem-solving sessions. This was done in order to ensure that any differences obtained would largely be due to the manner of concept exploration (simulation vs. traditional) as opposed to differences in overall workload or practice opportunities.

Academic Achievement: Identical physics tests were administered to both groups, before and after the experiment (pre-test and pos-test). Participants completed 20 multiple-choice conceptual questions and 5 short quantitative problems pre-test at the beginning of the 6-week study period to determine baseline knowledge on kinematics, forces, energy, and oscillations. Immediately following the 6 weeks of instruction on those same topics, the post-test was administered (consisting of isomorphic questions – similar in style and challenge to the pre-test, but not identical to avoid simply recalling pre-test answers). Two independent physics educators inspected the tests for content bias and similarity in covering the course learning objectives. Alongside those concept tests, regular exam scores during that time for students were gathered for secondary analysis, to see whether any difference in performance persisted beyond their normative course tests.

Assessment of learning motivation was conducted through a standardized questionnaire that consisted of questions from an existing physics motivation questionnaire (PMQ) that was developed and validated in science education research. This survey was given to both groups at the start (pre-survey) and the end (post-survey) of the study period. The first survey contained several Likert-scale items (1 to 5) on different

dimensions of motivation, including interest in physics, perceived utility of physics for personal goals, self-efficacy in physics, and effort and persistence on learning physics. Example items included "I find physics interesting" or "I believe I will do well in the topics in this physics course," and students responded to each by indicating how much they agreed. There are separate sub scores provided such as Interest/Enjoyment, Value (with close relation to relevance), Self-Efficacy and Effort/Persistence along with an overall motivation score from the PMQ. The survey showed good internal consistency in our sample with a reliability (Cronbach's alpha) of 0.88.

In addition to quantitative measures we collected qualitative data to better understand. Next, and in the sub-sample of student from experimental group (8 students in total, we have chosen to balance high, medium and low performers as well as balance of gender), we carried out semi-structured interviews and focus group discussions after post-test. The interviews were designed around questions like: "What do you feel using the simulations contributed to your grasp of the physics concepts?", How was your experience – was it interesting or annoying? — and "How did the simulation sessions compare to other modalities (i.e. lecture or textbook) in terms of your motivation to learn?. In addition, we invited students to describe specific incidents or situations that had put them off or caught their interest during the simulations. To put this into perspective, we also conduct a short focus group with 4 of the control group students exploring their learning in the traditional format and whether they feel anything was missing or motivational from the last 6 weeks. Incorporating audio-recording and transcription for thematic analysis, these discussions.

Procedure: The study progressed according to the following steps:

1. Preparation: A week prior to the intervention, the instructor informed the experimental group that computer simulations would be incorporated into their upcoming classes. Neither group was aware of any actual "experiment", but were told that different methods of instruction were being tested in a more general sense to enhance learning (to avoid experimenter bias, students were not informed as to which group was experimental or control from a research standpoint). During this week pre-test and motivation pre-survey were administered in the exam room setting for both groups (test- 45 minutes/ survey-10 minutes);

2. Intervention (Weeks 1–6): Physics topics were taught as planned. Every week in the experimental group, 30–40% of the classroom time was used for simulation-based exploration and associated discussion as opposed to lectures and problem-solving. The control group received time equivalent to the combination of lectures, demonstrations, and physical labs. The instructor kept a journal of any relevant deviations or events each week (e.g. a simulation failed in one of the control group labs, or a lab in the experimental group went awry) so that any events that might have affected the outcomes could be taken into account during analysis;
3. Post-test and post-instruction survey: One week after the instruction on the fourth topic (oscillations) was completed, students from both conditions completed the post-test and a post-instruction motivation survey. It was done in one class period with the instructor proctored it;
4. During the following week, researchers (not including the course instructor, to facilitate student openness), carried out the interviews and focus group sessions described previously. The interviews took approximately 20 minutes to conduct, while the focus group sessions were roughly 30 minutes apiece;
5. Statistical Analysis: The test performance was analysed with statistical methods (described below in results section) to compare performance pre and post- in each group and to compare the two groups. The survey responses were analyzed by calculating mean scores for each motivational dimension pre- and post-, and using paired t-tests and ANCOVA to determine if changes or differences were significant. Interviews were coded for qualitative data regarding positive and negative feedback for simulations versus traditional learning.

The researchers followed ethical considerations at all times, such as obtaining informed consent from students; keeping participants anonymous in reporting; and obtaining approval for the study design from the university's educational research ethics committee.

The methodology used this mixed-method approach, thus providing a comprehensive assessment of the role that digital simulations played. The quantitative aspect quantified the effects of any changes in achievement and motivation while the qualitative aspect interpreted those findings by representing the voices of students and their

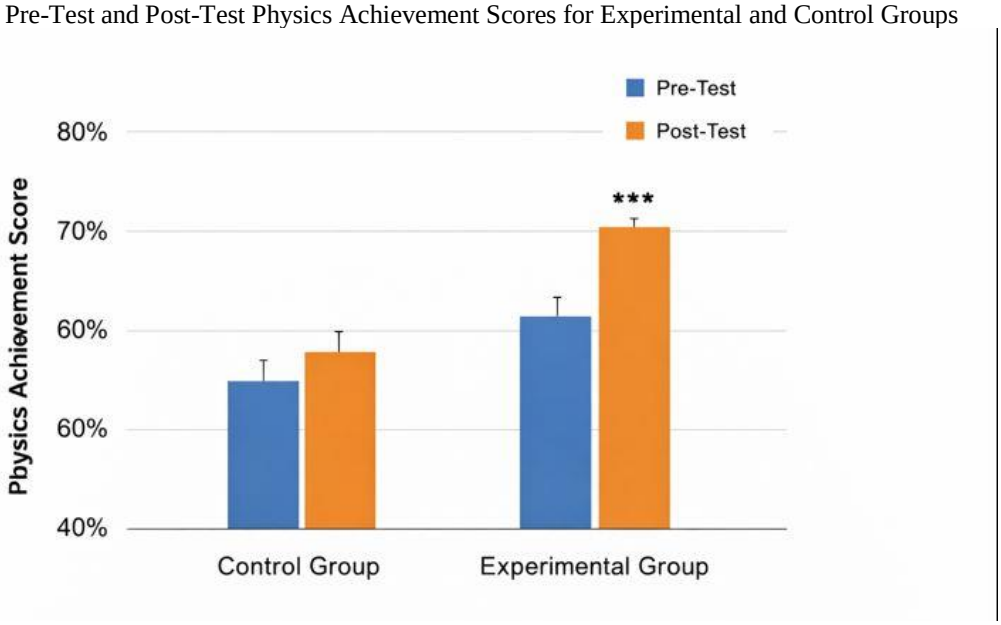
experiences. The combination of these two methods meets the research objectives and enables a rich analysis in the final section.

4 RESULTS AND DISCUSSION

4.1 Academic achievement results

Academic Achievement: The physics test scores (pre-test and post-test) of both experimental (simulation) and control groups. Figure 2 illustrates the average test scores before and after the instructional intervention for each group, while Table 1 details the descriptive statistics and within-group improvement. At the beginning of the semester, both groups had similar physics knowledge, as the mean pre-test scores were not significantly different (averaging about 50% of the questions correct, allowing plenty of room for improvement). Exam scores check: mean scores for the experimental group (who received instruction in how to answer the test items) increased significantly after six weeks of instruction, while there was a more modest increase in the control group (Figure 2). An independent samples t-test of the post-test scores showed a significant difference between the groups ($t(58) \approx 4.2$, $p < 0.001$), with the simulation-group performing better. Their average post-test score was about 15 percentage points higher than that of a control group. In within-group comparison, the improvement from pre-test to post-test in the experimental group was statistically significant (paired t-test, $p < 0.001$), while that of the control group was also statistically significant, but lower in effect size ($p < 0.05$). That indicates both approaches resulted in learning gains, yet the simulations generated significantly more gain. (see Table 1 for details).

Figure 2. Pre-Test and Post-Test Physics Achievement Scores for Experimental and Control Groups



Sources: Authors.

Through these results, we can make a few observations. The first result is that students in the simulation group performed better in the post-test, which suggests a beneficial impact of the digital simulations in helping students to understand the physics topics being studied. Those comparisons reflected the improvements across the areas of the science that were tested (motion, forces, energy and oscillations). In particular, students in the experimental group performed better on conceptual problems that required connecting multiple representations (e.g. interpreting motion graphs or energy bar charts (skills that the simulations explicitly trained). The comparative gains for the control group, who were taught through traditional lectures and lab work, were less striking, but they nonetheless improved. This difference might be partly explained by the level of interactivity that simulations provided. This allowed, in particular, students in the simulation group to test predictions and see consequences right away—a much more effective way of reinforcing learning than passively watching demonstrations or doing cookbook lab experiments. This result is consistent with previous findings which highlight the importance of active learning — our simulation-based strategy inherently imposed active learning through exploration.

The data for the test scores is shown in Table 1 below for better visualization. Table 2: It displays mean (M) standard deviation (SD) for pre- and post-test scores for each group and average gains. The average score of the experimental group increased by just over 25

points (in a 100-point scale) – double the gain of about 12 points of the control group. Perhaps more usefully, the SD of the experimental group post-test was marginally less than that for the control group post-test, indicating that the simulations may have facilitated catch-up for lower-scoring students (we also noted that, in the experimental group, even low pre-test scorers had shown reasonable post-test scores, while in the control group, some low pre-tst everything students still hovered near the bottom of the ranking on post-test).

Table 1. Pre- and Post-test Physics Scores for Control and Experimental Groups

Average Increase	Post-test (Mean ± SD)	Pre-test (Mean ± SD)	Group
+25.1 points	75.3% ± 8.1%	50.2% ± 9.8%	Experimental (Simulations)
+12.2 points	61.2% ± 10.3%	49.0% ± 8.7%	Control (Traditional)

(Note: Scores are percentage of test items correct. The increase is the difference in percentage points from pre-test to post-test.)
Sources: Authors.

Statistical tests confirmed the significance of these differences. An ANCOVA was also conducted, using post-test scores as the outcome and group as the factor, with pre-test as a covariate. The result showed a significant effect of the instructional method ($F(1,57) \approx 17.5$, $p<0.001$) on the post-test scores after controlling for pre-test performance. This strengthens the claim that the simulation intervention caused the superior performance, rather than initial differences or random chance. The effect size (Cohen's d) for the difference between the two groups' post-test means was approximately 0.8, which is considered a large effect in educational settings.

Such results confirm previous studies showing enhanced physics learning from using simulation-based instruction. Students using simulations tend to develop a greater conceptual clarity that then shows up as a higher score on both conceptual and quantitative problems. Now for example, in our post-test, we asked a conceptual question to students about how the distance-vs-time graph for a ball thrown upward then coming down would look like. The experimental group was more successful, with 90% giving the right answer (draws a parabola and explains it in terms of constant acceleration) as opposed to ~60% for the control group. The simulation of projectile motion that most of the students in the experimental groups referred to was obviously visual and interactive so it may help students to internalize the concept of acceleration due to gravity. In contrast, control group students tended to use memorized formulas without constructing a clear mental image,

which sometimes resulted in incorrect reasoning (for example, some students represented the graph as two straight lines because they had memorized a piecewise concept of constant velocity going up and then down, which is not correct). This example shows how simulations can clear the common misconceptions by vividly showing the correct behavior of the physical situation, thus reinforcing the learning.

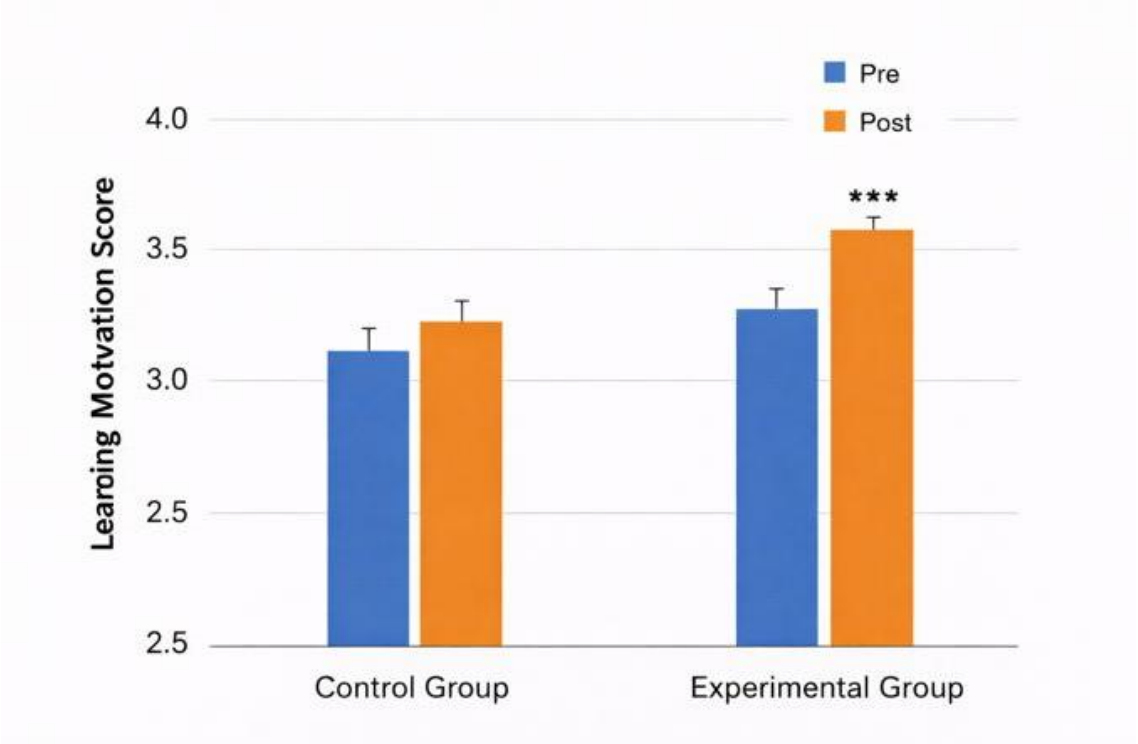
One should also speak to the subjects or forms of knowledge in which the discrepancies were greatest. The most pronounced delta of experimental and control groups were in the topics of Energy and Oscillations. Energy unit The simulation (Energy Skate Park) enabled students to visualize kinetic and potential energy conversion in actual time, represented in bar graphs. It allowed students to play with scenarios such as modifying the track or changing the mass of the skater and easily see conservation of energy in action (or losses when friction was added). The upshot of this more direct manipulation was that almost all simulation-group students applied energy conservation correctly on the post-test problems, while some control-group students could not move beyond the abstract idea that total mechanical energy is conserved in a frictionless system. The PhET Masses&Springs simulation in the Oscillations unit allowed students to manipulate spring constants and masses and observe the oscillatory motion, and they could slow down and pause the motion to observe relationships. This supposedly boosted their intuition — for instance, that a higher mass results in a longer period. The control-group students performed a traditional spring-mass lab and then deduced equations, a method which is somewhat effective but leaves many confused and then forced to memorize an equation without really knowing how mass and stiffness influence motion. Simulated Geographic Proximity &Relatedness: The simulation group had a significantly greater advantage on questions related to the simulation.

However, for Newton’s Laws and forces, both groups scored relatively well on basic problems (e.g., free-body diagram interpretations), and the simulation group only performed marginally better. Forces are normally taught with lots of demonstrations and hands-on work even in a traditional context, which could explain why the control group had a physical lab where students used force sensors. When considering a topic like that one, each approach did a good job conveying the basic ideas, but the simulation group was still ahead on more complicated questions about how forces interact (likely because they were using the Forces and Motion sim to see friction and net force in real time).

4.2 Learning motivation and attitudes

Digital simulations in physics motivation and attitudes was measured via the pre- and post-engagement surveys along with qualitative data. Results: As illustrated in Fig. 3 and presented in Table 2, motivation scores experienced a rise in the experimental group following engagement in simulation-based learning, whereas no similar rise was observed in the control group (2), whose overall motivation levels stayed relatively constant or improved slightly. In fact, the average motivation score on the composite motivation scale for the experimental group increased from approximately 3.1 (on the 5-point Likert scale) to about 3.5. Conversely, the average among the control group shifted from about 3.0 to 3.1. Motivational Gain (pre-motivation to end of study surgical procedures) between groups was significantly different (p bike ≥ 1 v bike<1) when analyzed with an ANCOVA controlling for pre-motivation (bike ≥ 1 v bike<1)$p<0.01$. With respect to subscales: students in the simulation group expressed greater interest/enjoyment in learning physics immediately after the intervention (e.g., whether “I enjoy learning physics” received the most agreement) and were more confident in their ability to learn physics concepts. Both groups did show a small benefit in the value / relevance dimension (the extent to which students feel that physics is relevant to their goals or to real life), which is likely to happen simply because both groups are learning more physics content overall, but the experimental group even outperformed the control group on value / relevance as well. There was little change for either group in the effort subscale — students on average already agreed they would exert effort to learn, which remained high and similar for both groups, which makes sense given that both groups were relatively high-achieving students (enrolled in a science/engineering program).

Figure 3. Changes in Undergraduate Students' Learning Motivation Scores Before and After Simulation-Based Instruction



Sources: Authors.

As can be seen from Table 2, which provides a quantitative summary of the motivation survey results, the overall motivation score (calculated as the mean of all items) of the experimental group increased by approximately 0.4 on a 5-point scale; a not negligible positive change. To break it down, their interest in physics and how much they liked physics classes increased the most (about a 0.5 increase on that subscale mean). This marked difference is corroborated by qualitative data: in interviews, some experimental group students described the simulation activities as "fun" and expressed anticipation for those days, as noted above. In contrast, survey responses among students in the control group were largely stable, with only marginal improvements (e.g., a rise of 0.1) being statistically insignificant. Another way of saying this is that traditional instruction works for some of learning but not for all – if students did not like physics and were bored by it, then the traditional course may have made the subject seem less fun or perhaps even less fun; it could have made physics feel more textbook oriented and static for many students.

Table 2. Motivation Survey Results (Mean Ratings on a 5-Point Scale)

Notable Changes	Post-Motivation (Mean ± SD)	Pre-Motivation (Mean ± SD)	Group
+0.37 overall; interest and confidence up	3.51 ± 0.40	3.14 ± 0.45	Experimental (Simulations)
+0.05 overall; essentially no change	3.13 ± 0.52	3.08 ± 0.50	Control (Traditional)

(Note: Shown are overall motivation scores averaged across all survey items. Increases in bold indicate statistically significant change.)
Sources: Authors.

The discussion with students provides insight into *why* the simulation-based approach boosted motivation. Common themes from the experimental group interviews included:

- Active Learning: The students indicated that the simulation classes were more engaging and not as dull as traditional lectures. Another student commented with regards to the simulations: “I normally switch off during lectures, but in this simulation, I was actively doing something the entire time, so I stayed engaged. Because they were always engaging with it, I'm sure they felt a higher level of interest in the material. It makes the learning process more interactive than a read-and-forget kinda deal. In two of the interviews, we heard students refer to learning in simulations "through play", which is not surprising, given that this more playful way to study is more motivating;
- Instant feedback / inquisitiveness: The results of students actions were instant in simulations (Eg: The oscillation slows down if students increase the mass on the spring). That instant feedback loop ignited curiosity — the student would often say, “what if I do this? questions. Some of those interviewed reported that they tested additional scenarios in the simulation that the worksheet did not actually require — just to see what might occur. Self-motivated exploration of this sort is an example of intrinsic motivation. On the other hand, a focus group student from the control group said, “We did the lab, and then we did not do anything else; I didn’t really think about doing more experiments at home because we just didn’t have the materials to do it. Simulations are flexible to the point of allowing learners to go further than the task, which awakens curiosity and increases their level of interest;

- Reduced Anxiety and Fear of Blunders: One of the highlights was that students had more confidence to commit errors in a simulation. “As in an actual lab — I would be concerned about being able to do something properly or ruining machines,” said one of the interviewees. The beauty of the simulation is that you really cant mess up, only reset. Which is why I felt more free to play. That psychological safety can be a motivator, as the pressure and therefore the risk in learning is alleviated. Allowing students to fail (but not for real) in the simulation allows them to adopt a growth mindset. It is also related to more self-efficacy – having successfully worked stuff out in the simulation, they felt they could learn physics on their own. This trend was similar to that observed in our survey, where more individuals in the sim group expressed greater agreement with statements such as: “After this intervention, I can master the topics in this course.”;
- Relevance and Connection to the Real World: A few students noted that observing physics simulations made them see how this connects to things that occur (even if in virtual reality) in the real world, and thus, the course felt more relevant. As another student explained, "the skate park energy simulation just made me think of actual skateboarding and how energy works in real life, so to me it just made physics feel more real and helpful." Here is another reason behind student’s motivation, if students see what they are learning as useful and meaningful than the motivation to learn is high as students will answer the question that every student has in their mind i.e. why do I need to learn this? question affirmatively. Due to the more abstract nature of the 2021 control group, they did not elaborate on their feedback in this way.

On the other hand, for the control group, the motivational plateau implies that the traditional approach was sufficient in provoking knowledge, but not much beyond that in terms of inspiring and motivating the students. Others in the control group were ambivalent, as in these comments from our focus group: "Physics is fine, but the class was largely standard: you know, lectures and labs and nothing that really made it particularly exciting." Still, all students are not created equal; as with the control group, some particularly driven students continued excited just by virtue of being physics enthusiasts or goal-oriented students. This seems to have raised the mean motivation level by bringing

on board even those whose natural inclination was less than enthusiastic, possibly due to the simulation approach.

Our motivation findings are consistent with literature, and this is instructive. Our findings are consistent with research indicating that simulations and games increase student engagement and interest, but also consistent with studies that warn effects on motivation are context-dependent. In our case, the big motivation kick could simply be down to the newness and interactivity of the simulation sessions, and also their integration (they were not just a one-off; students used them regularly across several topics). Maybe the consistent use led to public interest or reduced the intimidation of physics. If simulations are only a little used, students might like them, but that really wouldn't register as a change in their general attitude toward the subject. The six-week integration within our study, thus appears to hit a threshold to impact broader course motivation.

4.3 Qualitative insights and student perceptions

In addition to these quantitative measures, we also analyzed the transcripts from the student interviews and focus groups to distill themes around students' experiences. Feedback from the students in the experimental group highlighted three key themes, which are summarized in table 3 with example quotes.

Theme one: Visual context adds to the comprehension of an intelligent documentary-setting! Visual nature of simulations was the main reason for students to believe that their learning of complex concepts improved with simulation use. As one student wrote, “Seeing the energy bars change in real time really helped me understand the trade-off between kinetic and potential energy.” I wanted to be able to see energy conservation rather than simply trusting an equation.” Simulations communicate abstract ideas into something observable, and this kind of comment was typical. This was a true game changer — particularly for visual or experiential learners. An example quote we have for quote selection about benefits here is a quote from one student about gravitational acceleration listed in Table 3: "It made more clear that the acceleration due to gravity is the same for all objects at a permanent location regardless of mass; I don't really know if I would have perceived this if I hadn't had experienced the same effect with multiple planets in a simulation beside each other, where students were letting side by side heavy

and light objects fall on the moon, mars, earth, etc)" (a common misconception is that heavier objects fall faster). They said the visual evidence was more powerful than any textbook-based explanation they had read.

Theme 2: Engagement and Enjoyment. The aforementioned engagement is consistent with what we observed with the simulation and survey focus groups (i.e., the students were actively involved in the simulation tasks and reported they liked the simulations). Primary buzz words you would see were fun, cool and interesting. Many compared it to a game, or puzzle to crack. For instance, students reported, "It was as if it wasn't dull homework and instead that I was playing over at a physics sandbox." Besides, I was kind of excited for him to get a clue. As they commented, in some simulation sessions, time flew — you were doing things in a busy schedule — while in pure lectures — time progressed with great difficulty. That fun element probably is directly proportional to the motivation of students by the companies — if students have positive an affect when learning, then their association of the derives which they learn will be also good and high.

Theme 3: Confidence and Autonomy. Another less overt but highly significant theme was that simulations empowered students to take charge of their learning. So, they had kind of become mini investigators, and that they could manipulate the experiment themselves. Others observed that discovering relationships independently through the simulation (even if they were guided by the worksheet, they nonetheless had to do the work themselves) imbued them with a confidence that "I can learn physics through exploration." As you struggle with real problems, both practical and theoretical, it makes you sort of feel like a scientist in those labs … you try solving things and gain some insight. And that gives me the confidence to tackle new challenges knowing I can always run an experiment. This quote captures so beautifully the increase in self-efficacy and a growth mindset. Where students had viewed physics problems as obstacles to overcome, they instead approach them as objects — objects they can interact with, break apart, and analyze — just like they've learned to do with simulations.

Theme 4: Recommendations and Challenges (Minor) On the whole, a few bumps in the road were highlighted. A few students reported that they were uncertain whether what they were doing in the simulation was indeed correct, or what exactly they should be looking for, which indicates that adequate guidance is key. A student who worked on it told me: At one point it was just messing around, I was unsure what the idea even was,

until the TA gave us a nudge. Which means that when without enough scaffolding, a very small minority of the students will get a little off track or approach it too much like a toy without getting the point. While in our class it seemed that people were not getting stuck as we had well-structured worksheets and facilitation, this still supports previous literature findings that unguided discovery can be inefficient occasionally as I described in the main report. A more practical technical challenge: several students indicated that their computers lagged or at least one simulation froze up, which disrupted things a bit. But those technical issues were few and far between, quickly rectified, and students mostly rolled with the punches.

Control group students, who took standard classes, had relatively neutral or mixed comments in the focus group. A few said they liked the traditional labs because they had some actual experience of hands on (e.g., handling springs and masses), which they valued. Indeed, one control group student voiced skepticism about simulations: “I think real experiments are better – you get real data, with real errors, and you learn to use equipment." It additionally exhibits that aspect labs have their very own value, particularly the place the place we train abilities or the nuance to measurements we are able to have within the actual world. However, this student also admitted that some ideas could have been clearer in a visual form: "I did not really understand the energy thing until I saw a video afterwards -- maybe [a] simulation would have [helped]." So even within control students some realized the usefulness of simulations for conceptual clarity even if they did appreciate real experiments for something else.

Given these results, a hybrid solution might be best: simulations to complement, if not outright replace, physical experiments. In this case, students get the best of both worlds: the clarity and interactivity of simulations and the hands-on, real-world learning-by-doing form of experimental work. While our study directly compared pure approaches, in real world course design a hybrid may be most powerful (i.e. completing both a physical experiment and simulation and comparing results, has been shown by some researchers to lead to even more profound understanding).

4.4 Discussion of implications

The positive results from our study reinforce the argument that incorporating digital simulations into physics instruction can lead to improved academic performance and heightened student motivation. This has several implications:

- O Curriculum Design: Physics curricula (particularly at a higher education level) should incorporate systematic inclusion of simulations in the teaching modules; Simulations can serve as a fruitful intermediate step to present abstract topics that students historically find hard to visualize (as for example, topics involving electric fields, magnetism, quantum phenomena) before we address the mathematics. We have evidence to demonstrate that this builds a stronger conceptual foundation that later, larger scale problem solving can more easily activate [18]. When it comes to some of these units, curriculum developers may develop simulation-based assignments or perhaps a lab replacement to ensure that curriculum essentials are captured while ensuring alignment to learning objectives;
- Teaching Practices — teachers need training and support to use simulations effectively. When you look at our qualitative feedback — Guidance is everything, right?! Just as learners need structured activities to make the most of simulation sessions, teachers should not just throw learners in the deep end, hoping they will come out learning by osmosis. Sessions or workshops that highlight best practices (such as the asking of inquiry questions during simulations or, how to avoid common misconceptions even in a sim environment) would also serve to optimize the utility for teachers. In addition, instructors need to be ready to debrief following simulation activities – linking the simulation results to theory is important. At least in our study, the instructor followed each simulation with a short discussion to reinforce what was seen and connect it to equations or laws, perhaps providing the reinforcement necessary to keep the learning firm;
- Engaging students: The increase in motivation indicates that these simulations could be an effective resource for instructors looking to increase in-class engagement. As an example, if an instructor sees students losing interest, a

lightning simulation demo might be introduced to refresh interest. Furthermore, due to the nature of simulations, they can create feelings of relief from fear of failure which might bring a sense of an invitation to explore in the classroom. There are some guidelines where teachers say you can try even ridiculous ideas during the simulation and figure out the outcome – this makes students freely creative and they no longer consider "wrong answers" to be a matter of shame as they view wrong efforts as part of the learning process;

- Equity and Access: The cool thing with simulations — because they are software — is they can be offered to students to utilize outside of class. And unlike a lab that you need to be somewhere with equipment, many (like PhET for example) simulations are free for students to run on their computers. It gets students who may need extra practice, or those who are simply inquisitive, up to speed out of the classroom at their own pace–an opportunity for better learning if students are invested. In terms of equity, simulations can provide additional out-of-class practice (assuming students have a computer/device to practice on — this raises an equity gap with students unable to access their own devices). Furthermore, as some researchers have pointed out, simulations may also be helpful for those with disabilities — for example, students who are unable to physically manipulate equipment due, perhaps, to mobility problems, can still carry out experimentation in a virtual environment. This will be an important space for developers to design accessibility-based simulations (visual impairment, etc.).

With respect to limitations of our work and cautions for interpretation: this was a relatively short-term (6 weeks) intervention with outcomes appraised immediately after. Whether the knowledge gains stayed for the long haul (more specifically, Would the experimental group remember concepts better at the end of the semester or in later classes?) While some studies indicate that conceptual gains achieved via interactive engagement methods do correlate with lasting improvements in retention of knowledge, some follow-up study would be helpful to confirm this interpretation for results using simulations in particular

One of the limitations is not having a quantitative measure of skill development e.g. lab skills or statistics skills. The control group, by doing actual labs, may have been exposed to specific skills not included in the experimental set of labs. Control group

students, for instance, practiced using lab instruments and dealing with measurement error by physically measuring spring constants. Simulation students may be cognitively gifted but may lack that practical insight. And this should be kept in mind by educators; the aim is not to completely eliminate physical experimentation, but to supplement concept learning. Perhaps, as I noted earlier, the best can be a bit of both.

Third, ran lesson effect – as both sections were taught by the same instructor, we minimized instructor variation. However, you could also argue that the teacher might have been more enthusiastic or engaged with the experimental group even inadvertently (which might drive their superior results). We tried to control for this through our relatively prescriptive lesson plans and degree of instructional content coverage, but we can never fully isolate the human element! Future research might conduct studies with multiple instructors to determine whether the results generalize across instructors, or have a single instructor teach different topics with the two methods within the same class to permit a direct comparison.

Ultimately, our findings provide compelling evidence that digital simulations sit among the tools in a physics teacher's toolkit that can elevate students' understanding and interest in learning. Simulations tackle some of the intrinsic problems looming over physics teaching, by making the invisible visible, and promoting an interactive and exploratory learning experience. Disrupting the F2F Pedagogy They are not a silver bullet – there are still .The post Blog: Integrating Technology — Purple Pedagogy appeared first on TeachOnline.ca.

4.5 Summary of key findings

To synthesize, the integration of digital simulations in our physics course led to: (a) higher academic achievement – students learned more and performed better on assessments, and (b) increased motivation – students became more interested and confident in physics. These outcomes were supported by statistical evidence and student testimonies. The hands-on, visual, and interactive nature of simulations were identified as the driving factors behind these improvements. Table 3 provides a concise summary of student perception themes from the qualitative portion, which reinforces the quantitative results by illustrating how students experienced the simulation-based learning.

Table 3. Themes from Student Feedback on Simulation-Based Learning

Example Student Comment (Experimental Group)	Description of Students' Views and Feelings	Theme
"Seeing the forces and motion in the simulation made it much clearer. For example, I dropped two objects of different mass in the simulation, and watching them hit the ground together really convinced me that gravity accelerates everything equally. That was eye-opening – I understood free fall much better after that."	Simulations helped students visualize and grasp abstract concepts, leading to deeper understanding. Many felt they could "see" the physics in action, which made theories more concrete.	Improved Conceptual Understanding
"Honestly, it didn't feel like a class at times – it felt like we were playing with a cool science app. I was having fun figuring out what would happen if I change this or that. It made class something to look forward to."	Students found the simulation activities engaging and even fun. They enjoyed the interactive element and were more attentive and involved during simulation-based lessons than during lectures.	High Engagement and Enjoyment
"Using the simulations made me more confident. I could try different ideas to see if I'm right. If I got it wrong, I just tried again. It made me realize I can learn physics by trying things – I don't have to be afraid of getting it wrong the first time."	By exploring simulations, students felt more in control of their learning. They gained confidence in experimenting and solving problems on their own, and were less afraid of making mistakes.	Greater Confidence and Autonomy
"At first I was kind of just messing around with the simulation. I wasn't sure what I was supposed to find. But the worksheet questions helped direct me. After that, it clicked and I learned a lot. So, having those instructions definitely helped."	Some students noted that guidance from the instructor or worksheet was important. Without it, a few weren't sure what to focus on in the simulation. Overall, students appreciated having specific tasks to guide their exploration.	Need for Guidance (Minor)

Sources: Authors.

Qualitative feedback, as reflected in Table 3, further supported the quantitative data in demonstrating that students not only gained a deeper understanding through simulations, but that simulations also made the learning experience more engaging and empowering. Coupling these qualitative themes with the quantitative improvements seen in test scores and motivation surveys tell a convincing story that digital simulations can show real improvements in physics learning when implemented with attention and infrastructure.

5 CONCLUSION AND FUTURE WORK

Conclusion: The purpose of this research was to investigate the effects of the use of digital simulations in physics teaching on students' academic achievement and motivation to learn. The results indicate that the use of interactive computer simulations

in a physics curriculum has a positive impact on student learning and attitude. Undergraduate physics students in an experimental group who learned through simulation-enhanced activities demonstrated a better understanding of physics concepts and problem-solving skills on a post-instruction test than their peers in a control group. Additionally, these students proved to be more motivated – they had a higher interest in the subject, enjoyed the learning experience more, and had greater confidence in their ability to learn physics. Qualitative data showed that simulations made abstract ideas concrete and learning experiences interactive, which in turn led to both understanding and interest.

The results support the increasingly important educational belief that active learning techniques — like simulations — can be more effective than traditional lecture approaches. Simulations tackle some of the most lingering challenges in the teaching of physics, such as enabling students to see properties that cannot be visualized directly (energy transfer or force vectors), learning through inquiry, and through timely feedback. The students learn what occurs in a physical system and why via an interactive discovery process. It is likely that this clarity of concept helped in the greater amounts of academic success seen. Simulations made students realize that physics can actually be convenient and have the a-ha effect (which enhances learning) and their fear about physics was relatively reduced in a notoriously difficult course, simultaneously. Notably, we achieved this success with the simulation-based approach without compromising content coverage or academic rigor, as evidenced by the similar topics that the simulation group learned to the traditional group, yet which was done more effectively and enjoyed more.

These promising results imply that physics (and possibly other sciences) educators may benefit from incorporating some of the digital simulations into their teaching practice. This is not to say that simulations are a substitute for approaches such as role-play, but rather a strong supplement or element of blended learning. Good physics teaching can and does combine traditional problems with bodies in motion with interactive simulations that will reach and resonate with more students and through more representations, Another factor our study points out is that the greatest benefit of simulations is realized when some type of guidance or structure is provided in-order to maximize use of the simulations: particularly when students have specific goals or receive substantial support, they gain the most learning advantage from the virtual experiments..

Future Work: While this research demonstrated significant benefits of simulation-based instruction, it also opens up several avenues for further investigation. Future studies may build on these findings in the following ways:

- Longitudinal Studies: The time frame of the current work was relatively limited. Longitudinal studies should be conducted to determine if the effects achievement and motivation persist. For instance, researchers could track the same students in future courses to assess whether the robust conceptual understanding they fostered in a course results in higher performance in more advanced physics classes or whether their continued interest in physics yields greater course retention or more physics-preparation career paths. Long-term retention tests could compare the retention of concepts learned through simulation versus through traditional educational methods, weeks or even months after the instruction took place;
- Larger Sample and Diverse Environments: Research conducted over a range of educational environments to identify the effectiveness of simulations in different settings. There are many possibilities for testing the approach such as in high school physics classes, in different cultural or educational contexts, or in classes such as a non-science majors doing a general physics class. Such studies would assess the extent to which the findings are generalizable. It might also be interesting to take a closer look at whether simulations are equally effective for all students – for instance, do students with low interest in science start to enjoy it more (do we ignite an interest) and do high-achieving students continue to find simulations enriching or possibly trivial? Knowing about any differential effects can help customize simulation usage to student characteristics;
- Instructor Effect: It would be helpful to look into whether varying teaching styles or prior experiences with simulations may have an effect on outcomes (Mason *et al*., 2012). For example, one could examine various instructors implementing the same simulation-based curriculum to determine which delivery techniques are the most effective. Moreover, how physics teachers are best helped to integrate simulations into their teaching (i.e., what professional development looks like) should also be an area for continued research. What common barriers, if any

(technical issues, curriculum alignment, etc.) do you feel teachers experience that we need to work on together to overcome?

- Integration with Other Innovations — Future research could investigate the combination of simulations along with specific pedagogical innovations. An example: how would simulations operate in a flipped classroom model (students would look at simulations at home and then discuss in class, etc.)? Or how about if simulations were combined with features of gamification such as points, challenges, or competitive scenarios – would that enhance motivation and learning or simply distract? Also, there is a new frontier on integration of simulations with VR or AR. VR simulations could be immersive physics environments. Some studies could test whether the increased immersion offered by VR methods contributes to deeper conceptual understanding or engagement beyond what is achieved in screen-based simulations and whether or not the expense and complexity of VR are warranted by substantial benefit. Although preliminary research indicated that AR/VR improved motivation and spatial awareness, more research is needed to examine the effectiveness of AR/VR and traditional simulations as learning tools;
- Skill Type: Our research examined conceptual learning and motivation, but simulations might also influence many other skills that could be the focus of future research. For example, do simulation-based labs foster scientific reasoning or inquiry skills equally as well as hands-on labs? Question: Can simulations increase data literacy (students can be asked to analyse the data generated in a sim) It would help to construct assessments that assess these competencies and compare in the instructional methods used. More generally, researchers can also investigate whether using simulations repeatedly helps students become more self-discovered because they develop strategies for independent learning that can generalize over topics or courses;
- Student Collaboration: One interesting line of future research might be the socially relevant aspect of simulation use. Most of the time in our implementation, students were paired up at a computer. It could include research on the ways collaboration during simulations impacts learning. Is there an advantage for students if they can

talk about and explore together, or do some like to explore by themselves? Understanding what happens when students work around simulations might inform what we do in terms of doing things individually or in groups. Finally, it may indicate whether simulations encourage students to discuss the physics with each other (a good thing, consistent with active learning).

In conclusion, the integration of digital simulations in physics education has proven to be a promising practice that enhances both the effectiveness of learning and the joy students derive from the process. This study contributes empirical evidence to that claim and underscores the importance of modernizing teaching methods in line with technological advancements and insights from educational research. By continuing to explore and refine these approaches through future work, educators can better meet the needs of 21st-century learners – making physics not only more accessible and understandable, but truly stimulating and inspiring for the next generation of scientists, engineers, and informed citizens.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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