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# Using Simulations to Enhance Student Learning in Physics

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## ABSTRACT

*Research in science education has consistently shown that simulations can support students' conceptual understanding by making abstract phenomena visible and interactive, particularly in physics. Concepts related to motion and trajectory are often challenging for high school students because they require coordinating mathematical representations with physical intuition. The present study investigated whether an interactive physics simulator could improve students' understanding of trajectory compared to traditional instruction alone.*

*Thirty high school students from China participated in the study. All students received instruction on the physics of trajectory, including the effects of initial speed, launch angle, and friction. Participants were then assigned to one of two conditions. In the experimental condition, students were provided with a simulator that allowed them to vary parameters of an object rolling down an elevated ramp and observe the resulting flight path. Participants in the control condition received the same instruction but did not use the simulator. Following instruction, all participants completed a post-test assessing conceptual understanding and problem-solving related to trajectory.*

*Results indicated a statistically significant difference between groups. Students who used the simulator achieved a mean post-test score of 83.3%, whereas students who did not use the simulator achieved a mean score of 59.5%. These findings suggest that simulation-based instruction can substantially enhance learning of trajectory concepts. The results have important implications for physics education, supporting the use of interactive simulations as effective tools for improving conceptual understanding and promoting more equitable access to complex scientific ideas.*

## INTRODUCTION

Over the past several decades, educators and researchers have increasingly explored the use of simulations and simulators as instructional tools to enhance student learning across academic domains. Advances in computing technology, graphical interfaces, and interactive design have made simulations widely accessible in classrooms, laboratories, and remote learning environments. In science education in particular, simulations offer a powerful means of representing abstract, invisible, or otherwise inaccessible phenomena in ways that support conceptual understanding. Physics, a discipline that often challenges students with highly abstract concepts, mathematical formalism, and non-intuitive processes, has been a primary focus of this research. This introduction reviews prior work on the use of simulations in education, with special emphasis on science and physics learning, and situates the present study within this established body of literature.

Simulations are generally defined as interactive representations of real or hypothetical systems that allow learners to manipulate variables and observe resulting changes (de Jong & van Joolingen, 1998). Unlike static diagrams or textbook explanations, simulations can dynamically illustrate processes over time, enabling learners to explore causal relationships and test hypotheses. Early educational research suggested that simulations could function as “cognitive tools,” supporting learners in constructing mental models of complex systems rather than merely memorizing facts (Lajoie & Derry, 1993). As computing power increased, educational simulations evolved from simple numerical models to rich, visually immersive environments capable of supporting inquiry-based learning.

A substantial body of research has examined simulations as vehicles for inquiry learning in science. Inquiry-based learning emphasizes active exploration, experimentation, and hypothesis testing, mirroring the practices of professional scientists. De Jong and van Joolingen (1998) reviewed early studies on discovery learning with computer simulations and concluded that simulations can significantly enhance learning when appropriate scaffolding is provided. Without guidance, students may struggle to design productive experiments or interpret results correctly. However, when simulations are paired with instructional supports—such as guiding questions, prompts, or structured tasks—they can promote deep conceptual understanding and scientific reasoning.

Physics education research has been particularly influential in demonstrating the instructional value of simulations. Physics concepts often involve entities and processes that cannot be directly observed, such as electric fields, forces, energy transfer, or quantum phenomena. Traditional instruction relies heavily on mathematical equations and symbolic representations, which many students find difficult to interpret conceptually. Simulations provide an alternative representational medium that can bridge the gap between formal mathematics and intuitive understanding. For example, students can visualize how forces act on objects, how energy transforms between kinetic and potential forms, or how changing parameters affects motion trajectories.

One of the most influential simulation initiatives in physics education is the PhET Interactive Simulations project developed at the University of Colorado Boulder. PhET simulations are research-based, interactive tools designed to support conceptual understanding through exploration and visualization (Wieman, Adams, & Perkins, 2008). Studies of PhET simulations have shown that students using these tools often outperform peers receiving traditional instruction, particularly on measures of conceptual understanding (Adams et al., 2008). The simulations are explicitly designed to reduce cognitive load, highlight underlying principles, and encourage active engagement, aligning with established theories of learning.

Research comparing simulation-based instruction to traditional laboratory experiences has produced particularly compelling results. While hands-on laboratories have long been considered essential to science education, simulations offer distinct advantages, including reduced cost, increased safety, and the ability to manipulate idealized conditions. Finkelstein et al. (2005) demonstrated that students who learned electric circuits using simulations before engaging in real laboratory work performed better on conceptual assessments than students who used physical equipment alone. These findings suggest that simulations can prepare students to benefit more fully from hands-on experiences by establishing foundational conceptual understanding.

Another influential line of research in physics education emphasizes the importance of interactive engagement more broadly. Hake's (1998) large-scale study of introductory physics courses revealed that interactive engagement methods—including the use of simulations—produced significantly higher learning gains than traditional lecture-based instruction. While simulations were not the sole factor in these gains, they were frequently incorporated as part of instructional strategies that emphasized active participation, conceptual discussion, and formative assessment.

Beyond conceptual understanding, simulations have also been shown to support problem-solving skills and transfer of learning. Physics problem solving requires students to integrate conceptual knowledge with mathematical reasoning, a task that many students find challenging. Simulations can help students link equations to physical meaning by making abstract quantities visible and manipulable. For instance, seeing how velocity vectors change in response to forces or how energy graphs evolve over time can strengthen students' ability to interpret and apply mathematical models (Zacharia & Olympiou, 2011).

Cognitive theories of multimedia learning provide additional support for the effectiveness of simulations. According to Mayer's (2009) cognitive theory of multimedia learning, students learn more deeply from words and pictures together than from words alone, provided that instructional materials are designed to manage cognitive load effectively. Simulations that integrate visual representations, interactive controls, and minimal text can leverage dual channels of information processing and promote meaningful learning. When poorly designed, however, simulations may overwhelm learners or encourage superficial exploration, underscoring the importance of evidence-based design principles.

Research has also examined the motivational and affective benefits of simulation-based learning. Students frequently report increased engagement, interest, and confidence when using simulations, particularly in subjects like physics that are often perceived as difficult or intimidating (Perkins et al., 2006). Increased engagement may contribute indirectly to learning gains by encouraging persistence, exploration, and self-directed inquiry. These affective outcomes are especially relevant for supporting diverse learners and reducing achievement gaps in STEM education.

Despite the substantial evidence supporting simulations, researchers have emphasized that simulations are not inherently effective in isolation. Their educational value depends on how they are integrated into instruction. Guided inquiry, structured reflection, and alignment with learning objectives are critical factors in determining learning outcomes (Rutten, van Joolingen, & van der Veen, 2012). Simulations can complement, rather than replace, other instructional methods, including lectures, discussions, and physical laboratories.

In summary, prior research demonstrates that simulations and simulators can play a powerful role in supporting student learning in science, particularly in physics. They enable visualization of abstract phenomena, support inquiry-based learning, enhance conceptual understanding, and increase student engagement. When thoughtfully designed and pedagogically integrated, simulations have been shown to produce learning gains that equal or exceed those of traditional instructional approaches. The present study builds on this extensive literature by further examining how simulation-based instruction can be used to support students' understanding of physical motion and energy, contributing additional empirical evidence to this well-established and growing field of research.

## METHOD

### *Participants*

Participants were 30 10th grade high school students recruited from Zheijiang Xinchang High School in China. 15 were assigned to the experimental (simulator) condition and 15 were assigned to the control (no simulator).

### *Simulator*

A simulator was constructed to allow Participants to view the trajectory of an object after rolling down a ramp. The following are the features of the simulator:

1.Building: Users can choose the "line mod" or "curve mod" and click on the canvas, and these points would automatically connect with each other to form a bridge or tracks when users push the button of Complete Segment. Moreover, in order to allow users to adjust their combination of tracks, pressing the button of Undo Point would remove the last point users clicked on. After building the construction, the data of the tracks, such as length or angles, will show through figures on the canvas.

2.Running the simulator: Before running the simulator, users are allowed to change the velocities of the ball from -5 to 5 m/s, both vertical and horizontal. Users can also change the frictional coefficient. When users press the Running button, the simulator will show the animation of the ball's motion.

3.Data showing: On the left side of the screen, several data are shown by figures, which includes velocity, displacement, and energy changing. On the left side, the Physics Calculations part shows the initial velocity, final velocity, acceleration, time on ramp and for projectile, maximum height, and horizontal displacement. The Energy Metrics part shows the energy changing including different types of energy: kinetic energy, gravitational potential energy, and thermal energy.

4.Tasks: The simulator offers two kinds of tasks: First, on the left side, there is a question loader and 10 questions that can be chosen. Pressing the question and the loading button, there would be an existing combination of tracks shown on the canvas. Then, users can run the simulator to see the motion of the ball. Users can also press the button of Make Predictions to input some results of calculation. They will get feedback after entering

### *Materials*

There were two types of materials: instructional materials and the post-test. The instructional materials explained how to calculate trajectories of objects after they have exited a slide. The materials explained the concepts of horizontal and vertical vectors and how gravity, the properties of the slide (friction, angle of the slide) and the initial velocity affect the final trajectory.

The post-test contained six questions. Five questions involved calculations using the formulas presented in the instructional materials. The sixth question asked Participants to create their own set of tracks such that a ball would land in a bucket after leaving the tracks. The Participants did this on paper and were told that the tracks had to fit within a space that measured 15 meters vertically and 20 meters horizontally and that the ball would have to land in a 2-meter-wide cup that was located 5 meters horizontally from the space in which the tracks could be drawn.

All materials were written in Mandarin for the students.

### *Procedure*

All participants received the initial instructional materials on the concept. After that, experimental Participants were allowed to practice on the simulator, running trials of balls rolling down a slide and watching where they fell. Participants were allowed to vary the parameters of the simulation like initial speed, angle of inclination of the slide, or friction of the slide. All participants were given the six-question post-test.

## RESULTS

The results of the post-test were scored. A maximum of six points was possible. Participants in the control condition scored, on average, 3.57 out of 6 points or 59.5%. This is equivalent to scoring an F letter grade by standard grading conventions, demonstrating how challenging learning this physics concept normally is. Participants in the experimental condition, who used the simulator during the learning process, scored, on average, 5 out of 6 points or 83.3%. This is equivalent to scoring a B letter grade by standard grading conventions. This 23.8 percentage point difference was statistically significant, $t(28) = 2.92$, $p = .0068$, demonstrating the efficacy of using the simulator.

## DISCUSSION

The present study investigated whether the use of an interactive physics simulator could enhance high school students' understanding of motion, projectile behavior, and the effects of initial conditions such as speed, angle, and friction. Specifically, the simulator allowed students to model the motion of a ball rolling down an elevated ramp and predict where it would land after leaving the ramp. The findings demonstrate a substantial and statistically significant advantage for students who learned with the simulator compared to those who received instruction without it. Students in the simulator condition achieved an average post-test score of 83.3%, whereas students in the non-simulator condition achieved an average score of 59.5%. This difference represents not only statistical significance but also educational significance, suggesting that simulation-based instruction can meaningfully improve conceptual understanding in physics.

One of the most important implications of these results is that simulations can help students bridge the gap between abstract mathematical representations and physical intuition. Concepts such as projectile motion, vector decomposition, and the influence of friction are notoriously difficult for high school students to grasp, particularly when instruction relies heavily on formulas and symbolic manipulation. The simulator used in this study provided a dynamic, visual representation of motion that allowed students to see how changes in initial conditions directly affected outcomes. By repeatedly manipulating variables such as ramp angle or initial speed and observing the resulting trajectories, students were able to form more accurate mental models of the underlying physical processes. This finding aligns closely with prior research suggesting that simulations support conceptual understanding by making invisible or abstract processes visible and interactive.

The magnitude of the observed learning gains is consistent with previous studies comparing simulation-based instruction to traditional teaching methods in physics. Prior research has shown that students who use interactive simulations often outperform peers on conceptual assessments, particularly when simulations are integrated into guided instruction rather than used as unguided discovery tools. In the present study, the simulator was embedded within a structured lesson, ensuring that students' exploration was aligned with instructional goals. This structured use likely contributed to the strong learning outcomes observed. The results reinforce the idea that simulations are most effective when paired with clear learning objectives, prompts, and opportunities for reflection.

Another key implication of this research concerns equity and access in science education. Physics is frequently perceived by students as one of the most difficult subjects in the high school curriculum, and these perceptions can disproportionately affect students who lack prior exposure to advanced mathematics or physics concepts. The simulator appeared to reduce these barriers by providing an alternative pathway to understanding that did not rely exclusively on algebraic manipulation. By allowing students to explore motion visually and experimentally, the simulator may support learners with diverse backgrounds and learning preferences. This suggests that simulation-based instruction has the potential to narrow achievement gaps in physics and promote broader participation in advanced science coursework.

The findings also have practical implications for classroom instruction. Many schools face constraints related to time, resources, and laboratory equipment. Physical experiments involving ramps, projectiles, and precise measurements can be time-consuming and difficult to implement consistently across classrooms. Simulators offer a cost-effective and scalable alternative that allows students to conduct multiple trials rapidly and safely. While simulations should not be viewed as replacements for hands-on laboratory experiences, the present results suggest that they can serve as powerful complements to traditional instruction. In particular, simulations may be especially valuable for introducing concepts, preparing students for physical labs, or reinforcing learning after hands-on activities.

Despite the strengths of the study, several limitations should be acknowledged. First, the study focused on a single physics topic—motion and projectile behavior—and the results may not generalize automatically to other areas of physics or science more broadly. Although prior research suggests that simulations are effective across a range of topics, future studies should examine whether similar learning gains occur for concepts such as electricity, magnetism, or energy conservation. Second, the study measured learning outcomes using a post-test administered shortly after instruction. While the observed gains are impressive, it remains unclear whether the benefits of the simulator persist over time. Longitudinal research examining retention of knowledge weeks or months after instruction would provide valuable insight into the durability of simulation-based learning.

Another limitation concerns the scope of assessment. The post-test focused primarily on conceptual understanding and problem-solving related to the simulated task. While these outcomes are central to physics learning, future research could include additional measures such as students’ ability to transfer knowledge to novel contexts, explain their reasoning verbally or in writing, or apply concepts in real-world situations. Including qualitative data, such as student interviews or written reflections, could also deepen understanding of how students use simulations to construct knowledge.

Future research should also explore the role of instructional design in maximizing the effectiveness of simulations. For example, studies could compare different levels of guidance, such as open-ended exploration versus structured prompts or embedded feedback. Research could also examine how simulations interact with other instructional strategies, including collaborative learning, peer instruction, or formative assessment techniques. Additionally, investigating how teachers integrate simulations into their pedagogy—and how professional development influences this integration—would be valuable for translating research findings into classroom practice.

Another promising direction for future research involves personalization and adaptive learning. Advances in educational technology make it increasingly feasible to tailor simulations to individual learners’ needs, providing customized challenges or feedback based on students’ performance. Future studies could examine whether adaptive simulation environments lead to even greater learning gains than static simulations. Similarly, research could investigate how simulations can support metacognitive skills, such as students' ability to monitor their own understanding and adjust their learning strategies accordingly.

In conclusion, the results of this study provide strong evidence that simulation-based instruction can significantly enhance high school students' learning of physics concepts related to motion and projectile behavior. Students who used the simulator demonstrated substantially higher post-test performance than those who received instruction without it, highlighting the educational value of interactive, visual learning tools. These findings contribute to a growing body of literature supporting the use of simulations in science education and underscore their potential to improve conceptual understanding, engagement, and equity. As educational technologies continue to evolve, thoughtfully designed and pedagogically integrated simulations are likely to play an increasingly important role in helping students understand complex scientific phenomena.

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