2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #53071

Evaluating the Impact of Interactive Lecture Demonstrations in Large-Enrollment Physics Courses on Kinematics

Mr. José Manuel Peña, Universidad Técnica Federico Santa María

I have been deeply curious about how things work since an early age, which led me to study electronics. This path gradually sparked my interest in physics and the principles underlying technological systems. During my academic training, I noticed significant differences in teaching approaches among instructors, which motivated me to explore education more deeply. As a result, I pursued a Master's degree in Education, with a specialization in science education. I currently teach physics using active learning methodologies, and my work focuses on the intersection of physics, technology, and effective teaching practices.

Prof. Angeles Dominguez, Universidad Andres Bello, Chile; Tecnologico de Monterrey, Mexico

Angeles Dominguez is an adjunct researcher at the Institute for the Future of Education at Tecnologico de Monterrey, Mexico. She also collaborates with the School of Engineering at the Universidad Andres Bello in Santiago, Chile. Angeles holds a bachelor's degree in physics engineering from Tecnologico de Monterrey and a doctoral degree in Mathematics Education from Syracuse University, NY. Dr. Dominguez is a member of the Researchers' National System in Mexico (SNI-2) and has been a visiting researcher at Syracuse University, UT-Austin, and Universidad Andres Bello. Her main research areas are interdisciplinary education, teaching methods, faculty development, and gender issues in STEM education. She actively participates in several national and international mathematics, engineering, and science education projects.

Prof. Genaro Zavala, Tecnologico de Monterrey, Monterrey, Mexico; Universidad Andres Bello, Santiago, Chile

Genaro Zavala is the leader of the Socially Oriented Interdisciplinary STEM Education Research Group of the Institute for the Future of Education at Tecnologico de Monterrey. He collaborates with the Faculty of Engineering, Universidad Andres Bello in Chile. He is National Researcher Level 2 in Mexico. His research lines are interdisciplinary STEM education, social oriented education, conceptual understanding, active learning, assessment tools, and faculty development. Dr. Zavala was appointed to the editorial board of the PRPER (2015-18). In the AAPT, he was a vice-presidential candidate, member of the Committee on Research in Physics Education, member and chair of the International Education Committee, and elected member of Leadership Organizing Physics Education Research Council .

Evaluating the Impact of Interactive Lecture Demonstrations with Computer Simulations on Conceptual Understanding of Kinematics in Large-Enrollment Physics Courses

Abstract

Interactive Lecture Demonstrations (ILDs) have shown consistent benefits for conceptual learning in introductory physics by structuring prediction, observation, and reflection within lecture settings. This study examines a simulation-based ILD implementation to support students' understanding of one-dimensional kinematics graphs in a large-enrollment introductory physics course for engineering students at a private university in Chile (N > 1,000). Effectiveness was evaluated using an explanatory sequential mixed-methods design. Quantitatively, students completed the Test of Understanding Graphs in Kinematics as a pretest and post-test; learning was summarized through normalized gain and changes in score distributions. Mean performance increased from 46% (pre) to 63% (post), corresponding to an intermediate normalized gain (g = 0.33). Distributional analysis showed a shift in skewness from 0.38 to −0.66, suggesting that improvements were especially pronounced among students who initially performed at lower levels. Qualitatively, student surveys and semi-structured interviews with students and instructors indicated that the simulation-supported ILDs enhanced visualization and engagement, while also revealing implementation challenges in online and hybrid contexts—particularly related to pacing and the need for more structured feedback during reflection. Overall, the findings support simulation-based ILDs as a scalable approach for improving kinematics conceptual understanding in large courses, and they highlight design considerations for digital and blended delivery.

Keywords: Physics Education Research; Engineering Education Research; Interactive Lecture Demonstrations; Kinematics; Conceptual Understanding, TUG-K.

Introduction

Introductory physics courses constitute a central component of undergraduate engineering curricula, serving both as a gateway to disciplinary ways of thinking and as a foundation for subsequent technical coursework. These courses are expected to support students in developing conceptual understanding of physical principles, facility with multiple representations, and the ability to apply formal models to novel situations. However, decades of research in Physics Education Research (PER) have consistently shown that these expectations are rarely met under traditional instructional conditions, particularly in large-enrollment courses [1], [2], [3].

A substantial body of empirical evidence indicates that students often complete introductory physics courses with limited gains in conceptual understanding, even when they demonstrate proficiency in routine problem-solving [4], [5], [6]. This phenomenon has been documented across institutional types, student populations, and instructional settings. Early work by McDermott and collaborators revealed that many students retain robust pre-instructional conceptions about motion and force that are largely unaffected by conventional instruction [7], [8]. Similarly, [2] showed that traditional lecture-based instruction produces low normalized gains on standardized concept inventories, regardless of instructor experience or course rigor, proposing modeling instruction [9], [10], [11].

One-dimensional kinematics provides a particularly informative context for examining these issues. As one of the first topics introduced in mechanics, kinematics shapes students' initial conceptions of how physics represents motion and change. Although the mathematical structure of kinematics is relatively simple, involving linear relationships between position, velocity, acceleration, and time, students often struggle to interpret these relationships, especially when they are expressed graphically [7], [9]. Research has shown that many students treat graphs as literal depictions of physical situations rather than as abstract representations of functional relationships [12], [13]. For example, students frequently interpret a position–time graph as a picture of an object's path through space, leading them to associate slopes or curvature with physical features such as hills or turns. Similarly, students may conflate the shape of a velocity–time graph with the trajectory of motion or assume that a graph crossing the horizontal axis indicates that an object changes direction, regardless of the quantity being represented. These difficulties persist even after instruction and are remarkably resistant to correction through traditional problem-solving exercises [7], [12].

The persistence of these difficulties has important implications for learning beyond kinematics. Conceptual misunderstandings related to motion and graphical representations can interfere with students' ability to reason about Newton's laws, work and energy, and more advanced topics in mechanics. As a result, insufficient attention to conceptual understanding in kinematics can have cascading effects throughout the physics curriculum. Addressing these issues is therefore not merely a matter of improving performance on a single topic, but of supporting coherent learning across the discipline [2], [4], [14].

Traditional lecture-based instruction has been shown to be poorly suited to addressing these challenges [8]. In large-enrollment courses, instruction is often organized around the presentation of definitions, equations, and worked examples, with limited opportunities for students to actively engage with their own ideas. Students are rarely asked to articulate predictions, confront conflicting evidence, or reflect on the reasoning underlying their answers. Consequently, instruction often emphasizes procedural fluency at the expense of conceptual understanding.

In response to these limitations, PER has increasingly emphasized the importance of interactive engagement strategies [3], [11], [15]. A landmark meta-analysis by Hake demonstrated that courses incorporating interactive engagement methods achieve significantly higher normalized gains on conceptual assessments than courses relying on traditional instruction [16]. These findings have been replicated across a wide range of topics, institutional contexts, and student populations, providing strong evidence for the effectiveness of instructional approaches that actively involve students in the learning process [4], [17], [18], [19].

In the next section, the main theoretical pillars of this study are described. The section closes by addressing the need for the study and posing the research questions.

Theoretical Framework

The instructional design and analysis presented in this study are grounded in several complementary strands of research within PER and the broader learning sciences. In particular, the framework draws on theories of conceptual change, research on multiple representations in physics learning, and empirical findings related to interactive engagement strategies in large-enrollment courses. Together, these perspectives provide a coherent basis for understanding both the potential effectiveness and the limitations of Interactive Lecture Demonstrations, especially when implemented using computer simulations.

Interactive Lecture Demonstrations

Interactive Lecture Demonstrations (ILDs) represent one such research-based instructional strategy. Originally developed by Sokoloff and Thornton, ILDs were designed to introduce interactive engagement into lecture environments without requiring a complete restructuring of course format [20], [21]. An ILD typically follows a structured sequence in which students are first asked to predict the outcome of a physical situation, then observe the result of a demonstration or experiment, and finally reflect on discrepancies between their predictions and the observed behavior. This prediction–observation–reflection cycle is grounded in theories of conceptual change, which emphasize the importance of making students' pre-instructional conceptions explicit and subjecting them to empirical evaluation. By requiring students to commit to predictions before observing an outcome, ILDs create cognitive conflict that can motivate conceptual reorganization. Subsequent reflection and discussion provide students with opportunities to reconcile their initial ideas with formal physical models.

Empirical studies have demonstrated that ILDs can produce substantial improvements in conceptual understanding across a range of topics, including kinematics, Newtonian mechanics, and electricity and magnetism [18], [20], [22]. Importantly, these gains have been observed in large-enrollment courses, suggesting that ILDs offer a scalable approach to improving learning outcomes in contexts where small-group instruction may be impractical [21].

Early implementations of ILDs relied primarily on physical demonstrations conducted in lecture halls. While effective, this approach presents logistical challenges, particularly in very large classrooms or in instructional formats that incorporate online or hybrid components. In recent years, computer simulations have emerged as a promising alternative or complement to physical demonstrations [23], [24]. Simulations can visualize idealized physical systems, dynamically link multiple representations, and allow instructors to precisely control experimental conditions.

However, research has also shown that simulations are not inherently effective instructional tools. When used without appropriate pedagogical scaffolding, simulations may encourage passive observation rather than active reasoning [25]. Their effectiveness depends critically on how they are integrated into instructional activities and whether they engage students in prediction, explanation, and reflection [22], [26]. The ILD framework provides a structured approach to leveraging simulations that aligns with established principles of effective instruction.

Despite the extensive literature on ILDs and interactive engagement, several gaps remain. In particular, there is limited research on the large-scale implementation of simulation-based ILDs in Latin American higher education contexts. Moreover, the rapid expansion of online and hybrid instruction has created new instructional environments in which the dynamics of prediction, observation, and reflection may differ from those of traditional face-to-face lectures. Understanding how ILDs function under these conditions is essential for informing instructional design and policy.

Conceptual Change in Physics Learning

Research on conceptual change has played a central role in shaping contemporary approaches to physics instruction. Early studies revealed that students enter physics courses with well-developed pre-instructional conceptions about physical phenomena, often derived from everyday experience. These conceptions are not merely fragmented misconceptions, but coherent explanatory frameworks that students actively use to interpret physical situations [1], [3], [9]. As a result, learning physics frequently involves restructuring or replacing existing conceptual models rather than simply acquiring new information.

Classical models of conceptual change emphasize the role of cognitive conflict in promoting learning. According to these models, students are more likely to revise their conceptions when they encounter situations in which their existing ideas fail to account for observed phenomena [27]. However, subsequent research has shown that cognitive conflict alone is insufficient. For conceptual change to occur, students must also perceive the new conceptual framework as intelligible, plausible, and fruitful for explaining a range of phenomena [28].

In introductory physics, traditional lecture-based instruction often fails to create conditions conducive to conceptual change. Students may observe demonstrations or work through example problems without being required to articulate their own predictions or reflect on discrepancies between their expectations and formal models [20], [21]. Consequently, new information may be assimilated superficially without displacing underlying conceptions [1]. Instructional strategies that explicitly elicit students' ideas and engage them in reflective reasoning are, therefore, critical for promoting meaningful learning [3], [4], [10], [11].

ILDs are explicitly designed to align with these principles. By requiring students to commit to predictions prior to observing a demonstration, ILDs make pre-instructional conceptions visible and subject to evaluation. The subsequent observation phase provides empirical evidence that can challenge these conceptions, while structured reflection supports the construction of more coherent and productive conceptual models. From a conceptual change perspective, the strength of ILDs lies not in the demonstration itself, but in the epistemic activity surrounding prediction, comparison, and explanation.

Multiple Representations and Graphical Reasoning

Another key component of the theoretical framework concerns the role of multiple representations in physics learning. Expert physicists routinely coordinate between equations, graphs, diagrams, and verbal descriptions when reasoning about physical systems. For students, however, this representational fluency is neither automatic nor trivial. Research has consistently shown that difficulties in physics often stem from an inability to interpret or connect different representations, rather than from a lack of mathematical skill alone [29], [30].

Graphical representations play a particularly prominent role in introductory kinematics. Position–time, velocity–time, and acceleration–time graphs provide compact representations of motion that emphasize functional relationships and rates of change. Despite their importance, students frequently struggle to interpret these graphs correctly. As documented by Beichner, students often confuse graph shape with physical trajectory, misinterpret slopes and areas, or fail to distinguish between different kinematic quantities represented on similar-looking axes [12].

These difficulties persist even after instruction and are remarkably robust across instructional contexts. One contributing factor is that graphs are often introduced as tools for problem-solving rather than as objects of conceptual reasoning. Students may learn to extract numerical values or calculate slopes without developing an understanding of what these features represent physically. As a result, graphical reasoning remains disconnected from students' intuitive understanding of motion.

Instructional approaches that explicitly integrate multiple representations and emphasize their conceptual meaning have been shown to improve learning outcomes. In particular, activities that require students to predict graphical outcomes, compare graphs with physical motion, and explain discrepancies between representations can support the development of representational competence [7], [12]. ILDs provide a natural context for such activities, especially when demonstrations or simulations dynamically link motion, graphs, and numerical data.

When simulations are used within an ILD framework, they can simultaneously display multiple representations of the same physical process. For example, a simulation of one-dimensional motion may show an animated object alongside real-time position–time and velocity–time graphs. This simultaneity allows students to directly observe how changes in motion correspond to changes in graphical representations. However, without explicit guidance, students may selectively attend to surface features, fail to coordinate representations meaningfully, and connect ideas within the same context or between related contexts [14], [31]. The effectiveness of simulations, therefore, depends critically on how they are embedded within a pedagogical structure that promotes active reasoning [23], [24].

Interactive Engagement and Large-Enrollment Instruction

The concept of interactive engagement has become a cornerstone of PER-informed instructional reform. Interactive engagement strategies involve activities that require students to actively process information, articulate their reasoning, and receive feedback, often through peer discussion or instructor-facilitated dialogue. Hake's large-scale study demonstrated that courses employing interactive engagement methods achieve significantly higher normalized gains on conceptual assessments than traditional lecture courses [16]. These findings have since been corroborated by numerous studies across topics and institutions [18], [22].

One challenge in adopting interactive engagement strategies is their implementation in large-enrollment courses. In such contexts, instructors often face constraints related to time, physical space, and instructional resources. ILDs were originally developed to address these challenges, offering a structured yet flexible approach that can be integrated into lecture settings without extensive reorganization [21].

Research on ILDs has shown that their effectiveness depends on careful attention to implementation details. For instance, simply showing a demonstration without eliciting predictions yields little benefit. Similarly, allowing students to discuss predictions without subsequent reflection may limit learning gains. Effective ILDs typically involve explicit prompts, opportunities for peer discussion, and instructor-led synthesis that connects observations to formal models [22], [26].

In recent years, the expansion of online and hybrid instruction has introduced new complexities. While digital platforms can facilitate polling, breakout discussions, and real-time feedback, they may also reduce opportunities for spontaneous interaction or informal questioning. Understanding how interactive engagement strategies function in these environments is, therefore, an important area of ongoing research.

Simulations as Instructional Tools

Computer simulations have become increasingly prevalent in physics instruction, motivated by advances in technology and the need for flexible instructional resources. Simulations can represent idealized systems, eliminate extraneous variables, and visualize quantities that are otherwise inaccessible, such as instantaneous velocity or acceleration. Research by Wieman and colleagues has shown that well-designed simulations can support conceptual understanding, particularly when they encourage exploration and hypothesis testing [23], [25].

However, simulations are not inherently interactive in a pedagogical sense. Students may passively observe simulation outputs without engaging in meaningful reasoning, especially when simulations are used as replacements for lectures rather than as components of structured activities. From a PER perspective, the instructional effectiveness of simulations depends on the cognitive and epistemic activities they afford, rather than on their visual appeal alone [32].

Integrating simulations into ILDs offers a promising approach to addressing these concerns, with the added value that simulation activities can serve as a reference and be built upon, connecting topics across the curriculum. For example, the world pendulum "may fit in several positions of the curriculum: in mechanics generally, in oscillations, in measuring forces, in rotational motion and frames of reference, in the history of physics" [33, p. 612]. Within an ILD, simulations serve as the observational component of a broader instructional cycle that includes prediction and reflection. This integration helps ensure that simulations function as tools for testing ideas rather than as sources of authoritative answers. Moreover, simulations can be paused, reset, or modified to explore alternative scenarios, supporting iterative reasoning and deeper engagement.

Despite these advantages, relatively few studies have examined the large-scale implementation of simulation-based ILDs, particularly in non-U.S. contexts. Questions remain about how students perceive these activities, how instructors adapt them across different instructional modalities, and how learning outcomes compare with those reported for traditional ILDs using physical demonstrations. Addressing these questions requires empirical investigation grounded in a robust theoretical framework.

The present study builds on these theoretical perspectives to examine the use of simulation-based ILDs in teaching one-dimensional kinematics in a large-enrollment engineering physics course.

By situating the instructional intervention within established theories of conceptual change, representational competence, and interactive engagement, the study aims to contribute both empirical findings and design insights relevant to contemporary physics education.

The present study addresses these gaps by examining the impact of simulation-based ILDs on students' conceptual understanding of one-dimensional kinematics in a large-enrollment introductory physics course for engineering students at a private university in Chile. Using a mixed-methods research design, the study combines quantitative analysis of conceptual learning gains with qualitative data on student and instructor perceptions. The following research questions guide the investigation:

1. To what extent does instruction incorporating simulation-based ILDs improve students' conceptual understanding of one-dimensional kinematics?
2. How do score distributions on a standardized conceptual assessment change following ILD-based instruction?
3. How do students and instructors perceive the affordances and limitations of simulation-based ILDs in large and digitally mediated instructional environments?

Methods

This study employed a mixed-methods research design to examine the impact of simulation-based ILDs on students' conceptual understanding of one-dimensional kinematics in a large-enrollment introductory physics course. Specifically, the study used an explanatory sequential mixed-methods design (QUAN → qual), also known as a two-phase model, which "consists of first collecting quantitative data and then collecting qualitative data to help explain or elaborate on the quantitative results" [34, p. 542]. The methodological approach was informed by established practices in PER, combining quantitative measures of learning gains with qualitative data to capture participants' experiences and perceptions. This combination allowed for a more comprehensive analysis of both learning outcomes and instructional processes.

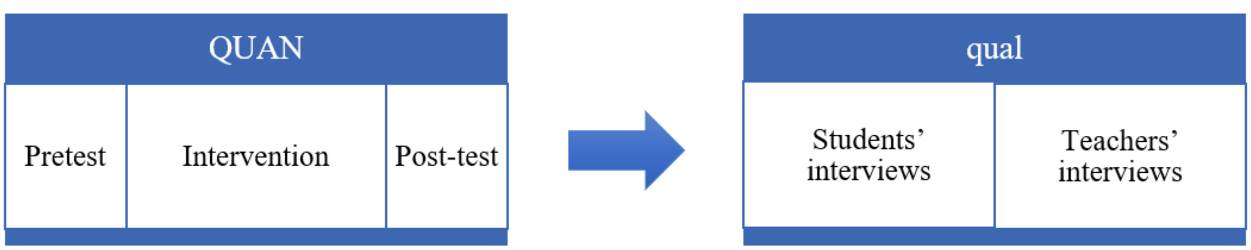

Figure 2. Exploratory sequential research design, QUAN → qual.

Institutional Context and Course Description

The study was conducted at a large private engineering university in Chile, where introductory physics is required of all first-year engineering students. These courses typically enroll several hundred students per semester and are delivered in a lecture-based format supplemented by problem-solving sessions and laboratory activities. Instruction is coordinated across multiple sections to ensure curricular consistency, including common learning objectives, assessments, and instructional materials.

The intervention took place within the first-semester mechanics course, which covers kinematics, Newton's laws, work and energy, and momentum. One-dimensional kinematics is introduced at the beginning of the course and serves as a foundational topic for subsequent instruction. Prior to the intervention, kinematics instruction relied primarily on lectures and traditional problem-solving exercises, with limited use of interactive engagement strategies.

Participants

Participants included more than 1,000 undergraduate engineering students enrolled in the introductory physics course over multiple academic terms. The student population was diverse in terms of prior physics preparation, with some students having completed advanced secondary-level physics courses and others having minimal formal exposure to the subject. Students were informed of the data collection for the study and that the pretest and post-test were required, but participation in the interviews was voluntary. All data were anonymized, and no personal information was collected during tests. Informed consent was signed for both teachers and students in accordance with institutional ethical guidelines. No compensation grade was given for participation in this study.

In addition to students, course instructors participated in the study by implementing the ILD activities and contributing qualitative data through interviews and surveys. Instructors had varying levels of teaching experience and familiarity with PER-based instructional strategies, offering a range of perspectives on the intervention's implementation and effectiveness.

Instructional Intervention

The instructional intervention consisted of twelve simulation-based ILDs embedded within regular lecture sessions during the kinematics unit, implemented approximately in weeks 9 and 10 of the semester and distributed across three class sessions. Each ILD lasted about 15 minutes. All activities followed a structured sequence consistent with the prediction–observation–reflection framework originally proposed by [20], [21]. The ILDs were specifically designed to address well-documented conceptual difficulties related to motion graphs, including the interpretation of slope and area, as well as the relationships among position, velocity, and acceleration.

The simulations were obtained from the PhET website, a collection of hundreds of simulations running on Java and HTML5, permanently maintained by the University of Colorado team [23]. The specific simulation used was "The Moving Man" [35].

- ***Prediction phase***, students were presented with a physical scenario involving one-dimensional motion and were asked to predict the corresponding graphical representation or the outcome of a simulated experiment. Predictions were collected using written responses. Students were encouraged to discuss their reasoning with peers before submitting responses.

- ***Observation phase***, the instructor displayed a computer simulation illustrating the scenario under consideration. The simulations dynamically linked the motion of an object with real-time graphical representations, allowing students to observe how changes in motion affected position–time and velocity–time graphs. Instructors controlled the simulations to highlight key features and, when appropriate, paused or replayed segments to focus attention on critical moments.
- ***Reflection phase*** involved a guided discussion led by the instructor. Students were prompted to compare their predictions with the observed outcomes and to articulate explanations for any discrepancies. Instructors emphasized conceptual reasoning over numerical calculation, drawing explicit connections between the observed behavior and formal kinematic principles. This phase also included opportunities for students to ask questions and clarify misunderstandings.

Research Instruments

Student learning was assessed using the Test of Understanding Graphs in Kinematics (TUG-K) administered as a pretest during the first week of instruction and as a post-test immediately after completion of the kinematics unit (Figure 2). The instrument, originally developed and validated by [12], consists of multiple-choice items designed to probe students' conceptual understanding of position–time, velocity–time, and acceleration–time graphs, with distractors based on documented student difficulties. A revised and updated version of the TUG-K has since been reported in the literature [36], as well as variants in other contexts [14], [31]. However, in the present study, we administered the original version of the TUG-K [12] translated into Spanish [13], [36], maintaining the original item structure and scoring scheme to maximize comparability with the larger body of prior PER studies that have used this version and to enable direct benchmarking against previously reported results. To minimize testing effects, students were informed that the assessments were diagnostic and did not contribute to course grades.

In addition to the TUG-K, qualitative data were collected through student surveys and semi-structured interviews with both students and instructors. Surveys included Likert-scale items and open-ended questions that addressed students' perceptions of ILD activities, the usefulness of simulations, and their engagement during lectures. Instructor interviews focused on experiences with implementing ILDs, perceived benefits and challenges, and adaptations made for different instructional modalities.

Data Analysis

Quantitative analysis focused on measuring changes in conceptual understanding as reflected in TUG-K scores. Normalized gain g was calculated using the standard formulation proposed by Hake [16], enabling comparison with previously reported results in the PER literature. In addition to mean scores and normalized gains, the distributions of pretest and post-test scores were analyzed using Pearson's coefficient of asymmetry to examine changes in distribution shape and skewness. To that end, the analysis included only students who responded to both tests, before and after the intervention ($n = 560$).

This distributional analysis provided insights beyond average gains, revealing how different segments of the student population were affected by the intervention. Changes in skewness were examined to assess whether learning gains were concentrated among higher-performing students or distributed more evenly across the cohort.

Qualitative data from surveys and interviews were analyzed using thematic analysis[37], [38]. Responses were coded iteratively to identify recurring themes related to student engagement, conceptual understanding, and instructional design. Coding was conducted independently by multiple researchers to enhance reliability, with discrepancies resolved through discussion. Representative quotations were selected to illustrate key themes while preserving participant anonymity.

Validity and Limitations

Several measures were taken to enhance the study's validity. The use of a well-established conceptual assessment instrument enhanced the reliability of quantitative findings, while triangulating quantitative and qualitative data strengthened interpretive validity. Implementing the intervention across multiple course sections and academic terms increased the robustness of the results.

Nevertheless, certain limitations must be acknowledged. The absence of a randomized control group limits the ability to attribute observed gains solely to the ILD intervention. Additionally, variations in instructor implementation and instructional modality may have influenced outcomes. These limitations are considered in the interpretation of results and discussed further in subsequent sections.

Overall, the methodological approach adopted in this study was designed to provide a comprehensive, contextually grounded evaluation of simulation-based ILDs in large-enrollment physics instruction, offering empirical evidence and practical insights relevant to ongoing efforts in physics education reform.

Results

This section presents the study's results, organized around quantitative measures of conceptual learning and qualitative evidence from student and instructor feedback. Together, these results provide a detailed account of the impact of simulation-based ILDs on students' understanding of one-dimensional kinematics in a large-enrollment instructional context.

Pre- and Post-Instruction Conceptual Performance

Students' conceptual understanding of kinematics graphs was assessed using the TUG-K administered before and after instruction. Pretest scores indicated a limited initial understanding of graphical representations of motion, consistent with prior findings in the PER literature [12]. The pretest score distribution showed a strong concentration of low scores, with many students demonstrating difficulty interpreting slope, area, and relationships among kinematic quantities.

Following instruction incorporating simulation-based ILDs, post-test scores improved across the cohort. The post-test mean score increased substantially relative to the pretest mean, indicating that students developed a more robust understanding of kinematic graphs (Figure 1). These improvements were observed across multiple course sections and academic terms, suggesting that the observed gains were not attributable to isolated instructional conditions.

The normalized gain, calculated using the formulation proposed by Hake [16], fell within the intermediate range commonly associated with interactive engagement strategies. This result aligns with previous studies of ILD implementations in kinematics and mechanics [21], supporting the conclusion that simulation-based ILDs can achieve learning gains comparable to those reported for traditional ILDs using physical demonstrations.

Figure 1 presents the distributions of students' TUG-K scores before and after instruction. The post-test distribution shows a shift toward higher scores relative to the pretest, indicating an overall improvement in performance across the cohort. Importantly, the distribution's shape also changes, suggesting that gains were not evenly distributed among students but concentrated in specific performance ranges.

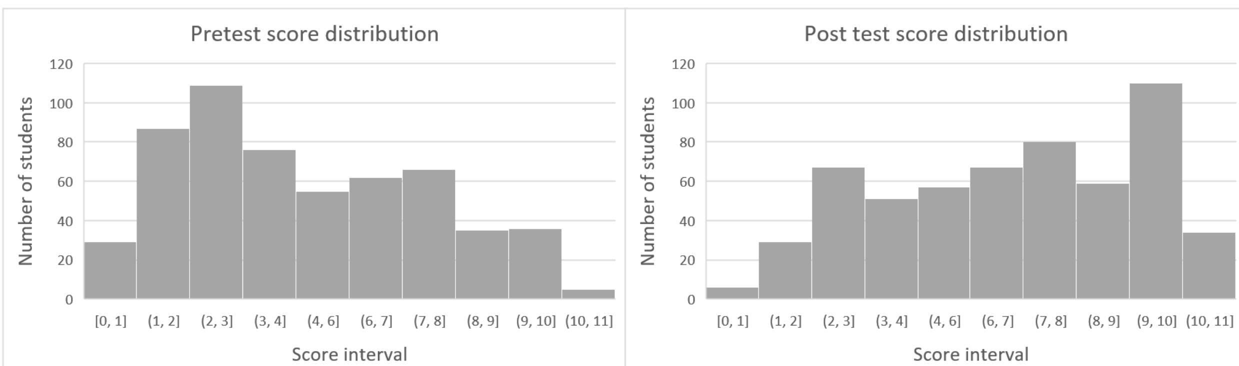

Figure 1. Pretest and post-test distributions of TUG-K scores for the study cohort, illustrating an overall shift toward higher performance after completion of the kinematics unit.

Table 1 summarizes the descriptive statistics for the pretest and post-test TUG-K scores. Mean performance increases from 46% (pre) to 63% (post), corresponding to a normalized gain of 0.33. The most notable change, however, is the shift in skewness from 0.38 (pre) to −0.66 (post), indicating that learning gains were not uniform across the cohort: improvements were especially pronounced among students initially clustered at lower performance levels, who shifted toward higher scores.

Table 1. Descriptive statistics for pretest and post-test TUG-K scores (mean and distributional measures), including skewness, for the study cohort.

	Pretest	Post-test	{g}
Score	46%	63%	0.33
Skewness	0.38	-0.66	-

Distributional Analysis of Learning Gains

In addition to examining mean scores and normalized gains, the analysis examined changes in the distribution of TUG-K scores from pretest to post-test. Pearson's coefficient of asymmetry was calculated for both score distributions to assess shifts in skewness. The pretest distribution exhibited positive skewness, reflecting a predominance of low scores and a long tail extending toward higher performance.

The average pretest score on the TUG-K was $\langle S_{pre} \rangle = 46\%$, indicating substantial initial difficulty in interpreting kinematic graphs. After instruction using ILDs supported by simulations, the average post-test score increased to $\langle S_{post} \rangle = 63\%$. These values correspond to a normalized gain of $\langle g \rangle = 0.33$, placing the intervention in the intermediate gain regime according to commonly used PER benchmarks [16].

Beyond changes in average performance, the shape of the score distributions exhibited a systematic evolution from before to after the intervention. The pretest distribution showed a positive skewness of $A_{pre} = 0.38$, reflecting a concentration of students at lower performance levels. After instruction, the skewness was $A_{post} = -0.66$, indicating a redistribution of scores toward intermediate and higher values. This shift suggests that the intervention was particularly effective in supporting students who initially demonstrated the greatest conceptual difficulties.

The reduction in skewness provides complementary evidence to normalized gain measures, highlighting the value of examining distributional characteristics when evaluating instructional effectiveness. While normalized gain captures average improvement, changes in distribution shape offer insights into equity and inclusivity in learning outcomes.

Performance on Specific Conceptual Categories

Item-level analysis of TUG-K responses revealed differential improvements across conceptual categories. Students showed particularly strong gains on items related to interpreting slope in position–time and velocity–time graphs, as well as distinguishing between different kinematic quantities represented on similar graphical formats. These gains are consistent with the instructional emphasis placed on linking motion, graphs, and verbal explanations during the ILD activities.

More modest gains were observed on items involving area under velocity–time graphs and the interpretation of acceleration in non-uniform motion. While improvements were still evident, these topics remained challenging for a significant fraction of students. This pattern mirrors findings from previous studies, which have noted that reasoning about area and accumulation processes requires more advanced representational competence [12].

These results suggest that while simulation-based ILDs effectively address certain conceptual difficulties, additional scaffolding may be necessary to support learning in more abstract or mathematically demanding aspects of kinematics.

Student Perceptions of ILDs with Simulations

Qualitative data were collected through semi-structured interviews conducted with five students and three instructors. Data from student surveys and open-ended responses provide further insight into the observed learning gains. Some of the included questions were:

1. According to the categories presented in Table 2 [12, p. 752] and addressed in the activity, which learning objective do you think you improved the most? Which one did you improve the least?
2. Based on Table 3 [21], which three characteristics do you think are most strongly promoted by this instructional strategy?
3. Based on the same table, which three characteristics do you think are least strongly promoted by this instructional strategy?

Table 2. Categorization of TUG-K test questions [12, p. 752].

	Provided	**Student is asked to**
1	Position–Time graph	Determine velocity
2	Velocity–Time graph	Determine acceleration
3	Velocity–Time graph	Determine displacement
4	Acceleration–Time graph	Determine change in velocity
5	Kinematics graph	Select the corresponding graph
6	Kinematics graph	Select the corresponding textual description
7	Textual description of motion	Select the corresponding graph

Table 3. Characteristics of an active learning environment, adapted from [21].

	Characteristics of an active learning environment
1	Students construct their knowledge based on practical observations. Authority comes from real-world physical observations.
2	Uses a learning cycle in which students are challenged to compare predictions (based on their beliefs) with observations from real experiments.
3	Students' beliefs are modified when they encounter discrepancies between their observations and their preconceptions.
4	The instructor's role is to act as a guide in the learning process.
5	Peer collaboration and shared learning are encouraged.
6	Experimental results are presented in an accessible way, often in real time with the support of technology.
7	Laboratory work supports the learning of basic concepts.

A majority of students reported that the ILD activities helped them better understand the meaning of kinematics graphs and their connection to physical motion. Students frequently cited the simulations' visual and dynamic nature as particularly helpful for clarifying abstract concepts.

Many students emphasized the value of making predictions prior to observing the simulation. This phase was described as prompting active engagement and encouraging them to reflect on their own understanding. Several respondents noted that realizing their predictions were incorrect motivated them to pay closer attention to the subsequent explanation and discussion.

However, some students reported challenges with the pacing of activities, particularly in online or hybrid instructional settings. In these contexts, delays in polling responses or limited opportunities for discussion were perceived as reducing the effectiveness of the reflection phase. These observations underscore the importance of careful instructional design when adapting ILDs to digital environments.

Instructor Perspectives

Instructor interviews revealed broadly positive attitudes toward the use of simulation-based ILDs. Instructors reported that the activities increased student participation during lectures and provided valuable opportunities to diagnose common misconceptions in real time. Several instructors noted that the structured nature of ILDs helped them manage interactions in large classrooms more effectively than open-ended questioning did.

At the same time, instructors identified implementation challenges. Preparing effective prediction questions and managing time constraints were cited as ongoing concerns. In online and hybrid formats, instructors also highlighted the need for clearer guidelines on facilitating discussion and providing feedback, particularly when non-verbal cues were limited.

Despite these challenges, instructors expressed interest in continuing and expanding the use of ILDs, particularly if additional support materials and training were available. Their feedback underscores the importance of institutional support and professional development for sustaining instructional innovations at scale.

Summary of Findings

Taken together, the quantitative and qualitative results indicate that simulation-based ILDs can produce meaningful improvements in students' conceptual understanding of one-dimensional kinematics in large-enrollment courses. The observed intermediate normalized gain ($g = 0.33$) and the shift in score distributions from pre to post support the intervention's overall effectiveness. In particular, the change in skewness from 0.38 (pre) to −0.66 (post) suggests that learning gains were not uniform across the cohort and were especially pronounced among students who initially clustered at lower performance levels and later shifted toward higher scores. At the same time, the results point to areas for refinement, including strengthening support for more complex conceptual categories and further adapting ILD facilitation (e.g., pacing and feedback during reflection) to digitally mediated instructional environments.

Discussion

The results of this study provide empirical support for the effectiveness of simulation-based ILDs in promoting conceptual understanding of one-dimensional kinematics in large-enrollment introductory physics courses. In this section, the findings are interpreted in relation to existing research in PER, and their implications for instructional design, large-scale implementation, and future research are discussed.

Interpretation of Learning Gains

The observed normalized gain is consistent with values reported for Interactive Lecture Demonstration implementations in introductory physics contexts [21]. However, it remains below gains typically associated with fully interactive engagement curricula, a result that is not unexpected given the large-enrollment setting and the partial integration of active-learning elements. In this sense, the present results align with broader PER findings indicating that instructional effectiveness depends not only on the strategy itself, but also on its depth of implementation and the available feedback mechanisms. This consistency suggests that replacing physical demonstrations with well-designed computer simulations does not diminish the instructional effectiveness of the ILD framework when its core pedagogical elements—prediction, observation, and reflection—are preserved. In this sense, the present findings extend earlier work by demonstrating that ILDs can be successfully adapted to digital formats without sacrificing learning outcomes.

The distributional analysis further enriches this interpretation. The reduction in skewness observed in post-test score distributions indicates that learning gains were not confined to a small subset of students with strong prior preparation. Instead, improvements were distributed more evenly across the cohort. This result is particularly significant in large-enrollment contexts, where instructional innovations may otherwise disproportionately benefit higher-performing students. From an equity perspective, the findings suggest that simulation-based ILDs have the potential to support broader participation in conceptual learning.

At the same time, students' post-test performance suggests that some conceptual areas remained challenging, particularly interpreting the area under velocity–time graphs and reasoning about acceleration in non-uniform motion. This pattern is consistent with longstanding findings in PER indicating that these topics often require more sophisticated representational reasoning and may not be fully addressed through brief instructional interventions [12]. Accordingly, while ILDs appear effective for targeting several common difficulties, they are best understood as one component of a broader instructional approach rather than a comprehensive solution.

Role of Simulations within the ILD Framework

One of the central contributions of this study lies in its examination of simulations as substitutes for physical demonstrations within the ILD framework. The positive learning outcomes observed here support the argument that the pedagogical structure of ILDs is more critical than the physicality of the demonstration. Simulations, when used appropriately, can provide clear visualizations of abstract quantities, dynamically link multiple representations, and allow instructors to control and repeat scenarios with precision.

However, the qualitative findings underscore that simulations are not inherently effective instructional tools. Students' positive perceptions were closely tied to the prediction and reflection phases of the ILDs, rather than to the simulations alone. This observation aligns with prior research cautioning against the uncritical adoption of simulations without adequate pedagogical scaffolding [25]. The present study reinforces the view that simulations function best as components of structured activities that actively engage students in reasoning and explanation.

Implications for Large-Enrollment and Digital Instruction

The large scale of the implementation provides important insights into the feasibility of adopting simulation-based ILDs in high-enrollment courses. Both quantitative and qualitative data indicate that ILDs can be integrated into lecture-based instruction without requiring extensive restructuring. Instructors reported that the structured nature of the activities helped manage student interaction, even in classes with several hundred students.

The transition to online and hybrid instructional modalities introduces additional considerations. While digital platforms offer tools for polling and visualization, they may constrain spontaneous interaction and informal feedback. The challenges reported by students and instructors highlight the need for clearer guidance on facilitating discussion and reflection in digitally mediated environments. Future implementations may benefit from more explicit prompts, structured peer discussion protocols, and targeted feedback mechanisms to support conceptual reasoning in these contexts.

Comparison with Prior Research

The findings of this study are broadly consistent with the interactive engagement literature summarized by Hake [16], reinforcing the conclusion that active instructional strategies yield superior conceptual outcomes compared to traditional lectures. In particular, the results align with prior studies that demonstrate the effectiveness of ILDs in kinematics and mechanics [21]. By situating the intervention in a Latin American higher education context and at a scale exceeding 1,000 students, the present study contributes to the generalizability of these findings.

Moreover, distributional analysis complements traditional gain measures and offers a nuanced perspective on learning outcomes. This approach may be especially valuable for evaluating instructional interventions aimed at improving equity and inclusion in physics education.

Limitations and Future Research

Several limitations should be acknowledged. The absence of a randomized control group limits causal claims about the intervention's exclusive impact. Additionally, variations in instructor implementation and instructional modality may have influenced results. Future studies could employ quasi-experimental designs or compare simulation-based ILDs directly with physical demonstrations to further isolate the effects of different instructional components.

Further research is also needed to explore how ILDs can be optimized to address more abstract kinematic concepts, such as area-based reasoning and acceleration. Longitudinal studies examining the persistence of learning gains and their impact on subsequent topics in mechanics would provide valuable insights into the broader curricular implications of ILD-based instruction.

Conclusions

This study demonstrates that simulation-based ILDs can effectively support conceptual understanding of one-dimensional kinematics in large-enrollment introductory physics courses. By combining quantitative evidence of learning gains with qualitative insights into student and instructor experiences, the findings highlight both the strengths and the challenges of implementing ILDs at scale and in digitally mediated environments.

Overall, the results support the continued use and refinement of ILDs as a research-based instructional strategy in physics education. When thoughtfully designed and implemented, simulation-based ILDs offer a flexible and scalable approach to promoting conceptual understanding, even in instructional contexts characterized by large enrollments and diverse student populations.

Acknowledgments

The authors gratefully acknowledge the leadership of the Department of Physics at the Universidad Federico Santa Maria, Chile.

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