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Exploring How the Timing of Computer Simulations Shapes Students' Conceptual Understanding of Newton's Second Law of Motion

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Abstract: Students often struggle to develop a conceptual understanding of Newton's Second Law while also mastering its mathematical applications. This study examined how placing computer simulations before or after teacher instruction was associated with students' conceptual and computational approaches. Fourteen secondary students from a bilingual private school in Mount Lebanon were stratified by grade point average and gender and randomly assigned to two groups. Group A received teacher instruction before completing PhET simulation activities, whereas Group B explored the simulations before instruction. The sequence remained consistent across projectile motion and motion on an inclined plane. A qualitatively driven, randomized comparative intervention design was used, drawing on classroom observations, two open-ended tests, and semi-structured interviews. Group B generated more questions about variable relationships, physical meanings, and real-world applications, whereas Group A focused more often on equations, procedures, and calculation accuracy. Written responses showed a similar pattern: Group B used more conceptual and partially conceptual reasoning, while Group A produced more computational responses and more fully correct solutions. In immediate post-unit interviews, Group B participants recalled exploratory processes and variable relationships, whereas Group A participants emphasized formulas and solution procedures. Within this small, context-specific sample, simulation before instruction was associated with conceptual exploration, while simulation after instruction was associated with computational consolidation. Because the study involved one school, guided activities, and no delayed assessment, the findings should be interpreted as preliminary and transferable only with caution. The study also offers practical recommendations for integrating computer simulations into physics lessons.

Keywords: Computer Simulations; Computational Understanding; Conceptual Understanding; Instructional Sequencing; Problem-Solving Strategies

1. Introduction

Physics is often perceived as difficult because of its abstract concepts and demanding mathematics [1], yet mastery requires deep conceptual understanding that lets students apply knowledge across contexts [2]. Laboratory activities support this learning, but limited resources constrain their use in many schools [3], and traditional experiments often cannot illustrate microscopic phenomena such as electric charge dynamics or photon behaviour [4–6]. Computer simulations, interactive modelling tools that use visualizations and animations to represent theoretical or simplified models of real processes and phenomena, offer one way to explore complex physics concepts [7].

The timing of simulations within an instructional sequence may itself be a significant factor in their effectiveness. Smetana and Bell [7] suggest that simulations can serve as introductory tools to build science skills, but note that using them after hands-on experience may enhance comprehension and application, and they call for more research on sequencing. De Jong et al. [8] likewise argue for moving beyond comparisons that pit inquiry-based approaches such as simulations against direct instruction, and toward deliberately combining the two. Earlier studies that examined this question reached contradictory conclusions about whether simulations are more effective before or after instruction [9–12]. More recent work, reviewed in detail below, has begun to clarify the debate by distinguishing the type of learning outcome affected by sequencing [13–16]. Nevertheless, the question of optimal timing remains unresolved and warrants further research.

Within the Lebanese context, this question is largely unexplored. Prior research has examined the use of simulations for teaching abstract physics concepts [4,6,17–19], and comparable work in the wider region reports gains in secondary students' engagement with physics when simulations are introduced [20]; however, none of this work investigates how the timing of simulations within a lesson affects conceptual understanding. Moreover, most of this work relies on quantitative measures such as multiple-choice tests, which can overlook the depth of students' comprehension [21]. This points to a need for qualitative research that can better capture students' conceptual understanding and the complexity of their learning.

Simulation-based instruction has been specifically studied for Newton's Second Law. AlArabi et al. [22] reported improved learning among secondary students through computer simulations, and Alabidi et al. [23] found gains in both conceptual and procedural understanding, a distinction that closely parallels the conceptual and computational orientations examined in the present study. A recent systematic review of teaching strategies for Newton's Second Law situates these findings in a wider pattern: simulations are among the most frequently studied approaches, yet the field remains small and predominantly quantitative, and instruction that omits conceptual support tends to promote procedural, formula-focused learning [24]. None of this work addresses when the simulation is introduced relative to teacher instruction.

To address these gaps, this study uses qualitative evidence to examine how students' reasoning differed when computer simulations were introduced before rather than after teacher instruction. The investigation focuses on Newton's Second Law because force, velocity, and acceleration are abstract concepts that are commonly associated with persistent misconceptions [25,26]. Observations, open-ended written responses, and student interviews were used to examine the questions students raised, the strategies they used, and the meanings they assigned to their learning experiences. The study, therefore, offers a context-specific account of instructional sequencing rather than a statistical test of which sequence is universally superior.

The study addresses one main research question:

How does the timing of computer simulations, pre-instruction versus post-instruction, shape students' conceptual understanding of Newton's Second Law of Motion?

Three sub-questions guide the study:

1. What types of questions and discussions emerge when students encounter computer simulations at different stages of learning Newton's Second Law?
2. How does the timing of computer simulations, before or after teacher instruction, shape students' conceptual understanding of Newton's Second Law as demonstrated in the strategies they use in their written work?
3. How do students perceive the role and effectiveness of computer simulations, introduced at different times, in aiding their understanding of Newton's Second Law?

2. Literature Review

2.1. Constructivism

Teaching an abstract topic such as Newton's Second Law requires students to construct their own knowledge so that they can conceptualize it and retain it in long-term memory; in this sense, teaching physics calls for a constructivist approach [27]. Educational constructivism holds that knowledge must be constructed by the individual learner using available interpretive resources rather than transmitted intact from teacher to student, and that learners are likely to misconstrue instruction unless teaching is informed by their existing ideas [26]. Because learning is interpretive, new material makes sense only in relation to prior knowledge and experience; instruction that draws on contexts familiar to students helps them activate that knowledge and construct more sophisticated understanding over time [28]. Read alongside situated cognition, this also implies that knowledge is contextual, shaped by the settings in which it is developed and used [28]. In practice, this supports learning environments in which students engage directly with phenomena, test ideas, and refine their understanding through interaction and reflection. For example, when learning Newton's Second Law, a student might vary the mass and applied force acting on an object in a simulation, observe the resulting acceleration, and revise an initial intuition that heavier objects always accelerate faster, refining a conception through cycles of action and reflection rather than receiving it ready-made [29,30].

2.2. Inquiry-Based Learning

This constructivist view aligns closely with inquiry-based learning, which emphasizes students' formulation and testing of hypotheses as a means of constructing knowledge [31]. A widely adopted inquiry framework is Bybee's 5E Instructional Model, comprising five phases, Engage, Explore, Explain, Elaborate, and Evaluate, designed to help students derive scientific concepts through hands-on experience [32]. In Engage, tasks activate prior knowledge and provoke curiosity; in Explore, students investigate phenomena to promote conceptual change; in Explain, they articulate and interpret observations; in Elaborate, they apply learning to new contexts; and in Evaluate, they reflect on and assess their learning [32]. Together, these phases foreground active meaning-making and provide a structured pathway toward conceptual understanding. Prior research integrating the 5E model with simulation-based science and physics instruction has reported gains in students' reasoning and conceptual understanding [18], and a recent meta-analysis of sixty-one randomized trials found a substantial overall advantage for 5E-based instruction on science outcomes [33], suggesting that a 5E-aligned use of simulations can support students' construction of concepts such as Newton's Second Law.

2.3. Information Processing Theory

Information processing theory complements constructivist and inquiry-based approaches by conceptualizing learning as a multi-stage cognitive process of encoding, storage, and retrieval, often likened to computer processing [34]. It is commonly described through three stages: sensory memory, working memory, and long-term memory [35]. Sensory memory briefly holds incoming stimuli, but only attended information passes into working memory, which has limited capacity and a retention window of roughly 5 to 20 seconds. Strategies that distribute and actively recall material, spaced practice and retrieval practice, support durable transfer into long-term memory, strengthening retention through repeated, effortful recall rather than passive review [36]. Long-term memory has extensive capacity and duration, making it essential that instruction supports attention, organization, and meaningful processing for durable learning [35].

2.4. Cognitive Theory of Multimedia Learning

The Cognitive Theory of Multimedia Learning explains how students learn from combinations of words and visual representations [37]. The theory is based on three assumptions: learners process verbal and visual information through separate channels, each channel has a limited processing capacity, and meaningful learning requires active cognitive processing. During learning, students select relevant verbal and visual information, organize it into coherent mental representations, and integrate these representations with one another and with their prior knowledge. In computer simulations, animations, graphs, numerical values, and verbal explanations can therefore help students connect abstract physical principles with observable changes in motion. However, these benefits depend on directing students' attention toward relevant information and avoiding unnecessary elements that may overload working memory.

2.5. Students' Problem-Solving Strategies in Physics

Research on problem-solving in physics highlights important differences between expert and novice approaches. Experts typically begin by using broad scientific principles to frame a problem, whereas novices often start by selecting equations and substituting numerical values [38,39]. These patterns map onto the distinction between conceptual and computational approaches that organizes the present study: a conceptual approach uses general principles to interpret situations and reason about relationships among variables, reflecting the expert-like behaviour of deeper comprehension, whereas a computational approach emphasizes equation selection and numerical calculation and may proceed, novice-like, without strong grounding in the physical meaning of the relationships being modelled [40,41]. This distinction is analytical rather than absolute, since expert problem-solving in physics integrates conceptual and quantitative reasoning rather than treating them as alternatives [41]. Because instructional tools shape how students engage with problems, examining whether a learning activity promotes conceptual sense-making or procedural calculation is an important focus of physics education research.

2.6. Pre- and Post-Instructional Computer Simulations

Because simulations let students visualize, manipulate, and experiment with phenomena in interactive environments, they are well aligned with constructivist learning and are widely used to support conceptual understanding in physics. PhET, for example, offers free, research-based interactive simulations that imitate real systems and provide an exploratory "play zone" for investigation [42,43]. Simulation-based learning has been shown to strengthen critical thinking, conceptual analysis, and transfer of physics knowledge to new situations [5,44–46]. Recent meta-analytic evidence supports these claims: pooling 47 effect sizes across 20 studies, PhET simulations produced a large overall advantage over traditional instruction, with effects strongest at the secondary level and in abstract content domains [47]. A parallel synthesis of 15 secondary-level studies reports a comparably large effect on physics achievement ($g = 0.94$) and notes that the simulation tools used, predominantly PhET, were typically integrated with constructivist instructional strategies [48]. Temsah and Safa [18], for instance, found that integrating the 5E inquiry model with simulations in Grade 5–6 science improved students' analysis, interpretation, and conclusion-drawing.

Building on evidence that simulations enhance learning, a growing body of research has asked whether the timing of simulations within an instructional sequence influences outcomes. Simulations may be used before lectures or laboratory work as pre-instruction tools that provide initial exposure and generate curiosity, or after instruction as reinforcement tools that consolidate and extend learning [9,12]. Early evidence on optimal sequencing was mixed. Brant et al. [9] reported better understanding in genetics among students who used simulations before lectures, and Stefaniak and Turkelson [12] similarly found greater post-test gains when simulation activities preceded a lecture; in contrast, Shaw [11] found that physics students scored higher when simulations followed instruction.

More recent research helps reconcile these mixed results by distinguishing the kind of learning that sequencing affects. A substantial literature on exploratory learning before instruction, described variously as productive failure, preparation for future learning, and explore-first designs, shows that engaging students with an exploratory activity such as a simulation or a problem to solve before instruction tends to deepen conceptual understanding and support transfer, whereas providing instruction first tends to favour procedural and computational performance [14,15,49]. This pattern has been demonstrated specifically in undergraduate physics: problem-solving before instruction improved conceptual knowledge relative to the reverse order [16,50–52].

Extending the work to interactive simulations, DeCaro et al. [13] found that having students explore a simulation before, rather than after, a lecture improved conceptual knowledge and transfer while leaving directly taught factual knowledge unchanged, provided students were given sufficient time to explore. Subsequent work has begun to specify the conditions under which this advantage holds: exploratory activity before instruction appears to deepen cognitive engagement, with benefits emerging most clearly where students would otherwise disengage from the task [53]. Sequencing alone, in other words, does not guarantee conceptual gains without attention to task design. Taken together, this literature suggests that simulation timing is a consequential design decision whose effect depends on the intended learning goal, conceptual depth versus procedural fluency. That work, however, has been almost entirely quantitative, leaving unanswered the questions of how and why introducing simulation before instruction enhances students' conceptual understanding. The present study examines these questions qualitatively in the context of Newton's Second Law.

3. Materials and Methods

3.1. Research Design

The study employed a qualitatively driven, randomized comparative instructional intervention design. Fourteen students were randomly assigned to two groups of seven students each, establishing the two sequencing conditions. Qualitative evidence was then used to examine how students reasoned and interacted within each condition. Group A engaged with the computer simulation after teacher-led instruction (post-instructional simulation), whereas Group B engaged with the simulation before instruction (pre-instructional simulation). Both groups received the same content, simulations, session durations, and assessment tasks; only the order of simulation and teacher instruction differed. Each group followed its assigned sequence across projectile motion and motion on an inclined plane. Because the study included only one small group per condition and did not use inferential statistics, randomization was intended to improve group comparability rather than to establish population-level causal effects.

3.2. Sample and Data Collection

The sample consisted of 14 students from a second-secondary class in the French scientific section of a bilingual private school in Mount Lebanon. The school was selected through convenience and purposive sampling: the physics teacher agreed to collaborate, and the school had the computer laboratory and installed PhET simulations needed for the intervention. Students were already familiar with PhET because the teacher regularly used simulations. This familiarity reduced the likelihood that basic navigation or novelty would dominate the sessions, but it also limits the transferability of the findings to students and schools without comparable technological experience or resources.

Students were assigned to Groups A and B through stratified random sampling based on grade point average (GPA) and gender. GPA was used as an approximate indicator of prior academic performance, and gender was included because engagement with spatial and technological learning activities may vary across learners [54]. The two groups had similar mean GPAs of approximately 75 out of 100. This procedure strengthened comparability, but GPA is an imperfect proxy for initial conceptual knowledge, and no separate conceptual pre-test was administered. Pseudonyms were used in all records and reporting.

The same physics teacher delivered the formal instruction to both groups, and the same laboratory instructor facilitated all simulation sessions. Keeping the instructors consistent reduced instructor-related variation between the two conditions, although it does not establish that sequencing alone produced the observed differences. The unit covered projectile motion and motion on an inclined plane (**Table 1**).

The procedure for each topic was as follows:

- On the first day, Group A received a 50-min teacher-instruction session on a topic (e.g., projectile motion) from the physics teacher, while Group B simultaneously engaged with a 50-min computer-simulation session on the same topic under the physics lab instructor.
- On the following day, the groups switched: Group A completed the 50-min simulation session, and Group B received the 50-min teacher-instruction session on the same topic.

After both groups had experienced both instructional methods for a topic, all students completed an assessment. The process was replicated for Motion on an Inclined Plane within the same unit over a two-week period.

Table 1. Instructional sequence.

Group	Day 1	Day 2	Day 3
Group A (Post-instructional Simulation)	Teacher Instruction	Simulation	Assessment given for both groups
Group B (Pre-instructional Simulation)	Simulation	Teacher Instruction	

This table summarizes the instructional sequence for each group, indicating whether computer simulation activities occurred before or after teacher instruction. By holding the instructional content, simulations, instructors, and session durations constant while varying the sequence, the design supported a focused comparison of the two conditions. Its primary purpose was to characterize patterns in students' questions, written reasoning, and perceptions, not to estimate effect sizes or make statistical generalizations.

3.3. Instruments

The study used three researcher-developed instruments, each serving a distinct purpose:

- Observation checklist, used during the simulation sessions to document the focus of students' real-time questions, answers, and comments, coded as computational (C) or conceptual (CC). Its purpose was to capture the kinds of thinking students engaged in while interacting with the simulation.
- Open-ended tests, two topic tests (Projectile Motion; Motion on an Inclined Plane), each comprising seven questions, used to assess how students approached physics problems in writing. Their purpose was to reveal whether students reasoned conceptually or computationally when solving problems.
- Semi-structured interviews, built around two guiding questions concerning students' perceived understanding and immediate post-unit recollections. The interviews were used to explore how students described the role of the simulation sequence in their learning.

All instruments were reviewed for content validity and piloted to refine them. Following the pilot, certain test items were revised for clarity: for example, the term "effort" was replaced with the more familiar "force" after students misinterpreted it, and prompts such as "justify" and "explain" were added to elicit fuller responses. For the open-ended tests, interrater reliability was established with a physics expert from another school (see Interrater Reliability under Research Question 2). For the observation checklist, content validity was established by deriving the indicators from prior work that distinguishes between conceptual and computational approaches to physics problems, in which conceptual problem-solving is characterized as identifying and applying the principles governing a physical situation, and computational problem-solving as carrying out symbolic or numerical calculations [40,41]. The checklist was applied by a single trained non-participant observer, and its computational/conceptual coding framework was the same scheme independently corroborated in the analysis of the open-ended tests (interrater agreement = 0.90). The two categories are treated here as analytically separable rather than psychologically distinct: conceptual and computational reasoning are closely intertwined in expert physics problem-solving [41], and the coding therefore records where a given utterance or written response placed its emphasis rather than assigning students to exclusive orientations.

3.4. Data Analysis

The researchers analyzed data from the observation sessions and the open-ended tests, organizing findings into two principal themes, a computational emphasis and a conceptual emphasis, drawing on Gick [38], Larkin et al. [39], and Park [40]. The study employed qualitative content analysis, treating textual data from observations, tests, and interviews as the primary source of meaning [55]. Using a deductive approach, predefined codes informed by prior research guided systematic coding and theme extraction [56,57], applying established conceptual and computational themes as a lens to examine a new variable: the timing of computer simulations in relation to students' conceptual understanding.

3.5. Positionality and Researcher Roles

This study was conducted from a constructivist epistemological position, which holds that learners actively build knowledge within specific social and material contexts. This orientation shaped both the choice to examine instructional sequencing qualitatively and the interpretive weight given to students' questions, written reasoning, and accounts of their own learning rather than to test scores alone.

The first author taught secondary physics for over two decades and served as a physics coordinator for more than ten years; she is now a doctoral researcher in educational technology working on the design of technology-supported science learning environments. This background afforded close familiarity with the curriculum, the French-language instructional setting, and students' recurring difficulties with force and acceleration, but it also carried an a priori expectation that exploratory, simulation-first activity would yield conceptually richer engagement. The second author is a professor and faculty member in educational sciences whose prior research examined inquiry-based science instruction and who supervised this work as the first author's master's thesis; this expertise informed the analytic framework while predisposing the team toward inquiry-oriented readings of classroom activity. The manuscript derives from that thesis.

Neither author delivered instructions nor facilitated the simulation sessions. The students' regular physics teacher taught both groups, and the same laboratory instructor facilitated all simulation sessions; keeping personnel constant reduced variation across conditions, although the presence of an observer may still have influenced how students participated. The first author attended each simulation session as a non-participant observer, recording students' questions and discussions without teaching, answering questions, or directing activities. Both authors participated in coding and interpretation.

These positions were mitigated by the design decisions described above: coding categories were drawn from published problem-solving research rather than generated by the authors, evidence was triangulated across three data sources, and the written responses were independently coded by an external physics expert. The authors nonetheless recognize that qualitative interpretation cannot be fully separated from their theoretical commitments.

3.6. Researcher Roles, Ethics, and Methodological Transparency

The students' regular physics teacher delivered all formal classroom instruction, and the same laboratory instructor facilitated the simulation sessions for both groups. The researcher attended each simulation session as a non-participant observer, recorded students' questions and discussions, and did not teach, answer questions, or direct the activities. Using the same personnel reduced variation across conditions, although the presence of the observer and instructors may have influenced students' participation. The researchers were also involved in coding and interpreting the data. Explicit coding definitions, triangulation across three data sources, and independent coding of the written responses were used to strengthen transparency and credibility, while recognizing that qualitative interpretation cannot be entirely separated from the researchers' theoretical perspectives.

The study was approved by the Ethics Committee of Saint Joseph University, Beirut, Lebanon (protocol USJ-2024-40; 16 February 2024). Informed consent was obtained from participants, and parental or guardian consent was obtained for participating minors in accordance with the approved protocol. Pseudonyms were used to protect identity. The study was conducted in French, and quotations included in the manuscript were translated into English by the authors. Translation may have reduced some linguistic nuance, and this should be considered when interpreting the interview and observation excerpts.

4. Results

4.1. Research Question 1: Insights from the Observation Sessions

What types of questions and discussions emerge when students encounter computer simulations at different stages of learning Newton's Second Law?

To address this question, the researcher conducted four observation sessions (**Table 2**) to monitor students as they interacted with simulations on Projectile Motion and Motion on an Inclined Plane. The sessions took place in a computer lab, with students divided into two groups of seven: Group B engaged in simulations before instruction (pre-instructional), and Group A engaged in simulations after instruction (post-instructional). Students used guided worksheets to explore the simulations, which fostered discussion among peers and with the instructor. Each student worked at a computer while the lab instructor moved among them, projecting his screen onto a wall display and demonstrating solutions to students' questions in real time.

The researcher attended every session as a non-participant observer, taking notes without interfering. Students' verbal interactions, questions to the instructor, and spontaneous group discussions served as the primary data. Each session lasted 50 min, and the design allowed a comparative analysis of how simulation timing influenced students' conceptual understanding and inquiry patterns.

Table 2. Observation sessions.

Session Number	Group	Instructional Stage	Simulation Topic
Session 1	B	Pre-instructional	Projectile Motion
Session 2	A	Post-instructional	Projectile Motion
Session 3	B	Pre-instructional	Motion on an Inclined Plane
Session 4	A	Post-instructional	Motion on an Inclined Plane

Table 2 presents the sequence of observation sessions across groups, instructional stages, and simulation topics.

Students' questions, answers, and comments were categorized into two dimensions using the observation checklist (**Table 3**): a computational focus (coded C), emphasizing procedural problem-solving such as numerical manipulation, algebraic solutions, and step-by-step calculation; and a conceptual focus (coded CC), emphasizing understanding of physics principles through exploring variable changes, interpreting equations, and relating theory to real-life applications [40,41]. The checklist recorded the frequency of students' queries, responses, and remarks for each indicator.

Table 3. Observation Checklist of Students' Computational and Conceptual Focus.

Theme	Code	Indicator	Obs 1	Obs 2	Obs 3	Obs 4
Computational focus	C1	Questioning simulation mechanics for calculation purposes	3	5	1	0
	C2	Discussing the steps/procedures required to solve a problem	4	2	3	4
	C3	Commenting on the immediate numerical result upon manipulating a variable	0	2	1	0
	C4	Questioning to clarify numerical variable replacement	0	0	1	1
	C5	Using units as calculation tools	1	1	0	0
	C6	Using algebraic solutions to answer questions	1	6	0	6
	C7	Ensuring accuracy in calculations	0	4	0	1
	C8	Using efficient problem-solving strategies	0	0	0	0
	C9	Predicting outcomes based on calculations	0	0	0	2
Conceptual focus	CC1	Inquiring about linking technical operations to physics concepts	1	0	0	0
	CC2	Discussing the link between variable-manipulation outcomes and related physics concepts	6	1	3	1
	CC3	Exploring consequences of altering variables beyond task requirements	0	0	0	0
	CC4	Using equations to explain/interpret physical situations	0	0	1	0
	CC5	Connecting physical meaning to the equation	0	0	1	0
	CC6	Connecting physical meanings to variables	7	3	2	2
	CC7	Interpreting relationships among variables	5	1	13	3
	CC8	Using mathematical concepts in physical explanation	2	1	2	0
	CC9	Relating physics concepts to real-life scenarios	2	0	2	0
	CC10	Predicting outcomes using qualitative explanations	4	1	0	0

This table presents the categorized indicators of computational and conceptual engagement across the four simulation sessions. The frequency columns record the number of student queries, responses, and comments aligned with each indicator.

4.1.1. Visual Analysis

Figures 1 and **2** show the number of conceptual and computational questions and answers (Q&A) generated by Groups A and B during the Projectile Motion and Inclined Plane sessions. Group B, which engaged with pre-instructional simulations, produced more conceptual Q&A (27 and 24) than computational Q&A (9 and 6) in both sessions. Conversely, Group A, which engaged with post-instructional simulations, generated more computational Q&A (20 and 14) than conceptual Q&A (7 and 6).

4.1.2. Narrative Analysis

The four sessions reveal a clear difference between the groups. Group B, which interacted with simulations before instruction, engaged more strongly with conceptual content, asking questions and offering answers that focused on understanding variable relationships and their physical meanings rather than applying pre-learned formulas. This virtual, hands-on, discovery-driven engagement is consistent with the Engage and Explore phases of the 5E model and with constructivist knowledge-building. In contrast, Group A, encountering simulations after instruction, relied more on computational methods and algebraic problem-solving (**Figures 1** and **2**).

Group A employed a formula-driven approach, applying established equations such as $P = m \cdot g$ to draw conclusions, for example, reasoning that if gravity were zero, the weight P would also be zero. They debated using the equation of a parabola and applied the range equation for a 60° angle. Their discussion included statements such as, "What equation determines the range?" "Should we write the equation of the parabola?" and "I used the equation for the range for an angle of 60° and got the same answer." (These quotations were originally in French and translated into English by the authors.) Their interactions reflected the structured application of prior knowledge, reinforcing a computational focus.

Group B, by contrast, engaged more deeply in conceptual exploration. Lacking prior formal instruction, their discussion centered on interpreting variable relationships, producing questions such as, "Does changing the mass affect the motion?" and "Why does pushing a bike up an incline feel easier once it is already moving?" They also observed, "This means there is a relation between the range and the shooting angle." (These quotations were originally in French and translated into English by the authors.) Their exploration, however, rarely extended beyond the task requirements.

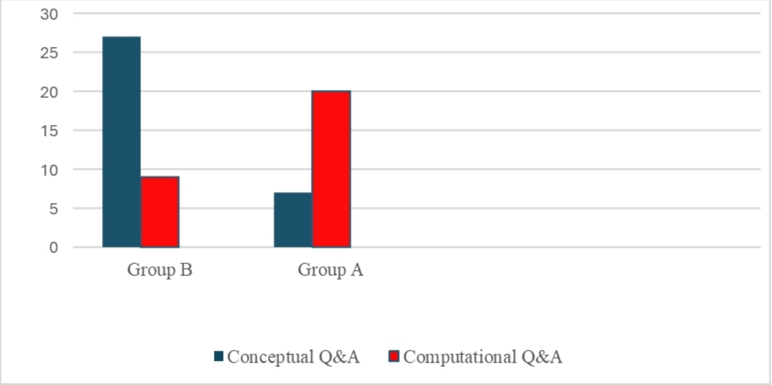

Figure 1. Conceptual and Computational Engagement in Projectile Motion. This figure compares conceptual and computational engagement during the Projectile Motion simulation session for Groups A and B.

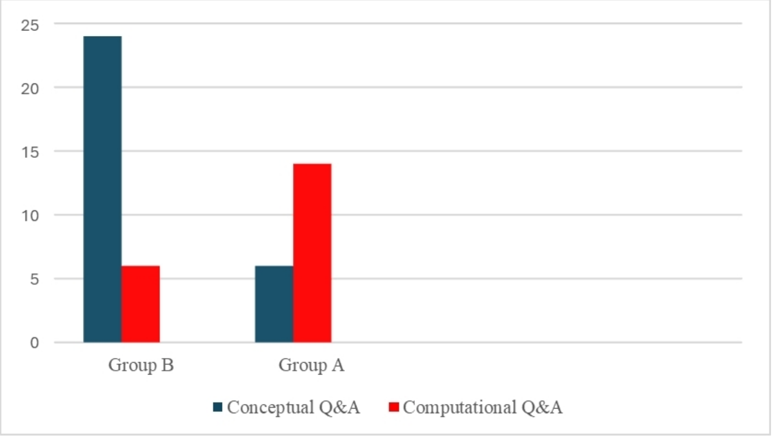

Figure 2. Conceptual and Computational Engagement in Motion on an Inclined Plane. This figure compares conceptual and computational engagement during Motion on an Inclined Plane simulation session for Groups A and B.

4.2. Research Question 2: Insights from the Open-Ended Tests

How does the timing of computer simulations, before or after teacher instruction, shape students' conceptual understanding of Newton's Second Law as demonstrated in the strategies they use in their written work?

To address this question, the researchers administered open-ended tests assessing understanding of Projectile Motion and Motion on an Inclined Plane. Both groups had experienced simulation and teacher instruction in their respective sequences. Students completed each test in approximately 30 min, and the same procedure was repeated for both topics.

4.2.1. Overview of the Tests

Test 1 (Projectile Motion) assessed key concepts including constant gravitational acceleration, the influence of launch angle on trajectory and range, the role of vertical velocity in determining maximum height, the (lack of) effect of mass in the absence of air resistance, and the conditions for maximum range. Test 2 (Motion on an Inclined Plane) assessed the purpose of an incline, the direction of the normal force, net-force analysis in frictionless conditions, the effect of incline angle on the normal force and on the force required to lift an object, and the role of friction. Both tests were designed to probe students' ability to apply theoretical principles to varied motion scenarios.

Responses were sorted into five categories:

- Computational: using equations for calculation without demonstrating conceptual understanding [39,40].
- Conceptual: applying physics principles directly [39] or using equations to interpret a physical situation [40].
- Partial Computational: beginning computationally but not reaching a complete solution.
- Partial Conceptual: beginning conceptually but remaining incomplete.
- Incorrect Response (IR): incorrect or missing.

4.2.2. Interrater Reliability

To strengthen confidence in the analysis, the researchers collaborated with a physics expert from another school. After a briefing to align both raters on the coding scheme, they independently coded student responses and compared results, reaching a high agreement rate of 0.90.

4.2.3. Analysis of the Open-Ended Tests

A clear distinction emerged between conceptual and computational approaches, particularly between the pre-instructional group (B) and the post-instructional group (A). All names are pseudonyms.

Projectile Motion (seven questions):

- Q1: What is the acceleration in projectile motion? Group B identified gravity (g) as the acceleration, with most using Newton's Second Law to calculate; Carla and Jad reasoned conceptually that acceleration acts vertically downward while horizontal velocity remains constant, and Rana noted that this vertical acceleration shapes the parabolic path. Group A correctly identified gravity but relied solely on Newton's Second Law computationally, without elaborating the conceptual implications.
- Q2: Which shooting angle gives the minimum horizontal range? Group B students (Samer, Jad, Carla) reasoned conceptually that a 90° angle yields the minimum range because the projectile travels straight up and returns to its launch point. Group A reached the same conclusion but strictly through the range equation, without conceptual justification.
- Q3: What affects the maximum height of a projectile? Most of Group B used equations, but Rana reasoned without them, emphasizing that both launch speed and angle matter, showing a strong conceptual grasp. Group A attempted equations but substituted cosine for sine, leading to errors.
- Q4: Does mass affect time of flight, velocity, force, range, or maximum height? Group B computed that mass does not affect these quantities in the absence of air resistance; Reem reasoned conceptually that force depends on mass while the others do not, though she did not link this to air resistance. Group A applied equations correctly but answered entirely computationally.
- Q5: What is the condition for maximum range? Justify. Rana (B) explained conceptually that maximum range occurs at 45° due to the symmetry of projectile motion; Carla (B) noted that initial speed and launch height contribute to range but did not connect them to the 45° angle. Group A determined 45° computationally without conceptual reasoning.
- Q6: Is there an angle where maximum height equals horizontal range? Group B struggled to analyze the relationship but did not reach a complete answer. Group A equated the two quantities but could not develop the calculation to find the angle.
- Q7: Is there a point where velocity is perpendicular to acceleration? Group B correctly identified the trajectory's peak. Group A generally failed to recognize this, except Leen, who used a diagram to depict the relationship correctly, a conceptual approach unusual in her group.

Motion on an Inclined Plane (seven questions):

- Q1: What is the purpose of an inclined plane? Group B described conceptually how an incline reduces the force needed to move an object. Group A leaned computational, with most (four students) emphasizing the decomposition of weight into components (Px and Py).
- Q2: In which direction does the normal force act? Why? Group B correctly stated that it acts perpendicular to the surface but struggled to justify why; Group A also identified the direction but did not explain the reasoning conceptually.
- Q3: With no friction, what is the net force on the object? Group B used mixed approaches; many computed it

via Newton's Second Law, while Jad conceptualized the net force as the x-component of weight, supported by a figure. Group A derived it computationally but lacked conceptual insight.

- Q4: How does the normal force change as the incline angle increases? Group B (Reem, Sami) correctly noted that it decreases but did not justify; all of Group A except Leen answered accurately by applying Newton's Second Law computationally.
- Q5: How does incline length affect the force needed to lift an object to the same height? Group B (Rana, Jad) explained conceptually that a longer incline reduces the required force by reducing the angle (Jad added a figure). Group A conflated net force with applied force, except Leen, who reasoned that a longer incline decreases the angle and thus the effort required.
- Q6: What happens to the required force as the incline angle increases? Group B (Samer, Jad) explained that as the angle increases, the x-component of weight increases, requiring more force. Group A again confused applied with net force, except Leen, who compared 90° and 60° scenarios to conclude that a larger angle requires more force.
- Q7: How does friction affect the force required? Group B (Carla, Rana, Samer, Jad) explained that friction opposes motion and increases the required force. Group A attempted to compute friction's effect via Newton's Second Law but could not reach correct conclusions.

Overall, Group B (pre-instructional) showed stronger conceptual reasoning, while Group A (post-instructional) relied predominantly on formula application, except Leen, who reasoned conceptually in several instances.

4.2.4. Graphical Analysis

Figures 3 and **4** present the distribution of Conceptual, Computational, Partial Conceptual, Partial Computational, and incomplete response (IR) categories in students' answers to the Projectile Motion and Motion on an Inclined Plane tests, respectively. Group B, which engaged with pre-instructional simulations, produced more Conceptual and Partial Conceptual responses, whereas Group A, which engaged with post-instructional simulations, produced more Computational and Partial Computational responses.

4.2.5. Overall Analysis

Group A's responses were notably uniform, consistently correct or incorrect across the board, indicating little variation in their comprehension. Group B's responses varied widely, with no predominant error pattern. Group A produced more fully correct answers across both tests, while Group B produced more partial answers, suggesting that although Group B did not always reach the correct solution, they engaged substantively with the material and frequently arrived at partially correct reasoning. In the problem-solving strategy, Group B leaned toward conceptual and partially conceptual approaches, while Group A leaned toward computational approaches, except for Leen. This divergence suggests that simulation timing influences students' solving strategies for Newton's Second Law, and Leen's outlier performance highlights the role of individual differences and the potential value of personalized learning pathways (**Figures 3** and **4**).

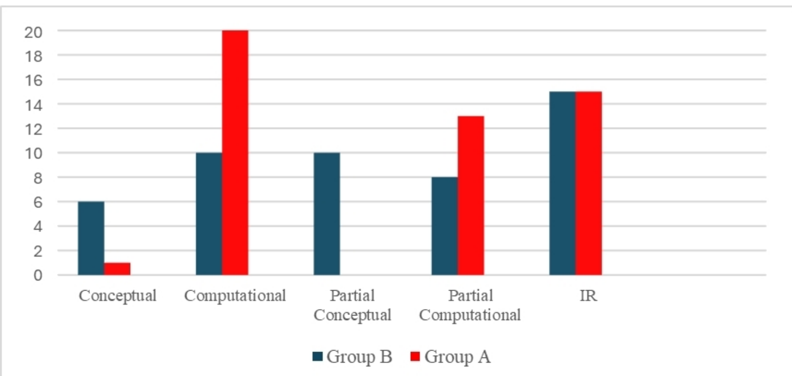

Figure 3. Projectile Motion test response analysis by group. This figure compares Groups A and B based on their responses to the Projectile Motion test.

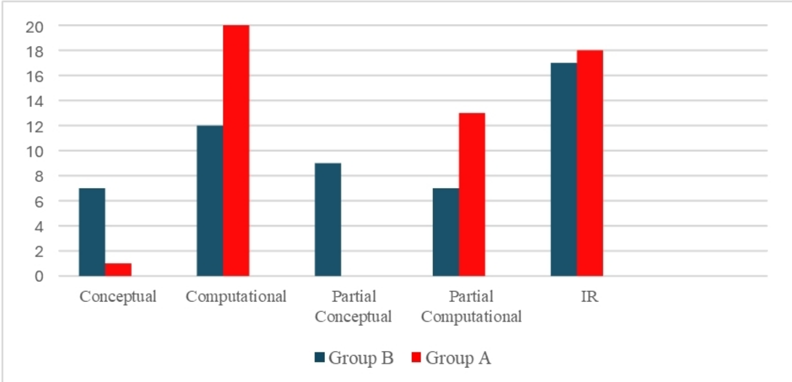

Figure 4. Motion on an Inclined Plane test response analysis by group. This figure compares Groups A and B based on their responses to the Motion on an Inclined Plane test.

4.3. Research Question 3: Insights from the Interviews

How do students perceive the role and effectiveness of computer simulations, introduced at different times, in aiding their understanding of Newton's Second Law?

The researchers interviewed five volunteers, two from Group A (post-instructional) and three from Group B (pre-instructional), to explore how simulation timing influenced their understanding. Interviews took place in a school conference room and were transcribed and translated from French to English. Two guiding questions addressed conceptual understanding and retention:

1. How did the timing of engaging with simulations, before or after instruction, help your understanding of Newton's Second Law?
2. Given when you engaged with simulations, how well do you believe you can remember what you learned about Newton's Second Law?

Interview Analysis

Group B engaged in simulations before instruction, and their responses emphasized exploration and connections with prior knowledge of force and motion (**Table 4**). Carla drew on the previous year's study of Newton's Second Law: "We studied this law last year; I remember it. However, this year, we are learning more things, like how to decompose forces and how to apply this law in real life." Jad described exploring how variable changes related to motion: "By starting with the simulation, I discovered various factors influencing projectile motion. For instance, by adjusting gravity within the simulation, I observed changes in the projectile's trajectory, range, and maximum height." Sami described a visual, hands-on experience of the force-motion relationship: "This was the first time I could visually see how changes in force affected motion."

Table 4. Thematic coding of student interview responses.

Question	Student (Group)	Application of Teacher-Taught Concepts	Concept Exploration via Simulations	Integration with Prior Knowledge	Retention of Mathematical Equations	Recollection of Explored Concepts
Q1	Hadi (A)	X				
	Sarah (A)	X				
	Carla (B)		X	X		
	Jad (B)		X			
	Sami (B)			X		
Q2	Hadi (A)				X	
	Sarah (A)				X	
	Carla (B)					X
	Jad (B)					X
	Sami (B)					

Note: X = theme present in the student's response; blank = theme not expressed.

This table presents the main themes that emerged inductively from students' interview responses across

Groups A and B. Group A, by contrast, applied newly acquired instruction within the simulations (**Table 4**). Hadi used class concepts through the simulation: "The simulation was a way to experiment with what we learned in class." Sarah adjusted variables based on what was covered in instruction: "I was changing the variables we learned in class to see how motion was affected."

At the immediate post-unit interviews, the groups emphasized different aspects of their experience. Group B participants recalled contextual features of their exploration. Carla stated, "I remember how changing the variables affected motion and the shapes of the graphs we created," and Jad recalled a collaborative moment that illustrates transfer to a real-world situation: "One moment that stuck with me was when we debated the shape of trajectories. A classmate decided to test this by throwing a rubber ball to see if its path formed a parabola." Group A participants emphasized equations and procedures. Hadi noted, "I can still remember the equations we were taught because we used them so often," and Sarah explained, "I could see how mass and force influence acceleration and how they are interconnected". These comments show what students recalled at the time of the interview; they do not establish that either form of knowledge persisted over weeks or months.

Overall, the students interviewed in both groups described the simulations as helpful, but they emphasized different benefits: exploration and interpretation in Group B, and application and procedural reinforcement in Group A (**Table 4**).

5. Discussion

5.1. Research Question 1

The observation sessions showed different dominant approaches within the two groups. Group B's questioning about variables, physical meaning, and real-life situations was consistent with constructivist learning and the Engage and Explore phases of the 5E model [32]. Encountering the simulation first may have encouraged students to notice patterns and formulate questions before receiving a formal explanation. Group A entered the simulation with equations and procedures already available and used the activity mainly to apply and reinforce them. These interpretations remain provisional. The differences may also reflect students' initial conceptions, peer interaction, prior familiarity with PhET, or the prompts provided by the guided worksheets.

5.2. Research Question 2

The written responses mirrored the observation data. Within this sample, Group B produced more conceptual and partially conceptual responses, whereas Group A produced more computational responses and more fully correct solutions. The conceptual and computational categories were used to identify the emphasis of students' reasoning; they should not be treated as independent or competing forms of expertise. Effective physics problem-solving requires students to interpret a situation, represent it mathematically, calculate accurately, and evaluate whether the result is physically plausible [38–40]. The findings, therefore, identify different emphases associated with the two sequences rather than demonstrating that one sequence produced complete understanding.

The results also help interpret apparently inconsistent findings in earlier sequencing studies. Brant et al. [9] and Stefaniak and Turkelson [12] reported advantages when simulation preceded instruction, while Shaw [11] reported stronger performance when simulation followed instruction. These studies differed in subject matter and in the outcomes they measured. The present findings suggest that some of this inconsistency may reflect whether assessment privileges conceptual exploration, procedural accuracy, or both. Brophy et al. [10], although not directly testing the same sequence, similarly distinguished factual recall from application.

This is consistent with, rather than contradictory to, the present findings, since the post-instruction group in this study also performed better on procedural and computational tasks. More recent work by DeCaro et al. [13] further supports the importance of sequencing by showing that placing a guided simulation before instruction can improve learning, interest, and perceived competence, although the study was conducted in chemistry rather than physics and did not explain the underlying mechanisms. Taken together, these studies suggest that the apparent contradiction in the literature may partly result from differences in the outcomes being measured: pre-instruction simulations may be especially useful for eliciting questions, exploration, and conceptual reasoning, whereas post-instruction simulations may be more effective for reinforcing formulas, procedures, and computational application.

The findings may also be interpreted through Mayer's Cognitive Theory of Multimedia Learning [37]. According to this theory, meaningful learning occurs when learners select relevant verbal and visual information, organize it into coherent mental representations, and integrate these representations with one another and with prior knowledge. From this perspective, Group B's pre-instructional simulation experience may have supported the construction of preliminary visual models of motion by allowing students to observe trajectories, manipulate variables, and identify physical relationships before encountering formal equations. Group A, in contrast, entered the simulation with the teacher's verbal and symbolic representations already introduced. The simulation may therefore have helped these students connect visual representations of motion with previously taught equations and procedures, supporting computational application. Nevertheless, pre-instructional simulation may also place greater demands on working memory when students lack sufficient prior knowledge, while post-instructional simulation may restrict exploration if students attend mainly to confirming taught procedures. Because cognitive load, attention, and multimedia processing were not directly measured, these possibilities remain plausible theoretical explanations that require further investigation.

Several alternative explanations must also be considered. Stratification by GPA and gender did not establish equivalence in students' initial physics conceptions, and only one small group represented each condition. Peer dynamics, individual differences, students' prior experience with PhET, French-medium instruction, translation into English, and the presence of the observer may have shaped the data. In addition, the identical worksheets improved comparability but may have constrained spontaneous inquiry; the absence of activity beyond the worksheet requirements is consistent with this possibility. These factors prevent attributing the observed patterns solely to simulation timing.

A practical implication is not that teachers must permanently choose between pre- and post-instructional simulations. Instead, the two placements may serve complementary purposes within a single lesson cycle. Initial simulation-based prediction and exploration can elicit ideas and questions; teacher explanation can then formalize the relevant concepts and equations; computational practice can consolidate procedures; and a second simulation encounter can allow students to test calculations, examine new cases, and explain the physical meaning of their results. This integrated sequence is consistent with the combined conceptual and computational demands of expert problem-solving, but it was not directly tested in the present study.

5.3. Research Question 3

The interviews provided a third, although limited, source of evidence. Group B participants described connecting the simulations with prior knowledge and recalled specific exploratory episodes, while Group A participants described using the simulations to apply instruction and rehearse equations. These accounts converged with the observation and written-response patterns. However, only five volunteers were interviewed, the reports were retrospective and self-perceived, and the interviews occurred shortly after the unit. The data therefore support conclusions about immediate recollection and perceived usefulness, not the durability of conceptual or computational knowledge.

6. Conclusions

In this small, context-specific study, the placement of simulations was associated with different emphases in students' reasoning about Newton's Second Law. Students who explored the simulations before instruction were more likely to question variable relationships, interpret their physical meanings, and use conceptual or partially conceptual approaches. Students who used the simulations after instruction applied equations and procedures more often and produced more fully correct computational responses. The interviews reflected the same immediate pattern: Group B emphasized exploratory episodes, whereas Group A emphasized formulas and solution steps. These findings do not establish that one sequence is generally superior, that timing alone caused the differences, or that the observed recollections persisted over time. Rather, they suggest that the instructional function of a simulation changes with its placement and that conceptual exploration and computational consolidation may be best treated as complementary goals. Individual variation, including Leen's departure from the dominant pattern in Group A, further supports flexible scaffolding that responds to students' observed reasoning rather than assuming a single approach will suit all learners.

7. Recommendations

Rather than using simulation exclusively before or after instruction, teachers may consider an integrated cycle that combines the strengths associated with both placements. A lesson can begin by asking students to predict outcomes and explore a guided simulation; the teacher can then use students' observations and questions to introduce formal concepts, representations, and equations. Worked examples and independent numerical problems can provide computational practice, after which students can return to the simulation to test their calculations, investigate contrasting cases, and explain the physical meaning of the results. Assessment should likewise require both accurate calculation and conceptual justification. This blended sequence is a recommendation derived from the observed patterns and existing theory; it requires direct empirical evaluation.

The level of worksheet guidance should also be treated as an instructional design decision. Identical guided worksheets were useful for controlling the comparison in this study, but they may have limited student-generated inquiry. Teachers and researchers should gradually shift from structured prompts to semi-structured or open-ended tasks, while monitoring whether greater freedom supports productive exploration or creates excessive cognitive demands.

Future studies should include delayed assessments to compare the persistence of conceptual and computational knowledge. Larger multi-school designs should involve public and private schools, different languages of instruction, learners with varying levels of simulation experience, and multiple classes or groups in each condition. A direct conceptual pre-test would improve baseline comparison. Research should also compare structured, semi-structured, and open-ended worksheets, examine physics topics beyond Newton's Second Law, and test the proposed blended sequence that combines exploration, formal explanation, computational practice, and re-exploration. Additionally, future studies could measure cognitive load, attention, and multimedia processing, as these constructs warrant further examination in the context of simulation-based physics instruction.

8. Limitations

Several limitations restrict the interpretation and transferability of the findings. The sample comprised 14 students from one technologically resourced, bilingual private school in Mount Lebanon, and students already had experience with PhET. Only one group represented each sequencing condition. Although students were stratified by GPA and gender, no conceptual pre-test was administered, so equivalence in initial physics understanding cannot be confirmed. The school context, French-medium instruction, previous simulation familiarity, peer dynamics, and individual variation may have contributed to the observed patterns. The focus on two mechanics topics within Newton's Second Law also limits transfer to other physics domains and educational settings.

The data and procedures introduce additional constraints. Guided worksheets strengthened comparability but may have restricted spontaneous inquiry. Observation data were recorded by one observer, and the observer's presence may have affected participation. Only five volunteers participated in the interviews, potentially introducing bias from the volunteers and self-report. Quotations were translated from French into English, which may have reduced nuance. Finally, all assessments and interviews occurred shortly after instruction; therefore, the study cannot determine whether the observed conceptual or computational patterns persisted over weeks or months. The findings should be read as preliminary qualitative evidence warranting replication in larger, more diverse settings.

Author Contributions

Conceptualization, S.J.; Methodology, S.J. and N.S.; Validation, S.J. and N.S.; Formal Analysis, S.J. and N.S.; Investigation, S.J. and N.S.; Data Curation, S.J.; Writing—Original Draft Preparation, S.J.; Writing—Review & Editing, S.J. and N.S.; Supervision, N.S. Both authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Saint Joseph University, Beirut, Lebanon (protocol no. USJ-2024-40; date of approval: 16 February 2024).

Informed Consent Statement

Informed consent was obtained from all participants involved in the study. As participants were minors (aged 16–17 years), parental or guardian consent was also obtained where required by the ethics protocol.

Data Availability Statement

The data presented in this study (classroom observation notes, open-ended test responses, and interview transcripts) are not publicly available to protect the privacy of the participating minors. De-identified data may be made available by the corresponding author upon reasonable request and subject to approval by the relevant ethics committee.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

Grammarly was used during the preparation of this manuscript to assist with language refinement, clarity, and drafting. No AI tools were used for data collection or analysis. The authors independently verified all scientific data, claims, and references, and maintain full responsibility for the integrity of the content.

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