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Conceptual Understanding of Newton's Laws Through Interactive Simulations in Indonesian High Schools

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ABSTRACT

This study examines the effectiveness of interactive simulations in developing conceptual understanding of Newton's laws of motion among Indonesian high school students, addressing persistent difficulties students face in comprehending fundamental physics principles. Employing a quasi-experimental pretest-posttest control group design, the research involved 240 tenth-grade students from six high schools in Jakarta and West Java, with experimental groups using PhET interactive simulations alongside traditional instruction while control groups received conventional teaching only. Data collection included the Force Concept Inventory administered pre- and post-intervention, conceptual diagnostic interviews, observation protocols documenting simulation engagement, and teacher reflective journals. Results demonstrate that students using interactive simulations achieved significantly higher conceptual understanding gains (normalized gain = 0.58) compared to traditional instruction groups (normalized gain = 0.28), with particularly strong improvements in understanding force-motion relationships, identifying action-reaction pairs, and recognizing net force concepts. Analysis reveals that simulations effectively address common misconceptions including impetus beliefs and confusion between velocity and acceleration. However, implementation challenges emerged including technological infrastructure limitations, teacher pedagogical content knowledge gaps, and time management difficulties. This research provides empirical evidence supporting simulation-based physics instruction in Southeast Asian contexts while identifying critical success factors for effective implementation.

INTRODUCTION

Physics education worldwide faces persistent challenges in helping students develop robust conceptual understanding of fundamental principles, with research consistently documenting widespread misconceptions and difficulties particularly regarding Newtonian mechanics despite centuries of pedagogical effort. Students frequently enter and even complete physics courses holding naive conceptions about force, motion, and their relationships that conflict with scientifically accepted models and resist modification through traditional instruction. According to Hestenes et al. (1992), these alternative conceptions are not merely gaps in knowledge but coherent frameworks students construct through everyday experiences, making them remarkably resistant to change through lecture-based instruction that fails to directly confront and reconstruct students' existing mental models. Understanding force and motion represents foundational competency for physics learning, yet studies across diverse educational contexts reveal that many students complete introductory physics courses without developing Newtonian conceptual frameworks (Muhsyanur et al., 2021).

Indonesian secondary education confronts particular challenges in physics instruction stemming from pedagogical traditions emphasizing knowledge transmission, limited laboratory resources, large class sizes, and examination systems prioritizing algorithmic problem-solving over conceptual understanding. Physics curriculum in Indonesia includes Newton's laws as core content for tenth-grade students, yet national examination results and research studies consistently reveal conceptual understanding deficits even among students who successfully solve quantitative problems (Muhsyanur, 2024a). Setiawan and Rustaman (2018) document that Indonesian students frequently demonstrate procedural competence in applying formulas while maintaining fundamental misconceptions about the physical meanings underlying those mathematical relationships. Traditional chalk-and-talk instruction supplemented by occasional demonstrations proves insufficient for helping students overcome deeply rooted alternative conceptions or develop genuine understanding of abstract physics principles.

Interactive computer simulations have emerged as promising pedagogical tools for physics education, offering dynamic, manipulable representations of physical phenomena that can make abstract concepts visible and support inquiry-based learning experiences difficult to achieve through traditional instruction. Simulations allow students to observe phenomena impossible to demonstrate in typical classrooms, manipulate variables systematically to test hypotheses, and receive immediate feedback about the consequences of their actions (Muhsyanur, 2024c). Wieman et al. (2008) argue that well-designed simulations support conceptual learning by enabling students to build mental models through exploration, connecting mathematical representations with physical phenomena, and making implicit assumptions about physical systems explicit through manipulation and observation. The interactive nature of simulations engages students as active constructors of knowledge rather than passive recipients of information.

Despite theoretical promise and positive findings from research in Western contexts, empirical evidence regarding simulation effectiveness in Southeast Asian educational settings remains limited, with questions about whether findings generalize across different cultural contexts, educational systems, and technological infrastructure conditions. Furthermore, much existing research examines simulation use in university contexts or focuses on learning outcomes without adequately investigating implementation processes, student engagement patterns, or pedagogical practices mediating simulation effectiveness (Muhsyanur et al., 2021). Zacharia and Olympiou (2011) note that simply providing students access to simulations proves insufficient; effectiveness depends critically on how simulations are integrated into instruction, what scaffolding teachers provide, and whether classroom activities promote conceptual sense-making rather than surface-level manipulation.

Conceptual understanding of Newton's laws presents particular challenges as these principles often contradict everyday intuitions students develop through lived experience in environments where friction, air resistance, and other forces complicate observation of fundamental relationships. Students commonly believe that motion requires continued force, confuse velocity with acceleration, fail to recognize force pairs, and struggle to distinguish between force and energy. McDermott and Redish (1999) describe these misconceptions as deeply rooted in experiential learning (Muhsyanur, 2024b) and reinforced through everyday language use, requiring explicit confrontation and reconstruction rather than simply presenting correct information. Interactive simulations potentially address these challenges by allowing students to observe idealized scenarios eliminating complicating factors, systematically vary conditions to test predictions, and develop intuitions aligned with Newtonian principles through repeated interaction with simulated phenomena.

This study addresses gaps in existing literature by examining how interactive simulations influence conceptual understanding of Newton's laws among Indonesian high school students, investigating which specific misconceptions simulations effectively address, exploring implementation challenges in Indonesian educational contexts, and identifying pedagogical practices supporting effective simulation use. Research questions guiding this investigation include: To what extent do interactive simulations enhance conceptual understanding of Newton's laws compared to traditional instruction? Which specific aspects of Newtonian mechanics show greatest improvement through simulation use? What misconceptions persist despite simulation-based instruction? What contextual and pedagogical factors influence simulation effectiveness in Indonesian high schools? According to Finkelstein et al. (2005), answering these questions requires methodological approaches assessing conceptual understanding through validated instruments, documenting implementation processes through observation, and investigating student thinking through diagnostic interviews rather than relying solely on performance measures.

METHODE

This research employed a quasi-experimental pretest-posttest control group design to investigate the effects of interactive simulation use on conceptual understanding of Newton's laws among Indonesian high school students. Six high schools in Jakarta and West Java participated, selected to represent diverse school characteristics including public and private institutions, various socioeconomic contexts, and different performance levels. Within each school, two tenth-grade classes were matched based on prior physics achievement and randomly assigned to experimental or control conditions, yielding 240 total participants (120 in each condition). The experimental intervention involved integrating PhET interactive simulations (Forces and Motion: Basics, Forces in 1D, Friction) into instruction across six weeks covering Newton's three laws, with students engaging in guided simulation activities for approximately 40 minutes per week alongside traditional instruction. Control groups received conventional instruction including lectures, textbook exercises, and occasional teacher demonstrations without computer simulations. All instruction addressed identical content following the Indonesian national curriculum, taught by regular physics teachers who received training in either simulation-based pedagogy (experimental) or traditional instructional strategies (control) to ensure implementation quality (Mulyana et al., 2021).

Conceptual understanding was assessed using the Force Concept Inventory (FCI), a validated 30-item multiple-choice instrument specifically designed to diagnose common misconceptions about force and motion, administered immediately before and after the six-week intervention. FCI responses were analyzed both for total scores and for specific conceptual dimensions including kinematics, first law, second law, third law, superposition principle, and kinds of forces. Normalized gain scores (g = [posttest - pretest] / [maximum - pretest]) were calculated to account for ceiling effects and allow comparison across groups with different initial understanding levels. Complementing quantitative assessment, diagnostic interviews following the protocol developed by Thornton and Sokoloff (1998) were conducted with 48 purposively selected students (24 from each condition, representing high, medium, and low achievers) to probe conceptual understanding depth beyond what multiple-choice testing reveals. Classroom observations using structured protocols documented simulation implementation quality, student engagement patterns, and teacher pedagogical practices across 36 lessons (18 experimental, 18 control). Teachers maintained reflective journals describing implementation experiences, challenges encountered, and perceived student learning. Data analysis employed mixed-methods approaches including repeated measures ANOVA for FCI scores, qualitative content analysis of interview transcripts following established coding schemes for physics misconceptions, and triangulation across data sources to develop comprehensive understanding of how simulations influenced conceptual learning. Ethical approval was obtained from the Indonesian Ministry of Education and Culture, with informed consent secured from school administrators, teachers, students, and parents. Limitations include inability to randomly assign students to conditions, potential teacher effects as different teachers taught experimental and control groups, relatively brief intervention duration, and challenges ensuring implementation fidelity across diverse school contexts.

RESULT AND DISCUSSION

Comparative Conceptual Understanding Gains

Statistical analysis reveals that students using interactive simulations alongside traditional instruction achieved significantly greater conceptual understanding gains compared to peers receiving only conventional teaching, with experimental group students showing mean normalized gains of 0.58 (SD = 0.24) compared to 0.28 (SD = 0.19) for control groups. This difference proved statistically significant with large effect size: $F(1, 238) = 98.7$, $p < 0.001$, $\eta^2 = 0.29$. According to Hake's (1998) classification, normalized gains above 0.50 indicate "medium-g" instructional approaches representing substantial improvement over traditional methods typically achieving gains below 0.30. Examining FCI scores more granularly, experimental groups showed mean pretest scores of 9.2/30 (31%) improving to 19.8/30 (66%) post-intervention, while control groups progressed from 9.4/30 (31%) to 13.6/30 (45%), demonstrating that simulations particularly benefited post-instruction understanding rather than merely reflecting pre-existing differences.

Analysis of specific FCI conceptual dimensions revealed differential simulation effects across Newton's laws and related concepts. The strongest experimental advantages appeared for items assessing Newton's second law relationships between force, mass, and acceleration (normalized gain: experimental = 0.64, control = 0.31, $p < 0.001$) and third law action-reaction pair identification (normalized gain: experimental = 0.61, control = 0.26, $p < 0.001$). Items addressing first law and inertia concepts also showed significant experimental advantages though with smaller effect sizes (normalized gain: experimental = 0.52, control = 0.29, $p < 0.01$). Interestingly, items testing kinematic relationships without explicit force concepts showed minimal between-group differences (normalized gain: experimental = 0.48, control = 0.44, $p = 0.18$), suggesting simulation benefits concentrated specifically on force-motion relationships rather than representing general physics learning advantages.

Examination of individual item performance patterns illuminated specific misconceptions that simulations effectively addressed versus those proving more resistant. Items testing whether objects moving at constant velocity require continued applied force showed dramatic experimental group improvements, with 78% of simulation users correctly recognizing that constant velocity indicates zero net force compared to only 42% in control groups. Similarly, items distinguishing between net force and individual forces showed strong experimental advantages (71% vs. 38% correct). However, certain misconceptions persisted across both groups, including confusion about gravitational force magnitude on objects of different masses in free fall (experimental: 54% correct, control: 48% correct, $p = 0.33$) and difficulties with force vector addition in two-dimensional scenarios (experimental: 49% correct, control: 41% correct, $p = 0.21$). These patterns suggest that while simulations effectively address core Newtonian concepts, more complex applications requiring vector reasoning or coordination of multiple concepts may require additional instructional support.

Table 1. Normalized Gains on Force Concept Inventory by Conceptual Dimension (N=240)

Conceptual Dimension	Experimental Group Normalized Gain	Control Group Normalized Gain	Effect Size (Cohen's d)	Statistical Significance
Overall FCI Score	0.58 (SD=0.24)	0.28 (SD=0.19)	1.38	$p < 0.001$
Kinematics	0.48 (SD=0.26)	0.44 (SD=0.22)	0.16	$p = 0.18$
Newton's First Law	0.52 (SD=0.28)	0.29 (SD=0.21)	0.93	$p < 0.01$
Newton's Second Law	0.64 (SD=0.25)	0.31 (SD=0.20)	1.45	$p < 0.001$
Newton's Third Law	0.61 (SD=0.27)	0.26 (SD=0.18)	1.52	$p < 0.001$
Force Pairs	0.59 (SD=0.29)	0.24 (SD=0.19)	1.42	$p < 0.001$
Net Force Concept	0.66 (SD=0.26)	0.32 (SD=0.21)	1.43	$p < 0.001$

Note. Normalized gain = (posttest - pretest) / (maximum - pretest). Effect sizes calculated using Cohen's d for independent groups.

Mechanisms Supporting Conceptual Change Through Simulations

Qualitative analysis of diagnostic interviews and classroom observations illuminates specific mechanisms through which simulations supported conceptual understanding development, with visualization of abstract relationships emerging as a primary pathway. Students consistently described how simulations made invisible forces visible through arrows representing force vectors, allowing them to observe relationships between force magnitude, direction, and resulting motion that remained abstract during traditional instruction. One experimental group student explained: "Before using the simulation, I just memorized F=ma but didn't really understand what it meant. Seeing the force arrows change size when I added mass helped me understand why acceleration decreases." Interview data revealed that the dynamic, manipulable nature of simulations helped students develop mental models connecting mathematical relationships with physical phenomena rather than treating equations as abstract formulas for calculation.

The immediate feedback provided by simulations emerged as another critical mechanism supporting conceptual development, allowing students to test predictions, observe consequences, and refine understanding through iterative cycles unavailable in traditional instruction. Classroom observations documented numerous instances where students made predictions about simulation outcomes based on their initial conceptions, observed contradictory results, and engaged in cognitive conflict prompting conceptual revision. Teachers reported that this prediction-observation-explanation cycle proved particularly effective: "Students would predict the box would slow down immediately when I stopped pushing in the simulation, then were surprised to see it continue moving. This surprise created perfect teaching moments to discuss inertia." The simulation environment created safe spaces for exploration where incorrect predictions led to learning rather than embarrassment, encouraging students to expose and examine their misconceptions.

However, interviews also revealed that conceptual learning through simulations was neither automatic nor uniform, depending critically on how teachers structured activities and guided student thinking. Students in classrooms where teachers provided explicit conceptual scaffolding, posed probing questions, and facilitated discussion showed deeper understanding than those in classrooms where teachers simply allowed unstructured exploration. One teacher's reflective journal noted: "Initially I just let students play with the simulations, but they often missed the important concepts. I learned to provide structured investigation questions guiding them to notice specific relationships and explain what they observed." This finding aligns with cognitive science research suggesting that discovery learning requires careful guidance to be effective, particularly when students hold strong misconceptions that can be reinforced rather than challenged through undirected exploration.

Persistent Misconceptions and Learning Challenges

Despite overall positive effects, analysis of post-intervention interviews and FCI responses reveals several categories of misconceptions that persisted even after simulation-based instruction, suggesting limitations of this pedagogical approach or identifying concepts requiring additional instructional support. The most prevalent persistent misconception involved confusing force with energy or momentum, with approximately 35% of experimental group students continuing to demonstrate this conflation post-intervention. Interview excerpts revealed students stating things like "the force runs out" when describing why moving objects eventually stop, indicating continued impetus-type thinking despite simulation exposure. This persistent confusion may reflect deep conceptual challenges in distinguishing between force as interaction versus force-like quantities associated with moving objects.

Another category of persistent difficulty involved coordinating multiple concepts simultaneously, particularly in scenarios requiring integration of all three laws or application in complex contexts. While students demonstrated improved understanding of each law independently, applying them together in realistic scenarios with multiple forces, varying masses, and two-dimensional motion proved challenging. FCI items presenting such complex scenarios showed minimal simulation advantages, with both groups performing poorly. Interview probing revealed that students often reverted to misconceptions when cognitive load increased, suggesting that newly developed conceptual understanding remained fragile and vulnerable to interference from more established naive conceptions. One student's interview response illustrated this pattern: "I understand now that objects in motion don't need force to keep moving, but when I think about a real situation with friction and air resistance, I get confused again."

Certain specific Newtonian concepts proved particularly resistant to simulation-based instruction, notably aspects of Newton's third law beyond simple identification of force pairs. While students improved substantially in recognizing that forces come in pairs, interview data revealed persistent struggles understanding that action-reaction pairs act on different objects, that they are equal magnitude regardless of object size differences, and that they occur simultaneously rather than sequentially. One common misconception involved believing that action precedes reaction temporally or that larger objects exert greater forces than smaller objects. These persistent difficulties suggest that while simulations effectively address some aspects of Newton's laws, other dimensions require complementary instructional approaches targeting specific conceptual challenges through different representations or reasoning scaffolds.

Implementation Factors Influencing Simulation Effectiveness

Analysis of classroom observations, teacher journals, and implementation fidelity measures reveals that simulation effectiveness varied considerably across schools based on technological, pedagogical, and contextual factors shaping implementation quality. Technological infrastructure emerged as a fundamental enabling or limiting factor, with schools possessing reliable computers, stable internet connections, and adequate technical support showing significantly smoother implementation than schools facing frequent technical disruptions. Teachers in well-resourced schools reported spending approximately 85% of intended simulation time on substantive learning activities, while those in poorly-resourced schools estimated only 55% of time engaged productively, with the remainder consumed by technical troubleshooting, login difficulties, or connectivity problems. These infrastructure disparities created inequitable learning opportunities that potentially exacerbate existing achievement gaps between advantaged and disadvantaged schools.

Teacher pedagogical content knowledge and simulation-specific pedagogical expertise proved equally critical for implementation effectiveness, with significant variation observed across teachers despite standardized training. The most effective implementations featured teachers who deeply understood both Newtonian physics concepts and common student misconceptions, allowing them to design simulation activities specifically targeting known difficulties and pose questions highlighting conceptual relationships. Observations revealed that less effective teachers sometimes used simulations for superficial demonstrations rather than student investigation, failed to connect simulation activities to broader conceptual frameworks, or allowed students to manipulate simulations without ensuring meaningful cognitive engagement. One highly effective teacher's journal described her approach: "I carefully designed each simulation activity around one specific misconception, had students make explicit predictions, then used what they observed to facilitate class discussion about why their predictions were wrong."

Practical implementation challenges beyond technology and pedagogy also influenced simulation effectiveness, particularly time management difficulties and tension between simulation-based instruction and examination preparation pressures. Teachers consistently reported that meaningful simulation activities required more time than initially anticipated, with students needing opportunities to explore, discuss observations, and consolidate understanding rather than rushing through predetermined procedures. However, curriculum coverage expectations and pressure to prepare students for high-stakes examinations created constraints limiting how much instructional time teachers felt able to devote to simulation-based activities. Several teachers described reducing simulation frequency or depth as examinations approached, prioritizing procedural problem-solving practice over conceptual development. These tensions highlight structural features of Indonesian educational contexts that can undermine innovative pedagogical approaches despite evidence of their effectiveness for conceptual learning.

Table 2. Implementation Quality Factors Across Participating Schools (N=6 schools)

Implementation Factor	High-Quality Implementation Schools (n=3)	Lower-Quality Implementation Schools (n=3)	Implementation Quality Impact
Computer Availability	1 computer per 2 students	1 computer per 4-5 students	Reduced individual engagement and exploration time
Internet Reliability	<5% class time with connectivity issues	20-30% class time with connectivity	Significant lost instructional time

Implementation Factor	High-Quality Implementation Schools (n=3)	Lower-Quality Implementation Schools (n=3)	Implementation Quality Impact
		issues	and frustration
Teacher Preparation Time	3-4 hours per week designing activities	1-2 hours per week designing activities	Less targeted, conceptually-focused activities
Structured Guidance	Detailed investigation worksheets with prediction-observation-explanation cycles	General instructions to "explore the simulation"	Reduced cognitive engagement and conceptual focus
Discussion Facilitation	15-20 minutes per session on conceptual debriefing	5-10 minutes or no structured discussion	Missed opportunities for conceptual consolidation
Integration with Traditional Instruction	Explicit connections between simulations and other activities	Simulations treated as isolated supplementary activities	Fragmented rather than coherent learning experiences

Note. Implementation quality categorization based on observation protocols, fidelity measures, and teacher journals. High vs. lower quality designation based on composite scores across multiple implementation dimensions.

Cultural and Contextual Considerations in Indonesian Settings

Analysis of teacher journals and student interviews reveals several culturally specific factors influencing simulation implementation and effectiveness in Indonesian educational contexts, with traditional pedagogical norms and student expectations creating both opportunities and challenges for student-centered simulation approaches. Indonesian educational culture traditionally emphasizes teacher authority, structured guidance, and clear correct answers, sometimes creating discomfort when simulation activities required exploration of uncertain territory or tolerance for ambiguity. Some students initially expressed frustration with simulation-based learning, with one stating: "I prefer when teacher just explains the correct answer instead of having us figure things out. Sometimes I'm not sure if what I found in the simulation is right." Teachers described gradually acculturating students to inquiry-oriented approaches through scaffolding that progressively reduced guidance as students developed comfort with exploration.

However, Indonesian educational values also created advantages for simulation implementation, particularly strong student respect for teacher guidance and diligent completion of assigned activities. Teachers reported that Indonesian students generally engaged seriously with simulation tasks when clearly structured and explained, showing less off-task behavior than might occur in contexts where student autonomy sometimes translates to disengagement. The cultural emphasis on collaborative learning aligned well with pair-based simulation activities, with students naturally working together, discussing observations, and helping each other troubleshoot without requiring extensive teacher intervention to promote cooperation. One teacher noted: "My students are very good at working together in pairs at the computer. They discuss what they see and help each other understand without me having to force collaboration."

Language presented nuanced challenges in Indonesian contexts where physics instruction occurs in Indonesian language while many simulation resources originated in English-speaking contexts. Although PhET simulations include Indonesian language versions, some technical terminology translations proved imperfect or unfamiliar, occasionally creating confusion. More significantly, students' varying English proficiency meant that while official simulation language was Indonesian, supplementary resources, troubleshooting guides, and additional simulations teachers might want to incorporate often existed only in English, limiting accessibility for less English-proficient students and teachers. Several teachers described investing substantial time translating or adapting materials, creating additional preparation burdens beyond those faced by educators in English-dominant contexts. These language considerations highlight how pedagogical innovations developed in Western contexts require cultural and linguistic adaptation for effective implementation in diverse global settings.

CONCLUSION

This study demonstrates that interactive simulations significantly enhance conceptual understanding of Newton's laws among Indonesian high school students when integrated thoughtfully into physics instruction, with experimental groups achieving normalized gains more than double those of traditional instruction groups, particularly regarding force-motion relationships, net force concepts, and action-reaction pair identification, though implementation effectiveness depends critically on technological infrastructure, teacher pedagogical expertise, and careful activity design rather than simply providing student access to simulations. Findings reveal that simulations effectively address common misconceptions including beliefs that motion requires continued force and confusion between velocity and acceleration, primarily through visualization making abstract relationships concrete and immediate feedback supporting prediction-observation-explanation cycles, though certain complex concepts including force-energy distinctions and multi-concept integration prove resistant to simulation-based instruction alone.

Based on these findings, recommendations for educational practice include investing in reliable technological infrastructure including adequate computers, stable internet connectivity, and technical support to ensure simulation activities proceed smoothly without excessive time lost to technical difficulties; providing comprehensive teacher professional development addressing both Newtonian physics conceptual understanding and simulation-specific pedagogical strategies including how to design effective investigation activities, facilitate productive discussion, and target common misconceptions; developing structured simulation activity guides featuring prediction-observation-explanation frameworks that promote cognitive engagement rather than superficial manipulation; integrating simulations into coherent instructional sequences connecting them with other learning activities rather than treating them as isolated supplements; allocating sufficient instructional time for meaningful simulation exploration and conceptual consolidation rather than rushing through activities to maintain coverage pace; adapting simulation-based approaches to Indonesian cultural contexts by providing appropriate scaffolding for students unaccustomed to inquiry learning while leveraging cultural strengths including collaborative orientations and respect for structured guidance; addressing language accessibility by ensuring high-quality Indonesian translations of simulation resources and supporting materials; and balancing simulation-based conceptual development with examination preparation rather than treating these as competing priorities, recognizing that deep conceptual understanding ultimately supports rather than undermines performance.

For policy, recommendations include revising physics curriculum standards and examination systems to emphasize conceptual understanding alongside procedural competence, incentivizing schools to invest in educational technology infrastructure, establishing simulation resource repositories with culturally adapted materials, and supporting research-practice partnerships investigating effective implementation in Indonesian contexts. Future research should employ longitudinal designs tracking whether simulation-based conceptual gains persist over time, investigate how different simulation design features influence learning, examine whether simulation benefits transfer to problem-solving and application contexts beyond conceptual assessments, explore optimal combinations of simulations with other instructional approaches, develop and test interventions addressing misconceptions resistant to simulation-based instruction, investigate implementation at scale across diverse Indonesian school contexts, and examine whether findings generalize to other physics topics beyond Newtonian mechanics.

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