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Scientific Conceptual Understanding in Physics through Momentum and Material-Dependent Collisions Using the Dual Situated Learning Model: A Mixed Methods Action Research Study

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ABSTRACT

From a materials science perspective, collision behavior depends on mass, velocity, and the mechanical responses of interacting materials, including elasticity, deformation, damping, and energy dissipation. This mixed-methods classroom action research examined the effectiveness of the Dual Situated Learning Model (DSLM) in improving students' conceptual understanding of momentum and material-dependent collisions. Thirty-nine Grade 10 students from a secondary school in Thailand participated in three instructional cycles. Quantitative data were obtained from prerequisite and cycle-specific conceptual assessments, while qualitative data included worksheets, classroom observations, interviews, and reflection records. The results showed significant improvement in conceptual understanding, representational competence, and confidence in scientific explanations. Material-dependent collision contexts helped students distinguish momentum conservation from kinetic-energy dissipation and supported meaningful conceptual reconstruction in physics learning.

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1. INTRODUCTION

From a materials science perspective, collision behavior is determined not only by mass and velocity but also by the mechanical properties of the interacting materials (Brilliantov et al., 2026). Elasticity controls shape recovery and rebound, plasticity causes permanent deformation, stiffness affects deformation during contact, damping governs energy dissipation, and toughness influences the ability of a material to absorb energy before fracture. Therefore, steel, rubber, foam, glass, and modeling clay may exhibit different rebound, deformation, sticking, or fracture behaviors under similar collision conditions. These material-dependent responses provide a clear context for distinguishing momentum conservation from kinetic-energy conservation.

Understanding these phenomena is challenging because students must simultaneously consider mass, velocity, direction, force, impulse, interaction time, system boundaries, and conservation principles. Many students confuse momentum with force, have difficulty relating impulse to momentum change, and struggle to translate collision events into vector, symbolic, and mathematical representations (Şekercioğlu and Kocakülah, 2008; Liu and Fang, 2016; Nguyen and Meltzer, 2003; Sakinah *et al.*, 2023). As a result, they may obtain correct numerical answers through formula substitution without fully understanding the physical process (Caleon and Subramaniam, 2010; Fulmer *et al.*, 2015).

Similar difficulties were identified among the 39 Grade 10 students in this study. Preliminary observations showed problems with vector direction, unit conversion, physical symbols, equation selection, and interpretation of collision outcomes. A two-tier prerequisite assessment adapted from the Force Concept Inventory also indicated weak connections among physical situations, scientific concepts, representations, and equations (Hestenes *et al.*, 1992). This finding is consistent with evidence that students may understand force, time, velocity, and momentum separately but fail to integrate them into a coherent explanation (Xu *et al.*, 2020).

The Dual Situated Learning Model (DSLM) was used to address these difficulties. DSLM supports conceptual change by identifying students' initial ideas, creating conflict between predictions and evidence, and providing the conceptual resources needed to reconstruct understanding (She, 2002; She, 2003; She, 2004). In material-dependent collision contexts, students predict outcomes, explain their reasoning, observe rebound or deformation, compare evidence with their initial ideas, and revise their explanations. Guiding questions, visual representations, peer discussion, and feedback support this process (Molin *et al.*, 2021).

Previous studies have reported persistent difficulties in learning momentum, impulse, and multiple representations (Kongmai *et al.*, 2025; Küchemann *et al.*, 2021; Rahim *et al.*, 2024; Xu *et al.*, 2020). However, limited attention has been given to how students connect momentum principles with materials science concepts such as elasticity, plastic deformation, stiffness, damping, toughness, rebound, and energy absorption. The novelty of this study lies in integrating DSLM, classroom action research, and material-dependent collision contexts. Rather than treating collisions only as mathematical events, the instruction connected momentum and impulse with observable material responses and used classroom evidence to refine teaching across three action-research cycles (Kemmis and McTaggart, 1988; Kemmis *et al.*, 2014).

Accordingly, this study investigated the development of Grade 10 students' scientific conceptual understanding of momentum and material-dependent collisions through progressively refined DSLM-based instruction. The study addressed the following questions:

(i) RQ1. How did students' post-instruction conceptual-understanding scores compare with their prerequisite baseline?
(ii) RQ2. How did students' understanding of momentum and material-dependent collision behavior develop across the three cycles?
(iii) RQ3. How did DSLM-based instruction influence students' learning behaviors and conceptual-change processes?
(iv) RQ4. How was reflection evidence used to improve instruction across the cycles?

2. LITERATURE REVIEW

2.1. Momentum and Collision Understanding

Momentum and collision problems require students to connect mass, velocity, direction, impulse, force, and interaction time within a defined system. Students commonly confuse momentum with force, ignore vector direction, and assume that momentum is not conserved when objects deform or stick together (Şekercioğlu and Kocakülah, 2008; Sakinah *et al.*, 2023; Xu *et al.*, 2020). They also experience difficulty distinguishing momentum conservation from kinetic-energy conservation and translating collision events into diagrams, symbols, and equations (Küchemann *et al.*, 2021; Nguyen and Meltzer, 2003). These difficulties indicate that learning should address not only mathematical calculations but also the physical mechanisms occurring during contact.

2.2. Materials Science Perspective on Collisions

In materials science, collision outcomes are strongly influenced by the mechanical properties of the interacting materials. Elasticity enables a material to recover its original shape and contributes to rebound, whereas plasticity produces permanent deformation. Stiffness affects the magnitude of deformation during contact, damping controls mechanical-energy dissipation, and toughness reflects the ability to absorb energy before fracture.

Accordingly, objects with similar mass and velocity may respond differently because of their material properties. Steel may show limited deformation and strong rebound, rubber may undergo reversible deformation, foam may absorb energy through compression, glass may fracture, and modeling clay may deform permanently or stick to another object. These responses (e) can be represented using the coefficient of restitution (see equation (1)):

$$e = \frac{\text{relative separation velocity}}{\text{relative approach velocity}} \quad (1)$$

A higher value of e indicates greater rebound, whereas a lower value indicates greater energy dissipation through deformation, heat, sound, vibration, or fracture. However, even when kinetic energy decreases, total momentum remains conserved if external forces are negligible. Therefore, material-dependent collisions provide a useful context for connecting macroscopic motion with elasticity, plastic deformation, damping, energy absorption, and fracture behavior.

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2.3. Conceptual Change and the Dual Situated Learning Model

Conceptual change occurs when students identify limitations in their initial ideas and construct explanations that are more consistent with scientific evidence (She, 2002; She, 2003; She, 2004). The DSLM facilitates this process by identifying students’ existing conceptions, determining the mental sets needed for scientific understanding, and designing learning events that connect cognitive conflict with conceptual support.

In collision learning, students may first predict whether objects will rebound, deform, fracture, or stick together. They then compare their predictions with observations and explain the results using momentum conservation and material properties. Guiding questions, diagrams, peer discussion, and feedback help students revise their explanations (Molin *et al.*, 2021). Thus, DSLM can connect abstract physics concepts with observable materials-science phenomena.

2.4 Conceptual Framework

This study assumes that students’ understanding develops through the following sequence: Material properties → contact response → observable collision behavior → scientific explanation.

Mechanical properties such as elasticity, stiffness, plasticity, damping, and toughness influence contact responses, including temporary deformation, permanent deformation, energy absorption, rebound, and fracture. These responses produce observable collision outcomes that students interpret using momentum, impulse, vector direction, and energy transformation.

DSLM supports this process by allowing students to predict outcomes, observe material-dependent evidence, identify inconsistencies in their initial explanations, and reconstruct their understanding. Classroom action research further enables the instructional activities to be improved through repeated planning, implementation, observation, and reflection. Therefore, the conceptual framework integrates materials science, momentum principles, conceptual change, and iterative instructional improvement.

3. METHODS

3.1. Research Design

This study employed classroom action research using the spiral model, consisting of planning, action, observation, and reflection conducted over three instructional cycles. The overall research framework is presented in **Figure 1**. The alignment between the research questions, evidence sources, and analytical focus is presented in **Table 1.** Each cycle incorporated reflection findings from the previous cycle to improve instructional implementation and students' conceptual understanding. A mixed-methods approach was adopted by integrating quantitative assessment data with qualitative evidence obtained from classroom observations, interviews, students' reflective responses, and teacher reflection.

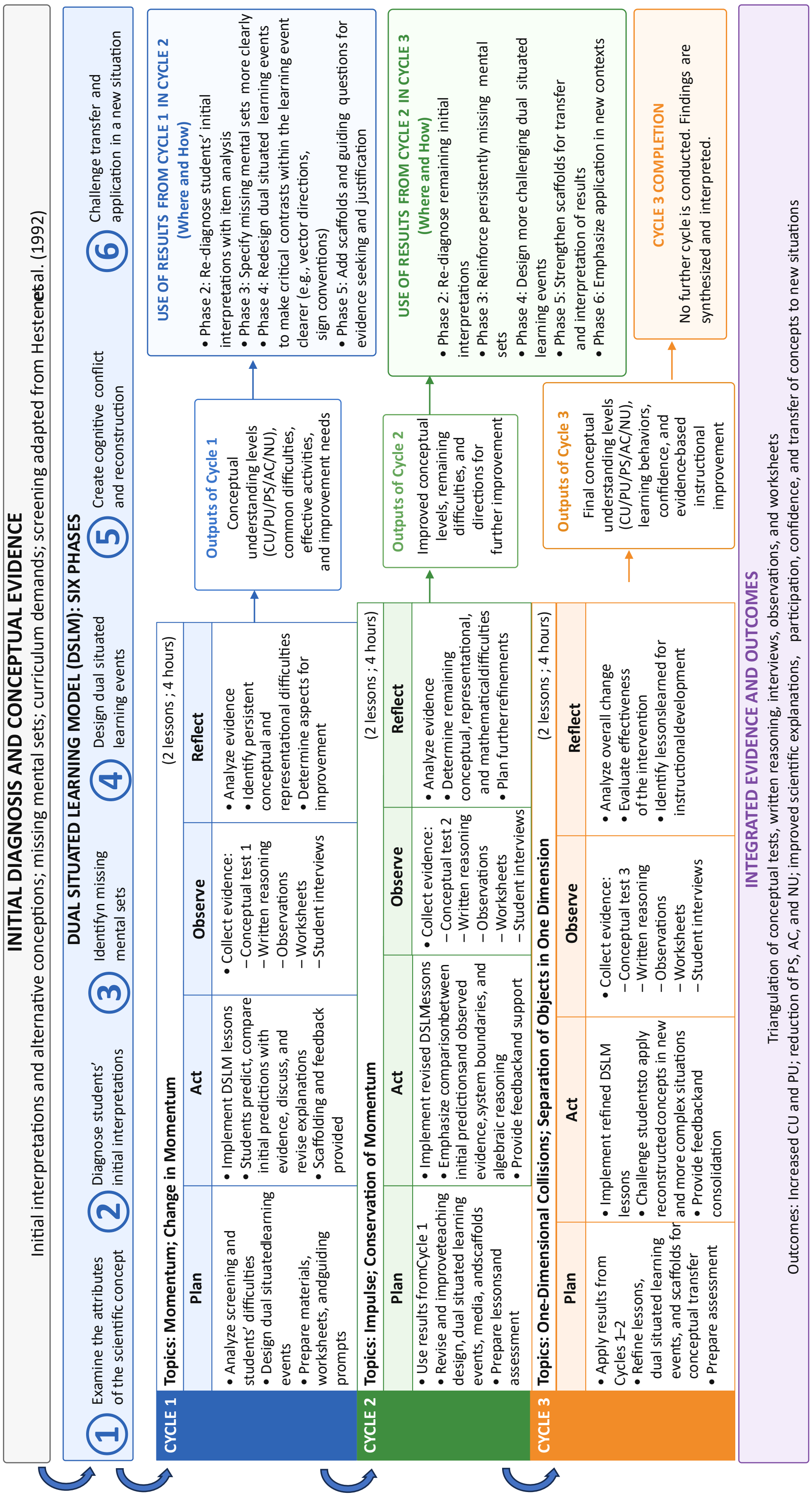

Figure 1. Conceptual and procedural framework of the DSLM classroom action research.

Table 1. Alignment of research questions, evidence sources, and analytical focus.

RESEARCH QUESTION	PRIMARY EVIDENCE SOURCES	ANALYTICAL FOCUS
RQ1: Comparison of prerequisite conceptual understanding and posttest scores across each cycle	Prerequisite conceptual-understanding screening task and three scientific conceptual-understanding tests	Comparison of prerequisite and post-instruction percentage scores using paired-samples *t*-tests, statistical significance, mean differences, 95% confidence intervals, and Cohen's *d* effect sizes
RQ2: Development of scientific conceptual understanding	Prerequisite conceptual-understanding screening task and scientific conceptual-understanding tests, including selected answers and written justifications	Frequencies and percentages of CU, PU, PS, AC, and NU responses; number and percentage of students meeting the all-item CU/PU criterion; and patterns of concept-specific attainment across the three cycles
RQ3: Learning behaviors and conceptual-change processes	Structured observations, interviews, worksheets, and written explanations	Prediction, comparison of predictions with observed evidence, evidence seeking, discussion, confidence, conceptual revision, and representational difficulties
RQ4: Reflection-driven instructional improvement	Cycle reflection records, problem-solution summaries, and revisions to lesson plans, instructional media, and scaffolds	How identified problems led to specific instructional changes and how evidence from the following cycle supported their interpretation

Note: CU = Complete Understanding; PU = Partial Understanding; PS = Partial Understanding with a Specific Alternative Conception; AC = Alternative Conception; NU = No Understanding.

3.2. Participants

The participants were 39 Grade 10 students from a public senior high school in Thailand during the 2024-2025 academic year. All students participated in three consecutive action-research cycles covering momentum, impulse, and collision concepts. Participation followed school regulations and ethical requirements.

3.3. Learning Intervention

The instructional content and conceptual demands across the three action-research cycles are summarized in **Table 2**. The intervention consisted of three instructional cycles based on DSLM. Each cycle included planning, classroom implementation, observation, and reflection. Learning activities required students to predict collision outcomes, explain their reasoning, observe demonstrations involving different materials, compare observations with scientific concepts, and revise their explanations through guided discussion. Material-dependent collision contexts were incorporated using objects with different mechanical properties, allowing students to compare rebound, deformation, sticking, and energy dissipation while relating these observations to momentum conservation and kinetic-energy transformation.

Table 2. Instructional content and conceptual demands across the three action research cycles.

CYCLE	LESSONS AND CONCEPTS	HOURS	PRIMARY CONCEPTUAL DEMAND
1	Momentum; force and change in momentum	4	Representing momentum as a vector quantity and understanding change in momentum in terms of initial and final momentum states
2	Impulse; conservation of momentum	4	Understanding impulse and its relationship to change in momentum and conservation of momentum within a well-defined system
3	One-dimensional collisions; one-dimensional separation or explosion	4	Applying momentum conservation to one-dimensional interactions using consistent system boundaries, before-and-after states, and vector signs

3.4. Instruments

The combination of quantitative and qualitative data enabled triangulation of the findings. Students' responses to the conceptual understanding test were classified as complete understanding (CU), partial understanding (PU), partial understanding with a specific alternative conception (PS), alternative conception (AC), or no understanding (NU). The criteria used to classify and score students' scientific conceptual understanding are presented in **Table 3**. Data were collected using multiple instruments.

(i) A prerequisite assessment adapted from the Force Concept Inventory (FCI) was administered before instruction to identify students' initial conceptions.
(ii) A conceptual understanding test was administered after each instructional cycle.
(iii) Classroom observations documented students' participation, misconceptions, and learning behaviors.
(iv) Reflection notes recorded instructional strengths, weaknesses, and planned improvements for the subsequent cycle.

3.5. Data Analysis

Quantitative data were analyzed using descriptive statistics and paired-samples t-tests. Mean scores and standard deviations were calculated for the prerequisite and cycle-specific posttests. Mean differences, 95% confidence intervals, p-values, and Cohen's $d_z$effect sizes were used to examine post-instruction performance relative to the prerequisite baseline. Qualitative data from classroom observations, interviews, worksheets, written explanations, and reflection records were analyzed thematically to identify recurring misconceptions, conceptual-change processes, learning behaviors, and instructional improvements. The quantitative and qualitative findings were integrated to provide a comprehensive evaluation of DSLM implementation.

4. RESULTS AND DISCUSSION

4.1. Post-Instruction Conceptual Understanding Relative to the Baseline

Students' post-instruction conceptual understanding in each cycle was compared with their prerequisite conceptual understanding. The prerequisite assessment represented students' foundational understanding before the cycle-specific instruction, whereas each posttest assessed different but sequentially related concepts of momentum, impulse, momentum conservation, and one-dimensional collisions. Therefore, the comparisons should be interpreted as cycle-specific attainment relative to a common prerequisite baseline, rather than as a direct progression measured using identical tests.

Table 3. Criteria for classifying and scoring scientific conceptual understanding.

SCIENTIFIC CONCEPTUAL UNDERSTANDING	PART 1 RESPONSE	PART 2 RESPONSE: WRITTEN JUSTIFICATION	TOTAL SCORE
CU	Correct	The justification is scientifically correct and complete and includes all essential elements of the concept	3
PU	Correct	The justification is scientifically correct but does not include all essential elements of the concept. It contains no scientific error or alternative conception	2
PS	Correct	The justification is partly correct but contains some scientifically inaccurate ideas or alternative conceptions	1
PS	Correct	The justification reflects an entirely scientifically inaccurate understanding or alternative conception	1
PS	Incorrect	The justification demonstrates scientifically correct or largely correct reasoning but is inconsistent with the selected response	1
PS	Incorrect	The justification is partly correct but contains some scientifically inaccurate ideas or alternative conceptions	1
AC	Incorrect	The justification reflects an entirely scientifically inaccurate understanding or alternative conception	0
NU	No response selected	No written justification is provided	0

As presented in **Table 4**, students' post-instruction performance was higher than the prerequisite baseline in all three cycles. However, the scores should not be interpreted as a continuous increase or decrease across cycles because the conceptual content and cognitive demands differed.

Table 4. Paired *t*-test results for prerequisite and cycle-specific posttests.

CYCLE	PREREQUISITE, M (SD)	POSTTEST, M (SD)	MEAN DIFFERENCE (95% CI)	*t*	*df*	*P*	COHEN'S *d*z	MAGNITUDE
1	35.88 (34.53)	68.80 (20.92)	32.92 (22.03, 43.81)	6.12	38	< 0.001	0.98	Large
2	35.88 (34.53)	59.19 (26.27)	23.31 (10.79, 35.83)	3.77	38	< 0.001	0.60	Medium
3	35.88 (34.53)	63.04 (17.50)	27.15 (14.93, 39.37)	4.50	38	< 0.001	0.72	Medium

Note: N = 39. Scores were converted to percentages before analysis. The mean difference was calculated as the posttest score minus the prerequisite conceptual-understanding score. Reported p-values are two-sided. Cohen's *d*z was standardized using the standard deviation of the paired difference scores. Magnitudes were interpreted as small at approximately 0.20, medium at 0.50, and large at 0.80.

The large difference in Cycle 1 indicates that students performed substantially better after learning to represent momentum as a vector quantity and relate force to a change in momentum. These concepts provide the foundation for analyzing interactions between objects. Previous studies have shown that students frequently experience difficulty distinguishing momentum from force and coordinating mass, velocity, impulse, and changes in motion (Şekercioğlu and Kocakülah, 2008; Nguyen and Meltzer, 2003; Rahim *et al.*, 2024). The Cycle 1 result suggests that the DSLM activities supported students in organizing these foundational quantities more scientifically. Nevertheless, the result does not demonstrate complete mastery because the posttest measured only the concepts addressed in that cycle.

Cycle 2 produced the smallest mean difference and a medium effect size. This result should not necessarily be considered a decline in learning. Cycle 2 introduced the more demanding relationships among impulse, changes in momentum, system boundaries, and momentum conservation. Students needed to identify the interacting system, distinguish internal from external effects, and coordinate initial and final momentum using appropriate vector signs. Such reasoning is more complex than identifying momentum from mass and velocity alone. Students' understanding of momentum is often fragmented, especially when they must integrate several related concepts within a single explanation (Nguyen and Meltzer, 2003; Rahim *et al.*, 2024). The Cycle 2 results therefore indicate meaningful post-instruction attainment while also showing that the conceptual demands remained challenging.

In Cycle 3, the mean posttest score remained higher than the prerequisite baseline, with a medium standardized difference. The third cycle required students to apply momentum conservation to one-dimensional collisions and separation situations. This application involved coordinating object masses, velocities, directions, system boundaries, and before-and-after states. The result indicates that students could apply the foundational concepts developed in the earlier cycles to more integrated collision situations, although the study did not use an identical assessment across the three cycles.

From a materials science perspective, the Cycle 3 content provides an important context for connecting the conservation of momentum with the physical response of interacting objects. Collision behavior is not determined only by mass and velocity. Observable outcomes such as rebound, separation, sticking, and deformation can also be interpreted through the mechanical response of the materials involved. Elastic recovery may contribute to rebound, whereas irreversible deformation and damping may increase the conversion of kinetic energy into internal energy, heat, sound, or permanent structural change. These processes do not mean that momentum disappears. Momentum conservation is evaluated for a defined system, while changes in kinetic energy depend partly on how the interacting materials respond during contact.

This distinction is educationally important because students may incorrectly assume that visible deformation or a reduction in speed indicates that momentum is not conserved. A materials-science interpretation helps separate two levels of analysis. At the system level, the total momentum before and after an interaction may remain constant when external impulse is negligible. At the material level, the contacting objects may undergo elastic recovery, temporary deformation, permanent deformation, or energy dissipation. Thus, two objects may have the same total momentum before and after collision while exhibiting different rebound or deformation behavior.

The present study did not directly measure elasticity, stiffness, damping, toughness, deformation, or the coefficient of restitution. Therefore, these properties should not be treated as experimental variables or study outcomes. Instead, they provide a scientific context for explaining why different collision outcomes may occur while the momentum-conservation principle remains applicable. This interpretation strengthens the connection between school-level collision mechanics and the broader study of material behavior without extending the findings beyond the evidence collected.

The DSLM framework was relevant to this conceptual distinction because it required students to make predictions, examine evidence, compare the evidence with their initial reasoning, and reconstruct their explanations (Sakinah *et al.*, 2023; Edelsbrunner *et al.*, 2023; Smith *et al.*, 2009). Conceptual change does not occur merely because students are shown an outcome that contradicts their expectations. They also require suitable conceptual resources for explaining why their initial interpretation is incomplete (Sakinah *et al.*, 2023; Edelsbrunner *et al.*, 2023; Smith *et al.*, 2009; Feldman, 1996). In collision learning, these resources include vector direction, system boundaries, before-and-after states, and the distinction between system-level momentum and material-level energy dissipation.

Accordingly, the results in **Table 4** indicate that the DSLM-based instruction supported higher cycle-specific conceptual performance relative to the prerequisite baseline. The findings do not establish that one cycle was universally more effective than another because each cycle assessed different content. Instead, they show that students demonstrated meaningful attainment in progressively related areas: momentum representation in Cycle 1, impulse and momentum conservation in Cycle 2, and the application of these concepts to collisions and separation in Cycle 3. The materials-science perspective further clarifies that collision outcomes should be explained by combining conservation principles with the mechanical response of the interacting materials.

4.2. Development of Conceptual Understanding Across the Three Cycles

The analysis of mean scores provides whole-class evidence but does not fully show whether students consistently selected scientifically acceptable answers and provided suitable explanations. Therefore, students' responses were also classified as CU, PU, PS, AC, or NU. A student met the cycle criterion only when all four responses in that cycle were classified as CU or PU.

As shown in **Table 5**, the number of students meeting the all-item CU/PU criterion increased from 14 students (35.90%) in Cycle 1 to 20 students (51.28%) in Cycle 2 and 31 students (79.49%) in Cycle 3. At the same time, the number below the criterion decreased from 25 students in Cycle 1 to eight students in Cycle 3. Unlike the comparisons of cycle-specific mean scores, this result indicates increasing consistency in scientifically acceptable reasoning across the successive instructional cycles.

Table 5. Students meeting the CU/PU criterion across cycles.

CYCLE	STUDENTS MEETING THE CRITERION, n (%)	STUDENTS BELOW THE CRITERION, n (%)
1	14 (35.90)	25 (64.10)
2	20 (51.28)	19 (48.72)
3	31 (79.49)	8 (20.51)

Note: Students met the cycle criterion when all four responses in the corresponding cycle were classified as CU or PU.

The distinction between answer correctness and reasoning quality is important in momentum and collision learning. Students may select a correct numerical or multiple-choice answer while retaining an incomplete explanation of force, velocity, impulse, or momentum (Şekercioğlu and Kocakülah, 2008; Nguyen and Meltzer, 2003). The two-tier assessment used in this study reduced the possibility of treating correct selection alone as complete conceptual understanding. It required students to connect their answers with written reasoning, enabling the classification to distinguish scientifically acceptable understanding from guessing, mixed reasoning, or alternative conceptions.

Table 6 presents the item-level results of students' conceptual understanding across the three cycles and shows that CU/PU percentages varied considerably among items. In Cycle 1, the proportion of CU/PU responses ranged from 28.21 to 92.31%. In Cycle 2, the range became narrower at 51.28-66.67%. In Cycle 3, CU/PU responses ranged from 79.49 to 89.74%. Students' understanding was not uniform across all concepts, particularly during the earlier cycles.

Table 6. Item-level conceptual understanding across cycles.

CYCLE	ITEM	CU, n (%)	PU, n (%)	PS, n (%)	AC, n (%)	NU, n (%)	CU and PU, n (%)
1	1	35 (89.74)	1 (2.56)	3 (7.69)	0 (0.00)	0 (0.00)	36 (92.31)
1	2	24 (61.54)	1 (2.56)	6 (15.38)	8 (20.51)	0 (0.00)	25 (64.10)
1	3	7 (17.95)	12 (30.77)	20 (51.28)	0 (0.00)	0 (0.00)	19 (48.72)
1	4	2 (5.13)	9 (23.08)	14 (35.90)	12 (30.77)	2 (5.13)	11 (28.21)
2	1	13 (33.33)	8 (20.51)	14 (35.90)	4 (10.26)	0 (0.00)	21 (53.85)
2	2	6 (15.38)	18 (46.15)	7 (17.95)	8 (20.51)	0 (0.00)	24 (61.54)
2	3	9 (23.08)	11 (28.21)	11 (28.21)	7 (17.95)	1 (2.56)	20 (51.28)
2	4	4 (10.26)	22 (56.41)	8 (20.51)	5 (12.82)	0 (0.00)	26 (66.67)
3	1	5 (12.82)	29 (74.36)	5 (12.82)	0 (0.00)	0 (0.00)	34 (87.18)
3	2	5 (12.82)	26 (66.67)	7 (17.95)	1 (2.56)	0 (0.00)	31 (79.49)
3	3	2 (5.13)	33 (84.62)	3 (7.69)	1 (2.56)	0 (0.00)	35 (89.74)
3	4	7 (17.95)	26 (66.67)	4 (10.26)	2 (5.13)	0 (0.00)	33 (84.62)

The wide range in Cycle 1 suggests that some foundational ideas were more accessible than others. Students could demonstrate scientifically acceptable understanding for certain momentum-related items but continued to experience difficulty when the questions required more coordinated reasoning. This pattern is consistent with previous findings that students may possess isolated pieces of knowledge without successfully integrating them into a coherent understanding of momentum (Nguyen and Meltzer, 2003; Rahim *et al.*, 2024). Consequently, a high level of performance on one item should not be interpreted as evidence that all related concepts were fully understood.

In Cycle 2, the narrower CU/PU range indicates greater uniformity across the four items, although PS and AC responses remained. Students were required to relate impulse to momentum change and apply momentum conservation within a defined system. The continued presence of PS and AC responses indicates that some students could identify parts of the relevant relationship but could not yet construct a fully scientific explanation. This finding supports the need for conceptual-change instruction that not only presents the correct equation but also helps students interpret its variables, vector directions, system boundaries, and physical meaning (Sakinah *et al.*, 2023; Edelsbrunner *et al.*, 2023; Smith *et al.*, 2009; Ruiz-Primo and Furtak, 2007).

By Cycle 3, CU/PU responses exceeded 79% for every item, and PS, AC, and NU responses were reduced. This result suggests that students' scientifically acceptable reasoning became more consistent when applying momentum concepts to one-dimensional collisions and separation situations. The improvement should be understood as evidence of greater conceptual consistency rather than as direct evidence that students measured or mastered specific material properties. Nevertheless, collision situations provided a meaningful context in which students could connect system-level momentum conservation with observable outcomes such as rebound, sticking, and separation.

4.3. Learning Behaviors and Conceptual Change during DSLM Instruction

The quantitative results indicate that students' scientifically acceptable responses became more consistent across the three cycles. However, the classification data alone do not explain how students' reasoning and classroom participation changed. To address this issue, evidence from classroom observations and student interviews was integrated. As summarized in **Table 7**, the learning process developed from hesitant prediction and reliance on everyday reasoning toward more systematic comparison of predictions, evidence, representations, and scientific explanations. Nevertheless, several representational and mathematical difficulties remained throughout the intervention.

Table 7. Convergence of observational and interview evidence across the three action research cycles.

CYCLE	OBSERVATION EVIDENCE	INTERVIEW EVIDENCE	INTERPRETATION
1	Many students hesitated to state predictions, relied on everyday explanations, and omitted vector direction or initial-final distinctions. Guiding questions and immediate feedback were often needed.	Students reported that prediction helped reveal differences between their ideas and the evidence, although some were initially worried about giving wrong answers. Visual situations were helpful, but vector signs and symbols were still confusing.	Students' initial ideas became visible, but participation and representational reasoning were still uneven.
2	Students were more engaged, compared predictions with evidence, and more frequently used before-and-after representations. However, system boundaries, subscripts, and equation selection were still problematic.	Students appreciated stepwise questioning, peer discussion, and adequate time to think. They still reported difficulty translating object-level events into system-level representations and equations.	Evidence-based reasoning improved, but system reasoning and symbolic translation remained barriers.
3	Students more systematically identified system boundaries, directions, variables, and sign conventions. Their explanations and discussions became more focused, although some difficulties with equation selection remained.	Students reported that variable checklists, visual distinctions, and interpretation prompts helped them connect physical situations with equations. Some still confused similar symbols and subscripts.	Participation and conceptual revision became more consistent, while some representational difficulties persisted.

In Cycle 1, many students hesitated to express predictions and were concerned about providing incorrect answers. Their initial explanations frequently relied on everyday interpretations, while vector direction and distinctions between initial and final states were sometimes omitted. Guiding questions and immediate teacher feedback were therefore frequently required. Students reported that the prediction stage helped them recognize differences between their initial ideas and the evidence, but vector signs and scientific symbols remained confusing. These findings indicate that the DSLM activities successfully made students' initial conceptions visible, although participation and representational reasoning were not yet consistent.

Making initial ideas explicit is an important part of conceptual-change instruction. Students cannot meaningfully evaluate an existing conception unless they first articulate the conception and compare it with an alternative explanation (Sakinah *et al.*, 2023; Edelsbrunner *et al.*, 2023; Smith *et al.*, 2009). In this study, prediction was not used merely to obtain a correct or incorrect answer. It provided an opportunity for students to reveal how they understood momentum-related situations before examining evidence. The students' hesitation in Cycle 1 also shows that the effectiveness of this process depended on a classroom environment in which incomplete answers could be examined and revised rather than immediately judged as failures.

From a materials-science perspective, everyday observation can support learning but can also produce incomplete interpretations of collision behavior. Students may observe that an object rebounds, stops, separates, or appears to deform and then explain the event only from the visible motion. However, visible motion represents the final result of an interaction rather than the complete mechanism. Scientifically acceptable reasoning requires students to distinguish the motion of each object from the behavior of the defined system and to recognize that material response may influence the visible outcome without invalidating momentum conservation.

For example, rebound may be interpreted conceptually as an outcome involving elastic recovery, whereas sticking may be associated with greater irreversible deformation and energy dissipation. These statements are explanatory materials-science connections, not results of mechanical-property measurements in this study. The observational and interview data did not establish which materials were more elastic, stiff, tough, or highly damped. Instead, the materials-science framework helps clarify why students needed to move beyond surface observations and analyze system boundaries, directions, and before-and-after states.

In Cycle 2, students became more active in comparing their predictions with the available evidence. They more frequently used before-and-after representations and benefited from stepwise questioning, peer discussion, and sufficient time to think. However, system boundaries, subscripts, and equation selection remained problematic. Students also reported difficulty translating object-level events into system-level representations and mathematical expressions. Thus, evidence-based reasoning improved, but the movement from observable events to symbolic and system-based descriptions remained a significant barrier.

The distinction between object-level and system-level reasoning is particularly important in collisions. At the object level, a student may focus on which object is moving faster, which one stops, or which one rebounds. At the system level, the student must identify all relevant objects, assign directions consistently, and compare total momentum before and after the interaction. Failure to establish the system boundary may lead students to treat the momentum lost by one object as momentum that has disappeared, rather than momentum transferred within the system.

The same distinction supports the integration of materials-science concepts. Material-level responses such as elastic recovery, damping, and irreversible deformation describe what may occur within the contacting objects. In contrast, momentum conservation describes the behavior of the selected system under the relevant external conditions. Therefore, the materials-science explanation complements rather than replaces the momentum analysis. Students need both levels of reasoning: the system level explains the conservation relationship, whereas the material level helps interpret differences in rebound, sticking, deformation, and energy dissipation.

Cycle 3 showed further development in students' organization of information. Students more systematically identified system boundaries, directions, variables, and sign conventions. Their explanations and peer discussions also became more focused. Interviews indicated that variable checklists, visual distinctions, and interpretation prompts helped students connect physical situations with equations. Nevertheless, some students continued to confuse similar symbols and subscripts, and difficulties with equation selection did not disappear completely.

These findings indicate that conceptual reconstruction was supported by several connected processes. Students first expressed an initial prediction, compared it with evidence, discussed alternative explanations, and then revised their reasoning with visual, verbal, symbolic, and mathematical support. This sequence is consistent with the central function of DSLM, which combines cognitive conflict with the conceptual resources required to construct a more scientifically acceptable explanation (Sakinah *et al.*, 2023; Edelsbrunner *et al.*, 2023; Smith *et al.*, 2009; Feldman, 1996).

The findings also demonstrate that cognitive conflict alone was insufficient. Showing that an initial prediction was inconsistent with an observed or problem-based outcome did not automatically enable students to construct a correct representation or equation. Students additionally required support for vector signs, system boundaries, variables, subscripts, and relationships among physical quantities. Previous research has similarly shown that conceptual understanding in physics is closely related to the ability to coordinate visual, verbal, symbolic, and mathematical representations (She, 2002; Ruiz-Primo and Furtak, 2007).

In materials-science-based collision learning, representational support is especially important because several processes occur during a short contact event. Before contact, the objects have initial momentum states. During contact, forces act over a short time, while the objects may experience temporary or irreversible deformation. After contact, the objects may rebound, stick, stop, or separate. A single equation does not visually display all these stages. Students must therefore relate the observed event to a simplified system model and select the representations needed to analyze it.

The observational and interview evidence does not show that every student achieved complete conceptual reconstruction. Some difficulties with equations, symbols, and subscripts remained in Cycle 3. The results instead indicate a gradual improvement in participation, evidence-based reasoning, and the ability to connect physical situations with representations. This interpretation is consistent with the CU/PU results, which showed higher conceptual consistency while still identifying students and items that required additional support.

4.4. Reflection-Driven Instructional Improvement

Reflection was used as an evidence-to-action process throughout the classroom action research. After each cycle, evidence from students' responses, observations, interviews, and classroom participation was used to identify learning barriers and modify subsequent instruction. **Table 8** summarizes the problems identified, the instructional modifications introduced, and the evidence observed in the following cycle.

Table 8. Reflection-driven instructional improvement across the three action research cycles.

REFLECTION POINT	EVIDENCE INFORMING REFLECTION	INSTRUCTIONAL MODIFICATIONS	SUBSEQUENT EVIDENCE
Cycle 1 to Cycle 2	Observations showed that students neglected vector direction, relied on everyday intuition, and produced incomplete explanations. Interviews indicated hesitation in making predictions and difficulty interpreting vector representations.	Greater emphasis was placed on direction arrows and vector magnitudes. Evidence-seeking questions, closer monitoring, immediate feedback, and student synthesis were added.	In Cycle 2, students were more active, compared initial and final states more carefully, and used evidence more frequently. All-item CU/PU attainment increased to 51.28%.
Cycle 2 to Cycle 3	Observations revealed problems with system boundaries, subscripts, equation selection, and sign conventions. Interviews confirmed that students struggled to translate situations they understood into symbols and equations.	System-boundary marking, visual distinctions between objects and time states, variable checklists, explicit direction conventions, and written interpretation prompts were introduced.	In Cycle 3, students organized information more systematically and connected physical situations with equations more successfully. All-item CU/PU attainment increased to 79.49%.
After Cycle 3	Eight students remained below the all-item criterion. Observation and interview evidence indicated continuing difficulties with equation selection, vector signs, and intuitive force-mass explanations.	Further equation-selection practice, explicit symbolic instruction, prerequisite review, and interactive experiments or simulations were recommended.	The remaining difficulties identified areas requiring continued instructional support beyond the three cycles.

After Cycle 1, the principal problems involved neglected vector directions, reliance on everyday intuition, incomplete explanations, hesitation in prediction, and difficulty interpreting vector representations. In response, Cycle 2 placed greater emphasis on vector direction and magnitude. Evidence-seeking questions, closer monitoring, immediate feedback, and opportunities for student synthesis were also strengthened. In the subsequent cycle, students became more active, compared initial and final states more carefully, and used evidence more frequently. The all-item CU/PU attainment increased to 51.28%.

After Cycle 2, reflection identified continuing problems with system boundaries, subscripts, equation selection, and sign conventions. Students could sometimes understand the physical situation but struggled to translate it into symbols and equations. Cycle 3 therefore incorporated explicit system-boundary marking, visual distinctions between objects and time states, variable checklists, direction conventions, and written interpretation prompts. In Cycle 3, students organized information more systematically, connected physical situations with equations more successfully, and achieved an all-item CU/PU attainment of 79.49%.

These changes should not be interpreted as isolated treatments with independently measured effects because several modifications were introduced together. Moreover, the three cycles addressed different sequential concepts. Nevertheless, the evidence shows how classroom reflection was used to make the instruction increasingly responsive to the difficulties identified during learning. This process is consistent with classroom action research, in which planning, action, observation, and reflection are used iteratively to improve instructional practice.

The materials-science framing can also be incorporated into this reflection process without claiming additional experimental findings. When students focus only on visible speed or direction, instructional prompts can direct attention to the distinction between system momentum and material response. For instance, questions can ask students to identify the selected system, compare total momentum before and after contact, describe the visible collision outcome, and then consider whether the outcome is conceptually consistent with elastic recovery, irreversible deformation, or energy dissipation. Such prompts strengthen interpretation while remaining within the conceptual scope of the present study.

In addition, this study adds new information regarding physics education, as reported elsewhere (Pardayeva, 2027; Magbarkhanovich *et al.*, 2026).

5. CONCLUSION

Progressively refined DSLM-based instruction supported students' scientific conceptual understanding of momentum and collisions. Post-instruction scores in all cycles were higher than the prerequisite baseline, while all-item CU/PU attainment increased. Observation and interview evidence indicated improved participation, evidence-based reasoning, system identification, and representational use, although difficulties with equations, vector signs, and subscripts remained. The materials-science perspective strengthened collision interpretation by connecting observable outcomes with elastic recovery, deformation, damping, and energy dissipation without treating these properties as measured variables. The findings support iterative, evidence-informed instruction integrating conceptual, representational, and materials-based explanations.

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7. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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