

Designing a Board Game to Support Students' Conceptual Change in Newton's Laws: A Design-based Research Study

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Abstract—This study investigates how an analog board game intervention, developed through Design Thinking and Design-Based Research (DBR), supports students' immediate conceptual understanding of Newton's Laws. A quasi-experimental design compared a Baseline condition, consisting of gameplay with general facilitation, with a Scaffolded condition, consisting of the same gameplay supplemented by brief, contingent academic clarification from a physics teacher. Participants were 50 Grade 11 students from a university-affiliated demonstration school in Thailand, with 25 students in each condition. Conceptual understanding was measured using the Force Concept Inventory (FCI), and qualitative data were analyzed thematically to examine learning mechanisms. Results revealed domain-specific patterns of learning. After correction for multiple comparisons, the clearest post-correction between-group difference favoring the Scaffolded condition was observed for Newton's Second Law reasoning. A positive pattern was observed for Newton's First Law, but this difference did not remain statistically significant after correction. No significant between-group differences were found for Newton's Third Law, suggesting that embedded board game mechanics may have supported immediate action-reaction reasoning in both conditions. Qualitative findings indicated that students' immediate conceptual gains were mediated by epistemic feedback embedded in consequential game mechanics, peer explanation, and brief academic clarification during gameplay. The study proposes a preliminary Physics-Game-Based Learning (Physics-GBL) conceptual change framework and discusses implications for designing domain-sensitive analog game-based learning in secondary physics classrooms.

Keywords—conceptual change, game-based learning, Newton's Laws, design-based research, scaffolding

I. INTRODUCTION

Research in physics education consistently shows that students enter mechanics instruction with persistent intuitive conceptions that hinder coherent Newtonian reasoning and are often insufficiently addressed by traditional instruction [1–6]. Because these misconceptions require conceptual restructuring rather than the simple addition of new information [7, 8], this study examines how tangible board game mechanics and brief, contingent academic scaffolding may support students' immediate conceptual gains.

This study is grounded in three complementary theoretical perspectives: conceptual change theory [9–12], scaffolding theory [13–15], and embodied cognition. Together, these perspectives informed the design of the board game, the use of embedded and contingent instructional supports, and the interpretation of students' immediate conceptual gains. Their integration with the intervention design is described in Section III-C.

II. LITERATURE REVIEW

A. Persistent Misconceptions in Newtonian Mechanics

Physics education research has consistently identified key misconceptions about Newton's Laws, including the impetus view (force as a property of motion), the dominance view (heavier objects exert greater force), and the activation view (force must be continuously applied to maintain motion) [3, 4]. These misconceptions persist across different cultural contexts and continue to be prevalent in classrooms today, as demonstrated by Bao *et al.* [5]. Prarokijjak *et al.* [16] also found that high school students in Thailand exhibited significant misconceptions regarding Newton's Laws, particularly related to force and motion, which were difficult to address through traditional teaching methods. Docktor and Mestre [6] found that traditional problem-solving instruction often fails to address these deep-rooted conceptual issues.

Interactive engagement strategies have shown promise [1], but McDermott and Shaffer [2] emphasized that conceptual change requires explicit attention to specific student difficulties. This suggests that generic active learning may not be sufficient for counter-intuitive concepts such as inertia. Misconceptions in Newtonian mechanics, such as the confusion between force and velocity or the misunderstanding of the relationship between force and acceleration, are not easily rectified through traditional teaching methods. Thus, effective interventions must target these misconceptions directly, rather than assuming they will be automatically corrected by exposure to more information.

These insights highlight the need for instructional strategies that actively engage students in revising their misconceptions and understanding the scientific principles behind Newton's Laws. The game-based approach proposed in this study aims to provide a tool for confronting these misconceptions in a more engaging and interactive manner.

B. Digital and Non-digital Game-based Learning

Meta-analyses by Wouters *et al.* [17] and Boyle *et al.* [18] confirm that serious games and Game-Based Learning (GBL) can significantly enhance learning across various domains, although the effects depend on factors such as design quality and instructional integration. Connolly *et al.* [19] found that games promoting reflection and explanation tend to yield better outcomes compared to those focused solely on speed or competition.

While most GBL studies focus on digital environments, Bayeck [20] emphasized that analog board games provide unique advantages in promoting spatial reasoning, social

negotiation, and tangible learning, which are particularly relevant for teaching vector concepts in physics. Othman and Ching [21] also noted that board games facilitate immediate peer feedback and support embodied interaction with abstract concepts. In contrast to digital games, which may rely on abstract simulations, board games involve direct, physical interaction with materials (e.g., cards, tokens) that require players to engage actively in the learning process.

Despite their potential, empirical studies on the effectiveness of board games for conceptual change in physics are still limited. Recent studies, such as those by Kuo *et al.* [22], have shown how scaffolding integrated into GBL environments can enhance students' conceptual understanding in physics, improving their learning outcomes and engagement. This supports the idea that board games, when designed thoughtfully, can be as effective as digital games in promoting deeper learning and conceptual change.

C. Design-based Research in Physics Educational Game Research

Design-Based Research (DBR) provides an iterative approach for developing and refining educational interventions in authentic learning contexts [23–26]. However, its application in physics educational game research remains limited, particularly in studies examining how game mechanics and instructional scaffolding jointly support conceptual change. Few studies have employed DBR to develop analog board games while also generating empirically grounded design principles for addressing persistent misconceptions in Newtonian mechanics [24, 26, 27]. This study addresses this gap by applying DBR to iteratively refine the board game intervention and synthesize design principles linking game mechanics, scaffolding, and conceptual change.

D. Research Gap and Questions

Despite the independent effectiveness of Game-Based Learning (GBL) and scaffolding in enhancing learning, their integration for fostering conceptual change remains under-explored. Most GBL studies focus on digital environments, overlooking the unique benefits of tangible analog games for physics education. In addition, scaffolding research has mainly concentrated on traditional classroom settings, with limited attention to dynamic scaffolding in game-based learning contexts. Furthermore, few studies have employed Design-Based Research (DBR) to develop design principles specifically aimed at addressing misconceptions about Newton's Laws.

This study aims to bridge these gaps by investigating how combining board game mechanics with adaptive scaffolding can facilitate conceptual change in various aspects of Newtonian mechanics (e.g., inertia, force-acceleration, and action-reaction). Specifically, it seeks to distinguish which concepts emerge naturally through gameplay and which strictly require targeted instructional mediation.

This study employs a Design-Based Research (DBR) approach integrated with Design Thinking to:

- (1) Develop a board game intervention targeting misconceptions about Newton's Laws through iterative prototyping.
- (2) Investigate how scaffolded game-based learning (with teacher facilitation) compares to baseline game-based

learning (gameplay alone) in promoting students' conceptual understanding.

- (3) Synthesize design principles that explain the relationship between game mechanics, scaffolding, and conceptual change mechanisms.

The research questions (RQs) guiding this study are:

RQ1: How can Design Thinking and DBR be applied to develop a physics board game that effectively addresses misconceptions about Newton's Laws of Motion?

RQ2: To what extent does a scaffolded game-based learning environment (combining gameplay with brief, contingent academic clarification) differ from a baseline environment (gameplay only) in promoting students' conceptual understanding, as measured by the Force Concept Inventory (FCI)?

RQ3: What design principles emerge?

III. RESEARCH METHODOLOGY

A. Research Design: Integrating Design-based Research and Design Thinking

This study utilized a Design-Based Research (DBR) framework [23, 24] combined with Design Thinking to address persistent misconceptions in physics, which represent a wicked problem [25]. DBR was chosen for its ability to generate dual outcomes: (a) a functional educational artifact (the physics board game) and (b) theoretical insights regarding the interplay between game mechanics and conceptual change [26, 27].

The research was conducted in four iterative phases aligned with the Design Thinking framework (Empathize, Define, Ideate, Prototype/Test) and DBR cycles (Analysis, Design, Implementation, Reflection):

Phase 1: Context Analysis and Empathy (Empathize/Define)

Phase 2: Design and Prototyping (Ideate/Prototype)

Phase 3: Implementation and Evaluation (Test/Implement)

Phase 4: Knowledge Synthesis (Reflect/Synthesize)

This design process ensured that the intervention (board game) evolved in response to feedback from stakeholders (teachers, students, and physics education experts), while maintaining a focus on improving conceptual understanding of Newtonian mechanics.

B. Participants and Context

The initial sample consisted of 55 Grade 11 students (aged 16–17) from a university-affiliated demonstration school in Thailand. All participants had prior exposure to traditional instruction on Newton's Laws, ensuring the presence of established misconceptions for the intervention [3, 4].

A pilot phase was conducted with 5 students to inform the intervention design; these students were excluded from the outcome analyses. The remaining 50 students formed the main analytic sample.

This study employed a quasi-experimental design. To preserve natural peer grouping and enjoyment during the board game activity, students were first allowed to select one of two available gameplay rooms/sessions. Students were not informed in advance which room would be assigned to the Baseline or Scaffolded condition. After room selection, the

two sessions were assigned to the Baseline and Scaffolded conditions, resulting in 25 students per group.

Operationally, the baseline condition refers to gameplay supported by general facilitators who helped students understand rules, manage turn-taking, and maintain the flow of play, without providing additional academic explanation of Newtonian concepts. The Scaffolded condition refers to the same gameplay structure, with the addition of brief, contingent academic clarification from a physics teacher when students asked conceptual questions or displayed uncertainty during gameplay.

Although students did not knowingly select a treatment condition, this procedure may still have introduced potential selection bias because room selection could have reflected existing peer relationships, participation preferences, or engagement tendencies. Therefore, baseline equivalence was examined using pre-test FCI scores. Mann–Whitney U tests indicated no statistically significant pre-test differences between groups. Nevertheless, because pre-test equivalence does not fully control motivational or social-grouping factors, between-group comparisons should be interpreted cautiously and should not be treated as evidence from a randomized controlled trial.

Baseline Group ($n = 25$): Gameplay with embedded hard scaffolds and general gameplay facilitation only.

Scaffolded Group ($n = 25$): The same gameplay structure with additional brief, contingent academic clarification from a physics teacher within the Zone of Proximal Development (ZPD) [28].

Power analysis confirmed that $n = 25$ per group was sufficient to detect medium-to-large effect sizes ($r \geq 0.30$) with $\alpha = 0.05$ [29]. This design enabled a structured comparison between the two conditions and supported examination of the role of scaffolding in conceptual change.

C. Intervention Design: Theoretical Framework

1) Conceptual change and embodied cognition

The game design was based on Conceptual Change Theory [10, 30] and Embodied Cognition [11]. It was hypothesized that tangible manipulation of physical objects (e.g., cards and tokens) would externalize abstract concepts, reducing cognitive load and promote conceptual change [20]. The approach followed Sessa's theory of knowledge-in-pieces [12], where intuitive fragments are reorganized into coherent scientific models.

By using physical elements (e.g., force cards, mass cards) within the board game, the intervention aimed to help students reframe their mental models of force, acceleration, and motion through embodied interaction. This was designed to help learners confront their misconceptions in a hands-on manner, promoting a deeper understanding of Newton's Laws.

2) Scaffolding in game-based learning

Hard scaffolds (e.g., embedded game constraints) and soft scaffolds (brief, contingent academic support) were distinguished within the game-based learning environment [13, 14]. According to Wouters *et al.* [17], soft scaffolding is crucial for concepts that are more distant from students' everyday intuitions, such as inertia and force-acceleration relationships.

In this study, soft scaffolding was provided through brief, contingent academic clarification during gameplay. The teacher responded to students' questions or uncertainty by helping them connect gameplay outcomes with Newtonian concepts. The scaffolding was designed to be contingent on students' needs and levels of understanding, encouraging self-correction and deeper engagement with the material.

3) Game components and mechanics

The game board was designed in the context of a "zombie outbreak city," with a grid layout where players move toward a safe zone by analyzing forces and motion. Areas on the board varied (e.g., rough surfaces, slippery roads, inclined planes), affecting the net force (ΣF) on objects. Concept Checkpoints required players to explain Newton's Laws before proceeding.

- Game Components included: Mass cards (2–10 kg) to determine character mass. Force cards (increase/decrease force, friction) to adjust the resulting force. Newton's Law cards (1st, 2nd, 3rd Law) for explaining scenarios. Concept Challenge cards to challenge misconceptions (e.g., "Objects in motion require continuous force" or "Action and reaction forces cancel each other"). Event Cards triggered by dice rolls to simulate physical scenarios that affect force.
- Core Mechanics: Players were required to (1) Predict motion (rest, constant velocity, acceleration) with justification. (2) Identify all forces acting on the object. (3) Calculate net force (ΣF). (4) Compute acceleration using $a = \frac{\Sigma F}{m}$. (5) Move according to the calculated results. Negative consequences occurred if predictions did not align with calculations, promoting cognitive conflict and aiding in the restructuring of concepts related to force and motion.

The game prototype was refined through four iterative cycles; details of each iteration are reported in Section IV.

D. Data Collection Instruments

1) Force Concept Inventory (FCI)

The Force Concept Inventory (FCI) [4] was used as a pre-test and post-test to assess students' conceptual understanding of Newton's Laws. The FCI has demonstrated reliability and validity in prior physics education research [6]. The Thai-language version used in this study was adapted from the researchers' previous implementation of the FCI with students from the same school in an earlier academic year [16]. This prior use helped ensure that the wording was appropriate for the local instructional context. No additional contextual modification was made in the present study in order to preserve the diagnostic structure of the original FCI. In the current sample ($N = 50$), internal consistency reliability was estimated using the Kuder–Richardson Formula 20 (KR-20), which is appropriate for dichotomously scored items. The KR-20 coefficient was 0.76. The pre-test was administered before the intervention to establish baseline understanding, and the post-test was administered immediately after the intervention to assess immediate conceptual gains.

The FCI consists of multiple-choice questions designed to probe common misconceptions about Newton's Laws, such as confusion between force and velocity, misunderstanding

of the relationship between force and acceleration, and misconceptions regarding action-reaction pairs.

2) *Qualitative data sources*

To supplement the quantitative data from the FCI, qualitative data were collected to provide deeper insights into students' thought processes and conceptual changes during the intervention. These data sources included:

Observational Protocols: The researcher documented instances where students used physics terminology, explained their reasoning, or experienced cognitive conflict. Observations also focused on the extent to which students engaged with the game mechanics and made connections between the game's scenarios and scientific principles.

Semi-Structured Interviews: These were conducted with 10 students and 2 teachers to probe conceptual insights, difficulties encountered, and perceptions of the game's effectiveness in addressing misconceptions. The interviews provided a more detailed understanding of how students internalized the game's mechanics and whether the scaffolding helped improve their understanding of Newton's Laws.

Design Logs: These logs were maintained throughout the iterative design process to document the changes made to the game and feedback received from the expert reviews and pilot testing. This provided insight into the development of the game and how its design evolved to better meet the learning objectives.

E. *Procedure*

The study followed four systematic phases:

1) *Phase 1: Context analysis and empathy*

An FCI pre-test was administered to establish baseline misconceptions. This allowed the researcher to understand the existing conceptual gaps and tailor the intervention accordingly. Empathy mapping workshops were conducted with students and interviews with teachers to identify barriers to learning. These workshops provided valuable insight into students' attitudes toward physics and their common misconceptions, which informed the game's design.

2) *Phase 2: Design and prototyping*

Weekly design sprints and expert review sessions were conducted with physics educators and board game designers. This iterative process allowed for rapid testing and refinement of the game. The prototypes were pilot-tested with 5 students to gather initial feedback on the game's mechanics and identify areas for improvement. The pilot test helped refine the game's rules, balance, and clarity before full implementation.

3) *Phase 3: Implementation and evaluation*

Students participated in either the Baseline or Scaffolded gameplay session as described in the Participants and Context section. During implementation, both conditions used the same board game, rules, gameplay duration, and general facilitation structure. At the beginning of each session, facilitators spent approximately 5–10 minutes explaining the rules and gameplay procedures. Students then played the game for the remaining session time. General facilitators were available in both rooms to support rule clarification, turn-taking, and procedural flow.

Prior to implementation, the physics teacher had played the game with the researchers and had become familiar with the rules, mechanics, and intended learning objectives. In the Scaffolded condition, the teacher provided brief, contingent academic clarification during gameplay when students raised questions or displayed uncertainty about Newtonian concepts. These clarifications usually lasted no more than 3–5 min and focused on linking game outcomes to concepts such as net force, acceleration, inertia, and action-reaction pairs. The teacher did not provide a separate post-game lecture or summary; academic clarification occurred only during gameplay. The Baseline condition did not include this additional physics-related clarification. The FCI post-test was administered immediately after the intervention to measure immediate conceptual gains.

4) *Phase 4: Knowledge synthesis*

Quantitative data using Wilcoxon Signed-Rank were analyzed for within-group comparisons and Mann-Whitney U for between-group comparisons to assess changes in conceptual understanding. Qualitative data were analyzed using thematic analysis [31] to identify key themes related to cognitive conflict, scaffolding uptake, and students' reasoning about Newton's Laws. To enhance credibility, preliminary qualitative interpretations were checked with participating students and teachers to ensure that they aligned with their reported experiences.

F. *Data Analysis*

1) *Quantitative data analysis*

Because FCI subdomain scores ranged from 0 to 3 and were treated as ordinal, non-parametric statistical procedures were employed. Within-group differences between pre-test and post-test scores for the baseline and scaffolded groups were examined using the Wilcoxon signed-rank test. Between-group differences in gain scores were analyzed using the Mann-Whitney U test. Effect sizes were calculated as standardized r values ($r = \frac{|Z|}{\sqrt{N}}$) and interpreted according to Cohen's conventions [32] to evaluate the magnitude of both within-group and between-group differences.

2) *Qualitative data analysis*

Thematic analysis was used to analyze qualitative data collected from observations, semi-structured interviews, and design logs [31]. The analysis focused on identifying patterns related to cognitive conflict, uptake of instructional scaffolding, and the development of conceptual understanding of Newton's Laws. Cognitive conflict episodes were defined as moments in which students' initial predictions or explanations of physical phenomena were challenged during gameplay. Scaffolding uptake referred to the extent to which students engaged with teacher prompts and used them to refine their reasoning. The analysis also examined students' evolving explanations of key physics concepts, including how their understanding of force, motion, and acceleration developed during the intervention. Discrepancies in coding were resolved through discussion until consensus was reached, and inter-rater reliability was established with Cohen's $\kappa = 0.84$, indicating strong agreement.

G. Ethical Statement

Ethical approval was granted by the Human Research Ethics Committee of Thammasat University (Social Sciences), Project No. SSTU-EC 105/2567, Certificate of Approval No. 079/2567. Written informed consent was secured from all participants and their guardians. Data were anonymized and securely stored, with only aggregated results reported. Participation was voluntary, and students could withdraw at any time without penalty.

IV. RESULTS

A. Phases 1 & 2: Design Process and Iterative Refinement

The zombie-themed physics board game was developed through four iterative design cycles following the principles of Design-Based Research (DBR) and Design Thinking. The design process included empathy mapping workshops, diagnostic FCI testing with students ($n = 50$), classroom observations, playtesting with physics educators ($n = 3$), board game designers ($n = 3$), and a pilot implementation with students ($n = 5$). The primary focus was on identifying key misconceptions related to Newton's Laws and designing game mechanics that could effectively challenge these misconceptions.

An analysis of diagnostic responses and classroom discussions revealed three recurring misconception clusters related to Newtonian mechanics. The first cluster reflected an impetus view, in which students described force as a sustaining property of motion and predicted that objects would stop when no force was applied, even in situations involving zero net force. A second cluster reflected a dominance view, where students predicted that heavier objects exert greater force than lighter ones during interactions. A third pattern involved force–velocity conflation, in which students used force and speed interchangeably and interpreted higher velocity as evidence of greater force.

These findings informed several design priorities for the board game intervention. First, force and mass were externalized through tangible game components that allowed players to manipulate and compare these quantities directly. Second, game progression was explicitly linked to the correct application of Newton's Second Law ($F = ma$). Third, the gameplay mechanics required players to articulate explanations of Newton's Laws before advancing, embedding conceptual explanation as an integral part of the learning process.

Four prototype versions (V1–V4) were developed and tested sequentially. Each iteration addressed specific mechanical and instructional issues identified during playtesting.

1) V1: Grid-based prototype

Findings. Initial playtesting with three physics teachers revealed that dice-based movement frequently took precedence over force calculations. As a result, students attributed motion outcomes to chance rather than to the relationship between net force (ΣF), mass, and acceleration. When predictions failed, students commonly explained discrepancies as “luck” instead of re-evaluating their force analysis.

Design reflection. The inclusion of randomness reduced the causal transparency of the game system. Because movement was not directly governed by Newtonian relationships, incorrect predictions did not consistently prompt recalculation or revision of force diagrams.

Revision. Dice were removed, and movement became strictly determined by force and mass cards. This modification ensured that gameplay outcomes directly reflected Newtonian relationships, increasing the likelihood that incorrect predictions would generate meaningful cognitive conflict.

2) V2: Card-driven prototype

Findings. Although calculation-based movement strengthened causal alignment, “dead turns” emerged in balanced-force scenarios ($\Sigma F = 0$). In these situations, some students continued to predict motion despite the absence of net force, reflecting persistence of impetus-based reasoning.

Design reflection. Zero-net-force situations created opportunities for conceptual tension; however, the game lacked mechanisms that required players to explain or re-analyze these outcomes. As a result, instances of cognitive conflict sometimes passed without deeper reflection.

Revision. Additional card variations and consequence-based mechanics were introduced, including penalties for incorrect predictions and structured comparison between expected and actual outcomes. These adjustments were intended to transform prediction errors into explicit opportunities for discussion rather than incidental gameplay events.

3) V3: Circular narrative prototype (“zombie escape”)

Findings. The introduction of a circular board layout and survival narrative increased student engagement and peer discussion. Students began to argue and justify their decisions more frequently during gameplay.

Design issue. However, some groups were able to succeed through positional strategies and resource management without consistently applying Newtonian reasoning. As a result, conceptual engagement varied across groups.

Design reflection. Although social interaction increased, the game lacked a mechanism that required players to articulate scientific reasoning as a condition for progression.

Revision. The scoring system was modified so that advancement required correct justification of force relationships before movement. This modification linked success in the game directly to principled reasoning.

4) V4: Dual-scoring prototype

Mechanism design. The final prototype introduced a dual-scoring structure consisting of kinematic points and reasoning points. Kinematic points were awarded for accurate motion calculations based on $a = \frac{\Sigma F}{m}$, whereas reasoning points were awarded for correct identification of forces and scientifically justified explanations. To obtain full credit, players were required to demonstrate both quantitative accuracy and conceptual coherence.

Functional consequence. Prediction–outcome mismatches could no longer be ignored. When calculations were correct, but explanations were inconsistent with the net force analysis, points were withheld. Conversely, when reasoning was correct, but the computation was incorrect,

players were required to revisit their evaluation of net force, mass, or acceleration.

Structural outcome. This redesign produced several shifts in gameplay. Progress became dependent on principled understanding rather than strategic positioning, and explanation became an explicit requirement for advancement. In addition, both balanced and unbalanced force scenarios functioned as recurring triggers for recalculation and discussion.

In the final version, epistemic tension was embedded within the rule structure of the game rather than occurring incidentally, thereby aligning gameplay progression systematically with the learning objectives of Newtonian mechanics

B. Phase 3: Comparative Effectiveness of Scaffolding Conditions

1) Descriptive statistics and baseline equivalence

Data were screened for normality using the Shapiro-Wilk tests, which indicated significant deviations from normality ($p < 0.05$), justifying the use of non-parametric procedures [29]. Table 1 presents median scores and Interquartile Ranges (IQR) for both conditions across pre-test, post-test, and gain scores.

Mann-Whitney U tests indicated no statistically significant pre-test differences between the Baseline and Scaffolded groups for total FCI scores ($U = 311.50$, $p = 0.992$) and all subdomains (First Law, $p = 0.291$; Second Law, $p = 0.513$; Third Law, $p = 0.092$). These results supported the descriptive comparability of groups on measured baseline conceptual understanding, although they do not rule out unmeasured motivational or social-grouping differences associated with the grouping procedure.

Table 1. Descriptive statistics for Force Concept Inventory (FCI) subdomain scores (ordinal scale 0–3)

Domain	Group	n	Pre-Test Median [IQR]	Post-Test Median [IQR]	Gain Median [IQR]
First Law	Baseline	25	1 [0–1]	1 [0–2]	0 [–1 to 1]
	Scaffolded	25	1 [0–1]	2 [1–2]	1 [0–2]
Second Law	Baseline	25	1 [0–1]	0 [0–1]	0 [–1 to 1]
	Scaffolded	25	0 [0–1]	1 [1–2]	1 [0–1]
Third Law	Baseline	25	0 [0–1]	1 [0–3]	1 [0–2]
	Scaffolded	25	1 [0–1]	1 [0–3]	1 [0–2]
Total	Baseline	25	2 [1–3]	3 [1–5]	1 [–1 to 3]
	Scaffolded	25	2 [1–2]	4 [3–6]	2 [1–5]

Note: Possible scores for each subdomain: 0 (no understanding), 1 (partial), 2 (developing), 3 (sound understanding). Gain scores range from –3 to +3. IQR = Interquartile Range (Q1–Q3).

2) Within-group conceptual gains

Addressing RQ2, Wilcoxon Signed-Rank tests were used to examine within-group pre-post change across conditions (Table 2). Effect sizes were calculated as standardized r statistics ($r = \frac{|Z|}{\sqrt{N}}$), where N represents the number of non-tied pairs in each Wilcoxon comparison. The corresponding N values are reported in Table 2. Effect sizes were interpreted using Cohen's [32] conventions.

Within-group comparisons showed that the Scaffolded group demonstrated statistically significant immediate gains across all domains ($p \leq 0.011$), with medium-large to large effect sizes ($r = 0.58$ – 0.88). In contrast, the Baseline group showed statistically significant immediate gains only for the

Third Law ($p = 0.007$), with non-significant pre-post changes for the First and Second Laws. This pattern suggests that baseline gameplay with embedded hard scaffolds may have supported immediate action-reaction reasoning, whereas inertia and force-acceleration reasoning appeared to benefit more from additional brief academic clarification.

Table 2. Within-group comparisons (pre- vs. post-test)

Group	Domain	Z	p	r	Interpretation
Baseline	First Law	–1.57	0.103	0.36	Non-significant
	Second Law	–0.62	0.508	0.16	Non-significant
	Third Law	–2.66	0.007	0.61	Large effect
	Total	–1.75	0.078	0.37	Marginal
Scaffolded	First Law	–3.58	<0.001	0.82	Large effect
	Second Law	–3.18	0.001	0.88	Large effect
	Third Law	–2.52	0.011	0.58	Medium-large effect
	Total	–3.91	<0.001	0.85	Large effect

Note: Effect sizes (r) were calculated as $r = \frac{|Z|}{\sqrt{N}}$, where N represents the number of non-tied pairs in each comparison (Baseline: First Law $N = 19$, Second Law $N = 15$, Third Law $N = 19$, Total $N = 22$; Scaffolded: First Law $N = 19$, Second Law $N = 13$, Third Law $N = 19$, Total $N = 21$).

3) Between-group comparisons

Mann-Whitney U tests comparing gain scores between conditions revealed differential patterns across FCI subdomains (Table 3).

Table 3. Between-group comparisons (gain scores)

Domain	U	Z	p	r
First Law Gain	213.00	–1.98	0.048	0.28
Second Law Gain	182.00	–2.68	0.008	0.38
Third Law Gain	334.50	0.44	0.671	0.06
Total Gain	235.50	–1.51	0.135	0.21

Because three FCI subdomains were analyzed, a Bonferroni-adjusted alpha level of 0.017 was applied to reduce the risk of Type I error inflation. Before correction, gain scores differed between conditions for the First Law ($p = 0.048$, $r = 0.28$) and the Second Law ($p = 0.008$, $r = 0.38$), whereas no significant difference was observed for the Third Law ($p = 0.671$, $r = 0.06$) or total FCI gain ($p = 0.135$, $r = 0.21$). After correction, the between-group difference in the Second Law gain remained statistically significant, whereas the First Law gain difference should be interpreted as a positive trend that did not remain significant after correction. Therefore, the clearest between-group evidence for the added value of the Scaffolded condition was found in students' immediate gains in Newton's Second Law reasoning.

The absence of a significant between-group difference for the Third Law gain suggests that the embodied and interactional structure of the board game may have supported immediate action-reaction reasoning in both conditions. This pattern is consistent with the possibility that some Newtonian concepts may be more accessible through embedded game mechanics, whereas more counter-intuitive concepts, such as force-acceleration relationships, may require brief academic clarification [12]. The non-significant difference in the total FCI gain further suggests that scaffolding effects were domain-contingent rather than uniform across all conceptual domains.

C. Qualitative Analysis: Mechanisms of Conceptual Change

To address RQ3, thematic analysis of observational field notes and semi-structured interviews ($n = 12$; 10 students and

2 teachers) identified three superordinate themes that appeared to mediate the quantitative outcomes observed between conditions.

1) *Cognitive conflict and epistemic disequilibrium*

Students in the Scaffolded condition frequently encountered gameplay outcomes that contradicted their initial predictions. A recurring pattern involved zero net force scenarios. For example, when a player applied equal opposing forces (e.g., +20 N and -20 N) and expected motion, the token remained stationary.

One student reflected:

“I played a +20 N force card and expected my zombie to move forward, but then the obstacle applied -20 N. The teacher pointed out that my net force was exactly zero. That was when I realized that balanced forces mean no change in motion”.

Across observed gameplay sessions, prediction–outcome mismatches were often followed by recalculation of ΣF , revision of free-body diagrams, and modification of verbal explanations. These episodes frequently included explicit reference to Newton’s First or Second Law, suggesting that anomalous outcomes triggered principled reanalysis rather than procedural correction alone.

In contrast, students in the Baseline group were less likely to revisit underlying assumptions after incorrect predictions. Unexpected outcomes were sometimes attributed to “game rules” or “bad luck,” and diagram use was comparatively infrequent. When reanalysis occurred, it was typically peer-initiated rather than systematically scaffolded.

Across cases, cognitive conflict most consistently resulted in conceptual reconsideration when attention was explicitly redirected to net force as a causal variable. This redirection occurred substantially more often in the Scaffolded condition.

2) *Scaffolded intervention within the zone of proximal development*

Teacher interventions in the Scaffolded group transformed gameplay errors into structured opportunities for conceptual refinement. Two recurring scaffolding patterns were identified: contingent prompting and comparative analysis.

Contingent prompting. When students produced correct calculations but relied on impetus-based explanations (e.g., “the force ran out”), teachers posed follow-up questions such as:

“What does Newton’s First Law say when net force equals zero?”

These prompts shifted students’ attention from surface descriptions of motion to underlying force relationships. The scaffolding helped students reorganize their intuitive explanations within the formal framework of Newton’s Laws, frequently resulting in self-correction and reformulated explanations that were scientifically consistent.

Comparative analysis. Teachers also encouraged students to compare successful and unsuccessful moves, directing attention to differences in net force (ΣF), mass, or acceleration. In several sessions, students revised earlier reasoning after contrasting structurally similar board states that produced different motion outcomes.

In the Baseline group, structured comparison episodes were rare. Peer discussion tended to focus on procedural aspects of gameplay rather than the underlying physical

principles. Misconceptions, particularly impetus-based reasoning, sometimes persisted across multiple turns without systematic challenge.

Overall, scaffolding appeared to increase both the frequency and depth of mechanistic reasoning, supporting transitions from descriptive explanations to principle-based reasoning.

3) *Social negotiation and enforced explanation*

The enforced explanation mechanic required players to justify card selections during Event Card challenges and Concept Checkpoints. This rule generated sustained peer-to-peer discourse and visible externalization of reasoning processes.

One student stated:

“I had to explain to my friend why the big zombie pushed the small one with equal force. I had to convince myself first. It didn’t make sense until I drew the force diagrams on the worksheet.”

Classroom observations indicated that articulation often preceded diagram construction and recalculation. In several groups, students revised predictions following peer questioning, and disagreements were typically resolved by referencing free-body diagrams or the equation $F = ma$.

In contrast, Baseline groups completed turns more rapidly and produced fewer explicit justifications. Diagram use was less frequent and was seldom initiated spontaneously.

Across cases, mandatory articulation appeared to function as an epistemic amplifier, transforming implicit intuitions into publicly examinable claims and increasing opportunities for immediate conceptual development.

4) *Domain-specific variation in conceptual change mechanisms*

Qualitative evidence suggested domain-specific variation in the intensity of scaffolding required. Impetus-based reasoning emerged frequently during early gameplay when students reasoned about Newton’s First and Second Laws. Students often described motion as sustained by force and required repeated prompting to reconceptualize force as a cause of acceleration determined by net force. These domains therefore appeared to involve stronger conceptual resistance and required explicit ontological clarification.

In contrast, reasoning related to Newton’s Third Law appeared to emerge more readily during collision scenarios. In several sessions, students spontaneously stated that “both objects push each other,” even without teacher prompting. This pattern was observed across both conditions and suggests comparatively lower ontological distance for Third Law reasoning.

Taken together, these observations indicate that conceptual change mechanisms in game-based environments are not uniform across content domains, but vary according to the epistemic structure of the target concept.

5) *Cross-theme synthesis*

Across the qualitative themes, three interacting mechanisms appeared to mediate conceptual change in the game-based environment. First, epistemic feedback was embedded within consequential game mechanics, ensuring that prediction–outcome mismatches generated opportunities for reflection. Second, contingent scaffolding redirected students’ attention toward net force as the causal variable

underlying motion. Third, socially distributed reasoning emerged through enforced explanation, which required players to articulate and defend their reasoning during gameplay.

Importantly, these mechanisms operated synergistically. Cognitive conflict alone did not reliably produce conceptual reconsideration. Instead, conflict became productive when combined with structured scaffolding and opportunities for peer articulation.

D. Phase 4: Emergent Design Principles

The iterative DBR process led to the identification of three empirically grounded design principles for the physics board game design.

Concept-specific scaffolding suggests that scaffolding resources should concentrate on conceptual domains characterized by persistent ontological resistance, such as reasoning about net force and acceleration, rather than being distributed uniformly across content areas.

Consequential validity indicates that game mechanics should mirror physical causality so that misconceptions produce visibly suboptimal outcomes. In this way, epistemic feedback becomes embedded directly within gameplay.

Social epistemic agency highlights the importance of mandatory peer articulation. Requiring players to explain their reasoning transforms gameplay from procedural interaction into collective knowledge construction, increasing the likelihood of diagram-based reasoning and conceptual clarification.

Together, these principles informed the development of a preliminary Physics-Game-Based Learning (Physics-GBL) Conceptual Change Framework as presented in the following section.

V. DISCUSSION

A. Interpretation of Findings

The corrected between-group results indicate differential effects across Newton's Laws. The clearest post-correction between-group differences favoring the Scaffolded condition was observed in Newton's Second Law reasoning. Although the Scaffolded condition showed a positive gain pattern for Newton's First Law, this between-group difference did not remain statistically significant after correction for multiple comparisons. No significant between-group difference was observed for Newton's Third Law. These results suggest that the cognitive demand for immediate conceptual gains varies according to the ontological commitment specific to each domain [8].

Newton's Third Law (action-reaction) appeared to be supported by the game mechanics embedded in the board game. The symmetric collision action allowed students to experience the perceptual-motor concept of equal and opposite forces [20]. When students observed the symmetric outcome of the collision, the embedded game constraints functioned as hard scaffolds that may have made the action-reaction relationship more accessible without additional academic clarification. This interpretation aligns with diSessa's [12] concept that some intuitive resources known as phenomenological primitives (p-prims) can be productively reorganized through embodied interaction.

In contrast, Newton's First and Second Laws appeared to be more conceptually demanding, particularly because they contradict deeply ingrained intuitive beliefs such as the impetus view of force as a property of motion and the conflation of force with velocity [3]. The corrected between-group results provide the clearest evidence for the added value of the Scaffolded condition for Newton's Second Law reasoning, while the First Law pattern should be interpreted more cautiously as a positive trend. In the Baseline condition, where additional teacher clarification was absent, students encountered cognitive conflict, for example when tokens failed to move despite force cards being played, they often interpreted these outcomes as arbitrary game rules rather than representations of physical principles. Brief, contingent academic scaffolding may have helped students connect these gameplay outcomes with Newtonian reasoning, especially in force-acceleration situations. This interpretation is consistent with Pol *et al.*'s [28] meta-analysis, which suggests that responsive scaffolding is especially important when target concepts are distant from students' existing knowledge structures.

An additional pattern warrants attention. In the Baseline condition, the median score for Newton's Second Law decreased from pre-test to post-test, although the change was not statistically significant ($p = 0.508$). This descriptive trend may indicate possible conceptual destabilization without sufficient interpretive support. Understanding the Second Law requires students to grasp the proportional relationships between net force, mass, and acceleration, a shift that departs substantially from intuitive force-as-speed reasoning. Without brief academic clarification, gameplay-induced conflict may have unsettled partially correct schemas without consolidating scientific causality. This interpretation is consistent with conceptual change in the literature showing that cognitive conflict alone does not necessarily lead to accommodation [8, 10]. Thus, it should be treated cautiously, because the descriptive pattern does not constitute definitive evidence that baseline gameplay caused conceptual decline.

Instead, the pattern suggests that for conceptually demanding domains such as force-acceleration reasoning, conflict generated by gameplay may require interpretive support to become productive for immediate conceptual gains. These findings align with research demonstrating that responsive scaffolding is crucial for guiding learners through conceptually demanding learning processes [22, 28].

While studies highlight the motivation benefits of card-based approaches [33], our findings extend this literature by clarifying when explicit scaffolding appears to be especially important, namely for counter-intuitive mechanical concepts rather than physically symmetric ones.

B. Theoretical Implications

This study proposes the preliminary Physics-Game-Based Learning (Physics-GBL) conceptual change framework, synthesizing insights from conceptual change theory, Embodied Cognition, and Scaffolding research (Fig. 1). To distinguish the learning mechanism proposed here from the Design-Based Research phases described earlier, the model is articulated in three sequential steps rather than phases. The model posits that effective physics learning through games may involve three sequential, but interdependent steps:

Step 1: Activation and Conflict Generation. Tangible game mechanics activate learners' intuitive schemas and generate epistemic conflict when outcomes contradict predictions. The consequences of game outcomes, in which miscalculations produce visibly suboptimal results [34], can create dissatisfaction with existing conceptions [10]. This provides the kind of anomalous experience often considered necessary for conceptual change.

Step 2: Cognitive Disequilibrium. Learners experience instability in their existing explanatory framework, particularly when net force relationships challenge force-as-speed intuitions [9]. The board game's physical constraints serve as hard scaffolds that externalize abstract vector relationships, reducing working memory load [18]. However, as observed in the Baseline condition, disequilibrium alone is insufficient for accommodation. Accordingly, the framework distinguishes between conflict generation and conflict resolution: game mechanics may generate cognitive conflict, but brief academic scaffolding may be needed to help students interpret and resolve such conflict into more coherent Newtonian reasoning.

Step 3: Scaffolded Accommodation. Through contingent instructional mediation, learners reorganize their ontological categorization of force, transitioning from substance-like to process-like reasoning [8]. Brief, contingent academic scaffolding bridges the Zone of Proximal Development (ZPD) [15], providing the soft scaffolds necessary to resolve disequilibrium. Through Socratic questioning and explicit connection-making, teachers guide students to reinterpret game events using Newtonian formalisms, transforming in-game procedural knowledge into transferable conceptual understanding.

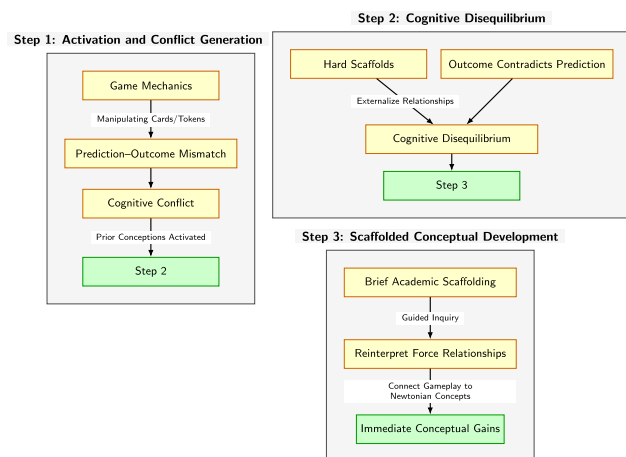


Fig. 1 The preliminary Physics-Game-Based Learning (Physics-GBL) conceptual change framework: Interplay between tangible game mechanics and brief academic scaffolding in supporting immediate conceptual gains.

C. Relation to Prior Literature

These findings extend the Game-Based Learning (GBL) literature in three significant ways.

First, although Wouters *et al.* [17] found that serious games generally enhance learning, they also reported that effect sizes vary according to the degree of instructional support. The present study helps clarify when such support is most needed: it appears to be especially important for concepts that may involve greater ontological restructuring, such as Newton's First and Second Laws, but less necessary for

concepts that correspond more directly to observable physical symmetry, such as Newton's Third Law. This pattern suggests that scaffolding is particularly important for counter-intuitive concepts, including inertia and the force-acceleration relationship, because these concepts often conflict with students' pre-existing mental models [3]. In contrast, Newton's Third Law appeared to be supported by the embedded game mechanics, because its symmetry was more compatible with students' intuitive understanding.

Second, this study responds to Bayeck's [20] call for more research on the unique affordances of analog board games. Unlike digital simulations, in which physical processes are hidden in code, the board game's tangible manipulatives, such as force cards, mass cards, and tokens, made force relationships visible and negotiable, thereby supporting the embodied dimensions of physics learning [35]. The socially situated nature of gameplay, which required students to explain, justify, and negotiate their moves with peers, also created opportunities for collective argumentation that extended beyond individual discovery learning [19]. In this way, the game supported not only individual sense-making but also social learning processes that can deepen conceptual understanding [19, 35].

Third, the findings refine Design-Based Research (DBR) approaches to educational game design [24, 27]. The iterative progression from Prototype V1 to V4 showed that consequential validity, namely ensuring that scientific reasoning determines game outcomes, is necessary but not sufficient for conceptual change [34]. In particular, the dual-scoring structure introduced in V4, which combined Kinematic Points with Reasoning Points, strengthened epistemic agency by requiring players not only to calculate correctly, but also to articulate principled justifications for their moves. This transformed gameplay into a site of collective knowledge construction rather than mere procedural success. The DBR process further showed that effective game mechanics must be complemented by pedagogical scaffolding explicitly designed to address domain-specific misconceptions [26]. Taken together, these findings suggest that embedding scientific reasoning in game outcomes alone is insufficient to ensure conceptual change, especially when the target concepts conflict with students' prior knowledge.

D. Limitations

Several limitations warrant consideration. First, the sample size ($N = 50$), while sufficient for detecting medium-to-large effects, limits generalizability. Second, the study employed a quasi-experimental design in which students selected one of two gameplay rooms/sessions before condition assignment; although students did not knowingly select the Baseline or Scaffolded condition, unmeasured selection effects related to peer relationships, motivation, participation preferences, or engagement tendencies may still exist. While baseline equivalence was established using pre-test FCI scores, such equivalence does not fully control these factors, and between-group findings should therefore be interpreted cautiously as suggestive rather than definitive causal evidence. Third, the intervention occurred within a single educational context (a Thai demonstration school); cultural variations in game-based learning acceptance may have

influenced transferability [5].

Fourth, the duration of the intervention (a single 90-minute session) and the use of an immediate post-test preclude conclusions about the retention or long-term stability of conceptual gains. Future research should incorporate delayed post-tests to examine whether immediate gains are retained over time [1].

Finally, while the Scaffolded condition included brief, contingent academic clarification from a physics teacher, students in this condition also received additional teacher attention compared with the Baseline condition. Therefore, some observed differences may reflect the combined influence of academic scaffolding and increased instructional attention, rather than scaffolding alone. The study did not systematically vary scaffolding types, teacher support intensity, or fading schedules, nor did it include formal fidelity coding of teacher-student interactions. Future studies should examine how different types and levels of scaffolding influence specific misconception types.

E. Implications for Practice

For physics educators, this study suggests that different forms of game-based learning may call for different levels of instructional support. Teachers can deploy light facilitation for concepts like action-reaction, where game mechanics alone create accurate intuitions. However, for counter-intuitive concepts (inertia, force-acceleration relationships), teachers must adopt active facilitator roles, utilizing just-in-time questioning to resolve cognitive conflicts as they emerge during gameplay [14].

The Design Conjecture Map [32] developed through this DBR process offers a useful template for curriculum designers. This template involves (1) identifying specific misconceptions through pre-testing, such as with the FCI; (2) designing game mechanics that create tangible conflict with those intuitions; (3) preparing scaffolding prompts that target the ontological categories in need of revision; and (4) planning post-game debriefing, where appropriate, as a follow-up activity to consolidate formal physics understanding after gameplay.

VI. CONCLUSION

This study examined the development and implementation of an analog board game designed to support students' immediate conceptual understanding of Newtonian mechanics. Through the integration of Design Thinking and Design-Based Research, the intervention was iteratively refined to align gameplay consequences with disciplinary reasoning. The findings suggest that the educational value of analog game-based learning depends not only on student engagement, but also on the extent to which game mechanics make scientific relationships visible and provide appropriate support when learners encounter conceptual difficulty.

The study contributes three empirically grounded design principles: concept-specific scaffolding, consequential validity, and social epistemic agency. These principles were integrated into a preliminary Physics-GBL Conceptual Change Framework, which highlights the interaction among tangible game mechanics, cognitive conflict, peer explanation, and responsive academic clarification. The framework offers a practical basis for designing educational

board games that move beyond procedural participation toward more explicit conceptual reasoning.

Because the intervention was conducted in a single educational context, involved one gameplay session, and used an immediate post-test, the findings should be interpreted as evidence of immediate conceptual gains rather than long-term conceptual change. Future research should examine the framework across diverse educational settings, incorporate delayed post-tests, compare different forms and intensities of scaffolding, and investigate how instructional support can be gradually reduced as learners develop greater conceptual independence.

STATEMENT ON THE USE OF GENERATIVE AI

In the preparation of this manuscript, Generative Artificial Intelligence (AI) tools, such as ChatGPT, were used for tasks including language editing and literature synthesis. These tools were applied to improve the clarity and coherence of the text. No substantial intellectual contributions or data fabrication were made by the AI. Full responsibility for the accuracy, originality, and ethical integrity of the manuscript lies with the authors. All AI-generated content was reviewed and integrated with human intellectual input to ensure adherence to academic standards.

CONFLICT OF INTEREST

The authors declare that there was no conflict of interest.

AUTHOR CONTRIBUTIONS

C.V. led the conceptualization and research design, coordinated the development and implementation of the board game intervention, conducted data collection and data analysis, and drafted the manuscript. S.T. contributed to the development and implementation of the intervention, data collection, validation of the research procedures, interpretation of the findings, and revision of the manuscript. W.P. contributed substantially to the conceptual framework and research methodology, supervised the research process, contributed to data analysis and interpretation, and critically reviewed and revised the manuscript. W.P. also served as a corresponding author and was responsible for academic communication concerning the manuscript. All authors read and approved the final version of the manuscript.

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