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Educational card games, creativity, and conceptual understanding in Biology learning

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ABSTRACT
Science learning in junior high schools tends to emphasize memorization over the development of higher-order competencies, and non-digital learning approaches are rarely used. This study aimed to determine the effectiveness of an educational card game in enhancing students' creativity and understanding of Biology. A convergent, quasi-experimental, mixed-methods study was conducted with 31 eighth-grade students in Bandung. The study was conducted over four weeks, with the experimental group designing a card game about the excretory system, while the control group created a conventional poster. Creativity was measured using the CPAM, and conceptual understanding was measured using a multiple-choice test. The results showed that the experimental group had higher creativity across all CPAM dimensions and demonstrated a significant increase in understanding with a moderate N-gain compared to the control group, which only achieved a low category. A strong correlation between creative engagement and conceptual growth suggests a mutually reinforcing relationship. Five qualitative mechanisms were identified: iterative design deepens understanding, peer playtesting provides formative feedback, creative constraints encourage problem-solving, collaborative knowledge construction, and kinesthetic learning through card manipulation. These findings confirm that creating card games is a practical, low-cost strategy for Biology classrooms with limited resources.

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ABSTRAK
Pembelajaran sains di SMP cenderung menekankan pada penghafalan materi daripada pengembangan kompetensi tingkat tinggi, selain itu pendekatan pembelajaran melalui permainan non-digital pun belum banyak dilakukan. Penelitian ini dilakukan untuk mengetahui efektivitas perancangan permainan kartu edukatif terhadap kreativitas dan pemahaman siswa dalam pembelajaran Biologi. Studi mixed-methods quasi-eksperimental konvergen dilakukan terhadap 31 siswa kelas VIII di Bandung. Penelitian dilakukan selama empat minggu dengan kelompok eksperimen yang merancang permainan kartu tentang sistem ekskresi, sedangkan kelompok kontrol membuat poster konvensional. Kreativitas diukur dengan CPAM dan pemahaman konseptual diukur melalui tes pilihan ganda. Hasil penelitian menunjukkan bahwa pada kelompok eksperimen, kreativitas lebih tinggi di seluruh dimensi CPAM dan menunjukkan peningkatan pemahaman yang signifikan dengan N-gain sedang dibandingkan dengan kelompok kontrol yang hanya mencapai kategori rendah. Korelasi yang kuat antara keterlibatan kreatif dan pertumbuhan konseptual menunjukkan bahwa hubungan keduanya saling memperkuat. Teridentifikasi lima mekanisme kualitatif, yaitu desain iteratif untuk memperdalam pemahaman, playtesting sejawat sebagai umpan balik formatif, batasan kreatif untuk mendorong pemecahan masalah, konstruksi pengetahuan kolaboratif, dan pembelajaran kinestetik melalui manipulasi kartu. Temuan ini menegaskan bahwa pembuatan permainan kartu merupakan strategi praktis berbiaya rendah untuk kelas biologi dengan sumber daya yang terbatas.
Kata Kunci: *kreativitas; pemahaman konseptual; pendidikan sains; permainan kartu edukatif*

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INTRODUCTION

Science learning is still carried out conventionally, prioritizing memorization over the development of creative thinking. Many practical classroom implementations of science learning still emphasize memorization (Bónus et al., 2024). On the other hand, the current global educational framework demands creativity, critical thinking, collaboration, and communication as essential competencies for addressing the challenges posed by a constantly changing world, as outlined in the OECD reports titled "*OECD Learning Compass 2030 Concept Note Series*" (Thornhill-Miller et al., 2023). Sawyer and Henriksen, in their book "*Explaining creativity: The science of human innovation (3rd ed.)*" explain that creativity is not an innate ability but rather a skill that needs to be honed through an appropriately designed learning environment. It would be better if there were structured training programs to foster creativity in diverse groups of students and consistently improve divergent thinking skills (Ritter et al., 2020).

In this regard, student engagement, shaped by the interaction between learner behavior and the learning environment, is a crucial determinant of meaningful learning outcomes (Heilporn et al., 2024; Li & Xue, 2023). Biology lessons in junior high schools, particularly those on the excretory system, are among the most conceptually challenging. The processes involved occur at the microscopic and biochemical levels, which cannot be directly observed, making it difficult for students to develop a deep understanding (Soeharto & Csapo, 2021). Furthermore, field studies have shown that some students can list the stages of urine formation without fully understanding their significance. This phenomenon reflects the fundamental limitations of conventional teaching, in which reading textbooks and completing worksheets merely convey facts rather than fostering deeper understanding (Kalogiannakis et al., 2021). Therefore, new learning models are needed to make classroom learning more enjoyable and easier for students to understand.

Game-based learning (GBL) can be an alternative approach to enhancing students' cognitive, affective, and psychomotor skills (Alotaibi, 2024). This method can enhance motivation, creative thinking, and problem-solving skills and shows significant potential through its simulation features and instant feedback when implemented effectively (Agbo et al., 2023). Although this game format has received less attention in the literature, educational card games offer advantages that are difficult to replicate with digital platforms, including tactile experiences, face-to-face interactions, minimal technology requirements, and high accessibility in resource-limited learning environments (Kao, 2020; Othman et al., 2025). Furthermore, physical card games enable kinesthetic learning while facilitating peer discussion and collaborative knowledge construction, showing promising potential in resource-limited educational contexts (Angrist et al., 2022; Kukulska-Hulme et al., 2023).

When students go beyond existing games and actively design their own, cognitive demands shift substantially. This constructivist approach demands the active transformation of content knowledge into new artifacts, thereby activating higher-order thinking skills not stimulated by passive play (Puttick et al., 2024). This principle of learning through design underpins the approach to card game creation in this study. In contrast, cooperative learning is one of the most empirically supported instructional approaches in educational research, with documented positive effects across decades, contexts, and age groups (Gillies, 2023;

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Tadesse et al., 2024; Veldman et al., 2020). Beyond improved academic achievement, evidence also shows tangible benefits for the quality of peer relationships and students' intrinsic motivation, suggesting that cooperative structures influence not only what is learned but also how students experience the learning experience (Roseth et al., 2019). Peer feedback adds an important dimension: when students evaluate each other's work, they engage in a formative process that deepens their own understanding and supports their peers' development, as confirmed by numerous research syntheses (Double et al., 2020).

Three theoretical perspectives are the primary focus of this study. First, social interdependence theory states that cooperative learning structures create positive interdependence among group members, in which individual success depends on shared success, thereby fostering collaborative efforts and collective creativity (Gillies, 2023). Second, cognitive load theory explains how card games can distribute cognitive demands among students and external representations, thereby optimizing the learning process (Hwang & Chen, 2017). Third, the creativity systems model proposes that creativity emerges from the interaction between individual abilities, domain knowledge mastery, and social evaluation, which serves as the basis for the iterative design-test-revise cycle and CPAM-based peer evaluation implemented in this study (Behnamnia et al., 2020).

Four key research gaps motivated this research: first, most GBL studies have focused on digital games, leaving the creation of non-digital card games underexplored (Othman et al., 2025). Second, studies simultaneously examining creativity and conceptual understanding as co-products are scarce. Third, the constructivist game design paradigm in non-digital, resource-constrained biological contexts has received little systematic empirical attention (Puttick et al., 2024). Fourth, equitable and low-cost pedagogical alternatives are urgently needed in resource-constrained educational settings.

Furthermore, in this study, peer evaluation was operationalized using the Creative Product Analysis Matrix (CPAM), a validated instrument that measures creativity across the dimensions of novelty, resolution, and elaboration (Alvarez-Icaza et al., 2024; Dumas et al., 2021). The CPAM was chosen because its dimensional structure has been validated across various educational contexts, allowing students to provide and receive specific, actionable feedback directly related to the products they design (Alvarez-Icaza et al., 2024; Chang, 2023; Dumas et al., 2021). Based on this, the study aims to determine the effectiveness of educational card games in fostering creativity using the CPAM framework, assess their influence on conceptual understanding of the excretory system, and examine the cooperative learning mechanisms of this learning experience.

LITERATURE REVIEW

Game-Based Learning and Educational Card Games

Over the past two decades, game-based learning (GBL) has become one of the most researched topics in education. Findings from various studies indicate that this approach has a significant positive impact on students' cognitive development, motivation, and social interactions (Agbo et al., 2023; Alotaibi, 2024). However, it should be emphasized that GBL's success is not simply a function of the game itself. The key lies in the game's design, which provides appropriate challenges, prompt feedback, and allows students to make independent

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decisions. This combination of factors is what maintains student engagement and encourages more meaningful learning outcomes (Hwang & Chen, 2017). Furthermore, GBL has been shown to foster intrinsic motivation, sharpen critical thinking skills, and develop problem-solving skills across various educational levels and subjects (Kalogiannakis et al., 2021).

While digital games still dominate the GBL literature for their ability to provide interactive simulations and real-time feedback, educational card games offer a distinct, equally important dimension (Hasibuan & Anas, 2025). These physical games provide a tangible, tactile experience, open up opportunities for direct collaboration between students, and can be implemented without relying on expensive technological infrastructure (Kao, 2020; Shao et al., 2024). More interestingly, several studies have found that physical games consistently outperform digital versions in fostering student interaction, enriching discussions, and increasing student engagement with the subject matter (Othman et al., 2025). This situation underscores the urgency of prioritizing the development and implementation of card games for Biology learning as part of pedagogical reform.

Constructionist Learning and Game Design

Constructivist learning theory provides a strong conceptual foundation for understanding why GBL can produce deeper learning impacts. At the heart of this approach is the idea that students learn most effectively when they are actively engaged in creating something meaningful (Puttick et al., 2024). In the context of game design, that artifact is the game that the students themselves create. This process inherently demands a deep understanding of the content, as students must translate their knowledge into logical game rules, meaningful challenges, and feedback mechanisms that others can understand. The core principle of constructivism is that creating something for others fosters far richer learning, both motivationally, cognitively, and socially, than simply constructing understanding in one's own mind.

This principle underpins the pedagogical design of this study. When students design a card game about the excretory system, they are not simply required to understand the material; they must also understand how to design a card game. They are required to present that understanding in a form that others can play and learn from. This dual demand combines conceptual mastery with communication skills and triggers a cognitive elaboration process rarely achieved through passive learning. Above all, the iterative design cycle of testing, receiving feedback, and revising aligns with the principles of distributed practice, which have long been shown to be effective (Hake, 1998).

Creativity in Science Education

In 21st-century education, creativity is a crucial skill for students. However, it remains under-recognized, particularly in science education, as outlined in the OECD reports titled "*OECD Learning Compass 2030 Concept Note Series*" (Thornhill-Miller et al., 2023). Sawyer and Henriksen, in their book entitled "*Explaining creativity: The science of human innovation (3rd ed.)*" explain that creativity in educational contexts needs to be understood as a process that can develop through open-ended tasks, iterative production, peer evaluation, and exposure to diverse ideas. Sustained, structured creativity interventions can yield reliable

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improvements in divergent thinking, confirming that creative capacity is indeed trainable (Ritter et al., 2020). In Biology learning, the development of creative thinking goes beyond general competency goals. Students who approach Biology content creatively demonstrate stronger hypothesis formation, more flexible conceptual representations, and better analogical reasoning about complex physiological systems (Bónus et al., 2024). These abilities are particularly relevant to the excretory system, whose abstract, microscopic processes make creative engagement a real cognitive necessity rather than an optional enrichment.

Cooperative Learning and Peer Feedback

Cooperative learning is rooted in the theory of social interdependence, which holds that individual success is inseparable from the contributions of other group members. This interdependent relationship fosters elaborate discussions, student-to-student conceptual explanations, and collaborative progress monitoring (Gillies, 2023). Previous research consistently confirms that student academic achievement is closely correlated with the quality of student relationships and their level of intrinsic motivation, which ultimately determines the quality of the overall learning experience (Gillies, 2023; Roseth et al., 2019; Veldman et al., 2020). Within this framework, peer feedback should be viewed as a valuable learning mechanism in its own right, not simply a complement to teacher feedback (Latifi et al., 2021).

From the perspective of the feedback provider, evaluating peers' work encourages them to identify assessment criteria and to formulate explicit, communicable judgments. This process demands high cognitive skills and deepens the feedback provider's understanding. From the recipient's perspective, feedback from someone who has faced similar challenges tends to be more readily digested and accepted than criticism from an authority figure (Schildkamp et al., 2020). This is why peer review is consistently associated with significant improvements in academic achievement (Double et al., 2020; Li et al., 2020). Equally important, feedback's effectiveness is optimal only when it is integrated into a recurring production cycle rather than provided as a single, isolated event (Kerman et al., 2024).

METHODS

This study employed a mixed-methods design, combining quantitative aspects to assess the intervention's effects on creativity and conceptual understanding with qualitative aspects to elucidate learning mechanisms that cannot be fully captured by statistical data alone. Based on Creswell & Creswell, in their book entitled "Research design: Qualitative, quantitative, and mixed methods approaches (6th ed.)," a quasi-experimental pretest-posttest control-group approach was combined with qualitative thematic analysis. A quasi-experimental design was chosen because random assignment is ethically and administratively impractical in a real-life school setting, yet it can still provide valuable insights when carefully implemented (Gopalan et al., 2020).

Data collection was conducted over four weeks with 31 eighth-grade students (aged 13-14) from an urban junior high school in Bandung during the 2023-2024 academic year. Respondents were divided into an experimental group (n=13, Class 8A) and a control group

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(n=18, Class 8B) based on full-class assignment. This non-random assignment introduced potential selection bias, limiting causal inference. However, the same Biology teacher taught both classes under the national curriculum to minimize teacher effects, and independent t-tests and chi-square tests confirmed that there were no significant baseline differences between the groups (all $p > 0.05$). In this study, the experimental group completed twelve 80-minute sessions structured around three stages.

In the preparation stage (Week 1), students formed cooperative groups of three to four. They received basic instruction on the excretory system, card game design principles, and the creativity dimensions of the CPAM. The Implementation stage (Weeks 2-3) involved groups iteratively creating, testing, and refining their games through structured peer feedback. The Evaluation stage (Week 4) asked groups to rate each other's games using the CPAM rubric, followed by a whole-class game. The control group completed traditional poster creation within the same timeframe and group structure. Intervention accuracy was monitored using a 24-item observer checklist, yielding high compliance in both conditions (experimental = 92%; control = 89%). Teacher reflective journals supplemented this.

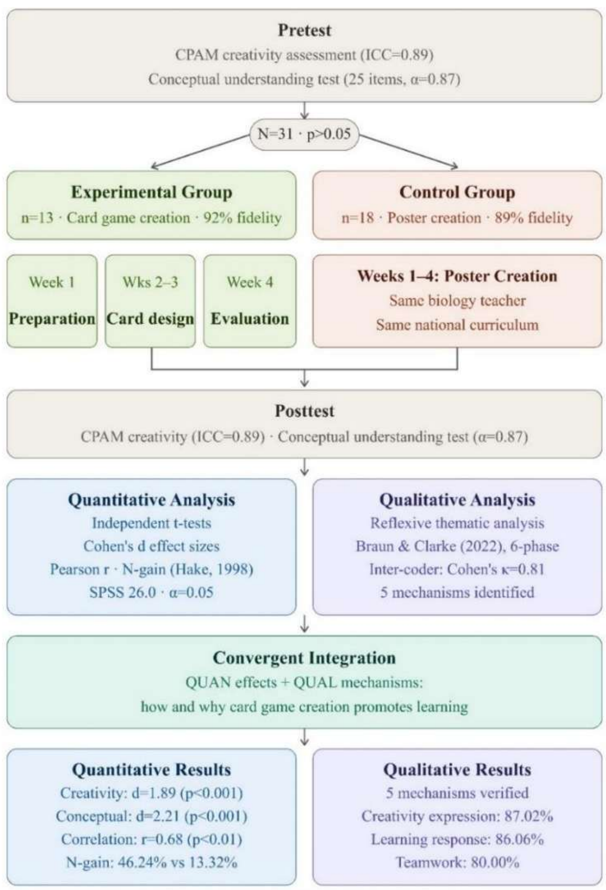

Figure 1. Research Design and Three-Stage Card Game Development Procedure
Source: Author Elaboration 2026

Based on **Figure 1**, the three-stage cooperative card game creation procedure was implemented over four weeks: Phase 1 Preparation (Week 1), Phase 2 Implementation (Weeks 2-3), and Phase 3 Evaluation (Week 4). The experimental group designed the educational card game, while the control group created a traditional poster within the same

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timeframe. Additionally, three validated instruments measured the outcomes. The CPAM assesses creativity across the dimensions of novelty, resolution, and elaboration using a 5-point scale (Alvarez-Icaza et al., 2024; Dumas et al., 2021). Three trained raters independently scored all products, resulting in excellent inter-rater reliability: ICCs of 0.89 for novelty, 0.87 for resolution, 0.91 for elaboration, and 0.89 overall (Liljequist et al., 2019).

The 25-item multiple-choice test measured conceptual understanding across excretory organ structure (7 items), urinary system function (16 items), and kidney disorders (2 items). Five biologists validated the content (CVR=0.80-1.00), and initial testing yielded item-total correlations of 0.32-0.68 and a Cronbach's alpha of 0.87. A 20-item Likert-scale questionnaire (1-4 items) assessed students' perceptions across the dimensions of teamwork, learning responses, creative expression, and play experiences (alpha = 0.82). Open-ended questions elicited qualitative reflections. Data analysis used descriptive statistics, independent t-tests with Cohen's d effect sizes, Pearson correlations, and normalized gain (N-gain) using Hake's formula (Hake, 1998).

Qualitative data from open-ended questionnaire responses and teachers' reflective journals underwent reflexive thematic analysis following the six-phase approach outlined in Braun and Clarke's "*Thematic analysis: A practical guide*". Inter-rater reliability was assessed using Cohen's kappa (kappa = 0.81), indicating strong agreement. Based on Creswell & Creswell in their book entitled "*Research design: Qualitative, quantitative, and mixed methods approaches (6th ed.)*", quantitative and qualitative aspects were integrated during the interpretation stage, with qualitative themes used to explain and describe the mechanisms underlying the quantitative results, and all analyses were conducted using SPSS 26.0 with an alpha of 0.05.

RESULTS AND DISCUSSION

Creativity Outcomes

The experimental group demonstrated significantly higher creativity across all CPAM dimensions. The experimental group demonstrated significantly higher creativity across all CPAM dimensions, with all comparisons reaching statistical significance ($p<0.001$) and uniformly large effect sizes (**Table 1**). Novelty demonstrated the largest effect, followed by resolution and elaboration, indicating that the card game design improved across the entire spectrum of creative production, not just isolated dimensions.

Table 1. CPAM Creativity Results by Dimension

CPAM Dimension	Exp. M% (SD)	Ctrl M% (SD)	t(29)	d
Novelty	83.33 (5.82)	46.30 (9.24)	8.94*	2.32
Resolution	88.89 (4.16)	70.37 (8.52)	6.42*	1.76
Elaboration/Synth	71.11 (7.64)	60.00 (6.89)	4.82*	1.24
Total Creativity	81.09 (6.24)	59.00 (8.15)	7.38*	1.89

*Note. Values in parentheses are standard deviations. *p<0.001.*
Sources: Research 2026

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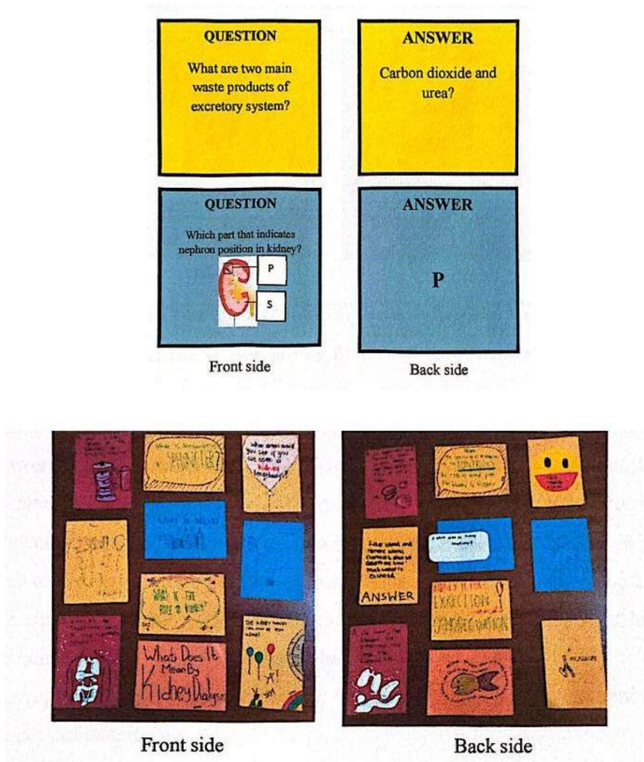
The largest effect emerged on the novelty dimension (d = 2.32). This confirms that the card game design activated divergent thinking. Students transformed biological content into original, playable formats for peers. This cognitive demand is qualitatively different from conventional product tasks. The resolution dimension showed a strong effect (d = 1.76). This indicates experimental group products were not only original but also educationally functional and logically coherent. Elaboration and synthesis yielded the smallest effect (d=1.24), though still large. This reflects the iterative design process as a powerful framework for creative integration. The overall creativity advantage (d=1.89) is much greater than effects typically reported in creativity training programs (Ritter et al., 2020).



Notes: Representative card game designs created by students in the experimental group, illustrating novelty, resolution, and elaboration across CPAM dimensions.
Figure 2. Examples of Student-Created Educational Card Games About the Excretory System
Source: Research Documentation 2023 – 2024

Figure 2 demonstrates the particular potential of constructivist card game design as a creativity-enhancing pedagogy.

Conceptual Understanding Outcomes

The experimental group demonstrated superior gains in conceptual understanding across all content areas. The experimental group achieved a medium N-gain category overall. In contrast, the control group remained in the low category across all content areas (**Table 2**), with the difference reaching statistical significance at a large effect size ($p<0.001$, d=2.21). Kidney disorders produced the highest experimental gains, while excretory organ structures showed comparatively lower but still substantially superior improvement, suggesting that

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card-based mechanics are particularly effective for content requiring cause-and-effect reasoning.

Table 2. Conceptual Understanding Results by Content Area

Content Area	Experimental N-gain %	Control N-gain %
Excretory Organ Structures	42.85 (9.14)	8.00 (4.62)
Urinary System Functions	43.95 (8.76)	22.23 (6.38)
Kidney Disorders	51.92 (11.25)	9.72 (5.84)
Average N-gain	46.24 (8.32) Medium	13.32 (5.18) Low

Note: N-gain interpretation: <30% Low, 30-70% Medium, ≥70% High. $t(29)=10.89$, $p<0.001$, $d=2.21$.
Sources: Research 2026

Variation across content areas reveals interpretively meaningful patterns. The kidney disorders content produced the highest experimental N-gain (51.92%), consistent with discrete relational game mechanics that naturally support repeated retrieval of cause-and-effect relationships through peer enactment. Excretory organ structures, which require spatial mental modeling, produced comparatively lower but still substantially superior gains (42.85%), suggesting that card-based representations may be somewhat less effective for spatially complex biological content. The control group's consistently low gains across all areas (8.00-22.23%) confirm that product creation without iterative testing and collaborative peer feedback is insufficient to drive substantive conceptual change, regardless of time on task.

Correlation Between Creativity and Conceptual Understanding

Pearson correlations calculated across the entire sample (N=31) revealed a strong positive association between overall CPAM creativity scores and N-gain scores in conceptual understanding ($r=0.68$, $p<0.01$), suggesting a synergistic rather than a zero-sum relationship between these outcomes. Students with stronger creative outcomes in product design also achieved higher conceptual gains, indicating elaborative coding, iterative self-correction, and communicative accuracy as shared cognitive processes underlying both dimensions of learning. Student perceptions remained positive across all dimensions measured, with creative expression scoring the highest (87.02%) and play experience the lowest (74.36%), while learning response (86.06%) and teamwork ability (80.00%) fell in between. The relatively lower play experience scores reflect the distinct cognitive challenge of designing a game that is both scientifically accurate and enjoyable for peers. This purposeful, creative demand distinguishes card game design from more routine creative product tasks (Puttick et al., 2024).

Qualitative Mechanisms Underlying Learning Outcomes

Qualitative thematic analysis identified five interrelated mechanisms that collectively explain how creating a card game fosters meaningful learning.

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1. The first mechanism is iterative design, a means of deepening understanding through generative coding. The process of designing the game directly forces students to confront and correct their own conceptual misconceptions. When groups discover errors in the cards during independent play, they are compelled to quickly correct them before other groups do, leading to authentic conceptual revisions born of real need. This is reflected in one student's reflection: *"Every time our group plays the game independently and finds an error in the cards, we go back and fix it, and that is when I realize I have been thinking about kidney function incorrectly."*
2. The second mechanism is peer feedback, which functions like authentic formative assessment. Unlike conventional teacher-mediated feedback, feedback in game testing emerges organically from the activity's dynamics. This process creates a direct and immediate corrective loop, allowing gaps in understanding to be identified and addressed in real time (Double et al., 2020; Li et al., 2020).
3. The third mechanism relates to creative constraints that actually drive productive problem-solving. The limited space on the cards and the need to play with peers encourage students to simplify complex biological processes into concise yet understandable representations. This task is cognitively demanding, and the resulting learning benefits have been well-documented in the literature (Puttick et al., 2024).
4. The fourth mechanism is collaborative knowledge construction, manifested through episodes of student-to-student explanation. One student remarked, *"I did not understand osmosis until my friend explained it using our card designs. Explaining to each other made us understand better."* This pattern of interaction reflects what cooperative learning theory calls promotive interaction, that is, interactions that actively encourage each other's learning progress (Gillies, 2023).
5. The fifth mechanism is embodied learning, which occurs through direct manipulation of the cards. The physical activity of cutting, arranging, and handling cards contributes to memory encoding and the formation of stronger conceptual connections. These findings are consistent with the theoretical framework of embodied cognition, which emphasizes the role of physical experience in knowledge formation (Shao et al., 2024; Tokatlidis et al., 2024).

Discussion

The creative excellence observed in this study substantially exceeded benchmarks from formal creativity training programs, although comparisons of effect sizes across studies require caution given the variability in instruments, populations, and research designs (Lakens, 2022; Ritter et al., 2020). The marked increase in novelty supports the proposition that constructivist game design creates optimal conditions for divergent thinking, requiring students to generate original biological representations for a peer audience, a qualitatively different cognitive demand than conventional tasks, consistent with Sawyer and Henriksen's in their book entitled "*Explaining creativity: The science of human innovation* (3rd ed.)" argument that creativity develops through open-ended, iterative, and peer-evaluated work. These findings explain that the digital GBL creativity framework can be applied to non-digital contexts, demonstrating that the constructivist mechanisms underlying creative development function independently of the technological medium, a finding relevant to under-resourced educational environments (Behnamnia et al., 2020; Bónus et al., 2024).

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The superior conceptual improvement reflects the integration of learning mechanisms enabled by the creation of card games. From a cognitive load theory perspective, restructuring biological knowledge into playable mechanisms encourages elaborative processing and schema construction beyond that afforded by passive content engagement (Hwang & Chen, 2017). The iterative design-test-refine structure introduces distributed practice, which supports memory consolidation through repeated, purposeful engagement with content. Peer testing serves as an authentic formative assessment that surfaces knowledge gaps in real time, while handling physical cards contributes to embodied cognitive encoding consistent with kinesthetic learning theory (Double et al., 2020; Gillies, 2023; Tokatlidis et al., 2024). Together, these mechanisms offer a theoretically grounded explanation for why card game creation may engage deeper learning processes than digital game alternatives, with the caveat that study contexts and measurement differ (Lakens, 2022).

Non-digital card games offer capabilities that complement, but do not necessarily surpass, digital alternatives. Manipulating physical cards creates an embodied cognitive experience that enhances creative thinking and spatial reasoning, while face-to-face collaboration facilitates spontaneous brainstorming and immediate peer feedback in ways that synchronous digital environments may not fully replicate (Kao, 2020; Othman et al., 2025). Minimal material requirements make card game creation accessible in resource-constrained settings, and evidence from large-scale trials confirms that low-tech interventions can improve learning outcomes in resource-constrained contexts (Angrist et al., 2022; Angrist et al., 2023; Kukulska-Hulme et al., 2023). Cooperative card game design is also inherently inclusive, as students with diverse strengths, including artistic, analytical, social, and content knowledge, all contribute meaningfully to the group product, potentially reducing socioeconomic achievement gaps through distributed expertise (UNESCO, 2023, accessed on https://www.unesco.org/sdg4education2030/en/education-financing).

The co-occurrence of increased creativity and conceptualization suggests that cooperative learning structures are important mediating mechanisms. The four core elements identified were embedded throughout the intervention: positive interdependence through shared play artifacts, individual accountability through assigned roles and public product presentations, promotive interactions through peer explanations and conceptual negotiation, and distributed cognition that enabled the management of design complexity (Gillies, 2023; Hwang & Chen, 2017; Veldman et al., 2020). These findings extend social interdependence theory to the context of creative production, suggesting that cooperative structures support the creative process itself rather than simply content acquisition, a link warranting further investigation in future research on 21st-century science curriculum design.

Several methodological limitations should be acknowledged. The quasi-experimental design with non-randomized whole-class assignment introduced potential selection bias that could not be fully eliminated by baseline equivalence checks, while the small overall sample size limited statistical power and generalizability of effect sizes (Gopalan et al., 2020; Lakens, 2022). The single-school, single-topic, four-week study design limits ecological validity, and the measurement of creativity relies solely on the product-based CPAM framework. The absence of an active control condition leaves open the question of whether the critical element is the card game design specifically or cooperative creative production more generally (Bacon, 2024). Future research should use randomized trials with larger sample

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sizes across multiple contexts, include an active control condition, examine long-term retention, and employ alternative measures of creativity (Dumas et al., 2021).

CONCLUSION

This study investigated three research questions, and convergent quantitative and qualitative evidence addressed each. Creating an educational card game proved significantly more effective at fostering creativity than creating a traditional poster, with large and meaningful differences across all CPAM dimensions, particularly in novelty. Conceptual understanding of the excretory system was also significantly higher among students who designed the card game, whose gains reached the medium N-gain category. In contrast, the control group remained in the low N-gain category. Qualitative evidence clarified the underlying processes: iterative design, peer feedback, creative constraints, collaborative knowledge construction, and embodied card manipulation combined to create a learning environment where content required genuine understanding rather than memorization. Importantly, creativity and conceptual understanding proved synergistic: students with stronger creative development also achieved greater conceptual gains, suggesting that these two outcomes reinforce one another when the instructional context is appropriately structured.

This study contributes theoretically by extending social interdependence theory to the context of creative production and demonstrating that the constructivist mechanisms underlying creative development function independently of the technological medium. These findings should be interpreted within the study's scope: a small sample from one school with non-random assignment, over four weeks, using a single Biology topic. Replication with a larger, randomly assigned, multi-context sample across multiple Biology topics remains a top priority. For classroom practice, it is recommended to follow an iterative design cycle that includes at least three 80-minute sessions. A peer feedback protocol aligned with CPAM dimensions that include scientific accuracy and game quality. An explicit role for collaboration to ensure positive interdependence. Creative constraints framed as productive challenges are consistent with evidence from constraint-based creativity research. Pre-cut card templates to maximize cost-effectiveness in resource-constrained contexts.

AUTHOR'S NOTE

The authors declare that there are no conflicts of interest associated with the publication of this article. The authors further affirm that the data and content presented in this manuscript are free from plagiarism. During the preparation of this manuscript, an AI language model was used to assist with paraphrasing and language refinement.

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