Design of an Online Computational Thinking Educational Game Integrating Scaffolding and Card Battle Mechanics

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Abstract

Computational thinking, as a core competency for programming and problem-solving, has become a crucial skill in information education in recent years. Nonetheless, many current instructional activities and educational games designed to teach computational thinking frequently integrate additional components such as spatial concepts and path analysis. This integration can lead to increased extraneous cognitive load for learners. To address this issue, this study employs card battle games as the core mechanism, enabling learners to manipulate computational logic more intuitively and concretely through combining computational function cards, thereby visualizing abstract problem-solving processes. Additionally, scaffolding design is incorporated, including dual-dimensional scaffolding of "task condition instructions" and "problem-solving hints," providing step-by-step guidance and immediate feedback. A total of 30 learners participated in the empirical study. Paired sample t-test were conducted to examine differences in learners' computational thinking self-efficacy before and after the game intervention. Results showed that post-test scores were significantly higher than pre-test scores. Furthermore, learners demonstrated moderate to high levels of flow state, low extraneous cognitive load, and relatively high germane cognitive load, indicating that the game not only engaged students and reduced learning costs but also promoted active thinking. Regarding the scaffolding design and overall user experience, results showed that learners generally held highly positive attitudes. The research findings confirm that game-based design integrating scaffolding and card battle mechanics can effectively support computational thinking learning and enhance the learning experience.

Keywords: computational thinking, game-based learning, scaffolding, card games

Introduction

Computational thinking (CT) is a fundamental cognitive skill underlying programming education and interdisciplinary systematic problem solving. In recent years, computational thinking has been recognized as one of the core competencies in global educational curricula (Liu et al., 2024). However, how to effectively support the learning of computational thinking remains a major challenge in educational practice. Traditional programming education often relies on text-based coding environments, which are particularly difficult for novices because learners must simultaneously grasp abstract logical structures and concrete syntactic rules.

To address these challenges, many educational settings have adopted block-based visual programming languages and game-based learning environments. Game-based learning (GBL) has been shown to effectively enhance learning motivation, engagement, and cognitive development (Barz et al., 2024). Nevertheless, many existing computational thinking educational games incorporate multiple cognitive demands, such as spatial reasoning, coordinate systems, and directional control, which inadvertently increase extraneous cognitive load. Prior research has indicated that visual complexity and the management of numerous blocks in visual programming environments may overload working memory (Khalid et al., 2025), thereby hindering the learning of computational thinking concepts (Hao et al., 2023). When acquired information cannot be transferred into long-term memory and instead overwhelms working memory, learning effectiveness in programming education is negatively affected (Ahn & Oh, 2024).

From the perspective of cognitive load theory (Sweller, 1988), effective instructional design should reduce extraneous cognitive load (cognitive demands unrelated to learning goals), manage intrinsic cognitive load (the inherent complexity of learning materials), and optimize germane cognitive load (cognitive resources devoted to schema construction). When educational games impose excessive extraneous load through complex spatial interfaces or cumbersome game mechanics, learners tend to allocate cognitive resources to navigating the game environment rather than understanding computational concepts. Therefore, optimizing cognitive load allocation in computational thinking educational games has become a critical issue in current programming and computational thinking research.

To overcome these instructional limitations, this study developed an innovative educational game using a card-battle mechanism as its core design. Unlike spatial movement-based learning games, card games allow learners to manipulate computational logic through concrete and controllable units—cards that represent specific computational functions. This design transforms abstract logic into tangible objects. By combining functional cards to construct computational sequences, learners can visualize and execute program logic step by step without bearing the cognitive burden of managing spatial coordinates or navigating virtual environments. Prior studies have demonstrated that concrete and manipulable objects facilitate learners' transition from concrete thinking to abstract conceptual understanding (Byrne et al., 2023).

In addition, a scaffolding system was incorporated to support learners with varying levels of proficiency. Drawing on Vygotsky's (1978) theory of the zone of proximal development, scaffolding provides temporary and adjustable learning support that enables learners to accomplish tasks slightly beyond their independent capabilities. This study adopted a dual-scaffolding framework (Hou & Keng, 2021), consisting of two components: (1) game instruction, which introduces basic functions and operational procedures, and (2) game hints, which provide strategic guidance without offering direct solutions. This progressive cognitive scaffolding structure was designed to foster learner autonomy while preventing excessive cognitive load (Chou et al., 2024), thereby guiding learners toward independent problem solving.

This study employed a quasi-experimental design involving 30 fourth-year junior college students to examine the effectiveness of the proposed game. Multiple dimensions were investigated, including learning achivement, computational thinking self-efficacy, cognitive load, flow state, and game user experience, with the aim of providing empirical evidence for the instructional value of integrating card-game mechanics and scaffolding design in computational thinking education.

Method

The educational game developed in this study, Code Battle, was a web-based application designed using JavaScript. A turn-based card-battle system served as the core game mechanism. The objective of the game was to construct a program sequence of up to four instruction cards to execute computational logic and attack the opponent; the player who reduced the opponent's HP to zero first was declared the winner.

The card system comprised six types of cards: (1) attack cards, which inflicted damage on the opponent; (2) healing cards, which restored the player's HP; (3) draw cards, which allowed players to draw cards from the deck; (4) variable cards, which provided numerical parameters for the aforementioned action cards; (5) loop cards, which repeated the execution of the previous action; and (6) conditional cards, which triggered effects when specific conditions were met. The game included five progressive challenge levels, each corresponding to a distinct NPC opponent with unique combat strategies and skill sets.

The game interface provided real-time visual feedback, including execution animations, computation result panels, action logs, and dynamically updated health bars, enabling learners to clearly observe the execution process and outcomes of program logic. The core mechanics emphasized fundamental programming concepts: action cards required variable cards to execute (representing parameter passing), loop cards embodied iteration logic, and conditional cards demonstrated conditional execution. Through card combination and sequencing, learners were required to strategically construct effective programs to defeat their opponents.

Two scaffolding systems were integrated into the game. The game instruction scaffolding provided comprehensive explanations of card types, turn procedures, and supplementary rules through an instruction button. The game hint scaffold was automatically triggered when learners encountered difficulties (e.g., failing to clear a level after a certain number of turns), presenting pop-up hints that offered improvement suggestions and strategic directions.

The participants consisted of 30 fourth-year students from a junior college in northern Taiwan. A one-group pretest–posttest design was adopted, and the intervention was conducted within a single instructional session lasting approximately 100 minutes. Participants first completed pretests on learning effectiveness and computational thinking self-efficacy. This was followed by a 10-minute game introduction. Participants then engaged in approximately 60 minutes of gameplay at their own pace to challenge the five levels. The game system automatically recorded all interaction data, including the number of turns used, number of retries, time spent on each level, and win–loss outcomes. After gameplay, participants completed posttests on learning effectiveness and computational thinking self-efficacy, as well as post-only questionnaires measuring flow state, cognitive load, scaffolding usage, and game user experience. Posttests and questionnaires required approximately 20 minutes to complete.

Paired-sample t-tests were conducted to examine pretest–posttest changes in learning effectiveness and self-efficacy. One-sample t-tests (test value = 3.0) were used to assess whether flow state, cognitive load, perceived scaffolding, and game user experience were significantly higher than the midpoint.

Results and Discussions

According to the paired-sample t-test results (Table 1), no statistically significant difference was found in learning effectiveness between the pre-test and post-test (pre-test: M = 10.43, SD = 1.91; post-test: M = 10.87, SD = 1.96; $t = 1.09$, $p > .05$, Cohen’s d = 0.20). This result may be attributable to the limited duration of the single-session intervention, the difficulty progression of the test items, or participants’ prior knowledge. However, the computational thinking self-efficacy scale showed a significant improvement (Table 2). The post-test score (M = 3.89, SD = 0.91) was significantly higher than the pre-test score (M = 3.58, SD = 0.97), $t = 2.56$, $p < .05$, Cohen’s d = 0.47. This finding indicates that the game-based intervention effectively enhanced learners’ confidence in their computational thinking abilities, likely through successful task completion experiences within the game environment.

Table 1
Paired-Sample t-Test Results for Learning Effectiveness (N = 30)

	Pre-test M	Pre-test SD	Post-test M	Post-test SD	*t*	*Cohen's d*
Learning Effectiveness	10.43	1.91	10.87	1.96	1.09	0.20

Table 2
Paired-Sample t-Test Results for Self-Efficacy (N = 30)

	Pre-test M	Pre-test SD	Post-test M	Post-test SD	*t*	*Cohen's d*
Self-Efficacy	3.58	0.97	3.89	0.91	2.56*	0.47

Note. *$p < 0.05$

The one-sample t-test results (Table 3) indicated that participants’ overall flow state (M = 3.85, SD = 0.86) was significantly higher than the midpoint value ($t = 5.46$, $p < .001$). Further examination of individual flow state dimensions revealed that, within the flow antecedents category, clear goals (M = 3.95, SD = 0.97, $t = 5.38$, $p < .001$) and unambiguous feedback (M = 3.95, SD = 1.00, $t = 5.19$, $p < .001$) both reached significant levels, suggesting that the game design successfully provided explicit task objectives and immediate feedback mechanisms. In addition, challenge–skill balance (M = 3.85, SD = 0.93, $t = 5.03$, $p < .001$) and sense of control (M = 3.98, SD = 1.09, $t = 4.96$, $p < .001$) were also significant, indicating that the difficulty design enabled learners to perceive an appropriate level of challenge while maintaining control over their actions.

Regarding the flow experience dimensions, concentration on the task (M = 3.86, SD = 0.86, *t* = 5.47, *p* < .001) and autotelic experience (M = 4.08, SD = 1.03, *t* = 5.69, *p* < .001) were particularly prominent, demonstrating that learners were highly focused on the game tasks and experienced strong intrinsic motivation. In addition, transformation of time (M = 3.50, SD = 1.12, *t* = 2.44, *p* < .05) and loss of self-consciousness (M = 3.53, SD = 1.24, *t* = 2.36, *p* < .05) also reached significant levels. Overall, the flow experience results indicate that the game successfully created an immersive learning experience.

Table 3
One-Sample t-Test Results for Flow State (N = 30)

Dimension	M	SD	*t*	*Cohen's d*
Overall Flow State	3.85	0.86	5.46^{***}	0.99
Flow Antecedents	3.85	0.93	5.03^{***}	0.91
Challenge-Skill Balance	3.95	0.97	5.38^{***}	0.98
Clear Goals	3.95	1.00	5.19^{***}	0.95
Unambiguous Feedback	3.98	1.09	4.96^{***}	0.91
Sense of Control	3.87	1.07	4.42^{***}	0.81
Action-Awareness Merging	3.50	1.12	2.44^{*}	0.45
Flow Experience	3.86	0.86	5.47^{***}	0.99
Concentration on the Task	3.91	1.04	4.79^{***}	0.87
Transformation of Time	3.53	1.24	2.36^{*}	0.43
Autotelic Experience	4.08	1.03	5.69^{***}	1.03
Loss of Self-Consciousness	3.63	0.98	3.53^{**}	0.65

Note. **p* < 0.05, ***p* < 0.01, ****p* < 0.001, Test value = 3

The cognitive load analysis (Table 4) revealed an ideal pattern of cognitive load allocation. Although overall cognitive load (M = 3.38, SD = 0.74) was slightly higher than the midpoint (*t* = 2.83, *p* < .01, Cohen's d = 0.52), intrinsic cognitive load (M = 3.22, SD = 1.03) was close to the midpoint and did not reach statistical significance, suggesting that the inherent complexity of computational thinking concepts was at an appropriate level for learners. Importantly, extraneous cognitive load was significantly lower than the midpoint (M = 2.39, SD = 1.44, *t* = −2.32, *p* < .05), indicating that the card-battle mechanism effectively reduced cognitive demands unrelated to learning goals. Learners did not need to expend cognitive resources on complex spatial navigation or interface manipulation.

More notably, germane cognitive load was significantly higher than the midpoint (M = 4.25, SD = 0.80, *t* = 8.57, *p* < .001), suggesting that learners actively engaged in meaningful cognitive processing, including schema construction, integration of prior and new knowledge, and the development of automated procedural knowledge. This pattern of "low extraneous load and high germane load" represents the ideal state of effective instructional design and aligns with the core principles of cognitive load theory, which emphasize maximizing learning-related cognitive resources while minimizing irrelevant cognitive interference.

Table 4
One-Sample t-Test Results for Cognitive Load (N = 30)

Dimension	M	SD	*t*	*Cohen's d*
Overall Cognitive Load	3.38	0.74	2.83^{**}	0.52
Intrinsic Cognitive Load	3.22	1.03	1.18	0.22
Extraneous Cognitive Load	2.39	1.44	-2.32^{*}	−0.42
Germane Cognitive Load	4.25	0.80	8.57^{***}	1.57

Note. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$, Test value = 3

Among the 30 participants, 24 learners (80%) used the game instruction scaffolding, 25 learners (83.3%) used the game hint scaffolding, and 22 learners (73.3%) used both types of scaffolding. The one-sample t-test results (Table 5) showed that participants' overall evaluation of scaffolding (M = 4.04, SD = 0.94) was significantly higher than the midpoint ($t = 5.21$, $p < .001$). Both the game instruction scaffolding (M = 3.98, SD = 0.99, $t = 4.67$, $p < .001$) and the game hint scaffolding (M = 4.09, SD = 1.03, $t = 5.51$, $p < .001$) received highly positive evaluations. These findings indicate that the scaffolding system effectively supported learners' understanding of game rules and problem-solving strategies. The high usage rates and positive perceptions suggest that learners regarded scaffolding as a valuable support tool that respected learner autonomy while providing necessary cognitive assistance.

Table 5
One-Sample t-Test Results for Scaffolding Usage

Dimension	M	SD	*t*	*Cohen's d*
Overall Scaffolding (N = 22)	4.04	0.94	5.21^{***}	1.11
Game Instruction Scaffolding (N =2 4)	3.98	0.99	4.67^{***}	0.95
Game Hint Scaffolding (N = 25)	4.09	1.03	5.51^{***}	1.10

Note. ***$p < 0.001$, Test value = 3

The overall evaluation of game user experience (Table 6) was significantly higher than the midpoint (M = 4.18, SD = 0.74, $t = 8.69$, $p < .001$). Within the game feedback dimension, usefulness demonstrated the strongest performance (M = 4.31, SD = 0.74, $t = 9.62$, $p < .001$), indicating that learners highly recognized the game's contribution to computational thinking learning. Ease of use was also significant (M = 4.04, SD = 0.86, $t = 6.68$, $p < .001$), reflecting the user-friendly interface design and smooth operational flow state.

Within the game elements dimension, sense of control (M = 4.17, SD = 1.05, $t = 6.07$, $p < .001$), uncertainty (M = 4.10, SD = 0.92, $t = 6.53$, $p < .001$), and sense of achievement (M = 4.17, SD = 0.89, $t = 7.17$, $p < .001$) all reached significant levels. These results indicate that the game successfully integrated key gamification elements, allowing learners to experience challenge while maintaining control and to gain a sense of achievement through successful level completion, thereby sustaining learning motivation and engagement. The highly positive user experience evaluations further validate the quality and educational value of the game design integrating scaffolding and card-battle mechanisms.

Table 6
One-Sample t-Test Results for Game Experience Feedback (N = 30)

Dimension	M	SD	*t*	*Cohen's d*
Overall User Experience	4.18	0.74	8.69***	1.59
Game Feedback	4.20	0.72	9.10***	1.66
Usefulness	4.31	0.74	9.62***	1.76
Ease of Use	4.04	0.86	6.68***	1.22
Game Elements	4.15	0.85	7.41***	1.35
Sense of Control	4.17	1.05	6.07***	1.11
Uncertainty	4.1	0.92	6.53***	1.19
Sense of Achievement	4.17	0.89	7.17***	1.31

Note. ***$p < 0.001$, Test value = 3

Overall, the findings demonstrate that the card-battle-based educational game developed in this study achieved multifaceted outcomes. Although learning achievement did not show a statistically significant improvement, the significant increase in self-efficacy suggests that the game effectively enhanced learners' confidence, which is consistent with prior research indicating that game-based learning can improve learners' self-efficacy (Barz et al., 2024). The high evaluations of flow state and user experience reflect the game's ability to create an immersive learning environment (Lin & Hou, 2023). Furthermore, the ideal cognitive load pattern of low extraneous cognitive load and high germane cognitive load confirms that the card-based mechanism successfully reduced irrelevant cognitive demands and enabled learners to allocate cognitive resources toward understanding and applying computational thinking concepts. This finding echoes Chang and Yang's (2023) assertion that digital game-based learning can effectively regulate cognitive load. The high usage rates and positive evaluations of the scaffolding system further support the effectiveness of the dual-scaffolding framework (Hou & Keng, 2021). Collectively, these findings indicate that a gamified design integrating scaffolding and card-battle mechanisms holds strong potential for promoting computational thinking learning, enhancing learning motivation and self-efficacy, and optimizing cognitive resource allocation.

Conclusions and Limitations

This study developed an educational game that integrates scaffolding and a card-battle mechanism to enhance learners' computational thinking abilities and learning motivation. To successfully complete the challenge tasks in each level, participants were required to select appropriate card combinations based on computational logic concepts and to execute serialized program instructions to attack opponents and achieve victory. Through real-time visual feedback, learners were able to observe program execution processes, utilize scaffolding systems to understand game rules and problem-solving strategies, and deepen their understanding of computational thinking concepts through iterative trial and error. This process enabled learners to make effective strategic decisions, enhanced their flow state, and avoided excessive cognitive load during gameplay, thereby strengthening their mastery of programming logic and computational thinking.

Despite these contributions, several limitations should be acknowledged. First, the study employed a one-group pretest–posttest design without a control group, which limits causal inference. Changes in learning effectiveness and self-efficacy may have been influenced by factors other than the game-based intervention. Second, the intervention duration was limited to a single session with approximately 60 minutes of gameplay. This relatively short exposure may have constrained the magnitude of learning effectiveness gains and prevented the assessment of long-term effects. Third, the current game levels primarily covered basic computational concepts, such as variables, conditions, and loops, and did not address more advanced computational thinking skills, such as functions.

Future research may extend this work in several directions. First, experimental designs incorporating both experimental and control groups could be adopted to compare the learning effectiveness of the card-battle game with traditional instruction or other gamified approaches, thereby enhancing internal validity and establishing causal relationships. Second, intervention duration could be extended across multiple sessions or several weeks to examine long-term learning effects and knowledge transfer. Third, additional levels covering advanced computational thinking concepts could be developed, along with adaptive difficulty adjustment mechanisms, to better accommodate learners with diverse skill levels. Through these research extensions, the educational value of integrating scaffolding and card-battle mechanisms in computational thinking education can be further validated and optimized.

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