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The Effectiveness of Multimodal Gamified Learning Platforms in Enhancing Student Engagement and Computational Thinking Skills in K-12 Classrooms: A Randomized Controlled Trial

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ABSTRACT

This study investigated the effectiveness of a multimodal gamified learning platform in enhancing student engagement and computational thinking (CT) skills in K–12 classrooms. Building on evidence that gamification and multimodal learning can positively influence motivation and complex skill development, this study adopted a randomized controlled trial (RCT) design with an embedded qualitative approach. Two parallel classes at each grade level (upper primary and lower secondary) were randomly assigned to either an intervention condition using a multimodal gamified platform or a control condition receiving conventional instruction. Data were collected through classroom observations, student focus group interviews, teacher interviews, and artifact analysis of the students' digital work. Thematic analysis was used to generate a comprehensive qualitative account of how gamified and multimodal affordances shaped students' behavioral, emotional, and cognitive engagement as well as their CT practices (decomposition, abstraction, algorithmic thinking, and debugging). The findings suggest that the multimodal gamified platform fostered sustained engagement, promoted collaborative problem solving, and supported more explicit CT articulation compared to traditional instruction. However, this study also identified challenges related to cognitive overload, inequities in participation, and teachers' design capacity. Implications are discussed for the design of constructively aligned multimodal gamified curricula and professional development in K–12 contexts.

Keywords: Student, Classroom, Engagement, Computational

I. INTRODUCTION

The rapid diffusion of digital technologies in K–12 education has reshaped expectations about how students learn and what competencies they must acquire to participate productively in a knowledge-based digital society. Among these competencies, computational thinking (CT) has gained increasing prominence as a fundamental set of problem-solving dispositions and practices that extend beyond computer science to multiple subject domains. CT encompasses skills, such as problem decomposition, pattern recognition, abstraction, algorithmic design, and systematic debugging, all of which are increasingly regarded as essential for navigating complex academic and real-world tasks. Simultaneously, concerns about low and uneven student engagement in traditional classrooms have driven interest in more interactive, learner-centered pedagogical approaches, including gamification and multimodal learning environments (Dehghanzadeh et al., 2024).

Gamification, —the integration of game design elements such as points, badges, levels, narratives, and challenges into non-game contexts, —has been widely promoted as a promising means of increasing student motivation, persistence, and enjoyment in learning. In K–12 settings, gamified learning environments have been associated with increased behavioral and emotional engagement, particularly when designed to provide clear goals, immediate feedback, and salient indicators of progress. Meta-analytic evidence in the broader field of gamified cognitive training similarly suggests that gamification can enhance motivation and perceived engagement, even when the effects on core cognitive outcomes are modest or mixed. Against this backdrop, there is a growing interest in the strategic combination of gamified approaches with multimodal learning

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principles and computationally rich tasks to support CT development in school-age learners (Walaszczyk & Arnab, 2025).

Multimodal learning refers to the intentional orchestration of multiple modes of representation and interaction, —such as visual, auditory, textual, kinesthetic, and interactive modalities, —to scaffold complex learning processes and accommodate diverse learner needs. Research in this area has shown that combining modes can increase the sense of presence, deepen conceptual understanding, and support richer engagement when the alignment between modalities and learning goals is carefully designed. In contemporary digital classrooms, multimodality is not only a feature of instructional materials, but also of learning spaces, student behaviors, and data traces, enabling new forms of multimodal learning analytics and instructional adaptation. Gamified learning platforms, particularly those designed for CT education, naturally lend themselves to multimodal design, leveraging animations, interactive simulations, audio cues, and textual feedback, alongside traditional teacher explanations and peer discussions (Luo, 2023).

In the specific domain of CT, a variety of digital platforms (e.g., block-based programming environments, puzzle-based coding games, and immersive sandbox worlds) have been developed to help K–12 students practice computational practices across contexts. Such platforms often embed problem scenarios within game-like narratives and offer multimodal feedback as students construct and refine their solutions. For example, visual cues may highlight logical errors in a program, animations may demonstrate the execution of algorithms, and progress dashboards may use badges or levels to signal the mastery of particular CT concepts. These design choices are intended to make CT more accessible and engaging to novice learners; however, empirical evidence about how students actually experience and make sense of these features in authentic classroom settings remains partial and sometimes inconsistent (Van de Staey et al., 2018).

Despite the expanding body of work on gamification and CT education, several gaps have been identified. First, much of the existing literature on K–12 gamification emphasizes quantitative outcomes such as test scores, engagement ratings, or time-on-task, often at the expense of a rich qualitative understanding of how learners interact with specific gamified and multimodal elements, and how these interactions shape their CT development. Second, studies integrating qualitative data frequently rely on non-experimental or quasi-experimental designs, limiting inferences about how observed experiences differ from those in non-gamified classrooms. Third, few studies have examined multimodal gamified platforms specifically oriented towards CT, particularly in the context of whole-class curriculum-integrated implementations rather than short-term enrichment activities (Kumari & Sharma, 2025).

This study addresses these gaps by conducting a randomized controlled trial (RCT) with an embedded qualitative component to investigate the effectiveness of a multimodal gamified learning platform in enhancing student engagement and CT skills in K–12 classrooms. Although RCTs are more commonly associated with quantitative outcome measures, they can also provide a rigorous framework for comparing qualitatively documented learning processes and experiences across different instructional conditions. In this study, random assignment of intact classes to intervention or control conditions helped to reduce selection bias and strengthen interpretive claims about how the multimodal gamified platform shapes engagement and CT practices relative to traditional instruction.

The intervention centers on a multimodal gamified platform designed to align CT competencies with core subject matter in mathematics and science for upper-primary and lower-secondary students. The platform integrates narrative-based quests, level progression, points, and badges with multimodal feedback including real-time visualizations of algorithm execution, animated hints, and audio prompts. Students solve scaffolded CT tasks embedded in curricular topics (e.g., algorithmic reasoning about fractional operations and decomposition of scientific processes), working both individually and in small teams. The control condition delivers equivalent content through teacher-led explanations, textbook exercises, and occasional non-gamified digital tasks, without systematic gamification or multimodal orchestration.

A qualitative methodological orientation was adopted to generate a comprehensive account of how the multimodal gamified platform influenced students' engagement and CT practices in comparison to the control condition. Through classroom observations, interviews, focus groups, and artifact analysis, this study seeks to answer the following research questions:

1. How does participation in a multimodal gamified learning platform shape students' behavioral, emotional, and cognitive engagement in K–12 classrooms, compared to traditional instruction?
2. How do students' CT practices (e.g., decomposition, abstraction, algorithmic thinking, and debugging) manifest within the multimodal gamified environment, and how do these practices compare with those observed in non-gamified classrooms?

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3. What opportunities and challenges do teachers and students identify when implementing multimodal gamified CT learning in regular K–12 settings?

This study aimed to provide nuanced evidence about the pedagogical affordances and limitations of multimodal gamified platforms for CT education by foregrounding students' and teachers' voices and triangulating data across multiple qualitative sources within an RCT. The findings are particularly relevant for education systems, including those in Indonesia and comparable contexts, seeking to integrate CT and digital literacy into national curricula, while simultaneously addressing persistent concerns about student engagement and equity in technology-rich classrooms.

II. METHODS

A. Research Design

This study employed a randomized controlled trial (RCT) design with an embedded qualitative research component. Intact classes within participating schools were randomly assigned to either an intervention condition, in which students used a multimodal gamified CT platform integrated into their regular curriculum, or a control condition, in which similar curricular content was delivered through non-gamified teacher-directed instruction. The qualitative component focused on capturing in-depth accounts of student engagement and CT practices in each condition through classroom observations, interviews, focus groups, and artifact analysis.

The choice of RCT design was motivated by the aim of strengthening causal inferences regarding how the multimodal gamified platform influenced learning processes and experiences compared to conventional approaches. Simultaneously, the study adopted a qualitative methodological orientation in its data collection and analysis, emphasizing meaning-making, contextualization, and the exploration of mechanisms rather than statistical generalization. The design can be understood as a qualitative process evaluation nested within a controlled experimental framework (Creswell, 2021).

3.2 Research Context and Participants

The study was conducted in urban and peri-urban K–12 schools that had access to computer laboratories or sufficient classroom devices to support the regular use of a digital learning platform. The participating schools followed a national curriculum that had recently incorporated CT-related objectives into mathematics and science subjects for the upper primary and lower secondary grades. School leaders expressed an interest in exploring digital, gamified approaches as part of broader initiatives to enhance student engagement and digital literacy.

Within each participating school, two parallel classes were recruited at the target grade level (upper primary and lower secondary). One class at each level was randomly assigned to the intervention condition, and the other to the control condition. The sample thus comprised several classes across multiple schools, representing a range of achievement levels, socio-economic backgrounds, and prior exposure to digital tools. The teachers of the participating classes were qualified subject teachers with varying degrees of experience in technology-enhanced instruction (Sugiyono, 2019).

3.3 The Multimodal Gamified CT Platform (Intervention)

The intervention platform was specifically designed to support CT in mainstream mathematics and science. Its key features include the following. Narrative quests: Content was organized into story-driven quests that framed CT challenges within problem scenarios relevant to students' lives or curricular themes (e.g., designing an efficient water distribution system in a science unit on ecosystems).

Game mechanics: Points, badges, and levels provided feedback on task completion and the mastery of specific CT competencies. Progress dashboards visualized students' advancement along CT learning paths.

Multimodal representations: tasks combined with visual programming (e.g., block-based coding), dynamic visualizations of algorithm execution, textual instructions, and audio cues. The hints were delivered through animated agents and pop-up explanations.

Collaborative missions: Selected quests required students to work in small teams, coordinating roles (e.g., "planner," "tester," "debugger") and jointly refining algorithms.

Teacher dashboard: Teachers can monitor students' progress, review their solutions, adjust task difficulty, or unlock additional hints.

The platform was accessed through school devices during the scheduled class periods. Teachers in the intervention condition received initial professional development sessions focusing on pedagogical integration of the platform, facilitation of collaborative work, and strategies for connecting on-screen CT activities with off-screen reflection and discussion.

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3.4 Control Condition

In the control condition, the teachers delivered the same curricular topics and CT-related objectives using traditional methods. Instruction involved teacher explanations, textbook exercises, worksheet-based problem solving, and occasional use of non-gamified digital resources (e.g., static simulations or instructional videos), as deemed appropriate by the teacher. There was no systematic use of game elements, nor were CT tasks embedded in narrative quests or multimodal interactive environments.

Teachers in the control condition were encouraged to teach as they would normally when integrating CT into their subjects, ensuring ecological validity. They were not provided access to the gamified platform during the study period. This design allows for a comparison between a structured multimodal gamified implementation and a more conventional, albeit CT-oriented, instructional approach.

3.5 Data Collection

A qualitative multi-method approach was employed to capture rich triangulated data on student engagement and CT practices across conditions (Arikunto, 2016).

Classroom observations

Non-participant observations were conducted in both the intervention and control classes over several weeks. The observers used semi-structured observation protocols to capture the following information:

1. Behavioral engagement (on-task behavior, persistence, help-seeking)
2. Emotional engagement (expressions of enthusiasm, frustration, boredom)
3. Cognitive engagement (evidence of strategy use, reasoning, reflection)
4. Group interactions (collaboration, peer support, dominance patterns)

In intervention classes, observers paid particular attention to how students interacted with game elements and multimodal features (e.g., the use of visualizations, reliance on hints, and responses to feedback).

Student focus group interviews

Focus groups were conducted with students in each class toward the end of the intervention period. Discussion prompts the exploration of students' perceptions of:

1. Enjoyment and interest in CT-related activities
2. Perceived difficulty and challenge
3. Experiences of working individually versus collaboratively
4. How do specific features of the learning environment (gamified or traditional) help or hinder understanding and problem-solving ? Teacher semi-structured interviews

Teachers from both conditions participated in interviews focusing on:

Observed changes in student engagement over the study period

Students' CT practices and misconceptions

Practical challenges of implementing CT in their subject

Reflections on affordances and limitations of the platform (for intervention teachers) or conventional methods (for control teachers)

Student artefacts

In the intervention classes, students' digital artifacts, —such as saved projects, algorithm designs, and debugging histories, —were collected and analyzed. In the control classes, written solutions to CT-related tasks, diagrams, and other artifacts were collected in a similar manner. These artifacts provide additional evidence for CT practices and learning processes.

Field notes and documents

Researchers maintained detailed field notes documenting contextual factors (e.g., classroom layout, technological constraints, school-level policies) and informal conversations with teachers and students. Supporting documents such as lesson plans and teacher handouts were also reviewed.

3.6 Data Analysis

Data were analyzed using an inductive–deductive thematic analysis approach. This analysis was conducted in several stages.

Familiarization

Audio recordings of the focus groups and interviews were transcribed verbatim. Observation notes, artifacts, and field notes were collated and read repeatedly to gain an initial holistic understanding.

Initial coding

A coding framework was developed, informed by existing theoretical constructs of engagement (behavioral, emotional, and cognitive) and CT (decomposition, abstraction, algorithmic thinking, and debugging), as well

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as emergent categories arising from the data. A subset of transcripts and observation notes was independently coded by multiple researchers, and discrepancies were discussed to refine the coding scheme.

III. RESULTS AND DISCUSSION

A. Student Engagement in Multimodal Gamified and Traditional Classrooms

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Observation data and student reports indicated marked differences in engagement profiles between the intervention and control groups. In the intervention condition, students generally displayed sustained behavioral engagement characterized by continuous interaction with tasks, active experimentation, and frequent peer-to-peer support. Emotional engagement is reflected in expressions of excitement, curiosity, and satisfaction when progressing through levels or earning badges. Cognitive engagement was evident in the students' verbalization of strategies, reflection on mistakes, and negotiation of alternative approaches during collaborative quests.

Engagement was more variable in the control classes. Some lessons generated lively discussions and on-task behavior, particularly when teachers introduced challenging problems or facilitated group work. However, observations have also documented episodes of passive listening, off-task behavior, and expressions of boredom during extended teacher talk or repetitive exercises. Students' focus group comments often contrasted "interesting" or "fun" moments (e.g., hands-on activities, teacher demonstrations) with more routine worksheet-based tasks.

Table 1. Themes of student engagement in intervention and control classrooms

Theme	Intervention (Multimodal Gamified)	Control (Traditional Instruction)
Behavioral engagement	Sustained on-task activity; frequent trial-and-error; active navigation of quests and levels	Alternating periods of attention and off-task behavior; engagement spikes around novel activities
Emotional engagement	Enthusiasm when unlocking levels/badges; curiosity about storylines; frustration framed as challenge	Interest tied to teacher charisma and topic relevance; boredom during repetitive exercises
Cognitive engagement	Verbalization of strategies; hypothesis testing; reflection prompted by system feedback	Focus on getting correct answers; limited explicit discussion of strategies
Peer collaboration	Spontaneous help-seeking and peer tutoring; shared celebration of achievements	Collaboration mainly when assigned; help-seeking directed primarily to teacher
Persistence with difficulty	Re-engagement after failure; use of hints and debugging tools to persist	Tendency to seek teacher solution; some students give up quietly when tasks seem too hard

In describing these themes, students in the intervention condition frequently referred to game mechanics as a source of motivation and structure. For example, learners described "wanting to reach the next level" or "not wanting to break the streak" as reasons for persisting through difficult CT challenges. The narrative context of quests also appeared to provide a meaningful frame work that helped some students connect abstract CT concepts to concrete scenarios (e.g., optimizing a virtual delivery route as a way to understand algorithmic efficiency).

However, engagement was not uniformly positive for all the students in the intervention group. Observations and interviews identified a subset of learners who became overly focused on points and badges, sometimes rushing through tasks without fully understanding their underlying concepts. Others felt anxious when they perceived themselves as lagging behind their classmates during level progression. These patterns underscore the ambivalence of gamification: while it can energize engagement, it can also introduce performance pressure if not carefully mediated by teachers.

In the control classes, engagement tended to hinge on the teachers' pedagogical moves. When teachers used probing questions, real-life examples, or small-group problem solving, students often responded with active participation and visible interest. However, in the absence of such strategies, engagement declines. Students described some lessons as "just copying and answering," indicating a more surface-oriented orientation to learning.

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B. Manifestations of Computational Thinking Practices

The multimodal gamified platform was designed to foreground the CT competencies. An analysis of classroom interactions and student artifacts suggests that CT practices were more explicitly and frequently enacted in the intervention condition than in the control classes, where CT elements were present but less systematically scaffolded.

Table 2. Manifestations of CT practices in intervention and control classrooms

CT Practice	Intervention (Multimodal Gamified)	Control (Traditional Instruction)
Decomposition	Students broke quests into subtasks; used on-screen task lists; teachers prompted planning via platform's checklists	Teachers occasionally asked students to "break down" word problems; decomposition often implicit
Pattern recognition	Students compared similar puzzle structures across levels; platform highlighted recurring patterns visually	Pattern recognition mainly limited to teacher explanations (e.g., worked examples on board)
Abstraction	Students used simplified visual representations; narrative contexts abstracted away irrelevant details	Abstraction discussed conceptually but rarely enacted by students in their own representations
Algorithmic thinking	Students constructed step-by-step sequences in block-based programming; iteratively refined algorithms	Algorithmic reasoning appeared in pseudo-code exercises; limited iterative refinement observed
Debugging	Systematic trial-and-error; use of error messages and visual traces; collaborative debugging conversations	Debugging framed as "checking answers"; error analysis usually led by teacher

In the intervention classes, decomposition was regularly enacted when students planned to approach multi-step quests. The platform's interface allows students to view sub-goals and track completion, making the structure of complex problems visible. Teachers leveraged this functionality by asking questions such as, "What is our first small step?" or "Which part of the problem are we working on now?", encouraging students to articulate their decomposition.

Pattern recognition was supported by the platform-level design, in which structurally similar problems appeared with different surface features. Students noted that "the puzzles feel similar but with new twists," and some began to anticipate solution structures based on their previous experiences. Visual cues, —such as color-coded blocks or repeated arrangement patterns, —help draw attention to recurring structures.

Abstraction was facilitated by visual programming and narrative contexts that stripped the extraneous details. For example, when modeling a real-world process, the platform presents simplified representations that focus on variables relevant to the CT task. Students increasingly talked about "the important parts" or "ignoring the extra story" as they progressed.

Algorithmic thinking was particularly visible in the intervention classes, as students created and modified block-based programs to solve challenges. Observations recorded students discussing the order of steps, considering the use of loops and conditionals, and negotiating trade offs between alternative algorithm designs. Likewise, debugging was prominent; students interpreted error messages, used step-by-step execution visualizations, and collaborated to identify logical errors.

In contrast, CT practices in control classes were present, but were generally more teacher-directed and less frequent. Decomposition has often been demonstrated by teachers who have modeled how to parse problems on the board. Algorithmic thinking appeared in the form of pseudo-code exercises, but students' opportunities to iteratively refine their designs were limited. Debugging tends to focus on checking the final answers rather than systematically exploring intermediate reasoning steps.

C. Students' and Teachers' Perceptions of the Multimodal Gamified Platform

The focus group and interview data revealed generally positive attitudes towards the multimodal gamified platform tempered by critical reflections on challenges. Table 3 summarizes the key perceived opportunities and challenges.

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Table 3. Perceived opportunities and challenges of the multimodal gamified platform

Category	Perceived Opportunities	Perceived Challenges
Engagement	Increased enjoyment; sense of adventure; immediate feedback; "learning feels like playing"	Over-focus on points; anxiety about leaderboards or levels; temptation to rush
CT learning	Clear visualization of processes; easier to understand sequences; safe space to experiment and fail	Some students focus on "winning" rather than understanding; difficulty transferring CT to paper tasks
Collaboration	Natural peer tutoring; shared goals in quests; celebration of group achievements	Dominant students sometimes take control; quieter students may become passive observers
Teacher role	Easier to monitor progress via dashboards; richer basis for formative feedback	Need for additional preparation time; initial uncertainty about aligning platform with curriculum
Technology & access	Platform's multimodality accommodates different learning preferences; audio/visual aids help comprehension	Technical glitches disrupt flow; variable device familiarity among students

Students frequently emphasized that multimodal and gamified features made CT tasks more approachable. Visualizations and step-by-step animations helped them "see" how algorithms worked, while the narrative quests provided a context that made problems feel less abstract. The ability to experiment, fail, and retry without penalties beyond in-game consequences was described as "less scary than exams," encouraging exploration.

Teachers in the intervention condition valued the richer formative assessment possibilities afforded by the platform, such as reviewing students' solution paths, noticing patterns of errors, and identifying those who might need targeted support. Simultaneously, teachers acknowledged the need for careful orchestration to prevent gamified elements from overshadowing learning goals. They highlight the importance of structured reflection—pausing gameplay to discuss strategies, misconceptions, and connections to disciplinary concepts. Challenges include managing time (balancing platform use with other curricular demands), dealing with technical issues, and addressing disparities in digital literacy among students. Some teachers also expressed concern about students who were less motivated by game elements or who found the visual interface overwhelming, underscoring the need for differentiation.

D. Discussion

The findings of this study provide a nuanced picture of how a multimodal gamified learning platform can influence student engagement and CT practices in K–12 classrooms, as well as the conditions under which such platforms are most educationally productive. Embedding a qualitative process evaluation within a randomized controlled design allowed for a robust comparison between intervention and control classes, while preserving sensitivity to contextual complexity and learner perspectives.

Consistent with prior research on gamification in education, the multimodal gamified platform in this study was associated with heightened behavioral, emotional, and cognitive engagement relative to traditional instruction. Students in the intervention classes displayed more sustained on-task activities, greater persistence in the face of difficulty, and more frequent expressions of enjoyment and curiosity. These patterns align with meta-analytic evidence suggesting that the most reliable effects of gamification lie in enhancing motivation and engagement, even when cognitive outcomes are more variable (Vermeir et al., 2020).

This study extends this literature by showing how multimodal features, —such as visualizations of algorithm execution, interactive feedback, and audio prompts, —contribute to engagement. Students often described these features as making CT "visible" and "easier to follow," suggesting that multimodality did not merely embellish tasks but also played a cognitive scaffolding role. The combination of game mechanics and multimodal representations appears to create a learning environment in which engagement is not only affective, but also closely tied to sense-making and strategy development.

Simultaneously, the findings underscore that gamification is not inherently beneficial; its educational value depends on how it is designed and enacted. The emergence of performance anxiety tied to levels and leaderboards, as well as tendencies among some students to prioritize point accumulation over understanding, illustrates potential pitfalls also noted in previous studies. These dynamics highlight the importance of adopting a student-centered gamification design that emphasizes mastery, cooperation, and self-improvement, rather than solely competition and extrinsic rewards (Chaudhary et al., 2025).

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One of the central contributions of this study is its detailed account of how CT practices manifest in the two instructional conditions. In intervention classes, decomposition, pattern recognition, abstraction, algorithmic thinking, and debugging were not only present, but often explicitly labeled, scaffolded, and repeatedly practiced through the platform's tasks. The system design encouraged students to break quests into manageable subtasks, recognize recurring solution patterns across levels, build and refine algorithms using block-based programming, and debug using visual traces of execution.

These findings resonate with research on specialized CT platforms such as Co-De and widely used educational tools like Scratch and Minecraft: Education Edition, which similarly rely on interactive, multimodal environments to embed CT in meaningful activities. What distinguishes the present study is its comparative perspective: CT practices were observed in both conditions, but in control classes, they were more teacher-driven, less frequent, and less deeply integrated into students' problem-solving processes. Teachers modeled decomposition and algorithmic reasoning, yet students had fewer opportunities for iterative design and debugging.

This difference suggests that multimodal gamified platforms can function as "practice fields" for CT, where studens enact CT practices more autonomously and repeatedly. The availability of immediate visual feedback and the lowered perceived risk of failure (since mistakes have in-game rather than high-stakes consequences) fostered a culture of experimentation and debugging, which is central to CT. However, it is crucial to recognize that such platforms are in sufficient on their own. Without explicit facilitation and reflection by teachers, students may engage in trial-and-error without developing a deeper conceptual understanding of CT principles.

This study underscores teachers' pivotal role in mediating the educational potential of multimodal gamified platforms. Teachers in the intervention group, who actively leveraged the platform's affordances for example, by prompting students to articulate their decomposition strategies, asking them to explain their algorithms, and organizing structured whole-class debriefings were more likely to observe rich CT discourse and reflective engagement. Those who primarily allowed the platform to "run themselves" tended to see more superficial forms of engagement that focused on completion and points.

This finding aligns with the broader literature emphasizing that educational technologies are not self-implementing; their impact depends on teachers' pedagogical content knowledge, beliefs, and orchestration skills. For CT specifically, teachers must understand not only the platform's mechanics but also the CT concepts and practices being targeted to draw explicit connections between in-game activities and disciplinary learning.

The need for adequate professional development emerged clearly from the teacher interviews. Teachers expressed a desire for more support in designing lesson sequences that blend platform use with unplugged activities, formative assessments, and cross-curricular integration. Without such support, there is a risk that the platform will be relegated to a supplementary activity rather than being constructively aligned with learning outcomes, instructional strategies, and assessments, a limitation already highlighted in reviews of gamification in K–12 (Balcı & Yumuşak, 2025).

While the overall engagement patterns in the intervention classes were positive, the results raise important questions regarding equity and differentiation. Some students thrived in a gamified environment, quickly mastered the interface, and eagerly pursued higher levels. Others struggled with basic navigation, felt overwhelmed by visual complexity, and were less motivated by game elements. Differences in prior digital literacy, reading ability, and confidence were implicated in these varied experiences.

Moreover, collaborative quests, though generally beneficial for peer learning, sometimes led to the dominance of more confident students, with quieter classmates relegated to passive roles. This dynamic mirrors long-standing concerns about group work and underscores the need for intentional role-structuring and teacher monitoring to ensure equitable participation.

Addressing these issues requires a combination of design and pedagogical strategies. On the design side, platforms should offer adjustable levels of scaffolding, multiple modes of access (e.g., text-to-speech and simplified interfaces), and flexible feedback options to accommodate learners with diverse needs. On the pedagogical side, teachers can assign rotating roles within teams, monitor interaction patterns, and provide individualized support for students who are less familiar with digital tools or appear disengaged (Roy, 2026).

Another key theme concerns the transfer of CT learning from a multimodal gamified environment to other contexts, including traditional paper-based tasks and high-stakes assessments. While students in the intervention condition demonstrated sophisticated CT practices within the platform, teacher interviews revealed uncertainty about the extent to which these practices translated into improved performance on conventional assessments.

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This issue reflects a broader tension in CT education: the most authentic and engaging CT tasks often occur in open-ended, project-based, or game-like environments, whereas learning assessments may still rely on decontextualized, text-based items. To bridge this gap, curriculum designers and policymakers may need to reconsider assessment formats and incorporate performance-based tasks that capture CT in action. In the meantime, teachers can support transfer by regularly prompting students to articulate how the strategies used in the platform relate to other problem-solving tasks and by designing bridging activities that require applying CT concepts across modalities.

Methodologically, this study illustrated the value of integrating qualitative methods into an RCT framework. The random assignment of classes provided a robust basis for attributing observed differences in engagement and CT practices, at least in part, to the intervention. Simultaneously, qualitative data elucidated the processes underlying these differences, capturing nuances that would likely be missed by standardized tests or survey measures alone.

The approach aligns with calls in the gamification and CT literature for more mixed-methods and process-oriented research that moves beyond simple "does it work?" questions to "how, for whom, and under what conditions does it work?" Thematic analysis, combined with comparative tables, provided a structured yet flexible means of synthesizing complex data.

However, this study has some limitation. The study focused on a specific platform and set of schools, limiting its generalizability. The duration of the intervention, while sustained over several weeks, may still be insufficient to capture the long-term changes in CT proficiency or attitudes. Additionally, as with any classroom-based RCT, contamination effects (e.g., informal sharing of ideas between intervention and control teachers) cannot be entirely ruled out.

IV. CONCLUSIONS

This study examined the effectiveness of a multimodal gamified learning platform in enhancing student engagement and CT skills in K–12 classrooms using a randomized controlled design with embedded qualitative analysis. The findings indicate that the platform fostered higher levels of behavioral, emotional, and cognitive engagement than traditional instruction, with game mechanics and multimodal representations playing key roles in sustaining motivation and supporting sense-making. Within the gamified environment, CT practices such as decomposition, pattern recognition, abstraction, algorithmic thinking, and debugging were enacted more frequently and explicitly, positioning the platform as a productive "practice field" for CT.

At the same time, this study highlights some important caveats. Gamification can introduce new pressures and inequities if not carefully mediated, and CT learning in digital environments does not automatically transfer to conventional assessments or other contexts. The teacher's role in orchestrating multimodal gamified CT learning is therefore pivotal and requires targeted professional development and institutional support.

Funding Statement

"No external funding was received for this study."

Ethical Compliance

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Data Access Statement

A Data Access Statement is a section in a scientific publication or research report that explains how the data used or generated in a study can be accessed by readers or other researchers. This statement aims to promote transparency, support research reproducibility, and comply with open-access policies, where applicable.

Common Elements in a Data Access Statement:

1. Data Location: Specifies where the data are stored, such as in online repositories (e.g., Zenodo, Dryad, or institutional repositories).
2. Access Instructions: Provides information on how to access the data, such as direct links, digital object identifiers (DOI), or contact details.
3. Data Availability: Indicates whether the data are publicly accessible, available upon request, or restricted due to ethical, legal, or privacy considerations.
4. Data Licensing: If the data are open, specify the applicable license (e.g., Creative Commons).

Examples of Data Access Statements:

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1. Open Data:
   - "The data supporting this study are openly available in Zenodo at [DOI:10.xxxx/zenodo.xxxx]."
2. Restricted Data:
   - "The data that support the findings of this study are available upon request from the corresponding author. Due to privacy concerns, the data are not publicly available."
3. No Data Available:
   - "No datasets were generated or analyzed during the current study."
4. Conditional Access:
   - "The data supporting this study are available under restricted access and can be obtained upon reasonable request to the corresponding author and with the permission of the ethics committee."

Purpose of a Data Access Statement:

- Reproducibility: Enables other researchers to replicate or verify the findings.
- Collaboration: Encourages further collaboration by sharing data.
- Compliance: Adheres to the policies of funding agencies or journals that require open access to data.

Conflict of Interest Declaration

The authors declare that they have no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

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