The Impact of a Gamified Online Learning Course on the Grade 4 Students' Engagement in Mathematics Learning: a Mixed Methods Research

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Abstract: *Gamification is increasingly used to address declining engagement in online mathematics learning, yet its application in primary education often relies on extrinsic rewards, which may undermine sustained cognitive involvement. This study investigates a pedagogy-driven gamified online course designed for this project, specifically for Grade 4 students, which integrates Self-Determination Theory (autonomy, competence, relatedness) and the 5E instructional model (Engage, Explore, Explain, Elaborate, Evaluate) within a narrative-driven design featuring historical mathematical discoveries. Using a mixed-methods approach, 72 students were divided into experimental (gamified course) and control (regular instruction) groups. Quantitative analysis using the Engagement Scale revealed significant improvements in emotional ($\eta^2 = .072$, $p = .024$) and cognitive engagement ($\eta^2 = .075$, $p = .021$), but no significant change in behavioral engagement ($p = .169$). Qualitative data from teacher and student interviews indicated that narrative elements and autonomy-supportive features enhanced intrinsic motivation and metacognitive skills, while speed-based scoring and leaderboards incentivized superficial participation. The study thus proposes a pedagogy-driven gamification paradigm that prioritizes the use of narrative depth and theory-aligned pedagogical structures to stress mathematics' intrinsic value, offering actionable insights for developing effective digital learning environments in primary mathematics education.*

Keywords: Gamification, Mathematics Engagement, Self-Determination Theory, 5E model, Pedagogy-Driven Design

1. Introduction

Sustaining student engagement is a persistent challenge in online education, especially in foundational disciplines such as mathematics, which is crucial for both academic and practical success (Karaoglan Yilmaz & Yilmaz, 2022). Evidence indicates that applying gamification can boost engagement and motivation (Alsawaier, 2018; Krath et al., 2021). Yet current systematic reviews highlight that most research focuses on higher education, while younger learners remain underexplored (Cavus et al., 2023; Zeybek & Saygı, 2024). Moreover, existing gamified approaches often yield only transient engagement, as students prioritize incentives over understanding (Sailer & Homner, 2020). Additionally, digital gamification alone may be insufficient to effectively motivate students' active learning engagement unless integrated with pedagogically sound instructional principles (Alt, 2023).

To address these gaps, *Magical Number Adventures*, a gamified online course for Grade 4 students, was developed. It systematically integrates Self-Determination Theory (SDT) (Deci & Ryan, 2004) with the 5E instructional model (Bybee et al., 2006) within a narrative-driven design. This approach aims to cultivate behavioral, emotional, and cognitive engagement (Sun & Rueda, 2012), transcending superficial gamification by highlighting mathematics' intrinsic value.

This study employed a mixed methods design to evaluate the course's impact. 72 Grade 4 students were randomly assigned to an experimental group (gamified course) or a control group (regular instruction). To comprehensively assess both the extent and the nature of this impact, the study sought to answer the following research questions through quantitative pre/post-tests (using a validated engagement scale) and qualitative interviews:

RQ1: Does the gamified online course significantly affect Grade 4 students' engagement in mathematics learning?

RQ2: If so, how does it influence students' behavioral, emotional, and cognitive engagement dimensions?

2. Literature Review

2.1. Engagement in Online Mathematics: A Persistent Issue

Sustaining engagement in online mathematics is particularly challenging for primary students. This challenge stems from several interconnected barriers in the digital context and the subject itself. Firstly, the online environment weakens key supports: reduced teacher-student interaction can limit personalized feedback (Karaoglan Yilmaz & Yilmaz, 2022), while the lack of physical supervision and classroom community can undermine motivation (Hassan et al., 2021). Secondly, mathematics itself poses high cognitive demands. The abstract nature of mathematical concepts can heighten the difficulty of maintaining focus and comprehension (Anthony & Walshaw, 2009), and sustained mental effort on such concepts can induce anxiety and further erode students' persistence (Ramirez et al., 2016). Finally, the developmental characteristics of primary school students can intensify these challenges, as their limited self-regulation capacity can create a mismatch with the concentration required for mathematical inquiry (Anthony & Walshaw, 2009). This convergence of environmental, cognitive, and developmental factors can create a persistent engagement crisis, underscoring an urgent need for instructional designs that can effectively address these barriers.

2.2. Gamification in Learning: Promises and Pitfalls

Gamification integrates game-design elements (e.g., points, avatars) into non-game contexts (Deterding et al., 2011). It boosts learning engagement, motivation, and performance (Alsawaier, 2018; Hassan et al., 2021) and enhances knowledge retention (Lo & Hew, 2020), showing promise for online mathematics education. However, existing implementations reveal significant pitfalls. An over-reliance on competitive, extrinsic rewards (e.g., points, leaderboards) can spur transient engagement while undermining intrinsic interest in mathematics, hindering deeper conceptual understanding (Hew et al., 2016; Sailer & Homner, 2020). Consequently, students may become more engaged with the game mechanics than with the underlying learning objectives. Furthermore, there is a notable scarcity of research focused on primary education contexts (Zeybek & Saygı, 2024). These limitations underscore the need to move beyond superficial game elements toward a pedagogy-driven gamification design that is firmly grounded in instructional theory.

2.3. Theoretical Foundations

2.3.1. Self-Determination Theory (SDT)

Self-Determination Theory (SDT) identifies three fundamental psychological needs: autonomy, competence, and relatedness (Deci & Ryan, 2004). **Autonomy** refers to the experience of choice and volition; gamification can support it by offering meaningful in-course decisions. **Competence** involves feeling effective and capable; it can be nurtured

through clear goals, timely feedback, and appropriately scaffolded challenges. **Relatedness** encompasses the need for social belonging; it can be addressed by integrating collaborative tasks or community features. Thus, SDT provides a robust framework for designing gamification that shifts learners from a passive to an active role.

2.3.2. Student Engagement

This study adopted the multidimensional model of student engagement (Fredricks et al., 2004), which encompasses behavioral (participation and effort), emotional (interest and affective reactions), and cognitive (investment in deeper understanding and self-regulation) dimensions. To enhance all three simultaneously, the study proposes an integrated framework (Figure 1) in which game elements, designed to satisfy the SDT needs of autonomy, competence, and relatedness, serve as the key mechanism driving engagement.

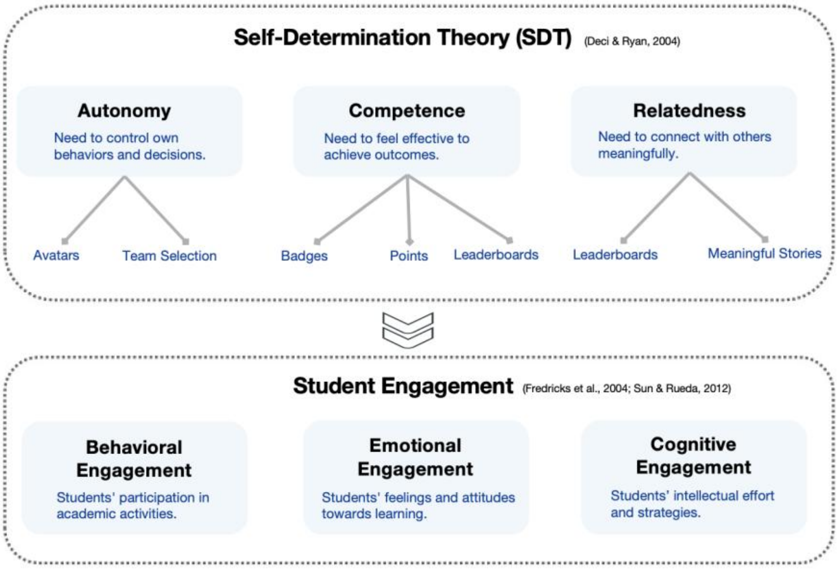

Figure 1: Theoretical framework

2.3.3. The 5E Instructional Model as Pedagogical Scaffold

To translate the proposed theoretical framework (Figure 1) into a concrete instructional design, the 5E Instructional Model (Bybee et al., 2006) was integrated into each module of *Magical Number Adventures,* the gamified mathematics online course designed in this project, to scaffold inquiry-based learning. Table 1 specifies how each 5E phase was implemented with corresponding gamification elements, all designed to address the key psychological needs of SDT as outlined in the framework. This structured approach ensured that gamification mechanics were purposefully tied to pedagogical objectives, moving beyond superficial engagement.

Table 1. 5E Model Gamification Integration Table (Aligned with SDT Engagement Framework)

5E Phase	Core Pedagogical Action	Gamification Integration	SDT Need Addressed
Engage	Activate prior knowledge and spark curiosity	Narrative storyline, character role-play	Relatedness
Explore	Guide inquiry and hands-on problem exploration	Interactive platform, collaborative (PK) challenges	Autonomy Competence
Explain	Facilitate concept articulation and clarification	Bonus point, instructional animations	Competence
Elaborate	Deepen understanding through extended application	Level-based game, extra bonus	Autonomy Relatedness
Evaluate	Assess learning and provide feedback	Adaptive quizzes, class leaderboard	Competence Relatedness

3. Methodology

3.1. Research Design and Participants

This study adopted a mixed methods design to evaluate the impact of a gamified online course on primary students' engagement. Participants were 72 fourth-grade students from the same class at an online education institution in Mainland China. Before the intervention, they were randomly assigned to an experimental group (n = 36) or a control group (n = 36) via random draw. Over four weeks, the experimental group completed *Magical Number Adventures* (1.5 hours online teaching + 0.5 hours weekly tasks). The control group received standard direct instruction, without gamification or the

5E inquiry structure. Both groups were taught by the same teacher to ensure consistency. All participants, teachers, guardians, and principals involved agreed to the consent form before data collection.

3.2. The Magical Number Adventures Course

The *Magical Number Adventures* course was developed from the integrated framework in Section 2.3 (Figure 1, Table 1), featuring a narrative-driven, gamified structure based on SDT and the 5E model. Focused on number sequences, it included four thematic modules (e.g., Pythagoras' Fun with Beans, Gauss and the Arithmetic Secret). Each module followed a complete 5E cycle within a historical narrative, with AI-generated "speaking portraits" of mathematicians enhancing immersion and coherence.

3.3. Data Collection and Analysis

Quantitative data were collected using the 19-item Engagement Scale (Sun & Rueda, 2012), which measures behavioral (5 items), emotional (6 items), and cognitive engagement (8 items). The scale showed good to excellent reliability in this sample (Cronbach's α: behavioral = .733, emotional = .915, cognitive = .819, overall = .894).

Shapiro-Wilk tests indicated that pretest scores were not normally distributed ($p < .05$). Therefore, Mann-Whitney U tests were conducted, revealing no significant baseline differences between the experimental and control groups across all engagement dimensions (all $p > .23$). Due to heterogeneous variances in posttest scores (Levene's test, $p < .05$), an analysis of covariance (ANCOVA) was conducted with pretest scores as covariates to evaluate post-intervention engagement.

Semi-structured interviews were conducted with six purposively sampled students from the experimental group (stratified by high, medium, and low post-test engagement scores) and their teacher. Each interview comprised 7 questions aligned with the three engagement dimensions. All interviews were audio-recorded and transcribed verbatim for analysis. Thematic analysis was used to group codes into themes aligned with the three engagement dimensions.

4. Results and Findings

4.1. Quantitative Analysis of Engagement Differences (RQ1)

Table 2. Descriptive Statistics and ANCOVA Results of Student Engagement Scale (*p < .05)

Dimension	**Group**	**Pretest**		**Posttest**		**ANCOVA**			
		Mean	SD	Mean	SD	F	df	Sig.	Partial η^2
Behavioral Engagement	Experimental	22.19	2.34	22.75	2.42	1.934	1,69	.169	.027
	Control	21.33	3.18	21.83	2.74				
Emotional Engagement	Experimental	26.89	3.82	28.22	2.54	5.319	1,69	.024*	.072
	Control	26.58	4.37	26.67	3.22				
Cognitive Engagement	Experimental	31.56	4.89	33.25	5.72	5.571	1,69	.021*	.075
	Control	30.28	5.43	30.11	6.77				
Overall Engagement	Experimental	80.64	9.12	84.22	7.76	5.723	1,69	.019*	.077
	Control	78.19	10.49	78.61	10.26				

To examine the differences in engagement between the experimental and control groups after the intervention, an analysis of covariance (ANCOVA) was conducted with pretest scores as the covariate. As presented in Table 2, the post-intervention outcomes varied across dimensions. Compared to the control group, the experimental group showed significant improvement with medium effect sizes in emotional (p = .024), cognitive (p = .021), and overall engagement (p = .019). However, no significant difference was found in behavioral engagement (p = .169).

4.2. Qualitative Insights on Engagement Dimensions (RQ2)

Thematic analysis of interviews with students (N=6) and the teacher (N=1) revealed the impact of the gamified course across three engagement dimensions. To ensure anonymity, students were assigned codes S1 to S6, corresponding to the order in which the interviews were conducted, and the teacher was assigned code T1.

4.2.1 Behavioral Engagement: Superficial Participation

Competitive game elements (e.g., leaderboards, badges) significantly increased students' observable behavioral participation. Students reported being “more attentive” (S3) and reading more carefully to answer quickly (S1). However, the quality of this participation was often superficial. Several students admitted to “just taking a wild guess” under time pressure (S5, S6). The teacher confirmed that "behavioral compliance doesn't guarantee conceptual understanding" (T1), noting many students answered quickly but with low accuracy. This finding suggests that while behavioral activity increased, its quality did not deepen, which may partially explain the lack of significant improvement in quantitative behavioral engagement scores (p = .169).

Table 3. Coding Table for **Behavioral Engagement**

Dimension	Themes	Codes	Examples
Behavioral Engagement	Gamification enhances classroom focus	Careful reading, Concentration improvement, Sustained focus	“With the game elements, I stayed attentive throughout the whole class.” (S3)
	Competition motivates learning	Get more points, Rank on the leaderboard	“To earn more points, I listen carefully to answer questions correctly.” (S1)
	Superficial participation	Random guessing behavior	“When some questions are a bit tough and I reall y have no clue, I just take a wild guess.” (S6)

4.2.2 Emotional Engagement: Affective Transformation

The narrative-driven design of the course effectively promoted positive emotional engagement. Students widely reported that the learning experience became more enjoyable, feeling that “time passed quickly” (S2). Competitive and collaborative mechanics sparked excitement, such as feeling “excited” when their group won first place (S5). The achievement system also boosted students' self-efficacy, with one student stating that “always answering questions correctly made me more confident” (S3). Although a few students felt reluctant when facing difficult problems (S6), the teacher generally assessed that students were “active and happy throughout the course” (T1). These positive affective changes are consistent with and support the significant quantitative improvement in emotional engagement (p = .024).

Table 4. Coding Table for **Emotional Engagement**

Dimension	Themes	Codes	Examples
Emotional Engagemen t	Boosting learning enjoyment	Pleasant experiences, Reduce the dullness, Time flies.	“This form of doing exercises makes me feel happy and not bored.” (S6) “I feel that time passes quickly in every class.” (S2)
	Enhancing a sense of achievement	Accomplishment, Confidence.	“I find that I can always answer questions correctly, and this has made me more confident.” (S3)
	Negative emotions	Reluctance to attend.	“I feel a little reluctant to listen when it’s difficult.” (S6)

4.2.3 Cognitive Engagement: Strategic Advancement

The gamified design successfully stimulated deeper cognitive engagement, manifested as knowledge transfer and the use of metacognitive strategies. Students demonstrated exploratory behaviors after, such as “searching online for Gauss's summation method” (S1) and explaining concepts to others (S3). Students began "spending more time thinking about patterns" (S4) and reviewing content voluntarily (S2), indicating metacognitive growth. However, the pressure from quantitative assessments occasionally triggered superficial tactics like “guessing” (S5). The teacher pointed out that this reflected “unbalanced challenge design” (T1). Overall, the qualitative data indicate a deepening of students' cognitive investment, consistent with the quantitative result of a significant increase in cognitive engagement (p = .021).

Table 5. Coding Table for **Cognitive Engagement**

Dimension	Themes	Codes	Examples
Cognitive Engagement	Knowledge transfer and internalization	Search for related materials, Share with peers.	“I like Gauss very much. After school, I took the initiati ve to search for information about him online.” (S1) “I shared the stories here with my younger sister.” (S3)
	Optimization of learning strategies	Adopt methods, Think more.	“I can finish over a minute faster than others.” (S4) “I prefer to take more time to think through them.” (S4)
	Enhancing learning initiative	Active thinking, Independent review .	“I will take it out to review again on weekends.” (S2)
	Superficial strategies	Random guessing.	“I have taken a wild guess for some tough questions.” (S5)

In summary, qualitative findings revealed the nature of engagement shifts suggested by the quantitative results. While the narrative and autonomy features fostered genuine emotional interest and cognitive investment, certain competitive mechanics drove a form of behavioral participation that was active yet superficial. These mechanisms provide a foundation for a deeper discussion on the differential impact of gamification design elements.

5. Discussion

5.1. Differential Impact on Different Engagement Dimensions

This study revealed a differential impact of the gamified course across engagement dimensions. Quantitative results showed significant improvements in emotional ($\eta^2 = .072$, $p = .024$) and cognitive engagement ($\eta^2 = .075$, $p = .021$), with a medium effect size, while no significant difference was found in behavioral engagement ($p = .169$, $\eta^2 = .027$).

Qualitative data help explain these patterns. The narrative-driven design and autonomy-supportive features enhanced students’ enjoyment, reduced anxiety, and promoted active exploration, aligning with significant improvements in emotional and cognitive engagement. This indicates the course successfully addressed the SDT needs, fostering intrinsic motivation and deeper learning strategies. It also aligns with existing research on the cognitive benefits of well-designed, pedagogy-driven gamification (Sailer & Homner, 2020).

In contrast, the non-significant behavioral engagement warrants careful interpretation. Competitive mechanics such as speed-based scoring and leaderboards increased participation frequency but also induced superficial strategies like random guessing, suggesting behavioral engagement may manifest as high-frequency yet low-quality activity. Moreover, the behavioral engagement dimension of the Engagement Scale (Sun & Rueda, 2012) primarily captures compliance-based behaviors (e.g., following rules, completing homework), which may not adequately distinguish meaningful engagement from surface-level participation. The relatively high baseline scores may have further limited the potential for detectable growth. Collectively, these factors help explain the non-significant quantitative finding.

5.2. Limitations of Competitive Gamification Mechanics

The findings highlight a critical limitation of extrinsic, competition-based mechanics. Elements designed to support competence, such as speed-based scoring and leaderboards, often encouraged superficial participation. Students reported rushing to guess answers to earn points, which aligns with the observation that high participation ≠ high comprehension. This supports existing warnings that extrinsic rewards can undermine intrinsic interest and promote surface-level, strategic compliance (Hew et al., 2016; Sailer & Homner, 2020).

This outcome underscores Ryan and Deci's (2020) crucial distinction: support for competence must be framed around mastery and skill growth, not social comparison. While motivating for some, leaderboards risked inducing performance anxiety or shifting focus from understanding to ranking, echoing concerns about excessive competition for young learners (Zeybek & Saygı, 2024).

5.3. Practical Implications for Gamified Mathematics Curriculum Design

This study offers two key implications for the design of gamified mathematics curricula. First, the pedagogical structure of the 5E model serves as a crucial scaffold, ensuring that game mechanics align with learning objectives rather than functioning as mere entertainment. By embedding game elements within specific inquiry phases, the design maintained an educational focus and prevented mechanics from overshadowing content. This supports the established view that gamification must be grounded in evidence-based pedagogy to be instructionally meaningful (Alt, 2023). Second, integrating mathematical history into narrative structures, such as using Gauss's summation of arithmetic sequences to contextualize number patterns, can make abstract concepts more tangible and relatable, fostering emotional engagement and intrinsic motivation.

This research advances beyond confirming the general motivational benefits of gamification (Alsawaier, 2018) by proposing a more refined design paradigm for primary mathematics education. It advocates shifting from extrinsically driven, competition-heavy models toward narrative-rich, intrinsically motivating designs that prioritize deeper engagement.

6. Conclusion

6.1. Key Findings and Contributions

This study developed and evaluated *Magical Number Adventures*, a gamified online course for primary mathematics. The findings demonstrate that the course significantly improved students' emotional and cognitive engagement, primarily through its narrative context and autonomy-supportive design, which effectively fostered intrinsic motivation. However, behavioral engagement did not show a significant improvement, as competitive elements such as speed-based scoring and leaderboards sometimes encouraged superficial participation rather than deep learning.

The core contribution of this work is the advancement of a pedagogy-driven paradigm for educational gamification. By integrating Self-Determination Theory with the 5E instructional model within a historical narrative framework, the study provides both a theoretical framework and empirical evidence that sustainable engagement arises from designs prioritizing intrinsic motivation and pedagogical coherence over extrinsic rewards. Ultimately, this research advocates shifting from gamification as a superficial behavioral incentive toward systematic, pedagogy-driven innovations that promote deeper, more meaningful learning in foundational education.

6.2. Limitations and Future Research Directions

There were several limitations in this study. Its single-site design and relatively small sample size (N=72) affect the generalizability of the results, and the short intervention period (four weeks) prevents conclusions about long-term effects. Future research should employ larger, diverse samples and longitudinal designs.

Additionally, the control group received neither gamification nor the 5E model, making it impossible to isolate the effects of these two components. Future studies could adopt a 2×2 factorial design to disentangle their respective contributions.

Regarding measurement, the Engagement Scale (Sun & Rueda, 2012), though reliable in our sample (behavioral $\alpha = .733$), was not primarily designed for primary education. It may not be sufficiently sensitive to capture superficial behaviors (e.g., guessing for points) in gamified contexts. Future research should develop or adapt engagement measures that include gamification-specific behavioral items (e.g., "I clicked quickly just to earn points") to more accurately capture surface-level participation in gamified contexts.

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