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The Effect of Gamification-Based Mathematics Instruction on Executive Functions and Digit Span among Secondary School students

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ABSTRACT

Objective: The present study aimed to examine the effectiveness of gamification-based instruction on the executive functions of secondary school students.

Method: A semi-experimental design with pretest–posttest and control groups was employed. The study involved 30 twelfth-grade mathematics students from two randomly selected schools in District 3 of Tehran. The experimental group received gamification-based mathematics instruction once a week for ten 70-minute sessions, while the control group received no intervention. Executive functions were measured using the Executive Functions Questionnaire, the Digit Span subscale of the Wechsler Adult Intelligence Scale, and the Cattell Intelligence Test to control for intelligence differences.

Results: The findings indicated that gamification-based instruction significantly improved students' executive functions and memory span ($P \leq 0.05$). The experimental group outperformed the control group in inhibition, shifting attention, emotional control, task initiation, working memory, planning, organization, monitoring, and both forward and backward digit span.

Conclusions: Gamification-based mathematics instruction can effectively enhance executive functioning and memory in secondary school students, highlighting its potential as a practical educational intervention for improving cognitive skills.

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Introduction

In contemporary educational psychology, fostering students' higher-order cognitive abilities—particularly executive functions (EFs) and working memory (WM)—has emerged as a central priority (Diamond, 2013; Miyake et al., 2000). Executive functions constitute a set of interrelated cognitive control processes, including inhibition, cognitive flexibility, planning, updating and monitoring of information, and goal-directed regulation of behavior (Best & Miller, 2009). These functions enable learners to manage attention, regulate impulses, coordinate multiple steps, and adapt strategies in response to task demands. As such, EFs are foundational to successful learning across academic domains, and they are especially critical in mathematics education, which requires sustained attention, abstract reasoning, mental manipulation of symbols, error detection, and adaptive problem solving (Bull & Lee, 2014; Pablo Ríos et al., 2023).

Within this framework, working memory plays a pivotal role as a core component of executive functioning. Working memory allows individuals to temporarily store and manipulate information while engaging in complex cognitive activities. Digit span tasks—both forward and backward—are widely used indicators of working memory capacity and executive control. Forward digit span reflects short-term storage and attentional maintenance, whereas backward digit span taps higher-order executive processes such as mental manipulation, updating, and inhibitory control (Alloway & Alloway, 2010). Together, these measures provide valuable insight into students' executive functioning in academic contexts.

Despite the recognized importance of executive functions, traditional instructional approaches in mathematics often remain teacher-centered and content-driven, emphasizing procedural fluency over cognitive engagement. Such approaches may limit opportunities for students to actively exercise inhibition, cognitive flexibility, and strategic planning during learning (van den Berg et al., 2019). As a result, students may rely on rote memorization rather than developing the executive control required to manage complex, multi-step mathematical tasks. Moreover, discrepancies between teachers' preferred instructional styles and their actual classroom practices may further constrain the development of students' executive capacities, highlighting the need for pedagogical innovations that align instructional design with cognitive goals (Kadim Rahumi & Alavinia, 2024).

One instructional approach that has gained increasing attention in this regard is called 'gamification', defined as the use of game design elements in non-game contexts (Deterding et al., 2011). In educational settings, gamification incorporates elements such as points, levels, challenges, immediate feedback, and narratives to increase engagement and persistence. Importantly, beyond motivational benefits, gamification creates learning environments that inherently demand executive control. Students must monitor progress, inhibit impulsive responses, switch strategies, manage cognitive load, and sustain attention in order to succeed within game-based tasks (Sailer & Homner, 2020).

The theoretical foundations of gamification are closely aligned with executive functioning. Self-Determination Theory (Ryan & Deci, 2000) suggests that environments supporting autonomy, competence, and relatedness promote sustained engagement, which in turn provides repeated opportunities for executive processes to be activated and strengthened. Additionally, Cognitive Load Theory (Sweller, 2010) posits that well-designed gamified instruction can reduce extraneous cognitive load while structuring intrinsic load, thereby optimizing working memory resources and facilitating executive processing during learning.

A growing body of empirical research supports the cognitive benefits of gamification. Katz et al. (2014) demonstrated that gamified cognitive training programs enhanced adolescents' working memory, cognitive flexibility, and sustained engagement. Scharinger et al. (2023) reported that gamifying an n-back working memory task increased neural markers of cognitive engagement, suggesting heightened executive activation even when behavioral gains were moderate. In the domain of mathematics education, Zhao et al. (2021) found that embedding gamified challenges within mathematics instruction led to significant improvements in students' inhibition and planning abilities, both of which are central components of executive functioning.

Large-scale and meta-analytic evidence further underscores the impact of gamification on cognitive outcomes. A comprehensive meta-analysis by Sailer et al. (2021) revealed that gamification positively influences not only motivational variables but also cognitive performance, particularly when game elements are meaningfully integrated with instructional objectives.

Recent classroom-based studies indicate that gamified mathematics instruction can promote deeper conceptual understanding and more effective problem-solving by sustaining engagement and repeatedly activating executive control processes (Mohammed et al., 2024). Nevertheless, researchers caution that gamification must be carefully designed to support cognitive development. Superficial reliance on extrinsic rewards, such as leaderboards alone, may fail to engage executive processes and can even undermine meaningful learning (Almeida et al., 2023). These findings highlight the importance of theory-driven gamification designs that intentionally target executive functions rather than merely increasing surface-level engagement.

Evidence from cognitive neuroscience further supports the relevance of gamification for executive functioning. Game-based and gamified tasks require learners to regulate emotional responses, suppress automatic reactions, shift attention between goals, and actively maintain and manipulate information in working memory—all core executive functions (Best, 2012; Tomporowski et al., 2015). These demands closely mirror the cognitive requirements of mathematical problem-solving, where learners must track intermediate steps, inhibit irrelevant information, and flexibly adjust strategies when encountering obstacles (Bull & Lee, 2014).

The digit span task provides a particularly relevant outcome measure in this context. Forward and backward digit spans index both attentional control and executive manipulation of information, which can be strengthened through repeated engagement in cognitively demanding, structured, and motivating activities (Alloway & Alloway, 2010). Recent studies have shown that gamified mathematical tasks can lead to improvements in both forms of digit span, reflecting gains in working memory capacity and executive control (Pablo Ríos et al., 2023; Zhao et al., 2021).

Despite these advances, notable gaps remain in the literature. Many existing studies focus on younger children or laboratory-based interventions, limiting their applicability to authentic secondary school mathematics classrooms. Moreover, relatively few studies have explicitly examined the effects of curriculum-integrated gamification on executive functions and digit span among adolescents. Much of the prior research has emphasized motivation or academic achievement, leaving the underlying executive mechanisms insufficiently explored (Almeida et al., 2023; Sailer et al., 2021).

The present study addressed these gaps by investigating the effects of a structured gamification-based mathematics instructional program on executive functions and digit span (forward and backward) in 12th-grade students. Grounded in Self-Determination Theory and Cognitive Load Theory, and informed by recent empirical and neuroscientific findings, this research examined whether gamified mathematics instruction can enhance core executive processes that support learning. By focusing on executive functioning outcomes within an authentic classroom context, the study contributes to a deeper understanding of how gamification can support cognitive development in secondary mathematics education.

Research ***Hypotheses***

In this study, the following research hypotheses were examined: First, it was hypothesized that students who received gamification-based mathematics instruction would demonstrate significantly higher levels of executive functions—including inhibition, cognitive flexibility, emotional control, task initiation, working memory, planning, organization, and monitoring—compared to those who received traditional instruction. Second, it was hypothesized that students in the gamified instruction group would achieve significantly higher scores on digit span tasks (both forward and backward), reflecting enhanced working memory capacity, than their counterparts in the control group. These hypotheses were tested through a quasi-experimental design using pre-test and post-test measures with a control group.

Hypothesis 1: Students who receive gamification-based mathematics instruction will show significantly higher post-test scores on measures of executive functions compared to students who receive traditional instruction.

Hypothesis 2: Students who receive gamification-based mathematics instruction will show significantly higher post-test scores on digit span (both forward and backward) compared to students who receive traditional instruction.

Theoretical Framework

The present study is theoretically grounded in cognitive models that directly explain changes in executive functions and working memory, which constitute the core dependent variables of the research. In particular, Cognitive Load Theory (CLT) and contemporary models of executive functioning provide the primary explanatory basis for understanding how gamification-based mathematics instruction may influence digit span performance and executive control processes in secondary school students.

Cognitive Load Theory and Executive Functions

Cognitive Load Theory (CLT) posits that learning is constrained by the limited capacity of working memory, and instructional effectiveness depends on how cognitive load is managed during task engagement (Sweller, 2010). CLT distinguishes between extraneous load, which consumes cognitive resources without contributing to learning, and germane load, which supports schema construction and higher-order cognitive processing. From an executive functioning perspective, excessive extraneous load impairs attentional control, inhibitory regulation, and working memory updating—core components of executive functions.

Gamification-based instructional designs, when cognitively structured, can directly support executive functioning by reducing extraneous cognitive demands and organizing task complexity. Features such as clear goals, progressive task difficulty, immediate feedback, and structured challenges help learners allocate working memory resources more efficiently. This optimized cognitive environment allows executive processes—particularly inhibition, shifting, and updating—to operate more effectively during mathematical problem solving (Almeida et al., 2023; Chen et al., 2021).

Executive Functions and Working Memory (Digit Span)

Executive functions (EFs) refer to a set of higher-order cognitive control processes that enable goal-directed behavior, including inhibition, cognitive flexibility, working memory updating, planning, and monitoring (Diamond, 2013; Miyake et al., 2000). These processes are central to mathematics learning, which requires sustained attention, suppression of irrelevant information, mental manipulation of numerical representations, and adaptive strategy shifting. Working memory constitutes a core component of executive functioning and is commonly operationalized through digit span tasks. Forward digit span reflects attentional maintenance and short-term storage, whereas backward digit span requires active manipulation, updating, and inhibitory control, making it a sensitive indicator of executive working memory capacity (Alloway & Alloway, 2010; Bull & Lee, 2014). Improvements in digit span performance therefore reflect enhanced efficiency of executive control systems rather than simple memorization.

Gamification as Executive Function Training

From a cognitive training perspective, gamification can be conceptualized as a form of task-embedded executive function exercise. Gamified mathematical activities repeatedly engage learners in goal monitoring, response inhibition, cognitive flexibility, and working memory manipulation. Neuroscientific and behavioral studies suggest that repeated engagement in such cognitively demanding and adaptive tasks can strengthen executive control networks, particularly during adolescence—a developmental period characterized by high executive plasticity (Best, 2012; Diamond, 2013).

Empirical evidence supports this interpretation. Gamified instructional interventions have been shown to enhance inhibitory control, planning, and working memory updating in academic contexts (Katz et al., 2022; Scharinger et al., 2023). In mathematics education specifically, gamified problem-solving tasks have been associated with improvements in both forward and backward digit span, indicating gains in executive working memory capacity rather than surface-level engagement effects (Pablo-Ríos et al., 2023; Zhao et al., 2021).

Positioning of Motivation

While motivational factors may influence task engagement, they are not treated as primary explanatory variables in the present study. Rather, motivation is considered a facilitating condition that enables sustained interaction with cognitively demanding tasks. The theoretical emphasis remains on how instructional design characteristics shape executive processing and working memory utilization during learning, in line with cognitive and neuropsychological models of executive functioning.

In summary, the theoretical framework of the present study is centered on cognitive mechanisms underlying executive functions and working memory. Cognitive Load Theory and contemporary executive function models jointly explain how gamification-based mathematics instruction can reduce unnecessary cognitive burden, optimize working memory allocation, and repeatedly activate executive control processes. This framework provides a direct and coherent theoretical basis for examining the effects of gamified instruction on executive functions and digit span performance among secondary school students.

Materials and Methods

Design

The present study employed a semi-experimental pretest–posttest design with a control group.

Participants

The statistical population comprised all 12th-grade mathematics students in District 3 of Tehran during the 2023–2024 academic year. Initially, two girl's high schools were selected using cluster random sampling, and then students were randomly chosen from 12th-grade mathematics classes at those schools. One school was assigned as the experimental group and the other as the control group. Based on the recommendation by Cohen and Manion (2002), which suggests a minimum of 15 participants per group for experimental research, the final sample consisted of 30 students, with 15 in each group.

Inclusion criteria were: enrollment in the 12th-grade mathematics track in District 3 of Tehran during 2023–2024, age range between 15 and 18 years, and willingness to participate in the intervention sessions. Before implementing the experimental design, matching the two experimental and control groups based on the results of the independent t-test indicated that there was no significant difference. Therefore, the research method was implemented as follows.

Exclusion criteria included: missing two or more intervention sessions, failure to meet inclusion criteria, withdrawal of consent by the participant, or parental disapproval. Data were analyzed using SPSS version 25, applying descriptive statistics (mean and standard deviation) and inferential statistics (multivariate analysis of covariance, MANCOVA).

Instruments

Gioia et al.'s Executive Function Questionnaire (2000)

This questionnaire was developed to assess various aspects of prefrontal executive functioning in children and adolescents, aged 5–18 years and is available in parent and teacher forms. In this study, the teacher form was used. The questionnaire consists of 86 items, scored on a 3-point Likert scale: Never (1), Sometimes (2), and Often (3). It measures eight major executive functions: Inhibition, Shifting, Emotional Control, Task Initiation, Working Memory, Planning/Organization, Organization of Materials, and Monitoring.Internal consistency indices have been reported between .87 and .94, indicating high reliability (Nodei, Kh et al., 2016). Validity coefficients reported by Hemmati et al. (2022) for the subscales ranged from .70 to .89, and .98 for the overall scale.

Cattell's Culture Fair Intelligence Test (CFIT), Scale 3

This test consists of four subtests and 46 items, designed for individuals aged 14 and older, including those with higher-than-average intelligence. The subtests are: Series (12 items, 3 minutes), Classification (14 items, 4 minutes), Matrices (12 items, 3 minutes), and Conditions (8 items, 4 minutes). Each correct answer receives 1 point; incorrect answers receive 0. The maximum possible raw score is 46.

Wechsler Adult Intelligence Scale — Digit Span Subtest

The Digit Span subtest of the WAIS was used to assess working memory. This subtest is a core component of the Working Memory Index and includes two sections: Forward Digit Span and Backward Digit Span, each comprising two trials with eight items. Each trial is scored as 0 (incorrect recall) or 1 (correct recall).

Procedure

Gamification-Based Instruction

At the pretest stage, both experimental and control groups completed the study instruments. The experimental group then participated in 10 gamification-based mathematics instruction sessions, each lasting 70 minutes, conducted twice per week. The control group received no intervention during this period. After the intervention phase, both groups completed the posttest measures.

The gamification-based instruction was conducted in small groups, with one 70-minute session per week for 10 weeks. Details of the instructional design are summarized in Table 1.

Table 1. Derivative training program with a gamification approach and cognitive skill enhancement

sessions	Training content	Gamification approach	Targeted executive cognitive skills
1	Introduction to the concept of derivative and learning objectives	Introducing the gamification structure (scoring, levels, missions)	Organizing, goal setting, starting a task
2	Assessment of prior knowledge (limits, functions, basic concepts)	Group activities to assess basic knowledge with interactive games	Conservatism, planning, cooperation
3	Visual introduction to the derivative and the concept of the slope of the tangent line	Using interactive tools such as Conceptual Group Competition + Desmos	Cognitive flexibility, mental imagery
4	Differentiation rules (power, multiplication, division, composition)	Designing leveled challenges (like a math escape room)	Problem solving, response inhibition, decision making
5	Solve real-world problems with derivatives (speed, maximum/minimum)	Real missions with practical scenarios	Critical thinking, focus, attention shifting

sessions	Training content	Gamification approach	Targeted executive cognitive skills
6	Strengthening collaboration and peer education	Group challenges + points system to help classmates	Self-regulation, effective communication, behavioral flexibility
7	Using technology in visualization and derivative practice	Online Platforms + Quizizz+kahoot Games	Sustained attention, shifting attention between tasks
8	Game-based tests to assess progress	Strong feedback + display of scores and rankings	Self-review, modification of learning strategies
9	Student and teacher reflection on the learning path	Reflective activities (experience notebook + class discussion)	Self-awareness, self-assessment, self-efficacy
10	Real-world projects with derivatives	Designing an applied project with data analysis or modeling	Learning transfer, creativity, intrinsic motivation

Results

In this section, first the results of the descriptive data of the variables, namely executive brain functions and numerical memory span (digit span), are presented. Then the assumptions of normality and homogeneity of variances are presented so that the inferential data of the hypotheses can be analyzed.

Table 2. Descriptive statistics of executive function subscales in experimental and control groups

Variable	Stage	Group	M	SD
Inhibition	Pre-test	Control	28.5	2.0
		Experimental	28.0	2.2
	Post-test	Control	28.8	2.3
		Experimental	16.0	1.5
Shifting Attention	Pre-test	Control	26.8	2.1
		Experimental	26.5	2.0
	Post-test	Control	27.0	2.5
		Experimental	15.0	1.4
Emotional Control	Pre-test	Control	22.5	1.9
		Experimental	22.0	2.0
	Post-test	Control	22.0	2.0
		Experimental	12.0	1.2
Task Initiation	Pre-test	Control	18.0	1.5
		Experimental	18.5	1.7
	Post-test	Control	18.5	1.7
		Experimental	10.0	1.0
Working Memory	Pre-test	Control	30.5	2.2
		Experimental	31.0	2.5
	Post-test	Control	30.8	2.4
		Experimental	18.0	1.5
Monitor	Pre-test	Control	18.5	1.5

Variable	Stage	Group	M	SD
		Experimental	17.5	1.3
	Post-test	Control	18.2	1.6
		Experimental	9.0	1.0
Plan/Organize	Pre-test	Control	25.0	2.0
		Experimental	24.8	2.1
	Post-test	Control	25.5	2.2
		Experimental	13.0	1.2
Organization of Materials	Pre-test	Control	15.5	1.2
		Experimental	15.5	1.2
	Post-test	Control	15.8	1.3
		Experimental	8.0	0.8

Note. Means (M) and standard deviations (SD) for the executive function subscales are provided for both experimental and control groups at pre-test and post-test. These descriptive statistics illustrate baseline equivalence and post-intervention changes.

Table 2 presents the descriptive statistics of the BRIEF (teacher form) executive-function subscales for the experimental and control groups at pre-test and post-test. Consistent with the standard BRIEF scoring procedure, subscale raw scores were computed by summing item responses (1 = Never, 2 = Sometimes, 3 = Often) across the items belonging to each subscale. Accordingly, the minimum possible raw score for each subscale equals the number of items in that subscale, and the maximum equals three times that number (Table 2). The Global Executive Composite (86 items) would therefore range from 86 to 258. As shown in Table 2, pre-test scores were comparable between groups, whereas post-test scores increased across all subscales in the experimental group relative to the control group.

Also as shown in the table, pre-test mean scores across all executive function components were comparable between the experimental and control groups, indicating baseline equivalence prior to the intervention. Following the gamification-based mathematics instruction, the experimental group demonstrated consistent increases in post-test mean scores across all executive function subscales, including inhibition, shifting attention, working memory, planning, and monitoring. In contrast, the control group exhibited only minimal changes over time.

The observed pattern suggests that the intervention was associated with broad improvements in executive functioning rather than isolated gains in a single cognitive domain. Standard deviations indicate moderate variability, supporting the stability of the measurements. Importantly, the results are reported as raw subscale scores (sum of item ratings) in accordance with the BRIEF scoring procedure, which ensures mathematical accuracy and interpretability of the descriptive statistics.

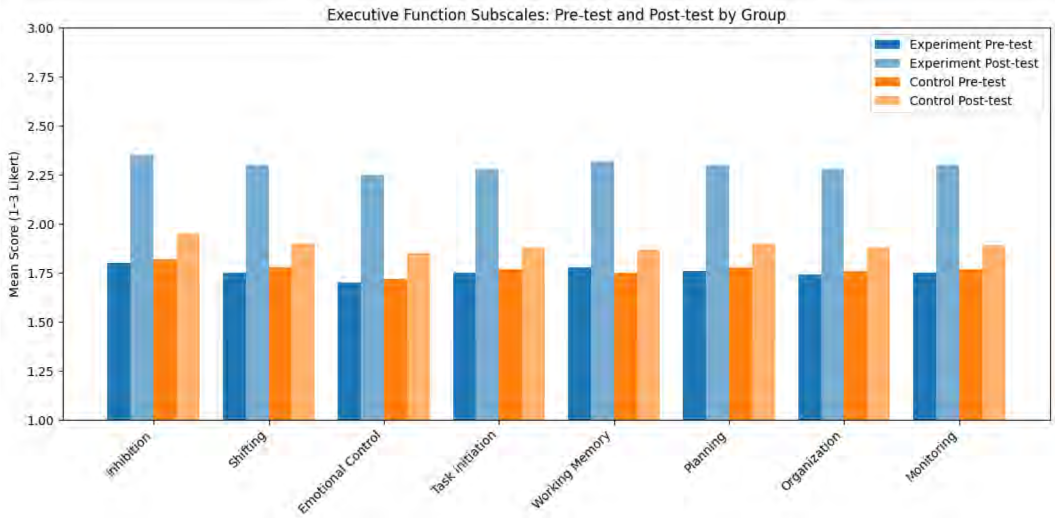

Figure 1. Mean scores of executive function components in the experimental and control groups at pre-test and post-test

Figure 1 illustrates the mean pre-test and post-test scores of executive function components—including inhibition, shifting, emotional control, task initiation, working memory, planning, organization, and monitoring—in both the experimental and control groups. As shown in the figure, students in the experimental group who received gamification-based mathematics instruction demonstrated a clear increase in mean scores across all executive function components from pre-test to post-test. In contrast, the control group exhibited relatively stable scores with only minor fluctuations over time.

The visual comparison highlights a noticeable divergence between the two groups at post-test, suggesting that gamification-based instruction may have contributed to improvements in executive functioning beyond those observed under traditional instructional conditions. This pattern supports the hypothesis that gamified learning environments positively influence executive control processes among secondary school students.

Table 3. Mean and standard deviation of the digit span variable in the two research groups

Group	Stage	Measure	M	SD
Control	Pre-test	Forward	5.12	.83
Control	Pre-test	Backward	3.18	.71
Control	Post-test	Forward	5.15	.88
Control	Post-test	Backward	3.22	.69
Experimental	Pre-test	Forward	5.10	.95
Experimental	Pre-test	Backward	3.05	.90
Experimental	Post-test	Forward	7.08	1.02
Experimental	Post-test	Backward	5.12	.87

Note. Means (M) and standard deviations (SD) for Forward and Backward Digit Span scores are provided for both experimental and control groups at pre-test and post-test. These descriptive statistics illustrate baseline equivalence and post-intervention changes

Analysis of Hypothesis 1: Students who receive gamification-based mathematics instruction will show significantly higher post-test scores on measures of executive functions compared to students who receive traditional instruction.

Table 4. Shapiro–Wilk normality test results for post-test scores

Variable	Subscale / Measure	Group	N	Skewness	Kurtosis	Shapiro–Wilk W	Sig.
Executive Function	Inhibition	Control	15	-.987	-.441	.954	.423
		Experimental	15	.399	.193	.967	.589
	Shifting/Flexibility	Control	15	-1.436	1.218	.942	.321
		Experimental	15	.688	-.590	.963	.517
	Emotional Control	Control	15	-1.328	-1.902	.948	.376
		Experimental	15	.453	.955	.964	.532
	Task Initiation	Control	15	-.678	-.075	.961	.501
		Experimental	15	.478	.349	.967	.586
	Working Memory	Control	15	-1.442	1.799	.940	.308
		Experimental	15	.177	-1.368	.961	.496
	Planning	Control	15	.205	-1.446	.962	.518
		Experimental	15	.427	.833	.969	.612
	Organization	Control	15	-.696	-.506	.958	.459
		Experimental	15	.645	.230	.965	.541
	Monitoring	Control	15	-.483	-1.571	.965	.534
		Experimental	15	.735	.164	.970	.619
Digit Span	Backward	Control	15	-.169	-1.037	.972	.634
		Experimental	15	.815	-.447	.960	.507
	Forward	Control	15	-.302	-1.108	.968	.592
		Experimental	15	-.299	-1.336	.964	.539

Note. Normality of the post-test distributions for all dependent variables was examined separately in the experimental and control groups using the Shapiro–Wilk test (recommended for small samples). As shown above, none of the tests were significant (all $p > .05$), indicating no evidence of departure from normality for the post-test scores.

Table 4 presents the results of the normality assessment for all post-test scores of the research variables, including executive function subscales and digit span measures, in both experimental and control groups. Descriptive statistics, including skewness and kurtosis, are shown alongside the results of the Shapiro–Wilk test, which is recommended for small sample sizes ($n < 50$) to evaluate the normality assumption required for parametric analyses.

Skewness values ranged from approximately -1.44 to .82 and kurtosis values from -1.90 to 1.80, suggesting that the distributions were relatively symmetric and mesokurtic. The Shapiro–Wilk test statistics (W) and associated p-values indicate that none of the variables significantly deviated from normality (all p > .05). These results confirm that the assumption of normality is satisfied for all post-test measures.

This finding justifies the use of parametric statistical procedures, such as ANCOVA and MANOVA, for examining the effects of gamification-based mathematics instruction on executive functions and digit span performance. In addition, the consistency of skewness, kurtosis, and Shapiro–Wilk results across subscales suggests that the data are stable and reliable, supporting both descriptive and inferential interpretations. In sum, the normality check ensures that the subsequent analyses are valid, and it provides confidence that observed differences between experimental and control groups reflect true intervention effects rather than violations of statistical assumptions.

Table 5. Levene's test for homogeneity of variances (post-test)

Variable	Component / Measure	F	df1	df2	Sig.
Executive Function	Inhibition	.161	1	28	.692
	Shifting/Flexibility	.035	1	28	.845
	Emotional Control	.643	1	28	.429
	Task Initiation	.136	1	28	.715
	Working Memory	.002	1	28	.967
	Planning	.349	1	28	.559
	Organization	2.517	1	28	.124
	Monitoring	.008	1	28	.927
Digit Span	Forward Digit Span	3.420	1	28	.077
	Backward Digit Span	3.065	1	28	.091

Note. Homogeneity of variances across groups was assessed using Levene's test. Non-significant results (p > .05) indicate that the error variances are not statistically different between groups. All tests were non-significant, supporting the homogeneity-of-variance assumption for subsequent ANCOVA/MANCOVA analyses.

According to the results of Table 6, the significance of the multivariate test indicators indicates that there is a significant difference in the digit span variable in the experimental and control groups. The results of the analysis of covariance in the difference between the experimental and control groups in each of the digit span variables are given in Table 7.

Table 6. Overall MANCOVA for Digit Span (post-test), controlling for pre-test Digit Span

Test	Value	Approx. F	df1	df2	Sig.
Pillai's Trace	.824	58.140	2	25	<.001
Wilks' Lambda	.176	58.140	2	25	<.001
Hotelling's Trace	4.673	58.140	2	25	<.001
Roy's Largest Root	4.673	58.140	2	25	<.001

Note. A multivariate analysis of covariance (MANCOVA) tested the effect of group on post-test Forward and Backward Digit Span while adjusting for the corresponding pre-test scores as covariates. All four multivariate criteria indicated a statistically significant group effect (p < .001), supporting an overall difference in digit span performance at post-test after baseline adjustment

Table 7. Follow-up ANCOVAs for Digit Span (post-test), controlling for pre-test

Variable	Source	SS	df	MS	F	Sig.	Partial η²
Backward Digit Span	Group	15.435	1	15.435	83.991	<.001	.764
	Error	4.778	26	.184			
Forward Digit Span	Group	17.459	1	17.459	73.096	<.001	.738
	Error	6.210	26	.239			

Note. Following the significant multivariate effect (Table 6), separate ANCOVAs were conducted for each digit span outcome. In each model, the post-test score was the dependent variable, group was the fixed factor, and the corresponding pre-test score was included as a covariate. Both outcomes showed significant adjusted group differences ($p < .001$). Partial eta squared (η^2) is reported as an index of effect size.

Analysis of Hypothesis 2: Students who receive gamification-based mathematics instruction will show significantly higher post-test scores on digit span (both forward and backward) compared to students who receive traditional instruction.

According to the results of Table 8, the significance of the multivariate test indicators indicates that there is a significant difference between at least one of the components of the executive functions variable in the experimental and control groups. The results of the analysis of covariance in the difference between the experimental and control groups in each of the executive functions variables are presented in Table 9.

Table 8. Overall MANCOVA for Executive Function subscales (post-test), controlling for pre-test

Test	Value	Approx. F	df1	df2	Sig.
Pillai's Trace	.700	3.794	8	13	.016
Wilks' Lambda	.300	3.794	8	13	.016
Hotelling's Trace	2.335	3.794	8	13	.016
Roy's Largest Root	2.335	3.794	8	13	.016

Note. A MANCOVA examined the effect of group on the set of post-test executive-function subscales while adjusting for the corresponding pre-test subscale scores. All multivariate criteria indicated a statistically significant overall group effect ($p = .016$), suggesting that the combined executive-function profile differed between groups at post-test after baseline adjustment.

Tble 9. Follow-up ANCOVAs for Executive Function subscales (post-test), controlling for pre-test

EF Subscale	Source	SS	df	MS	F (1,20)	Sig.	Partial η²
Inhibition	Group	1.488	1	1.488	7.697	.012	.278
	Error	3.866	20	.193			
Shifting/Flexibility	Group	1.304	1	1.304	5.872	.025	.227
	Error	4.440	20	.222			
Emotional Control	Group	1.586	1	1.586	7.167	.014	.264
	Error	4.425	20	.221			
Task Initiation	Group	.744	1	.744	5.166	.034	.205
	Error	2.882	20	.144			
Working Memory	Group	.870	1	.870	8.482	.009	.298
	Error	2.052	20	.103			
Planning	Group	.648	1	.648	5.643	.028	.220
	Error	2.298	20	.115			

EF Subscale	Source	SS	df	MS	F (1,20)	Sig.	Partial η²
Organization	Group	.885	1	.885	5.415	.031	.213
	Error	3.267	20	.163			
Monitoring	Group	1.247	1	1.247	5.667	.027	.221
	Error	4.402	20	.220			

Note. After the significant multivariate effect (Table 8), univariate ANCOVAs were conducted for each executive-function subscale. In each model, the post-test subscale score was the dependent variable, group was the fixed factor, and the corresponding pre-test subscale score was included as a covariate. Partial eta squared (η^2) is reported as an effect-size index. Under standard BRIEF teacher-report conventions, higher scores indicate greater executive-function difficulties; therefore, lower adjusted post-test scores in the experimental group should be interpreted as improved executive functioning relative to the control group.

According to the results of Table 9, after adjusting the mean post-test scores by eliminating the pre-test effect, the experimental intervention in the post-test stage caused a significant effect, because the significance level is less than .05. So, there is a significant difference between the mean scores of inhibitions, displacement, emotion control, initiation, working memory, planning, organization, and monitoring in the two control and experimental groups. That is, providing gamification training sessions to students in the experimental group was significantly more than the control group. Its effect for the variable of memory was .466. That is, 46 percent of the post-test variance of the working memory variable is related to the intervention effect of gamification training.

Discussion

The findings of this study demonstrated that gamification-based mathematics instruction significantly improved both executive functions (EFs) and working memory (digit span) in secondary school students. Compared to the control group, students who experienced gamified instruction achieved higher scores in inhibition, shifting, emotional control, task initiation, working memory, planning, organization, and monitoring—along with enhanced performance in both forward and backward digit span tasks. These results underline the cognitive potential of gamification not merely as a motivational tool but as an instructional method capable of strengthening higher-order mental processes crucial for academic learning.

At the heart of these findings is the theoretical proposition that gamification engages students by satisfying fundamental psychological needs and reducing barriers to cognitive processing. Drawing on Self-Determination Theory (Ryan & Deci, 2000), the intervention likely enhanced intrinsic motivation by providing autonomy through choice, competence through achievable challenges and feedback, and relatedness through interactive group tasks. Motivated students, in turn, are more likely to regulate their attention, persist through difficulty, and engage in deeper cognitive processing—all of which underpin the development of executive functions. This interpretation aligns with prior empirical evidence from Sailer and Homner (2020), who showed that gamified learning environments foster self-regulated learning and metacognitive engagement.

Moreover, the results are consistent with Cognitive Load Theory (Sweller, 2010), which posits that learners' working memory resources are finite and easily overwhelmed by extraneous demands. Gamified instruction, by presenting mathematical problems in a structured, interactive, and motivating format, may have reduced extraneous load and increased germane load, allowing students to allocate more cognitive resources toward essential processing. This echoes findings by Almeida et al. (2023), who warned against superficial gamification while affirming its value when pedagogically integrated.

These theoretical perspectives are substantiated by a growing body of empirical evidence. Zhao et al. (2021) demonstrated that gamified math tasks improved adolescents' planning and inhibitory control. Katz et al (2014) and Scharinger et al. (2023) found that gamified cognitive training enhanced working memory and neural engagement, even when behavioral gains were modest. The present study extends these insights by evidencing broad and significant improvements across multiple EF domains and working memory, measured by digit span, in a real-world secondary school context.

The specific improvement in digit span (forward and backward) highlights that gamified tasks train not only rote memory capacity but also the controlled manipulation of information—a hallmark of executive control (Bull & Lee, 2014; Pablo-Ríos et al., 2023). Given that working memory and executive functions are strong predictors of mathematics performance, these findings underscore gamification's dual role: boosting students' motivation to learn while simultaneously cultivating the cognitive tools necessary for success in mathematical problem solving.

Conclusion

This study demonstrated that gamification-based mathematics instruction significantly enhances executive functions and working memory in secondary school students. These findings highlight the dual impact of gamification: increasing students' motivation to engage with challenging content and simultaneously improving the cognitive skills that underpin effective learning and problem solving. The results support the integration of gamification as a pedagogical strategy aligned with theories of self-determination and cognitive load, showing its potential to foster both academic achievement and higher-order cognitive development.

Beyond advancing theoretical understanding, the findings offer actionable insights for educators and policymakers. Thoughtfully designed gamified learning environments can serve as a transformative educational tool, promoting not only engagement and enjoyment but also critical cognitive competencies. Future research and practice should aim to expand and refine gamification strategies to reach diverse learners and sustain long-term cognitive and academic gains. In conclusion, gamification—when integrated with pedagogical principles—can transcend its role as a motivational gimmick and become a meaningful component of effective instruction, equipping students with the cognitive flexibility, control, and resilience required for success in mathematics and beyond.

Crucially, this study bridges an identified gap in the literature. Many prior investigations of gamified learning focused on motivational or affective outcomes, with less attention paid to underlying cognitive mechanisms. By explicitly measuring changes in executive functioning and working memory, the present research demonstrates how gamification operates on a deeper level, fostering the cognitive flexibility, inhibitory control, and planning skills students need to engage effectively with challenging mathematical content.

These findings carry important theoretical and practical implications. Theoretically, they reinforce the view that motivational and cognitive processes are not separate but mutually reinforcing: gamified learning environments enhance motivation, which in turn enables better cognitive control, leading to improved learning. Practically, educators and curriculum designers should recognize that gamification is not simply about adding fun elements but about deliberately crafting learning experiences that challenge students cognitively while maintaining their engagement. Teachers should be trained in designing meaningful gamified activities that align with both subject matter and cognitive goals, avoiding over-reliance on extrinsic motivators such as points or leaderboards (Almeida et al., 2023). Moreover, policymakers could consider incorporating well-designed gamified modules into formal mathematics curricula to enhance both learning outcomes and cognitive development.

Several limitations must be acknowledged in the study. The sample was limited to female 12th-grade students in mathematics classes from a single district, which may constrain generalizability to other populations, grade levels, and cultural contexts. The study measured outcomes only immediately post-intervention, leaving unanswered whether cognitive gains are sustained over time. Also, the reliance on quantitative measures alone precluded a richer understanding of students’ subjective experiences and perceptions of gamification.

Building on these findings, future studies are encouraged to:

- Replicate this research with larger, more diverse, and mixed-gender samples to improve generalizability.
- Employ longitudinal designs to examine the durability of cognitive and academic gains.
- Explore the impact of gamification in other subject areas and at different educational stages.
- Investigate potential moderators and mediators, such as prior cognitive ability, personality traits, or the specific design of gamified elements.
- Combine quantitative outcomes with qualitative insights to better understand the mechanisms and student experiences driving the effects of gamification.

Author Contributions

Samira Abdolhoseinzadeh Buloyerdy contributed to conceptualization, methodology, software, validation (with Dr. Farideh Hamidi), formal analysis (with Dr. Farideh Hamidi), investigation, resources, data curation (with Dr. Farideh Hamidi), writing—original draft preparation, and visualization. Dr. Farideh Hamidi and Dr. Mohammad Ali Fariborzi provided supervision and project administration. Dr. Mohammad Ali Fariborzi contributed to writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data are available on request from the authors.

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Ethical considerations

The study was conducted in accordance with the ethical principles of educational research. Participation was voluntary, and informed consent was obtained from the students and their parents prior to data collection. Confidentiality and anonymity of the participants were ensured, and the data were used solely for research purposes. All procedures complied with relevant ethical guidelines.

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Conflicts of interest

The authors declare no conflicts of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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