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How game–project learning enhances creative thinking in elementary geometry?

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ABSTRACT

The rapid advancement of technology and the demands of 21st-century competencies require mathematics instruction to move beyond procedural learning toward strengthening students' creative mathematical thinking. However, elementary students' creative thinking remains low, particularly in geometry problem solving. Although gamification and project-based learning (PjBL) have shown positive effects, empirical studies integrating both approaches to foster creative mathematical thinking in elementary geometry are still limited. This study examined the effect of game–project-based learning (GPBL) on fifth-grade students' creative mathematical thinking in geometric problem solving. A quantitative quasi-experimental pretest–post-test control group design was employed involving 84 students assigned to an experimental group and a control group. The experimental group received GPBL supported by game and project activities, while the control group received direct instruction. Data were collected using a creative mathematical thinking test and analyzed using repeated measures analysis of variance (ANOVA). The results showed significantly greater improvement in the experimental group than in the control group, indicated by significant time effects, a significant time×group interaction, and significant between-group differences with medium-to-large effect sizes. These findings suggest that GPBL promotes progressive concept exploration and encourages solution strategies. Therefore, GPBL can be integrated into elementary geometry instruction to foster students' creative mathematical thinking.

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1. INTRODUCTION

The rapid advancement of technology has brought fundamental changes to various aspects of human life, including educational practices and learning paradigms. Dependence on technology has not only enhanced the efficiency and accessibility of learning but has also transformed how students interact with knowledge and construct conceptual understanding [1]–[3]. This transformation is further reinforced by the emergence of disruptive technologies such as artificial intelligence, data-driven systems, and gamification, which collectively shape the demands of 21st-century competencies, including creativity, problem solving, decision making, and reflective thinking [4]–[6].

In mathematics education, these challenges become increasingly complex. One persistent issue is students' low motivation and limited learning engagement, particularly among learners who lack intrinsic motivation toward mathematics [7]. Wilson and Mack [8] reported that students' motivation to learn mathematics tends to decline as they progress through formal schooling, which subsequently affects their engagement in mathematical thinking. This condition is reflected in international assessments, where Indonesian students' mathematical performance remains substantially below the global average. Programme for International Student Assessment (PISA) 2022 reported an average mathematics score of 366 for Indonesian students, far below the Organisation for Economic Co-operation and Development (OECD) average of 472 [9]. Similarly, Trends in International Mathematics and Science Study (TIMSS) 2019 ranked Indonesian fourth-grade students 45th out of 58 participating countries [10]. These findings highlight the urgent need for instructional innovation that can promote deeper reasoning and strengthen students' creative mathematical thinking. In this context, game–project-based learning (GPBL) is particularly relevant, as it integrates game-based challenges with project-oriented activities that support exploration and meaningful mathematical understanding. Therefore, mathematics instruction should shift from predominantly teacher-centered approaches toward learning environments that provide greater opportunities for students to explore, experiment, and develop mathematical thinking.

Creative mathematical thinking plays a strategic role in equipping students to address complex real-world problems. Mathematical creativity extends beyond the ability to generate multiple answers; it encompasses flexibility in selecting strategies, originality in constructing solutions, and the capacity to meaningfully develop new ideas [11]–[13]. Empirical studies have demonstrated that mathematical creativity develops optimally through engagement with non-routine problems, open-ended tasks, and learning activities that allow for multiple solution strategies [14]–[16]. Nevertheless, research consistently shows that many students remain at an imitative level of thinking, relying heavily on teacher-modeled procedures and struggling to produce original solutions independently [17]–[19].

To address these challenges, various instructional approaches—such as inquiry learning, discovery learning, and open-ended problem solving—have been implemented. These approaches have been shown to enhance certain dimensions of creative mathematical thinking, particularly fluency and flexibility [20], [21]. However, their effectiveness is highly dependent on task design, instructional context, and the continuity of students' learning experiences [22], [23]. In this case, Subanji *et al*. [19] conceptualized creative mathematical thinking as a progressive cognitive developmental process consisting of five stages: i) pre-imitation, in which students recognize a problem but are unable to formulate a solution; ii) imitation, where students replicate solution strategies demonstrated by the teacher; iii) modification, where students adapt or refine existing strategies; iv) combination, where students integrate two or more strategies to generate a solution; and v) construction, where students independently develop novel solution strategies. Despite its potential, empirical implementation of this model remains limited, especially at the elementary education level and within gamified learning contexts.

Alongside the digital transformation of mathematics education, GPBL has emerged as a promising approach to enhance students' motivation and cognitive engagement. A systematic review by Mayrhofer *et al*. [24] reported that gamification in mathematics learning generally produces positive effects on students' motivation, engagement, and learning outcomes, although its impact depends strongly on instructional design quality. Supporting evidence also indicates that gamification can improve students' mathematical achievement and learning engagement compared to traditional instruction [25]–[27], and may contribute to the development of students' thinking skills and learning motivation [28]. In broader educational contexts, technology-supported gamified environments, project-based games, and simulations have been found to foster higher-order thinking and conceptual understanding through authentic learning experiences [29]–[31]. Moreover, integrating visual and exploratory technologies such as augmented reality can strengthen conceptual understanding through contextual visualization and exploration [32], [33]. However, gamification that relies mainly on points, scores, and competition may fail to promote higher-order thinking unless it is meaningfully aligned with pedagogical goals [34], [35].

Project-based learning (PjBL) has been widely recognized as an effective instructional approach to support creativity, problem-solving skills, and collaboration. Previous studies have reported that PjBL can improve students' creative thinking and mathematical problem-solving compared to conventional instruction [12], [36], [37]. When supported by technology, PjBL also provides more meaningful learning experiences through contextual activities and product-oriented tasks. However, most studies still discuss PjBL and gamification separately, and only limited research has examined how both approaches can be integrated into one learning design to specifically develop students' creative mathematical thinking, especially in elementary geometry learning.

Therefore, a research gap remains regarding how an integrated GPBL approach can foster students' fluency, flexibility, and originality in solving non-routine mathematical problems. The novelty of this study lies in the implementation of GPBL through a game-based instructional design structured as a sequence of level-based missions, which function as scaffolding to gradually guide students from initial exploration of geometric concepts toward deeper conceptual understanding. The outcomes of this exploration are then extended into a final project task, enabling students to transform their in-game discoveries into meaningful mathematical products, particularly through deriving and applying geometric formulas. In addition, this study assesses students' creative mathematical thinking using explicit indicators of fluency, flexibility, and originality, thereby providing a more targeted evaluation of creativity development. To address this gap, this study aims to examine the effect of GPBL on fifth-grade students' creative mathematical thinking in geometry learning.

2. METHOD

This study employed a quantitative approach using a quasi-experimental pretest–post-test control group design involving two groups: an experimental group and a control group. Both groups were administered a pretest to assess students' initial levels of creative mathematical thinking, followed by different instructional treatments, and subsequently a post-test to measure changes in creative mathematical thinking after the intervention. The experimental group consisted of Class VA, which received instruction using the GPBL model, while Class VB served as the control group and was taught using direct instruction. The research participants were fifth-grade students at Islamic Elementary School of Hasyim Ashari, Malang, Indonesia, during the second semester of the 2024/2025 academic year, with a total of 84 students. The use of intact classes was chosen to keep the learning process natural and to avoid disrupting the school schedule. However, since this study was conducted in only one school, the results may not be the same in other schools. Therefore, future research is recommended to implement this model in several schools with different student characteristics and locations to strengthen the findings.

The research implementation comprised three stages: preparation, implementation, and data analysis. During the preparation stage, the researchers developed game- and project-based geometry learning media utilizing the Python programming language through the Thonny as a visualization and conceptual exploration tool. The media were designed to facilitate learning on the topic of the surface area of cylinders through a sequence of activities involving observation of cylindrical shapes, exploration of net representations, and the conceptual derivation of formulas. In addition, an instrument to measure students' creative mathematical thinking was developed based on key indicators of mathematical creativity—fluency, flexibility, and originality—and was validated by experts prior to its implementation. To ensure clarity and alignment between indicators and test items, the operationalization of these indicators into test item characteristics is presented in Table 1.

Table 1. Creative thinking indicators in test items

Indicator	Focus	Test item characteristics
Fluency	Generating more than one solution strategy	Items require students to explore different variations of solid geometry dimensions (length, width, height, or radius) and provide more than one valid solution step or method
Flexibility	Using varied representations	Items require students to explain solutions using solid geometry diagrams or net representations and describe the relationship between the net and the 3D shape.
Originality	Construct solutions with logical justification	Items require students to construct surface area formulas based on nets or component parts of solid figures and justify their reasoning in their own words.

The research implementation began with administering a pretest to students in both the experimental and control groups. The pretest aimed to measure students' initial abilities, particularly their understanding of geometry concepts and their creative mathematical thinking skills prior to the intervention. The pretest was administered to all students in both groups under the same time allocation. The pretest instrument consisted of five open-ended questions designed to assess indicators of creative mathematical thinking. The next stage was the instructional intervention. In this phase, the experimental group received geometry instruction using a Python-based educational game integrated into the learning module. Although the game was designed for solid geometry topics, this study specifically focused on the surface area of a cylinder. At the beginning of the lesson, students were first introduced to the learning module used in the study. In addition, students in the experimental group received technical guidance on how to operate the game, including how to select and run each level and how to input values (the radius and height of the cylinder).

To illustrate the step-by-step the Python-based game, the sequence of learning levels is summarized in Figure 1. Students explored the learning content through five sequential levels: i) observing a three-dimensional cylinder model displayed in the game; at this level, students generated initial ideas and stimulated fluency by describing the characteristics of the cylinder and identifying its key elements (radius, diameter, and height); ii) exploring the cylinder through 3D visualization by adjusting input values (radius and height) and observing changes in the model, thereby supporting fluency through repeated trials and experimentation; iii) identifying geometric forms through net representations by unfolding the cylinder and examining the relationship between the curved surface and a rectangular shape, which supported flexibility by shifting students' reasoning from three-dimensional visualization to two-dimensional representation; iv) analyzing relationships among geometric elements, particularly the relationship between the rectangle's length and the circle's circumference, as well as the relationship between the rectangle's width and the cylinder's height, thereby strengthening flexibility as students were required to connect multiple concepts and representations; and v) constructing the formula and solving problems. At Level 5, students completed a group-based project task in which they derived the surface area formula of a cylinder based on their exploration of the cylinder net in the game and recorded their findings on a worksheet. They then applied the derived formula to solve the given problems.

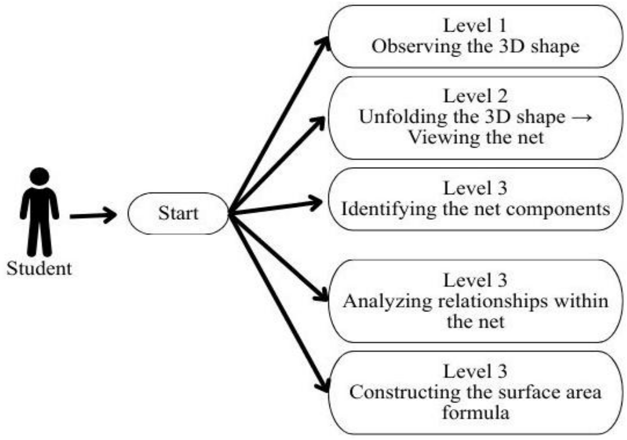

Figure 1. Game levels for learning cylinder surface area

Meanwhile, the control group received direct instruction using the same learning module and the same topic (surface area of cylinders), but without the Python-based game media. Direct instruction was implemented through a teacher-centered learning sequence consisting of explanation of cylinder elements and net representation, teacher demonstration of the surface area formula derivation on the board, guided practice through sample problems, and individual exercises using questions. Students primarily followed the teacher's procedural explanation and solved tasks using the formula provided, with limited opportunities for exploration and independent strategy construction. The intervention was conducted over three meetings within a two-week period, with each meeting lasting 2×35 minutes. Both groups received the same number and frequency of instructional sessions. After the completion of the instructional intervention, a post-test was administered to both groups to measure students' improvement in creative mathematical thinking skills.

Data were collected using a creative mathematical thinking test administered as both a pretest and a post-test to students in the experimental and control groups. To ensure content validity, the instrument was reviewed by experts in mathematics education and educational technology. Expert judgment was conducted using a validation sheet evaluating the relevance of items to learning objectives, clarity of wording, appropriateness for learners, and alignment with creative thinking indicators. The reliability of the instrument was examined through internal consistency analysis, and the coefficient indicated that the test had acceptable reliability for research purposes. The students' scores were then processed and quantitatively analyzed using JASP software. The initial stage of analysis involved descriptive statistics to examine the mean scores, standard deviations, and changes in pretest and post-test results within each group. Next, the assumptions for parametric analysis were tested, including a normality test using the Shapiro–Wilk test and a homogeneity of variance test using Levene's test.

After the assumptions were met, the data were analyzed using a two-factor repeated measures analysis of variance (ANOVA), consisting of a within-subject factor (time: pretest and post-test) and a between-subject factor (group: experimental and control). This analysis was conducted to examine: i) differences in students' creative mathematical thinking before and after the intervention (main effect of time); ii) differences between the experimental and control groups (main effect of group); and iii) differences in the pattern of improvement between the two groups (interaction effect of time×group). To strengthen the interpretation of the results, effect size was reported using eta squared (η^2). If a significant interaction effect was found, further analyses were conducted using post hoc pairwise comparisons to identify specific differences between conditions. All statistical tests were performed at a significance level of 0.05.

3. RESULTS AND DISCUSSION
3.1. Development of game–project-based learning

This study commenced with the development and preparation of a GPBL instructional intervention designed to stimulate students' creative mathematical thinking in solving non-routine problems in geometry, particularly the concept of the surface area of a cylinder. The learning media were developed using the Python programming language through Thonny, enabling students to directly interact with geometric visualizations presented in a level-based educational game format. The dashboard of the Python-based GPBL media used in this study is shown in Figure 2.

As illustrated in Figure 2, the interface presents several stages of exploration that guide students gradually toward conceptual understanding. Figure 2(a) displays the initial visualization of a three-dimensional cylinder that allows students to observe the object as a complete geometric solid. Figure 2(b) shows an interactive cylinder model in which students can manipulate the radius and height values to explore how changes in these parameters affect the visualization. Figure 2(c) presents the net representation of the cylinder after unfolding the three-dimensional model. Through this visualization, students begin to recognize the geometric components forming the cylinder. Figure 2(d) highlights the identification of the lateral surface as a rectangular shape derived from the curved surface of the cylinder. Figure 2(e) further demonstrates the relationship between the rectangular lateral surface and the circular base and top of the cylinder. Finally, Figure 2(f) illustrates the stage in which students construct the surface area formula of the cylinder based on the relationships they have observed during the exploration process.

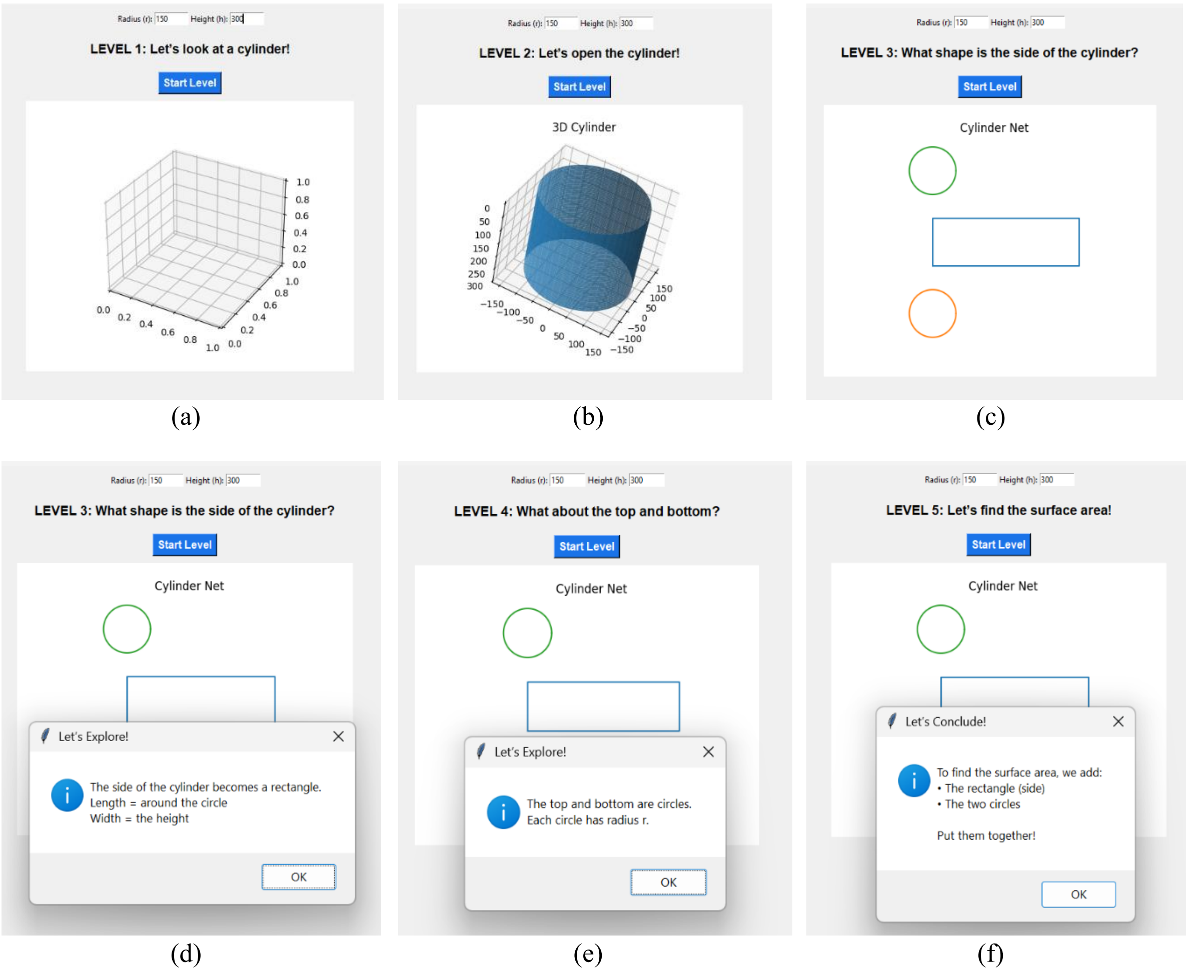

Figure 2. Dashboard of the Python-based GPBL media developed using Thonny: (a) observing the cylinder shape, (b) unfolding the cylinder into its net, (c) identifying the lateral surface form, (d) the lateral surface is a rectangle; its length is the base circumference and its width is the cylinder height, (e) analyzing the base and top surfaces, and (f) constructing the surface area formula

The learning media were structured into several progressive and exploratory levels. Level 1 guided students to visually observe the cylinder as a complete three-dimensional solid. Level 2 facilitated exploration of the cylinder through interactive three-dimensional visualization, which could be unfolded into a net representation. Level 3 directed students to identify the lateral surface of the cylinder through the net visualization, leading them to discover that the lateral surface forms a rectangle.

At Level 4, students were encouraged to analyze the relationship between the lateral surface and the base and top of the cylinder, represented as two congruent circles. This exploration was reinforced through exploration prompts, which guided students to relate the radius of the circular base to its circumference and the height of the cylinder to the width of the rectangular lateral surface. At Level 5, students were required to construct the formula for the surface area of a cylinder by integrating the areas of the lateral surface, the base, and the top. Through this process, the formula was derived through conceptual reasoning rather than memorization. To support the instructional implementation, the researchers prepared complementary instruments, including a creative mathematical thinking test and validation sheets for both the learning media and the assessment instruments.

3.2. Expert validation of the media

The instructional prototype was subsequently validated by experts in mathematics education and educational technology to ensure content appropriateness, clarity of instructions, visual design quality, and material accuracy. The results of the expert validation of the project-based game prototype are presented in Table 2. The validation results indicate that the average feasibility percentage exceeded 90%, suggesting that the prototype was highly feasible for implementation with fifth-grade students at Islamic Elementary School of Hasyim Ashari, Malang. The learning intervention was conducted across several sessions, beginning with an introduction to the game mechanics, followed by active engagement in completing mathematical project missions, and concluding with reflection and evaluation of students' work.

3.3. Descriptive analysis of creative mathematical thinking

To quantitatively describe students' creative mathematical thinking abilities in both the experimental and control groups based on pretest and posttest results, descriptive statistics were computed. These statistics included the number of participants, mean scores, standard deviations, standard errors, and coefficients of variation. The descriptive analysis was used to examine the equivalence of students' initial abilities between the two groups and to identify changes in creative mathematical thinking following the implementation of different instructional approaches. The results of the descriptive statistics are presented in Table 3.

Descriptively, at the pretest stage, the mean creative mathematical thinking score of the experimental group (M=72.64, SD=5.249) was comparable to that of the control group (M=71.95, SD=3.622), indicating that both groups had equivalent initial abilities. Following the instructional intervention, both groups demonstrated score improvements; however, the increase in the experimental group was substantially greater. The post-test mean score of the experimental group increased to 81.93 (SD=4.193), whereas the control group reached a mean score of 74.33 (SD=3.213). Normality testing using the Shapiro–Wilk test indicated that all datasets were normally distributed ($p>0.05$). In addition, Levene's test confirmed that the variances between groups were homogeneous for both pretest and post-test scores ($p>0.05$), indicating that the homogeneity assumption was satisfied. This trend is also clearly illustrated in Figure 3. As shown in Figure 3, the experimental group demonstrates a steeper increase from pretest to post-test compared to the control group. This suggests that students who learned through the GPBL model experienced a stronger improvement in creative mathematical thinking than those who received direct instruction.

Table 2. Expert validation results of the project-based game prototype

Evaluation aspect	Obtained score	Maximum score	Percentage (%)	Category
Content appropriateness	56	60	93.3	Valid
Visual design	45	50	90.0	Valid
Material quality	47	50	94.0	Valid

Table 3. Descriptive statistics of creative mathematical thinking

Creative thinking ability	Group	N	Mean	SD	SE	Coefficient of variation	Shapiro-Wilk	P-value of Shapiro-Wilk	Levene's F	p
Pretest	Experimental	42	72.64	5.249	0.810	0.072	0.929	0.062	6.410	0.053
	Control	42	71.95	3.622	0.559	0.050	0.966	0.235	6.410	0.053
Post-test	Experimental	42	81.93	4.193	0.647	0.051	0.959	0.138	4.738	0.092
	Control	42	74.33	3.213	0.496	0.043	0.951	0.070	4.738	0.092

Note: N=number of participants; SD=standard deviation; SE=standard error; F=F statistic from Levene's test; p=significance value.

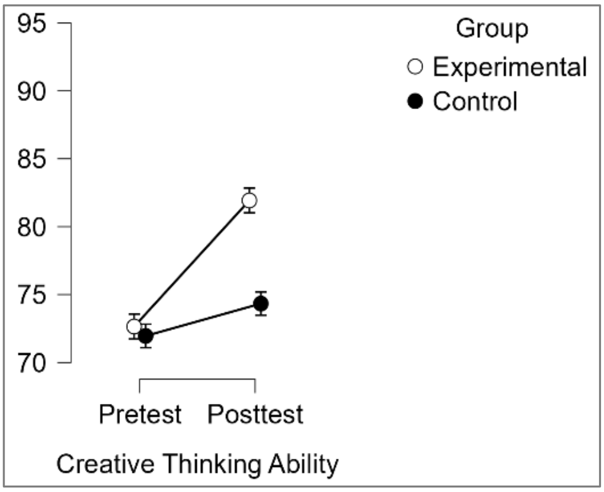

Figure 3. Pretest and post-test mean scores of students' creative thinking in the experimental and control groups

3.4. Inferential analysis using repeated measures ANOVA

To examine the statistical significance of changes in students' creative mathematical thinking abilities over time and to compare improvement patterns between groups, a repeated measures ANOVA was conducted. The within-subjects' effects are presented in Table 3, while the between-subjects effects are presented in Table 4. As shown in Table 4, the analysis revealed a significant main effect of time, $F(1, 82)=176.96$, $p<0.001$, $\eta^2=0.262$, indicating a substantial improvement in students' creative mathematical thinking from pretest to post-test across both groups. Moreover, a significant interaction effect between time and group was found, $F(1, 82)=61.98$, $p<0.001$, $\eta^2=0.092$, suggesting that the magnitude of improvement differed significantly between the experimental and control groups. This interaction effect indicates that the instructional model played an important role in shaping students' learning gains.

Table 4. Within-subjects effects of repeated measures ANOVA

Cases	Sum of squares	Df	Mean square	F	P	H²
Creative thinking ability	1429.2	1	1429.167	176.96	<0.001	0.262
Creative thinking ability✻group	500.6	1	500.595	61.98	<0.001	0.092
Residuals	662.2	82	8.076			

Note: F=F statistic from the ANOVA test; p=significance value; η^2=eta squared effect size indicating the proportion of variance explained by the factor.

The stronger improvement observed in the experimental group may be attributed to the GPBL design, which provided students with structured and progressive learning experiences through level-based missions. During these missions, students manipulated geometric parameters (radius and height) and directly observed changes in both three-dimensional and net representations of the cylinder. Such repeated exploration likely encouraged students to generate multiple solution ideas, supporting fluency. Moreover, the transition from 3D visualization to net representation helped students view the concept from different perspectives, thereby supporting flexibility. At the project stage, students were required to derive the surface area formula based on their exploration results, which promoted originality by encouraging reasoning-based solutions rather than reliance on memorization.

Furthermore, the between-subjects analysis presented in Table 5 showed a significant difference between groups, $F(1, 82)=27.50$, $p<.001$, $\eta^2=0.132$. This result demonstrates that students in the experimental group achieved significantly higher creative mathematical thinking scores than those in the control group. Collectively, these findings confirm that GPBL significantly improved creative mathematical thinking compared to direct instruction.

Table 5. Between-subjects effects of repeated measures ANOVA

Cases	Sum of squares	Df	Mean square	F	P	H²
Group	720.9	1	720.86	27.50	<0.001	0.132
Residuals	2149.4	82	26.21			

3.5. Post hoc analysis

To clarify the nature of the interaction between group and time, post hoc comparisons were conducted. The results are presented in Table 6. The post hoc results indicate that no significant difference existed between the experimental and control groups at the pretest stage (p=0.485), confirming the equivalence of initial creative mathematical thinking abilities. In the experimental group, a highly significant improvement was observed between the pretest and post-test scores (p<0.001), demonstrating the effectiveness of GPBL in enhancing creative mathematical thinking. Although the control group also exhibited a statistically significant improvement, the magnitude of this gain was notably smaller. Importantly, the comparison of post-test scores between the experimental and control groups revealed a significant difference (p<0.001), indicating that students in the experimental group outperformed their counterparts in the control group after the intervention.

Table 6. Post hoc comparisons of creative mathematical thinking scores

Group comparison		Mean difference	SE	df	t	p_{holm}
Experimental, pretest	Control, pretest	0.690	0.984	82	0.702	0.485
	Experimental, post-test	-9.286	0.620	82	-14.974	<0.001
	Control, post-test	-1.690	0.904	82	-1.871	0.130
Control, pretest	Experimental, post-test	-9.976	0.904	82	-11.041	<0.001
	Control, post-test	-2.381	0.620	82	-3.839	<0.001
Experimental, post-test	Control, post-test	7.595	0.815	82	9.318	<0.001

Note: SE=standard error; df=degrees of freedom; t=t statistic; p_{holm}=Holm-adjusted p-value for multiple comparisons.

3.6. Effect size interpretation

The magnitude of the instructional effects was further examined through effect size interpretation. The η^2 value of 0.262 for the time effect indicates a large effect, reflecting substantial improvement from pretest to post-test. The η^2 value of 0.092 for the time×group interaction corresponds to a medium effect, suggesting that the instructional model contributed meaningfully to differences in learning gains between groups. Additionally, the main effect of group yielded an η^2 value of 0.132, indicating a medium effect size, which suggests that GPBL significantly improved students' creative mathematical thinking compared to direct instruction.

3.7. Polynomial contrast analysis

To examine the pattern of change in students' creative mathematical thinking abilities more deeply, a polynomial contrast analysis was conducted. The results are presented in Table 7. The results indicate that all tested contrasts were statistically significant (p<0.001), demonstrating a consistent and meaningful pattern of change in creative mathematical thinking abilities. In Contrast 1, the positive estimate (3.365) indicates that the improvement from pretest to post-test was substantially stronger in the experimental group than in the control group. This finding aligns with the contrast coefficients, which reveal divergent trajectories of change between the two groups, with the experimental group exhibiting a more pronounced increase. Furthermore, Contrasts 2 and 3 yielded significant negative estimates (−3.452 and −6.314, respectively), indicating differences in both the direction and magnitude of change across groups and measurement occasions. These results further confirm that GPBL produced a distinct and more robust pattern of improvement in creative mathematical thinking compared to direct instruction.

Table 7. Polynomial contrast analysis of creative mathematical thinking

Comparison	Estimate	SE	df	t	p
1	3.365	0.528	82.00	6.374	<0.001
2	-3.452	0.439	82.00	-7.873	<0.001
3	-6.314	0.733	82.00	-8.611	<0.001

3.8. Discussion

The findings suggest that GPBL provides a meaningful learning environment that supports the development of students' creative mathematical thinking in geometry problem solving. By integrating game-based exploration with project-based tasks, GPBL encourages students to actively investigate geometric concepts through visualization, object manipulation, and reflective reasoning rather than relying on memorized formulas. This learning mechanism enables students to construct conceptual understanding progressively and to generate more flexible and original solution strategies. These results align with the systematic literature review by Mayrhofer *et al*. [24], which emphasized that gamification can positively influence motivation and cognitive engagement when instructional designs go beyond point-based and scoredriven systems. Consistent with several studies [25]–[27], the present study further indicates that gamification becomes more effective when it is embedded in challenging problem-solving activities that promote exploration and metacognitive awareness. Therefore, the game component in GPBL functioned not merely as an engagement enhancer but as a scaffolding tool that facilitated deeper conceptual construction and creative reasoning.

More specifically, the level-based game structure within GPBL played a crucial role in shaping students' creative thinking processes. Levels 1 and 2 supported students in understanding the cylinder as a three-dimensional object through visual exploration, whereas Levels 3 and 4 encouraged students to connect the net representation with key geometric elements of the cylinder, such as radius, height, and circumference. These stages enabled students to observe the relationships among geometric components more concretely through dynamic visualization and immediate feedback from input changes. This learning mechanism aligns with the several findings [29], [30], [33], who emphasized the importance of authentic contexts, simulation, and interactive visualization in strengthening cognitive processing and conceptual understanding. The visualization of the cylinder and its net through the game provided a more meaningful learning experience compared to conventional instruction, which often tends to be procedural. At Level 5, students were required to construct the cylinder surface area formula based on the net they explored and then apply it to problem solving through collaborative project tasks. This project stage represents a key feature distinguishing the present study from more general gamification implementations. Students were not only completing game missions but also producing a meaningful cognitive product in the form of a derived formula and problem-solving strategies. This finding strengthens the arguments [27], [28], who reported that gamification positively affects the cognitive domain when designed to promote decision making and problem solving. However, this study extends those findings by demonstrating that when gamification is integrated with PjBL, its impact becomes stronger because students are encouraged to organize ideas, justify reasoning, and construct mathematical strategies more independently.

Using the indicators of creative mathematical thinking, the GPBL mechanism provides a clear explanation of how fluency, flexibility, and originality developed throughout the learning process. Fluency was primarily stimulated in Levels 1 and 2, where students observed a three-dimensional cylinder model and repeatedly experimented with different input values (radius and height), enabling them to generate multiple possible solution steps. Flexibility was developed in Levels 3 and 4, as students were required to shift across various representations, including three-dimensional visualization, net representation, and relational analysis among geometric elements before constructing the formula. These activities encouraged students to approach the concept from different perspectives and apply diverse strategies. Meanwhile, originality emerged most strongly in Level 5, when students were required to derive the surface area formula based on their own exploration during the project stage rather than memorizing or copying formulas provided by the teacher. This mechanism is consistent with Baran *et al.* [38] and Coxbill *et al.* [11], who argued that mathematical creativity develops through problem-solving situations that allow multiple strategies. Activities such as unfolding cylinder nets, linking circle circumference to the length of the lateral surface, and independently formulating the surface area equation represent non-routine tasks aligned with previous studies [13], [14], who emphasized the effectiveness of open-ended problems in fostering flexibility and originality.

Furthermore, the findings clarify that gamification combined with PjBL produces a more consistent impact than superficial gamification designs. Several previous studies have reported that gamification effects on higher-order thinking tend to be moderate or unstable when gamification focuses primarily on external elements such as points, rewards, or competition. In the present study, the game was not implemented as an isolated motivational tool but as part of a PjBL sequence that required exploration, conceptual construction, and application in problem solving. As a result, students were encouraged to engage in deeper thinking processes, which is consistent with previous studies [29], [30], [33], regarding the importance of authentic and simulation-based learning designs to strengthen conceptual understanding.

In addition, Subanji *et al.* [19] five-stage model of creative mathematical thinking provides a developmental lens to explain how GPBL supported students' progression from imitation toward construction. At the beginning, students tended to operate at the imitation stage, replicating solution strategies demonstrated by the teacher when describing cylinder properties and determining surface area. This condition is consistent with the findings of Susilowati *et al.* [18], who reported that many elementary school students remain at the imitation stage in creative mathematical thinking. However, through game-based activities that allowed students to manipulate radius and height values and directly observe changes in outcomes, students began to move into the modification stage by adapting and refining existing strategies based on their explorations. When students unfolded the cylinder and examined its net representation, the modification process became more evident as they revised their understanding by shifting from a three-dimensional perspective to a two-dimensional representation. Furthermore, during the analysis stage, students demonstrated characteristics of the combination stage by integrating two or more concepts or strategies, such as linking the circumference of a circle with the area of a rectangle to explain the lateral surface and relating it to the base area. Finally, through the project task, students reached the construction stage, independently developing solution strategies by deriving the surface area formula from the net structure and applying it to solve problems.

Compared to inquiry and discovery learning approaches [20]–[22], this study suggests that game-based technology integration offers added value through dynamic visualization and immediate feedback. In this study, inquiry and discovery processes still occurred; however, they were enriched by digital media that allowed students to explore concepts more concretely and interactively. These findings support the research by Shaw *et al*. [23], who emphasized that mathematical creativity can be improved through open-ended tasks that allow reflection and idea exploration, particularly when students are given opportunities to actively construct knowledge.

Based on the overall results, the major contribution of this study lies in its explicit integration of gamification, PjBL, and the development of creative mathematical thinking within one coherent instructional design. Most previous studies have examined gamification, game-based learning, or PjBL separately. This study demonstrates that the synergy of these three components produces a stronger effect on students' creative mathematical thinking, as reflected in the moderate-to-large effect size values. Despite the positive results, this study has several limitations. The sample involved only 84 students from one school, and the intervention lasted only two weeks, which may limit generalizability and long-term conclusions. Teacher effects may also have influenced learning outcomes. In addition, this study did not analyze fluency, flexibility, and originality separately nor map students' processes to Subanji *et al*. [19] five-stage model. Future research should involve larger multi-school samples, longer interventions, deeper indicator-based analysis, and may explore emerging technologies such as augmented reality to enrich GPBL implementation.

4. CONCLUSION

Based on the analyses, the implementation of GPBL is effective in enhancing students' creative mathematical thinking in geometric problem solving. Instruction that integrates gamification with project-based activities encourages students to actively engage in conceptual exploration, enabling them to move beyond procedural execution toward the construction of understanding through flexible, original, and meaningful reasoning. These findings directly address the research objective by demonstrating that improvements in creative mathematical thinking were substantially greater in the experimental group than in the group receiving direct instruction. The primary contribution of this study lies in strengthening empirical evidence that the synergy between gamification and PjBL represents a relevant and effective pedagogical design in mathematics education, particularly for fostering students' higher-order thinking skills. By positioning game mechanics as cognitive tools rather than merely motivational elements, the GPBL approach offers a structured pathway for supporting creative mathematical thinking in classroom practice.

Mathematics teachers are encouraged to implement GPBL by utilizing accessible and low-cost digital tools, such as Python-based applications (Thonny), GeoGebra, or other interactive visualization media. Instruction can be designed with step-by-step scaffolding, starting from observing 3D shapes, unfolding, and examining nets, analyzing relationships among geometric elements, and finally constructing formulas and applying them in project tasks. Through this process, the game functions as a learning tool that supports conceptual understanding and reasoning, rather than serving as entertainment alone. Despite the positive outcomes, this study has several limitations. It did not examine the development of each creative mathematical thinking indicator (fluency, flexibility, and originality) separately. In addition, the content scope was limited, the sample size was relatively small, and the intervention period was relatively short. Therefore, future research is recommended to implement GPBL over a longer duration, involve multiple schools with diverse student characteristics, and extend its application to other mathematics topics beyond geometry. Moreover, these findings are consistent with Indonesia's current curriculum direction, which emphasizes competency-based learning and the development of 21st-century skills. Thus, GPBL may serve as a practical instructional model to support students' creativity, critical thinking, and problem-solving abilities.

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

INFORMED CONSENT

The authors confirm that informed consent was obtained from all individuals participating in this study.

ETHICAL APPROVAL

This study involved human participants and was conducted in accordance with all applicable national regulations and institutional policies, in line with the principles of the Declaration of Helsinki. Ethical approval for the study was granted by the Institute for Research and Community Service (LPPM), Universitas Wisnuwardhana, acting as an equivalent ethics committee. All participants provided informed consent prior to their participation in the research.

DATA AVAILABILITY

The data supporting the findings of this study can be obtained from the corresponding author, [AP], upon reasonable request.

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