



# ARGeo Math: An alternative media to improve students' mathematical creative thinking skills on geometry topics

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## ABSTRACT

Mathematical creativity is a crucial component of 21<sup>st</sup> century education, yet limited research has examined how augmented reality (AR) can systematically enhance this ability in elementary mathematics. Grounded in the cognitive theory of multimedia learning (CTML) and constructivist perspectives, this study investigates the effectiveness of ARGeo Math, an AR-based learning application that transforms abstract geometry concepts into interactive 3D visualizations to foster creative mathematical thinking. A quasi-experimental design involving 49 fifth-grade students in Indonesia was conducted, with one class serving as the control group and another as the experimental group using ARGeo Math. Quantitative analyses using normalized gain (N-gain) and t-tests revealed a significant improvement in students' creative thinking skills in the experimental group (N-gain = 76.84%, effective category). Beyond statistical gains, ARGeo Math supported cognitive engagement, flexible problem-solving, and deeper understanding by linking visual and symbolic representations. The findings extend educational technology theory by demonstrating a clear mechanism through which CTML principles particularly integrated multimodal cues can be operationalized to stimulate generative mathematical reasoning. This study offers practical, scalable insights for designing AR-enhanced STEM learning in primary education, and its theoretical model provides a distinct contribution for guiding future creativity-oriented AR instructional design. Nonetheless, the quasi-experimental design with limited sample size and short intervention duration constrains the generalizability of results, indicating the need for longitudinal and multi-site research to further validate the model.

**Keywords:** augmented reality, elementary education, elementary students, geometry, mathematics education

## INTRODUCTION

The development of higher order thinking skills has become a priority in 21<sup>st</sup> century education, with creativity emerging as a central competency across global frameworks such as UNESCO's education 2030 and the OECD's PISA agenda (PISA, 2024; Sulistyanto et al., 2022; Surya et al., 2022; Thornhill-Miller et al., 2023; UNESCO, 2024). Despite this emphasis, creativity remains underdeveloped in mathematics classrooms, where procedural instruction and limited conceptual exploration often restrict students' opportunities to engage in flexible and original thinking (Newton et al., 2022). These challenges are particularly evident in geometry, a domain that requires spatial reasoning and the ability to connect concrete and abstract representations, skills that many elementary students struggle to develop through traditional two-dimensional materials (Harris, 2023; Thom et al., 2024). This persistent gap highlights the need for learning environments that better nurture creative mathematical reasoning through meaningful visualization and exploratory tasks.

Augmented reality (AR) offers a promising pathway for addressing these challenges by enabling students to manipulate digital 3D objects within authentic contexts, thereby supporting spatial reasoning and conceptual understanding without relying solely on static materials (Cardoso et al., 2023). Grounded in constructivist principles and the cognitive theory of multimedia learning (CTML), AR environments integrate visual-verbal information in ways that reduce extraneous load and promote active knowledge construction (Mayer, 2001; Piaget, 1970; Vygotsky, 1978). However, despite these pedagogical advantages, empirical research investigating how AR can systematically foster mathematical creativity, especially in elementary geometry remains limited.

Various studies have explored the integration of AR in mathematics education, particularly in geometry learning and creative thinking development. Prior work has reported positive impacts, such as improvements in mathematical creative thinking through ethnomathematics-based AR applications Richardo et al. (2023), enhanced creativity and spatial ability identified in systematic reviews Hidajat (2024), and increased motivation, spatial skills, and creative thinking in geometry-based AR implementations (Islim et al., 2024). Studies with younger learners also highlight the value of AR for strengthening geometric reasoning, reducing cognitive load, and promoting flow experiences Wu et al. (2024). Additional contributions include AR-based instructional materials that support geometric visualization and surface-area reasoning Koparan et al. (2023), as well as evidence from head-mounted AR systems that improve geometric reasoning and embodied sense-making (Walkington et al., 2025). Meta-analytic findings further demonstrate moderate effects of AR on achievement, especially in spatial and visualization tasks Li et al. (2023), while recent syntheses on embodied AR interactions emphasize AR's capacity to support mental transformation and geometric imagination (Yang et al., 2025).

Taken collectively, this body of research provides substantial evidence that AR holds considerable potential for strengthening learners' conceptual understanding, spatial reasoning, and dimensions of creative thinking. However, a closer examination reveals a clear research gap: most existing studies emphasize visualization, engagement, or spatial enhancement, but few investigate how AR can be intentionally designed and theoretically grounded to cultivate mathematical creative thinking. In particular, there is limited research that systematically aligns AR features with constructivist and multimedia learning principles to stimulate generative processes such as fluency, flexibility, originality, and elaboration in geometry learning. This gap highlights the need for AR interventions that go beyond perceptual benefits and explicitly target creativity, thereby underscoring the significance of developing ARGeo Math as a theory informed and pedagogically meaningful learning medium.

The ARGeo Math application allows learners to scan geometric markers, visualize three-dimensional objects, and manipulate them through interactive gestures such as rotation and scaling. These features were designed based on constructivist and multimedia learning principles, enabling students to connect abstract mathematical reasoning with concrete visual experiences. By engaging students in exploration and discovery, ARGeo Math seeks to transform geometry learning into an active, creative process.

This study aims to examine the effectiveness of ARGeo Math in improving students' mathematical creative thinking skills. Specifically, it investigates whether students taught using ARGeo Math demonstrate significantly higher creative thinking performance compared to those receiving traditional instruction. The

research hypothesizes that integrating AR-based visualization enhances students' fluency, flexibility, originality, and elaboration in solving mathematical problems. The novelty of this study lies in its explicit use of constructivist and multimedia learning principles to guide the design of an AR learning environment that directly targets mathematical creative thinking, a focus that has received very limited attention in previous AR research. While earlier studies highlight AR as a tool for improving visualization and spatial reasoning, they rarely demonstrate how AR features can be purposefully connected to learning theories to activate creative thinking processes such as fluency, flexibility, originality, and elaboration. By introducing a theory informed AR intervention and examining its effectiveness through a quasi-experimental design, this study provides a clear and distinctive contribution by showing that AR can function not only as a visualization aid but also as a cognitive and pedagogical mechanism for fostering creativity in elementary geometry learning.

## LITERATURE REVIEW

### AR in Elementary Mathematics Learning

AR has been recognized as a medium that enhances visualization and contextualization in mathematics learning, particularly in geometry (Azuma, 1997; Schutera et al., 2021). Although prior studies report increased engagement and representational understanding, many AR implementations emphasize visual enhancement rather than cognitive development. Interventions that replace static images with 3D models often lack tasks that require generative reasoning or creativity (Chang et al., 2022; Czerkawski & Berti, 2021; Garzón, 2021). Literature also shows that AR designs frequently underutilize theoretical or pedagogical frameworks, resulting in learning experiences that are visually rich but cognitively shallow. This persistent gap underscores the need for AR designs that embed structured inquiry, conceptual reasoning, and creativity rather than relying on visualization alone. ARGeo Math is situated to address these shortcomings by grounding AR activities within coordinated learning frameworks.

### CTML and Its Implications for AR Design

Mayer's (2021, 2022) CTML emphasizes the importance of organizing multimedia information to manage working memory and reduce extraneous cognitive load. AR environments, when not designed carefully, can introduce unnecessary complexity or misalignment between narration and visuals (Krüger & Bodemer, 2022). Reviews show that many AR applications do not fully implement coherence, contiguity, or redundancy principles (Çeken & Taşkın, 2022). ARGeo Math incorporates CTML by structuring AR scenes with focused 3D models, aligned verbal-visual cues, and minimal decorative detail to optimize germane processing for mathematical reasoning and creativity. These CTML-based decisions serve as foundational constraints that ensure AR support, rather than overwhelms, cognitive processing.

### Constructivism and AR-Based Knowledge Construction

Constructivist theory highlights active exploration, meaning-making, and iterative refinement of understanding (Bruner, 1966; Vygotsky, 1978). AR is theoretically aligned with these principles due to its interactivity, yet empirical research indicates that many AR applications provide virtual objects without scaffolding, reflection, or opportunities for multiple-solution exploration (Bödding et al., 2023). The constructivist mechanisms in ARGeo Math exploration of 3D shapes, guided inquiry, and reflection-oriented tasks encourage learners to construct and reorganize mathematical ideas, supporting creative reasoning rather than passive observation.

### TPACK Framework

The TPACK framework emphasizes the interaction among technological, pedagogical, and content knowledge (Mishra & Koehler, 2006). However, existing AR studies often focus on technological novelty at the expense of pedagogical coherence or content reasoning (Al-Ansi et al., 2023). The design of ARGeo Math operationalizes TPACK by tightly aligning AR manipulation features (technological knowledge), inquiry-based structures (pedagogical knowledge), and geometry concepts (content knowledge). This integration ensures that AR functions as a coherent instructional system that responds to the cognitive demands of elementary geometry.

## Substitution, Augmentation, Modification, and Redefinition Framework

The substitution, augmentation, modification, and redefinition (SAMR) framework provides a lens for understanding the degree of pedagogical transformation enabled by technology (Hamilton et al., 2016). Most AR applications in mathematics remain at the substitution or augmentation levels of the SAMR framework (Blundell et al., 2022). They enhance visualization but do not transform the learning task (Wen et al., 2023). ARGeo Math operates at the modification and redefinition levels by enabling exploratory manipulation of spatial structures, strategy comparison, and generative problem-solving tasks infeasible using traditional media. This reflects a shift from enhancement to transformation.

## Embodied Learning

Embodied learning emphasizes the role of perception, gesture, and spatial interaction in mathematical thinking (Skulmowski & Rey, 2018). Although AR naturally affords embodied interaction, many applications do not intentionally design tasks that leverage bodily movement or spatial orientation (Nikolarakis & Koutsabasis, 2024). ARGeo Math integrates embodied learning principles by requiring rotation, translation, and viewpoint control of 3D shapes, enabling learners to coordinate perceptual-motor actions with conceptual reasoning.

## Integrated Conceptual Foundation for ARGeo Math

The literature reveals that CTML, constructivism, TPACK, SAMR, and embodied learning address complementary dimensions of AR-based instruction. When combined, these frameworks provide a coherent basis for designing ARGeo Math. CTML governs cognitive efficiency, constructivism guides exploratory knowledge construction, TPACK ensures technological-pedagogical-content alignment, SAMR frames the transformation of tasks, and embodied learning supports sensorimotor pathways essential for geometric reasoning. The convergence of these frameworks forms the conceptual logic that informs ARGeo Math's design as a generative and cognitively principled AR learning environment. **Figure 1** depicts the conceptual framework.

## METHODS

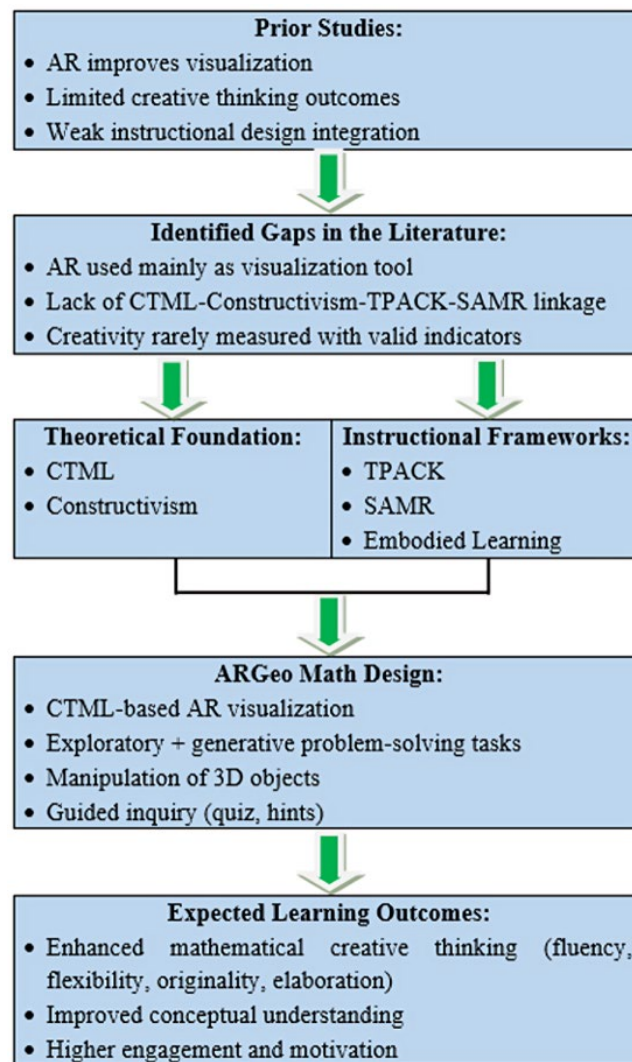
### Research Design

This study employed an experimental research design with a quantitative approach to determine the causal relationship between the use of ARGeo Math and students' mathematical creative thinking. Experimental research is suitable for examining the effect of a specific intervention under controlled conditions by comparing the outcomes between different groups (Gulyaeva et al., 2019). A quasi-experimental design was adopted because random assignment of participants was not feasible within the natural classroom setting. Nevertheless, comparable learning conditions were maintained across groups to ensure internal validity.

The design applied was a non-equivalent control group design, which included both a control group and an experimental group. The experimental group was taught using the ARGeo Math application as an AR-based learning medium, while the control group received conventional instruction following the same geometry curriculum. Both groups completed a pre-test to assess their initial creative thinking ability before treatment and a post-test after treatment to measure changes in performance. The comparison between pre-test and post-test results across groups allowed the researchers to evaluate the impact of AR-based learning on students' fluency, flexibility, originality, and elaboration.

### Population, Sampling, and Sample

This study initially involved 100 fifth-grade students at one of the elementary schools in Indonesia. However, for the purpose of the quasi-experimental design, the sample was determined using cluster sampling rather than individual random sampling. Specifically, two intact classes were selected: class 5B (24 students) served as the control group, which was taught the same mathematics topics as stipulated in the curriculum using conventional instruction without the ARGeo Math intervention, whereas class 5C (25 students) constituted the experimental group and received instruction on the same topics with the aid of



**Figure 1.** Conceptual framework (Source: Authors' own work)

ARGeo Math learning media. The selection of these two classes was conducted randomly from the available fifth-grade classes, but the students remained in their original classroom groups without any regrouping or rearrangement. Therefore, the randomization referred to in this study applies to the class selection process, not to the reassignment of individual students. Although the sample size was relatively small, it was sufficient for classroom-based experimental design (Cohen, 1992). Nevertheless, the limited number of participants constrains the generalizability of findings beyond similar educational contexts. Future studies with larger samples across different schools are recommended to enhance external validity.

### Instruments

The data collection instruments used in this study included observations, tests, and interviews. The observations were conducted in both the experimental and control classes with the primary purpose of monitoring student engagement, instructional strategies employed by the teacher, and the overall classroom learning dynamics. All classroom activities and interactions were systematically recorded using a structured observation sheet. In addition, semi-structured interviews were conducted with selected participants, including teachers and a sample of students from both groups, to gain deeper insights into their perceptions of the learning process and the effectiveness of the instructional media. The interview procedure involved guided questions focusing on learning experiences, challenges, and levels of understanding, while allowing participants to elaborate on their responses. These combined approaches ensured that the data reflected not only measurable outcomes but also qualitative insights into the learning context.

**Table 1.** Rubric for students' creative thinking

Aspect	Students' response in test	Score
Originality	Their own answer is not clear	1
	Their own answer is clear but not finish	2
	Their own answer is clear but the result is incorrect	3
	Their own answer is clear and correct	4
Fluently	The idea is not relevant for problem-solving	1
	The idea is relevant but the answer is incorrect	2
	The idea is variative but the answer is incorrect	3
	The idea is variative and the answer is correct	4
Flexibility	The only one answer is incorrect	1
	The only one answer in correct	2
	The variative answers but incorrect	3
	The variative answers are correct	4
Elaboration	The answer is incorrect and not detail	1
	The answer is incorrect and in less detail	2
	The answer is incorrect but detail	3
	The answer is correct and detail	4

Data was collected through test techniques to measure mathematical creative thinking after being treated. The test consists of 10 mathematical problems. The test instrument is validated by validators who are experts in the field of mathematics education research and learning. The suggestions are

- (1) the selection of diction so that it is understood by class 5<sup>th</sup> students,
- (2) the final answer is in the form of an integer, and
- (3) the level of difficulty is adjusted to the duration of the test.

The final instrument consisted of open-ended problem-solving tasks that required students to generate multiple solutions, apply flexible strategies, elaborate their reasoning, and propose original ideas in real-world fraction contexts. Each item required students to demonstrate reasoning skills, with increasing complexity from basic operations to contextual problem-solving. The validity and reliability of the instrument were rigorously examined. A strong degree of inter-rater agreement was established through Cohen's kappa. Subsequent content validity analysis, based on Aiken's coefficient, confirmed that each item possessed a validity score exceeding 0.8 (Retnawati, 2016). The use of Aiken's V was chosen because it provides a quantitative estimation of expert agreement on item relevance, which complements the qualitative judgment process typically used in instrument development within educational research contexts. Moreover, the reliability analysis performed with ANATES V4 yielded a coefficient of 0.64, interpreted as high reliability according to the classification by (Bendig, 1954). ANATES was selected because it provides item-level diagnostic information such as item discrimination and difficulty indices, enabling a comprehensive evaluation of internal consistency beyond conventional alpha estimates. Collectively, these findings confirm that the instrument demonstrates acceptable levels of content, construct, and reliability evidence, making it suitable for application in both pre-test and post-test implementations.

Their answer sheets were analyzed, and their mathematical creative thinking was measured based on the criteria in **Table 1**, the data of mathematical creative thinking skills in the range of 80 to 116, with interval data types.

### Data Analysis

The data analysis techniques used in this research were classical assumption testing, hypothesis testing, and the normalized gain (N-gain) test. The classical assumption stage consists of a normality test and a homogeneity test. The results of the normality test analysis were obtained using the Kolmogorov-Smirnov method with a significance level of 0.05 (5%) for each sample. The results of the homogeneity test analysis were obtained using the Levene statistic method for each sample. Then, the hypothesis test obtained using the independent t-test analysis can be used to analyze the mean difference (mean) in the form of interval data scales or ratios between two groups.

Meanwhile, the results of the obtained N-gain test analysis can be used to analyze the effectiveness of ARGeo Math learning media on mathematical creative thinking skills. The N-gain was calculated using the

**Table 2.** Categorization of N-gain score

Percentage (%)	Category
0 < 40	Not effective
40-55	Less effective
56-75	Effective enough
> 76	Effective

**Table 3.** Coding results and emerging themes from interview data

Theme	Category	Initial codes (examples)	Representative quotes	Interpretation/connection to quantitative findings
Visualization	3D and spatial representation	<ul style="list-style-type: none"> <li>Seeing geometry in 3D</li> <li>Easier to imagine shapes</li> <li>Realistic model view</li> </ul>	"When I rotated the AR object, I could easily understand the shape and volume."	Students' improved spatial visualization supports the significant N-gain in creative mathematical thinking.
Interactivity	Hands-on exploration	<ul style="list-style-type: none"> <li>Manipulating objects</li> <li>Trying different angles</li> <li>Interactive feedback</li> </ul>	"I liked touching and moving the shapes; it made learning feel like playing."	Direct interaction increased engagement and experimentation, explaining students' higher creative performance.
Learning motivation	Enjoyment and engagement	<ul style="list-style-type: none"> <li>More enthusiastic</li> <li>Less bored</li> <li>Learning feels fun</li> </ul>	"Learning with ARGeo Math was exciting; I didn't get bored easily."	Enhanced motivation led to longer attention spans, aligning with improved quantitative results.
Problem-solving strategy	Cognitive process and flexibility	<ul style="list-style-type: none"> <li>Trying alternative methods</li> <li>Testing ideas visually</li> <li>Reflecting on mistakes</li> </ul>	"After seeing the 3D model, I tried a new way to solve the problem."	The use of ARGeo Math fostered flexible problem-solving strategies, consistent with higher creativity scores.
Technical issues	Device and application constraints	<ul style="list-style-type: none"> <li>Limited device compatibility</li> <li>Slow app loading</li> <li>Internet dependency</li> </ul>	"Sometimes the app didn't work properly on my phone."	Technical issues explain minor variations or lower gains among some students in the experimental group.

formula:  $N - gain = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}}$ , where  $S_{post}$  is the post-test score,  $S_{pre}$  is the pre-test score, and  $S_{max}$  is the maximum possible score.

The category of effectiveness of determining the N-gain value according to Pujiastuti and Haryadi (2024) is presented in [Table 2](#).

Quantitative data were analyzed using descriptive statistics and inferential tests (independent samples t-test) to compare post-test scores between the experimental and control groups. In addition to significance testing, effect size analysis was conducted to estimate the magnitude of the treatment's practical impact. The effect size was calculated using Cohen's  $d$ , obtained by dividing the difference between the group means by the pooled standard deviation (SD) of both groups:  $d = \frac{M_1 - M_2}{SD_{pooled}}$ , where  $SD_{pooled} = \sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}}$ .

Interpretation followed Cohen's (1988) criteria: 0.20-0.49 (small), 0.50-0.79 (medium), and  $\geq 0.80$  (large). This procedure aligns with best practices in educational technology research to report both statistical and practical significance (Lakens, 2013).

Qualitative data obtained from student and teacher interviews were analyzed through a thematic analysis procedure to validate the quantitative findings (see [Table 3](#)). Interview transcripts were carefully transcribed, read repeatedly, and coded inductively to identify meaningful patterns related to the use of ARGeo Math in mathematics learning. Through open and axial coding, the data were categorized into emerging themes such as visualization, interactivity, learning motivation, problem-solving strategy, and technical issues. To ensure the credibility and dependability of the qualitative interpretation, two independent coders reviewed and coded all interview transcripts. Inter-coder reliability was established through a consensus coding process and quantified using Cohen's kappa, which resulted in a coefficient of 0.82, categorized as almost perfect agreement based on Landis and Koch's (1977) criteria. Any discrepancies between coders were resolved through iterative discussion until full consensus was reached, ensuring that the thematic structure was stable, replicable, and free from subjective bias. These themes were then compared with the quantitative results (N-gain of students' mathematical creativity) to interpret and confirm the statistical outcomes. The triangulation

**Table 4.** Data of students' creative thinking

	N	Minimum	Maximum	Mean	SD
Pre-test experiment	25	80	116	100.56	11.01
Post-test experiment	25	80	116	112.24	8.72
Pre-test control	24	80	116	100.96	9.65
Post-test control	24	80	116	107.50	10.25

**Table 5.** Result of normality data

		Kolmogorov-Smirnov		
		Statistic	df	Significance
Students' creative thinking	Pre-test experiment	.168	25	.067
	Post-test experiment	.167	25	.072
	Pre-test control	.139	24	.200
	Post-test control	.174	24	.059

**Table 6.** Results of homogeneous post-test variance test

Levene statistic	df1	df2	Significance
2.149	1	47	.149

**Table 7.** Independent samples test

		Levene's test equality of variances		t-test for equality of means		
		F	Significance	t	df	Sig. (2-tailed)
Students' creative thinking	Equal variances assumed	2.15	.149	38.785	47.000	.000
	Equal variances not assumed			38.760	47.755	.000

between qualitative and quantitative evidence provided a comprehensive understanding of how ARGeo Math effectively enhanced students' creativity and engagement in mathematical learning.

### Ethical Consideration

Ethical approval for this research was obtained from the University Research Ethics Committee (983.1/C.6-II/FKIP/IX/2024). Participation was voluntary, and written informed consent was secured from students' parents and school administrators. Participants' identities were anonymized to maintain confidentiality. The study adhered to ethical guidelines outlined by the American Educational Research Association (2019), ensuring respect, fairness, and data protection throughout the research process.

## RESULTS

### Descriptive Statistical Analysis

Descriptive statistical analysis was conducted to examine the distribution of pre-test and post-test scores in both the experimental and control groups (Table 4). Prior to the intervention, the two groups exhibited comparable pre-test means, indicating similar baseline conditions. Following the implementation of ARGeo Math in the experimental group, the post-test data showed a marked increase in scores, whereas the control group experienced only a modest improvement.

### Classical Assumption Test (Normality and Homogeneity)

The assumption testing was conducted prior to inferential analysis to ensure that the dataset met the requirements for parametric procedures. The Kolmogorov-Smirnov results in Table 5 show that all pre-test and post-test scores in both the experimental and control groups had significance values greater than 0.05, indicating that the data were normally distributed. Additionally, Levene's test (Table 6) produced a p-value above 0.05, confirming that the variances between the groups were homogeneous.

### Independent Sample Test

The independent sample t-test was conducted to compare the post-test scores of the experimental and control groups (Table 7).

**Table 8.** Effect size of the ARGeo Math intervention

Measure	Mean difference	Pooled SD	Cohen's d	Interpretation
Pre- and post-test comparison within the experimental group	5.47	3.92	1.40	Large

**Table 9.** N-gain score test

	Group	Statistic	
N-gain <sub>person</sub>	Experiment	Mean	76.8473
		Minimum	55.9300
		Maximum	83.7800
	Control	Mean	10.5698
		Minimum	4.4100
		Maximum	23.3800

As Levene's test indicated homogeneous variances ( $p > 0.05$ ), the analysis proceeded using the equal variances assumed row. The t-test result showed a statistically significant difference between the two groups ( $p < 0.05$ ).

### Cohen's d

In addition to the significance testing, an effect size analysis was conducted using Cohen's d to evaluate the magnitude of the difference between the experimental and control groups (Table 8). The calculation produced a Cohen's d value of 1.40, which falls within the range classified as a large effect.

### N-Gain Test

The N-gain analysis was conducted to examine the extent of improvement in mathematical creative thinking across the two groups (Table 9). The experimental group demonstrated a considerably higher average N-gain score compared to the control group.

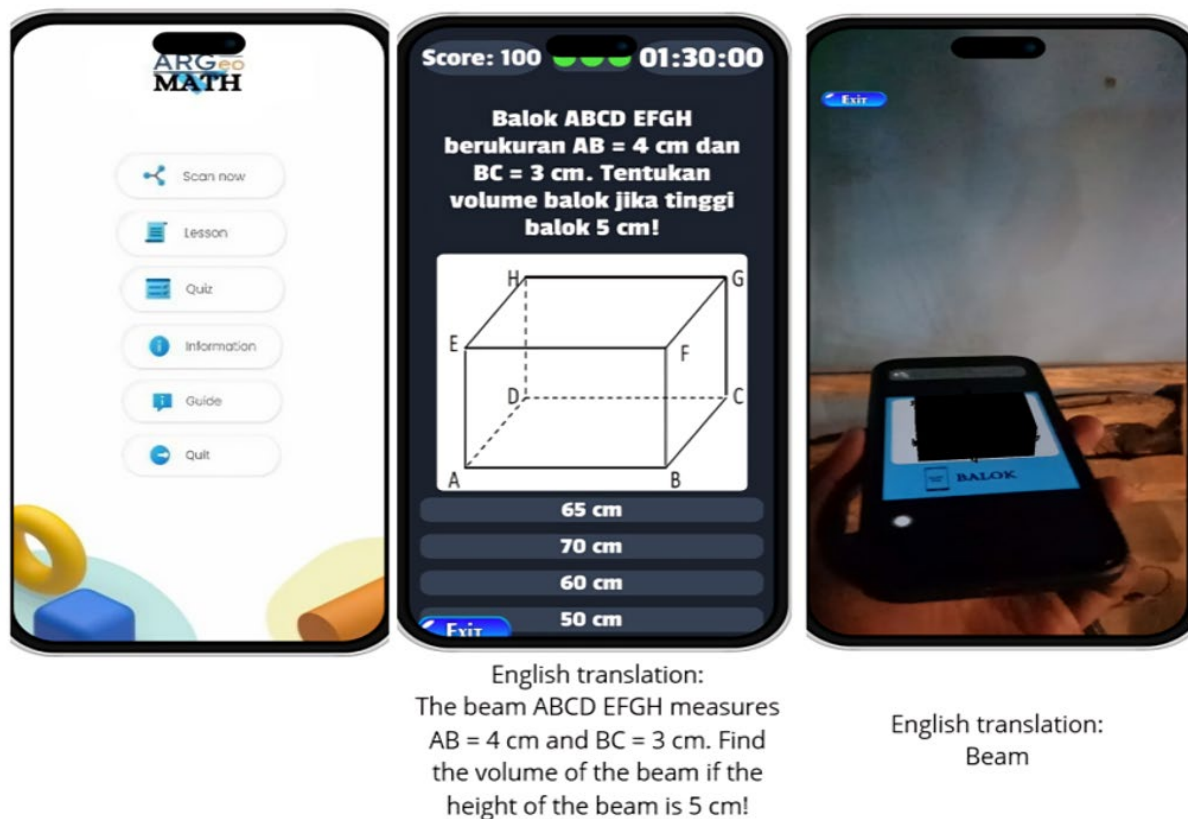
### Sub-Analysis of Creativity Dimensions

A descriptive inspection of rubric-based scoring patterns showed that fluency exhibited the largest gain, followed by flexibility, originality, and elaboration. These results indicate that ARGeo Math most strongly enhanced students' ability to generate varied solution ideas, while improvements in detailed reasoning (elaboration) were comparatively smaller. This pattern confirms that the intervention predominantly strengthened divergent thinking processes.

## DISCUSSION

The improvement of mathematical creative thinking skills in the experimental group through the use of ARGeo Math demonstrated a substantial effect compared to the control group, as confirmed by the quasi-experimental analysis. This result underscores that the integration of AR technology in mathematics instruction particularly in geometry can provide immersive, cognitively rich learning experiences that promote higher-order thinking skills. AR-based learning environments enhance students' ability to connect visual and symbolic representations, bridging abstract geometric ideas with tangible three-dimensional objects. This finding aligns with previous evidence suggesting that visual realism and interactivity in AR learning media strengthen students' conceptualization and imagination in mathematics (Cellupica et al., 2024; Hidajat, 2024; Ropawandi et al., 2022).

These quantitative improvements were further corroborated by the interview data. Students reported that the AR objects made it easier for them to "try different ideas", "see changes instantly", and "explain geometry in detail", which correspond directly to the statistically significant improvements in flexibility, originality, and elaboration. This convergence indicates that the AR-based manipulation and real-time feedback mechanisms not only enhanced measurable creative thinking outcomes but were also perceived by learners as supporting exploratory reasoning processes. Teachers' observations of increased hypothesis-testing behaviors further clarify why the experimental group outperformed the control group, suggesting that ARGeo Math initiated generative cognitive engagement consistent with both the CTML framework and the reported behavioral patterns. This qualitative-quantitative alignment is consistent with prior AR studies showing that exploratory



**Figure 2.** ARGeo Math look (Source: Authors' own work)

manipulation of dynamic visualizations supports idea generation and solution testing (Walkington et al., 2024), and that AR designs combined with reflective prompts or guided reflection enhance deeper conceptual processing and creative problem solving in mathematics (Hidajat, 2024; Hidayat & Wardat, 2024). The mechanisms underlying these improvements can be further explained through principles of multimedia learning (Figure 2).

The design of ARGeo Math reflects intentional pedagogical integration rather than superficial technological enhancement. The structured features scan, lesson, guide, and quiz were arranged to activate the core principles of Mayer's (2021, 2022) CTML. The coherence principle is reflected in the reduction of extraneous visual elements so that students focus on information that is directly relevant to the task. The contiguity principle is implemented through the close alignment of textual or audio explanations with the appearance and manipulation of AR objects, which facilitates more efficient integration of verbal and visual information. The generative processing principle is activated when students manipulate three-dimensional models, test hypotheses, and reorganize geometric relations as they move through the sequence of scan, lesson, and quiz. These CTML mechanisms not only reduce extraneous load but also free cognitive resources that students can allocate to generative tasks, which are essential for creativity development. Through these mechanisms, ARGeo Math functions not merely as a visually enriched tool but as a cognitively generative learning environment. This is aligned with international findings that emphasize the importance of well-structured AR design for supporting deeper learning (Elford et al., 2022; Krüger & Bodemer, 2022).

From a constructivist perspective, the enhancement of students' creative thinking in this study aligns closely with foundational principles proposed by Bruner (1966) and Vygotsky (1978). Bruner highlights that learning occurs through active exploration and discovery, while Vygotsky (1978) emphasizes scaffolded interaction and the internalization of guided experiences. These principles are reflected in the design of ARGeo Math, where the features scan, lesson, guide, and quiz form a sequenced instructional cycle that prompts learners to explore geometric representations, formulate hypotheses, revise interpretations based on feedback, and evaluate their reasoning. This pattern reflects constructivist assumptions that creativity develops through iterative meaning-making rather than through exposure to visual novelty. Evidence from

international studies supports this interpretation. Krüger and Bodemer (2022) reported that AR environments designed with opportunities for conceptual manipulation and reflection supported reorganization of mental models and the generation of multiple solution strategies. Similarly, Rebollo et al. (2022) found that spatial interaction combined with guided reflection resulted in stronger gains in students' creative originality. Systematic reviews such as Hidajat (2024) also conclude that AR is most effective for creativity when feedback, guidance, and sequencing are deliberately integrated into the design of learning activities. These convergent findings indicate that ARGeo Math's structured scaffolding likely enabled students to externalize, refine, and reorganize ideas in ways that support creative mathematical thinking.

Pedagogically, these findings carry meaningful implications for curriculum design, teacher professional development, and EdTech innovation. For curriculum developers, integrating AR-based tasks into geometry instruction can provide a more concrete entry point before formal symbolic reasoning, aligning with the concrete, pictorial, abstract (CPA) approach (Leong et al., 2015). For teachers, the study highlights the need for TPACK-oriented training that emphasizes both the technological and pedagogical dimensions of AR integration specifically, designing inquiry-driven lessons that stimulate creative thinking (Mishra & Koehler, 2006; Prasetyo et al., 2022). For educational technology developers, ARGeo Math demonstrates the value of embedding instructional scaffolds such as guidance, assessment, and reflection prompts within the AR interface to support sustained learning rather than short-term engagement (Sulistyanto et al., 2024). These implications align with the SAMR model, which advocates for technology's transformative role when it enables new learning experiences previously unattainable through conventional media (Blundell et al., 2022; de Morais Bicalho et al., 2023; Hamilton et al., 2016).

Recent international studies provide comparative context that strengthens the interpretation of ARGeo Math's contributions. The systematic review by Hidajat (2024) concluded that AR applications enhance mathematical creativity when they incorporate structured feedback and scaffolded exploration. AlAli et al. (2025) demonstrated that AR environments combining spatial manipulation with reflective prompts improved originality and flexible problem-solving. Schutera et al. (2021) reported that spatial representations in AR improved students' reasoning pathways in geometry within a technology-enhanced mathematics learning context. Buchner (2022) and Moser and Lewalter (2024) argued that AR systems structured around generative learning tasks supported conceptual restructuring and the production of multiple solution paths. Collectively, these findings align with ARGeo Math's emphasis on coherence, contiguity, and generative processing. At the same time, ARGeo Math makes a unique contribution by fully operationalizing these principles within a complete instructional workflow designed for elementary geometry.

Although the present study provides meaningful theoretical and practical contributions, several limitations should be acknowledged. First, the intervention focused exclusively on geometry, which limits the generalizability of the findings to other mathematical domains such as algebra or measurement. Second, the application was implemented only on an Android platform, leaving questions regarding cross-platform functionality, including iOS and web-based AR. Third, the study used a modest sample size and did not include a longitudinal follow-up, which limits the ability to determine whether the gains in creative thinking are sustained over time or transferred to non-AR tasks. Future research should examine cross-platform adaptability, domain transferability, and long-term retention in order to more fully evaluate the potential of ARGeo Math across diverse instructional contexts.

In summary, the findings reinforce that ARGeo Math effectively integrates technological innovation, CTML-based instructional design, and constructivist scaffolding to support the development of mathematical creativity. By grounding its design in coherence, contiguity, and generative processing and by demonstrating consistency with international AR research the study contributes a theoretically robust and practically scalable model for AR-based mathematics instruction.

## CONCLUSION

This study provides a novel theoretical contribution to the field of educational technology by demonstrating how AR can operationalize and extend core principles from the CTML and constructivist learning theory within a fully scaffolded instructional workflow. While prior AR-based studies typically emphasize visualization or motivational gains, the findings of this research clarify the specific cognitive

mechanisms through which AR supports creativity. In particular, ARGeo Math shows how coherence, contiguity, and generative processing can be systematically embedded in AR environments to activate higher-order cognitive engagement, enabling learners to reorganize mental models, generate multiple solution pathways, and construct creative mathematical ideas. This positions AR not only as a representational tool but as an instructional architecture that advances theoretical understanding of how multimedia principles function in interactive, spatially enhanced learning contexts.

Practically, the study contributes a theoretically informed design model for structuring AR-based learning environments. Rather than treating AR merely as an auxiliary visualization tool, ARGeo Math demonstrates how instructional scaffolding, feedback mechanisms, and reflective prompts can be embedded into AR interfaces to operationalize pedagogical decision-making within the TPACK framework. This extends prior interpretations of TPACK by illustrating how technological, pedagogical, and content dimensions interact dynamically in spatial, interactive learning settings. The findings also refine the SAMR model by providing empirical evidence that AR can consistently achieve the modification and redefinition stages when learning tasks incorporate multimodal generative processing. Furthermore, the study suggests that CPA-based instructional sequencing can be reconceptualized for AR environments, where concrete-pictorial-abstract transitions occur iteratively rather than linearly. These findings also highlight the potential for broader scalability, including the integration of AR-based instructional workflows across different subject areas and the development of teacher professional development models that prepare educators to design and facilitate AR-supported learning. These theoretical insights offer a foundation for scalable AR-based instructional models and can inform policy-level digital learning strategies aligned with SDG 4 by highlighting how AR-mediated cognitive engagement can be equitably integrated into elementary education. Future research should examine the scalability of AR-based environments through cross-subject implementation, longitudinal impact on creativity, and integration into national digital education initiatives.

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**AI statement:** The authors confirm that generative AI tools were used only for language editing and improving the clarity of the manuscript. All research design, analysis, and conclusions were developed by the authors.

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**Data availability:** Data generated or analyzed during this study are available from the authors on request.

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