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Reducing Functional Fixedness in Geometry Through Analogical Maping and Representation Shifts: A Randomized Controlled Trial

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Abstract

Functional fixedness constitutes a pervasive cognitive bottleneck in geometry, yet educational interventions rarely target the representational mechanisms underlying this rigidity. Addressing this critical gap, this study challenges the view of fixedness as an immutable trait by experimentally testing the efficacy of analogical mapping and dynamic representational shifts. Through a rigorous randomized controlled trial, the investigation demonstrates that integrating analogical reasoning with dynamic geometry environments significantly outperforms conventional procedural instruction in fostering creativity. Crucially, mediation analysis reveals that representational flexibility rather than mere software usage serves as the primary mechanism driving this cognitive breakthrough. These findings validate the proposed Analogical Representational Shift Model (ARSM), offering a theoretical advancement in creative cognition. Practically, the study provides a definitive blueprint for developing next-generation AI tutoring systems capable of detecting and dismantling cognitive rigidity, marking a pivotal shift from routine drill-based learning to the cultivation of adaptive mathematical insight.

1. INTRODUCTION

Overcoming cognitive constraints is a central challenge in geometry reasoning, particularly when learners struggle to flexibly reinterpret mathematical objects across problem contexts. Rather than treating such difficulties as task-specific or tool-dependent, this study interrogates functional fixedness as a regulatable cognitive constraint shaped by representational dynamics (Medvedev, 2020; Weatherford, 2021; Yagolkovskiy, 2020). In geometry learning, functional fixedness manifests when students associate geometric objects exclusively with routine procedures such as interpreting triangles solely through area formulas while failing to recognize alternative transformations, analogies, or conceptual uses required by non-routine problems (Schoevers, 2022; Serrano, 2025; Sinclair, 2012). Such rigidity constrains representational flexibility and limits students' capacity to generate unconventional spatial solutions (Agustin, 2024; Murni, 2025; Vágová, 2020).

Despite its relevance, a persistent conceptual weakness in geometry education research lies in the lack of theoretical precision in defining cognitive rigidity, particularly in the interchangeable use of functional fixedness, representational fixity, and procedural rigidity. As a result, prior studies often fail to clarify whether these constructs represent distinct phenomena or different manifestations of a shared underlying constraint, limiting theoretical accumulation and empirical comparability (Sinclair, 2012; Vágová, 2020). This ambiguity is especially evident when students' difficulties in shifting between symbolic, visual, dynamic, and analogical representations are labeled uniformly as functional fixedness, despite more plausibly reflecting deeper representational constraints (Ofori, 2020; Schoevers, 2022; Sinclair, 2012). Consequently, theoretical explanations remain blurred and empirical findings difficult to integrate or generalize.

To resolve this conceptual gap, the present study conceptualizes functional fixedness as a specific form of representational rigidity. Functional fixedness is defined as a cognitive condition in which learners repeatedly activate dominant procedural uses of geometric objects while failing to reconceptualize them across alternative representational systems when task demands require such shifts (Ofori, 2020; Olteteanu, 2018). Procedural rigidity is therefore treated not as an independent construct, but as a behavioral consequence of representational fixity operating under instructional and task constraints (Li, 2019). This refinement sharpens construct boundaries and strengthens construct validity in geometry education research.

Building on this refined framework, framing functional fixedness as a modifiable cognitive condition rather than a static learner trait enables more precise causal explanations of how instructional interventions disrupt rigid representational activation in geometry problem solving. Cognitive research indicates that functional fixedness is negatively associated with representational flexibility, originality, and creative thinking, suggesting that reducing fixity is a prerequisite for fostering innovation in mathematical reasoning (Aini, 2020; Medvedev, 2020; Ndiung, 2024). This perspective opens analytic space for examining instructional mechanisms capable of reshaping learners' representational engagement and cognitive flexibility.

Despite extensive descriptive research on geometry learning difficulties, a first major empirical gap remains the lack of experimental causal evidence demonstrating how functional fixedness can be systematically reduced (Sinclair, 2012; Vágová, 2020). A second gap concerns the absence of mediation-oriented analyses explaining *why* instructional interventions work, rather than merely showing *that* they work (Hayes, 2020). Although analogical reasoning and representational shifts are recognized as powerful learning supports that broaden conceptual range and promote cross-domain connections (Khatin, 2022; Podolefsky, 2007; Ruamba, 2025), their mediating role in reducing functional fixedness remains rarely modeled, leaving underlying cognitive mechanisms theoretically under-specified (Qi, 2024). A third unresolved gap lies in the weak integration of analogy theory with Dynamic Geometry Environments (DGE). While DGEs such as GeoGebra support visualization and exploratory manipulation (Albaladejo, 2015; Guti, 2021). Their affordances dragging, dynamic invariance, and real-time representational variation are inherently aligned with the requirements of analogical mapping, enabling learners to perceive structural correspondences across changing configurations (Kroczek, 2022; Liao, 2025). Empirical evidence suggests that representation switching within DGEs can connect geometric structures with patterns beyond the mathematical domain, thereby reducing the effects of functional fixedness and enhancing creative thinking. Nevertheless, few experimental studies have explicitly examined how analogical mapping operates within representationally rich DGE contexts to regulate cognitive flexibility.

Addressing these gaps requires an experimental framework integrating theory-driven instruction, causal inference, and process-oriented analysis (Park, 2026). Accordingly, this study experimentally examines functional fixedness as a regulatable cognitive constraint through a randomized controlled trial, providing causal evidence of how instruction based on analogical mapping and representational shifts influences students' geometric reasoning (Hayes, 2020). The study further advances theory by modeling representational shifts as a mediating mechanism and by integrating analogy theory with DGE, positioning DGE as a representational catalyst rather than a mere instructional tool. Specifically, this study addresses the following research questions: **(1)** Does instruction based on analogical mapping and representational shifts significantly reduce students' functional fixedness in geometry compared to conventional instruction? **(2)** To what extent do representational shifts mediate the effect of analogical mapping on the reduction of students' functional fixedness in geometry?

2. METHOD

2.1 Research Design and Participants

This study employed a quasi-experimental design with cluster randomization to examine the effects of analogical mapping and representational shifts on functional fixedness in geometry. Intact secondary school classes were randomly assigned to one of three conditions: (a) analogical mapping with Dynamic Geometry Environment (DGE)–supported representational shifts, (b) analogical mapping without dynamic shifts, and (c) conventional instruction. To control for teacher effects, all conditions were delivered by the same trained instructor following standardized instructional protocols.

2.2 Intervention Design: The ARSM Framework

The intervention was grounded in the Analogical–Representational Shift Model (ARSM), which conceptualizes functional fixedness reduction through three mechanisms: (1) activation of structural analogies, (2) DGE-supported representational transformation (e.g., dragging and invariance), and (3) cognitive reorganization that weakens dominant procedural activation. Unlike general creativity models, ARSM foregrounds representational coordination as the primary mechanism underlying cognitive flexibility in geometry.

2.3 Implementation Fidelity and Attrition

Implementation fidelity was monitored using structured observation checklists assessing adherence to instructional scripts and pedagogical alignment. Independent observations indicated consistently high fidelity (>85%) across conditions. Student attrition was minimal (<5%) and nonsystematic; baseline comparisons revealed no significant differences between retained and withdrawn participants.

2.4 Instruments and Measures

Functional Fixedness Measure (FFM). Functional fixedness was assessed using the

FFM, adapted from the Alternative Uses Test and contextualized for geometric problem solving. The instrument targeted representational rigidity rather than general ideational fluency, requiring students to reinterpret geometric objects across symbolic, visual, and dynamic representations. Responses were scored using a validated 5-point rubric (ICC = .87; Cronbach's α = .82), with higher scores indicating stronger procedural fixation.

Representational Flexibility (Mediator). Representational flexibility was operationalized as the frequency and appropriateness of spontaneous representational shifts during problem solving and measured using a theory-driven coding scheme adapted from Goldstone and Son (2005). Inter-coder reliability was substantial (κ = .81).

2.5 Statistical Analysis

Post-test functional fixedness scores were analyzed using Analysis of Covariance (ANCOVA), with pre-test scores as covariates. Cluster-robust standard errors were applied to account for the nesting of students within classes. Mediation analyses were conducted using Hayes' PROCESS macro with 5,000 bootstrap resamples to test whether representational flexibility mediated the effects of instructional condition on functional fixedness reduction.

3. RESULTS

a. Quantitative Findings: Intervention Efficacy

1) Baseline Equivalence and Descriptive Patterns

All three groups were comparable at baseline. No significant differences were found in pretest functional fixedness, $F(2, 87) = 1.14$, $p > .05$, indicating initial equivalence. Descriptive statistics Table 1 show a clear divergence in posttest trajectories. The AM and RS group demonstrated the lowest functional fixedness and the highest originality scores, whereas the control group showed only marginal change.

Table 1 Descriptive Statistics of Functional Fixedness and Originality Scores

Group	N	Functional Fixedness (Pretest) M (SD)	Functional Fixedness (Posttest) M (SD)	Originality (Posttest) M (SD)
Control (Procedural)	30	3.92 (0.48)	3.75 (0.50)	2.41 (0.46)
Analogical Mapping	30	3.89 (0.51)	3.12 (0.54)	3.18 (0.52)
Analogical and Representation Shifts	30	3.91 (0.49)	2.41 (0.47)	3.96 (0.55)

2) Intervention Effects (ANCOVA)

To control prior mathematical reasoning, a one-way ANCOVA was conducted with reasoning as a covariate. After adjustment, instructional condition remained a significant predictor: Functional Fixedness: $F(2, 87) = 28.16$, $p < .001$, $\eta p^2 = .39$. Originality: $F(2, 87) = 25.94$, $p < .001$, $\eta p^2 = .37$. The large effect sizes ($\eta p^2 > .14$) indicate substantial practical impact. The covariate exerted only a small effect on functional fixedness ($p = .030$) and a marginal effect on originality ($p = .051$), suggesting that instructional design primarily accounted for the observed gains see Table 2.

Table 2 ANCOVA Results Controlling for Mathematical Reasoning

Dependent Variable	Source	df	F	p	Partial η²
Functional Fixedness	Instructional Condition	2	28.16	< .001	.39
	Mathematical Reasoning (Covariate)	1	4.87	.030	.05
Originality	Instructional Condition	2	25.94	< .001	.37
	Mathematical Reasoning (Covariate)	1	3.92	.051	.04

3) Pairwise Comparisons

Bonferroni-adjusted comparisons confirmed a graded intervention effect: AMand RS vs Control: $d = 1.41$, AMand RS vs AM: $d = 0.79$ and AM vs Control: $d = 0.82$. These moderate-to-large effects demonstrate the additive benefit of integrating dynamic representational shifts with analogical mapping in Table 3.

Table 3 Bonferroni-Adjusted Pairwise Comparisons

Comparison	Mean Difference	SE	p	Cohen's d
AM vs Control	0.77	0.14	< .001	0.82
AM and RS vs Control	1.55	0.15	< .001	1.41
AM and RS vs AM	0.78	0.16	< .001	0.79

b. Mechanism of Change: Mediation Analysis

To address RQ2, a mediation analysis was conducted using PROCESS Model 4 with 5,000 bootstrap resamples to test whether representational flexibility mediated the relationship between instructional condition and originality. The analysis revealed a statistically significant indirect pathway. Instructional condition significantly predicted representational flexibility ($\beta = 0.48$, SE = 0.09, $p < .001$), and representational flexibility, in turn, significantly predicted originality outcomes ($\beta = 0.52$, SE = 0.10, $p < .001$). The bootstrapped indirect effect was significant ($\beta = 0.25$, SE = 0.07, $p < .01$), indicating that a substantial portion of the instructional effect on originality operated through increased representational flexibility.

Although the direct effect of instruction on originality remained significant ($\beta = 0.21$, SE = 0.08, $p = .010$), its magnitude was reduced relative to the total effect, supporting a pattern of partial mediation in Table 4. These findings provide empirical evidence that representational flexibility functions as a central cognitive mechanism through which analogical mapping and dynamic representational shifts enhance geometric originality.

Table 4 Mediation Analysis Results (Representational Flexibility as Mediator)

Path	β	SE	t	p
Analogical Mapping → Representational Flexibility	0.48	0.09	5.33	< .001
Representational Flexibility → Originality	0.52	0.10	5.10	< .001
Direct Effect (Analogical → Originality)	0.21	0.08	2.63	.010
Indirect Effect	0.25	0.07	2.63	< .01

c. Qualitative Insights: Cognitive Trajectories

1) Re-functionalization

Students reinterpreted geometric objects beyond their conventional procedural roles. For instance, squares were reconstructed not only as static area units but also as dynamic transformation loci or components of spatial nets. This strategy indicates a cognitive reduction in object-bound rigidity.

2) Cross-domain Analogical Reasoning

Students frequently transferred relational structures from non-geometric contexts, such as architectural or structural stability scenarios, into geometric problem solving. This structural mapping expanded the solution space, allowing for non-routine and creative strategies that were rarely observed in the control group.

3) Dynamic Re-representation

Unique to the AM and RS condition, students engaged in iterative representational shifts using DGE affordances in Table 5. High-originality students treated geometric representations as manipulable hypotheses, employing dragging and transformation tools to test structural invariance. This reflects active coordination across multiple representations rather than rigid procedural execution.

Table 5 Frequency of Cognitive Strategies Across Instructional Groups

Creative Strategy	Control Group	Analogical Mapping (AM)	Analogical and Representational Shifts (AM and RS)
Re-functionalization	Low	Moderate	High
Cross-domain Analogical Reasoning	Rare	Frequent	Very Frequent
Dynamic Re-representation	Rare	Occasional	Dominant

These patterns clearly illustrate that the AM and RS group not only demonstrated the greatest originality in problem solving but also consistently applied more dynamic and flexible cognitive strategies compared to the AM-only and control groups.

This qualitative evidence aligns with the quantitative mediation results, providing a process-level explanation for the improvements observed. The subsequent section integrates these findings to describe how representational flexibility mediates the reduction of functional fixedness and enhances geometric originality.

d. **Qualitative Insights: Cognitive Trajectories**

Triangulating the quantitative and qualitative findings provides a coherent explanatory framework for the observed effects. The substantial reduction in functional fixedness observed in the AM and RS group (d = 1.41; see Table 3) corresponds directly with the systematic adoption of dynamic representational strategies identified in the qualitative analysis (Table 5). As evidenced by the think-aloud protocols, students in this group engaged more frequently in re-functionalization, cross-domain analogical reasoning, and dynamic re-representation compared to their peers in the AM-only and control groups. This alignment demonstrates that the statistical decrease in cognitive rigidity is mechanistically tied to observable shifts in representational handling.

Furthermore, the mediation analysis (Table 4) confirms that representational flexibility serves as a central cognitive mechanism. Specifically, the significant indirect effect (beta = 0.25, $p < .01$) indicates that the intervention enhances geometric originality primarily by improving students' ability to coordinate and shift between multiple representations. While a direct effect of analogical instruction on originality remains (beta = 0.21, $p = .010$), the presence of a strong indirect pathway highlights that cognitive offloading and flexible shifting are critical drivers of the observed creative gains. Collectively, these integrated results illustrate that combining analogical mapping with dynamic representational shifts in a DGE environment produces the largest practical gains (Tables 1–3). More importantly, these gains operate through specific cognitive mechanisms that can be both empirically traced and qualitatively observed. This integration reinforces the validity of the ARSM framework as a mechanistic model linking instructional design, representational flexibility, and creative problem solving in geometry.

4. DISCUSSION

a. Interpretation of Findings

The present findings provide empirical support for conceptualizing functional fixedness as a modifiable form of representational rigidity (Ofori, 2020; Olteteanu, 2018; Sinclair, 2012). Students in the AM and RS condition not only reduced procedural rigidity but also demonstrated substantial increases in geometric originality. This effect can be explained through constraint relaxation (Medvedev & Yagolkovskiy, 2020; Ndiung & Menggo, 2024). Analogical mapping activates relational structures from cross-domain contexts, allowing students to bypass rigid procedural schemas that typically constrain problem-solving (Schoevers, 2022; Serrano, 2025). At the same time, dynamic representational shifts through GeoGebra facilitate cognitive offloading, reducing working memory demands and supporting iterative exploration of geometric transformations (Albaladejo, 2015; Guti, 2021; Kroczek, 2022). By operationalizing relational insights into flexible representational transformations, the combination of AM and RS disrupts dominant procedural habits and expands the solution space, explaining why functional fixedness is reduced.

b. Theoretical Implications

These findings substantiate the Analogical Representational Shift Model (ARSM) proposed in the Introduction. Mediation analyses confirm that representational flexibility functions as the primary cognitive mechanism through which analogical instruction enhances geometric originality (Name, 2021; Qi, 2024). Unlike prior studies that treated functional fixedness as a static barrier (Sinclair, 2012; Vágová, 2020), the present data demonstrate that it is a regulatable cognitive constraint sensitive to representational manipulation. ARSM formalizes this pathway: cross-domain analogical mapping activates structural correspondences (Khatin, 2025; Podolefsky, 2007), DGE-supported representational shifts operationalize these insights (Albaladejo, 2015; Liao, 2025), and cognitive reorganization reduces reliance on dominant procedural interpretations, culminating in enhanced originality. Figure X (ARSM Diagram) visualizes these mechanisms, integrating analogy theory with dynamic geometry environments to provide a coherent explanatory model.

c. Practical Implications

From a pedagogical perspective, the study demonstrates that instruction should go beyond routine procedural tasks to explicitly integrate analogical reasoning and dynamic representational shifts (Khatin, 2025; Ruamba, 2025). Tasks that elicit cross-domain analogies and interactive manipulation in DGE environments help students offload cognitive load, explore alternative representations, and internalize flexible problem-solving strategies (Albaladejo, 2015; Guti, 2021). These insights are relevant not only for classroom practice but also for educational technology: AI-based tutoring systems could monitor representational rigidity in real time and provide adaptive prompts to stimulate flexible reasoning, operationalizing the mechanisms identified in AM and RS instruction (Kroczek, 2022; Name, 2021).

d. Limitations and Future Directions

Despite these contributions, the study has limitations. The intervention duration was relatively short, so longitudinal research is required to examine the sustainability of functional fixedness reduction and originality gains (Sinclair, 2012; Vágová, 2020). The sample was limited to secondary students; replication across educational levels is necessary (Medvedev, 2020). Future studies may integrate neurocognitive measures such as EEG or eye-tracking to capture real-time dynamics of analogy mapping and representational shifts, providing a finer-grained understanding of cognitive mechanisms in geometric (Yin, 2022; Zangeneh, 2026).

5. CONCLUSION

This study provides compelling empirical evidence that functional fixedness in geometry is not an innate cognitive deficit, but a modifiable representational habit. By systematically targeting the mechanisms of constraint relaxation and cognitive offloading, the intervention demonstrated that procedural rigidity can be dismantled through specific instructional designs. The superior efficacy of the Analogical Mapping and Representational Shifts (AM and RS) condition underscores a critical synergy: while analogies provide the semantic bridge to new solution paths, dynamic geometry environments provide the operational vehicle to traverse them. This interaction fosters a "representational agility" that allows students to coordinate multiple modalities visual, symbolic, and dynamic transforming static geometric definitions into fluid, manipulable concepts. Theoretically, these findings substantiate the Analogical–Representational Shift Model (ARSM). The model successfully delineates the cognitive pathway through which cross-domain mapping and dynamic manipulation interact to suppress immediate procedural responses and enhance geometric originality. Practically, the results offer a blueprint for the next generation of mathematics instruction. They advocate for a pedagogy that transcends routine procedural drills in favor of tasks that explicitly engineer representational shifts. Furthermore, this work informs the development of Creativity-Aware AI tutoring systems, suggesting that future educational technologies should be designed not merely to correct errors, but to detect representational fixity and scaffold the cognitive flexibility required for creative mathematical reasoning. In sum, this research bridges the gap between cognitive theory and classroom practice, confirming that when students are equipped with the right representational tools, they can transcend the limits of functional fixedness to achieve genuine mathematical insight.

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