Prospective Mathematics Teachers' Cognitive Flexibility in STEAM-Based Nature Geometry Exploration Across Mathematics Anxiety Levels

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Abstract. This study investigated the cognitive flexibility profiles of prospective mathematics teachers during STEAM-based nature geometry exploration using Lindenmayer Systems (L-System), examined across different levels of mathematics anxiety. Employing a descriptive-qualitative approach with document and artifact analysis, four female prospective teachers representing low and high mathematics anxiety cohorts (with baseline-controlled cognitive disposition and prior geometry achievement) were examined using an integrated five-dimensional cognitive flexibility framework: Adaptation, Selective Focus, Strategy Flexibility, Strategy Assessment, and Strategy Adjustment. The results revealed that prospective teachers with low mathematics anxiety exhibited high-order cognitive flexibility, successfully formulating multi-rule rewrite grammars, adapting angular parameters, and critically assessing recursive depths supported by real-time visual simulator feedback. Conversely, prospective teachers with high mathematics anxiety displayed marked cognitive rigidity, adhering to single-template grammars, fixed rotation angles, and premature termination due to affective interference. Furthermore, low general self-reported cognitive dispositions did not constrain situated performance when supported by interactive digital environments and low anxiety levels. These findings underscore the necessity for mathematics teacher education programs to integrate exploratory STEAM modeling while establishing supportive, low-anxiety learning environments.

Keywords: Cognitive Flexibility, Mathematics Anxiety, STEAM Education, L-System, Prospective Teachers, Nature Geometry Exploration.

1 Introduction

1.1 Integration of STEAM and Cognitive Flexibility in L-System Modeling

Contemporary mathematics education demands interdisciplinary integration capable of bridging abstract theories with real-world phenomena [1], [2]. The Science, Technology, Engineering, Art, and Mathematics (STEAM) approach facilitates prospective

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teachers in exploring natural geometric patterns through technology-assisted mathematical modeling [2], [3]. An authentic manifestation of nature geometry exploration is biological fractal modeling using Lindenmayer Systems (L-Systems) [4]. An L-System is a formal grammar based on recursive relations originally developed to model the developmental processes and branching morphology of plants [4], [5]. In executing this task, students simultaneously integrate botanical morphological observation (Science), the utilization of an interactive web-based L-System simulator (Technology), the formulation of string-based recursive algorithms (Engineering), fractal aesthetic appreciation (Art), as well as rotation angles and recursive relations (Mathematics) [1], [3], [4].

The transformation from asymmetric, real plant structures into precise formal mathematical representations requires higher-order cognitive activity, particularly cognitive flexibility [6], [7]. Cognitive flexibility is defined as an individual's mental capacity to adapt thinking strategies, shift conceptual representations, and switch between changing task demands [7], [8]. Martin and Rubin emphasized that cognitive flexibility encompasses an awareness of alternative options, a willingness to adapt to new situations, and self-efficacy in exhibiting flexible behavior [6]. In the context of the STEAM-based L-System modeling task, prospective teachers' cognitive flexibility performance is operationalized into five dimensions: Adaptation, Selective Focus, Strategy Flexibility, Strategy Assessment, and Strategy Adjustment [6], [8], [9]. These five dimensions are objectively evaluated through the artifact analysis of student task reports and digital visual outputs, as summarized in Table 1.

Table 1. Dimensions and Operational Indicators of Cognitive Flexibility in STEAM-Based L-System Modeling Tasks.

Dimension	Operational Definition	Artifact Analysis Indicator
Adaptation	Adapting formal L-System rules to the natural variations and asymmetries of real plant structures	Adjusting branching angles (θ), segment lengt ratios, or implementing bracketes L-Systems to emulate the original plant structure
Selective Focus	Prioritizing essential geometric characteristics while filtering out non-essesntial minor botanical details	Abstracting the primary skeletal branching structure into formal string symbols ($F, +, -, [,]$) without being distracted by micro-irregularities of foliage
Strategy Flexibility	Exploring multiple alternative production rules or manipulating various simulator parameters	Documenting multiple trial rules, recur-

		sive structures, or iteration parameter variations within the web application
Strategy Assessment	Evaluating the fidelity and geometric accuracy of the digital visual simulation against the real plan object	Providing written analytical evaluations comparing the visual digital ouput with the actual morphological proportions of tge specimen
Strategy Adjustmen	Modifying production rules or parameters when the initial visual output fails to represent the target structure	Demonstrating an iterative revision trail (*trial-and-error)* from preliminary rules to the final optimal structural representation

1.2 The Role of Mathematics Anxiety and Research Objectives

Although technology-enhanced STEAM tasks are designed to provide exploratory learning experiences, translating real-world phenomena into formal algorithmic models often triggers emotional barriers, notably mathematics anxiety [10], [11]. Mathematics anxiety is defined as feelings of tension, apprehension, and discomfort experienced when manipulating numbers, learning mathematical concepts, facing evaluative situations, or participating in mathematical courses [11], [12]. Juniati and Budayasa revealed that mathematics anxiety among undergraduate students exerts a significant negative effect on problem-solving performance and mathematical achievement [11]. Such anxiety imposes an extraneous cognitive load on students' mental capacity [11], [13], which may consequently constrain their cognitive exploration, leading to reluctance in modifying recursive rules or prematurely settling for inaccurate models [8, 12].

Integrating nature-based geometric patterns into STEAM learning allows prospective teachers to connect abstract mathematical principles with natural visual structures. In this study, the mathematical modeling tool referenced in the STEAM exploration is an interactive, web-based Lindenmayer System (L-System) computational generator powered by Turtle Graphics algorithms, which translates symbolic procedural rules into dynamic fractal plant models. By bridging symbolic coding and visual geometric forms, this tool provides an authentic environment for observing prospective teachers' cognitive processes during nature-inspired problem solving.

Most prior studies on L-Systems have primarily focused on pure computational algorithms and computer graphics applications [4], [5]. Meanwhile, cognitive flexibility investigations have largely been limited to routine algebraic tasks, leaving nature geometry exploration within interdisciplinary contexts relatively underexplored [7], [14]. Therefore, this study aims to describe the cognitive flexibility profiles of prospective

mathematics teachers in completing STEAM-based nature geometry exploration tasks using Lindenmayer Systems, specifically contrasting how prospective teachers with high and low mathematics anxiety demonstrate the five dimensions of cognitive flexibility during the modeling process [6], [11].

2 Method

2.1 Research Design and Participants

This study employs a descriptive-qualitative approach utilizing document and artifact analysis to investigate the cognitive flexibility profiles of prospective mathematics teachers in completing STEAM-based nature geometry exploration tasks. The participant pool comprised undergraduate students enrolled in the Mathematics Education study program who had completed the fractal geometry instructional unit and finished the Lindenmayer System (L-System) modeling assignment. A purposive sampling technique was employed to select four female representative subjects consisting of two primary subjects (one with high mathematics anxiety and one with low mathematics anxiety) and two additional subjects for source triangulation (one with high mathematics anxiety and one with low mathematics anxiety). To eliminate confounding cognitive and demographic variables, all selected subjects were female, possessed an equivalent level of prior geometry achievement, and demonstrated a baseline of low general cognitive flexibility disposition [6], [11].

2.2 Instruments and Data Collection Procedures

Data collection was conducted using three primary instruments without direct interviews. The first instrument is the general cognitive flexibility questionnaire adapted from the Cognitive Flexibility Scale (CFS) developed by Martin and Rubin [6]. This instrument measures students' self-perceptions across awareness of alternative options, willingness to adapt, and cognitive self-efficacy using a 6-point Likert scale ranging from 12 to 72 [6]. The second instrument is the mathematics anxiety questionnaire adapted from Juniati and Budayasa, which assesses emotional tension across three domains: learning mathematical concepts, attending mathematics lectures, and facing mathematics tests or evaluations [11]. The questionnaire uses a 4-point Likert scale to classify students into high anxiety (scores ≥ 38) and low anxiety (scores ≤ 37) categories [11]. Prior geometry achievement records were also documented to confirm cognitive equivalence among the selected subjects.

The third instrument comprises the STEAM-based Nature Geometry Exploration Task mediated by a specialized mathematical modeling tool. The digital tool utilizes is an open-access, web-based Lindenmayer System (L-System) computational generator powered by Turtle Graphics algorithms, accessible at https://www.kevs3d.co.uk/dev/lsystems/ . Conceptually, an L-System is a formal, string-rewriting procedural grammar designed to model the recursive growth architectures of botanical specimens. Within this exploratory modeling environment, the tool

operates through four fundamental mathematical components, namely the axiom, production rules, turning angle parameters, and stack operators. The axiom represents the initial string of geometric symbols, such as X or F, defining the starting structural state. The production or rewriting rules denote formal recursive algebraic instructions that simultaneously substitute variable symbols with expanded successor strings during each generation cycle. The turning angle parameter (θ) dictates the precise angular rotation executed by the virtual turtle cursor upon reading clockwise (+) or counter-clockwise (−) turn symbols. Furthermore, the stack operators, represented by push ([) and pop (]) brackets, temporarily store and recall turtle coordinates and heading angles, which enables the generation of multi-tiered branch nesting without severing the structural continuity of the main stem.

In this exploratory task, prospective teachers integrated botanical observation (Science), string algorithm design (Engineering), digital computational rendering (Technology), fractal visual aesthetics (Art), and geometric parameter calculations (Mathematics). The analyzed student documents encompassed photographs of real botanical specimens, formal algebraic formulations of axioms and production rules, numerical configurations of turning angles and recursion depths, simulation output screenshots, and reflective evaluations regarding the geometric fidelity of the resulting digital models. In this setting, the L-System generator functions as an interactive cognitive and visual scaffold that enables prospective teachers to externalize mental models by translating abstract symbolic algebraic rules into dynamic, real-time geometric plant fractals.

2.3 Data Analysis Procedures

Qualitative data analysis was carried out following the interactive analysis model of Miles, Huberman, and Saldaña [15], comprising data condensation, data display, and conclusion drawing and verification. In the data condensation stage, questionnaire scores and geometry achievement data were tabulated to categorize participants and confirm subject equivalence, followed by compiling the completed task reports and digital artifacts from the web simulator [11]. In the data display stage, representative snippets of L-System code formulations, parameter values, and rendered visual models from both anxiety groups were systematically presented and coded against the five dimensions of cognitive flexibility in Table 1 (Adaptation, Selective Focus, Strategy Flexibility, Strategy Assessment, and Strategy Adjustment) [6], [8], [9]. n the conclusion drawing and verification stage, data trustworthiness was established through source triangulation by comparing the artifact analysis results of the primary subjects with those of the triangulation subjects within the corresponding anxiety categories. Finally, characteristic patterns were synthesized to contrast how prospective teachers with high and low mathematics anxiety demonstrate cognitive flexibility during nature geometry modeling tasks.

3 Result and Discussion

3.1 Overview of Subjects' Baseline Dispositions and Anxiety Classifications

The initial assessment evaluated prospective mathematics teachers' general cognitive flexibility dispositions and mathematics anxiety levels to establish baseline participant profiles. Administration of the Cognitive Flexibility Scale (CFS) adapted from Martin and Rubin revealed that all participating students fell into the low general cognitive flexibility disposition category, with individual total scores consistently remaining below the empirical normative threshold of 55. This uniform baseline indicated that, in terms of general self-perception, the students perceived themselves as having limited confidence in identifying alternative pathways, adapting spontaneously to unfamiliar situations, and exercising cognitive self-efficacy.

Conversely, the mathematics anxiety assessment adapted from Juniati and Budayasa demonstrated clear differentiation among participants, segmenting the cohort into high anxiety (scores ≥ 38) and low anxiety (scores ≤ 37) classifications across the situational domains of learning concepts, attending lectures, and undergoing evaluations. From this distribution, four representative subjects with equivalent prior geometry achievement were selected: two primary subjects comprising Subject 1 (S_1, Low Mathematics Anxiety) and Subject 2 (S_2, High Mathematics Anxiety), alongside two triangulation subjects comprising Triangulation Subject 1 (T_1, Low Mathematics Anxiety) and Triangulation Subject 2 (T_2, High Mathematics Anxiety). Controlling prior geometry competency ensured that observed variations in executing the STEAM-based L-System modeling tasks stemmed primarily from emotional and cognitive self-regulatory mechanisms rather than disparities in prerequisite geometric knowledge.

3.2 Cognitive Flexibility Profiles of the Low Mathematics Anxiety Group (S_1 and T_1)

The artifact analysis of prospective mathematics teachers in the low mathematics anxiety group ($S_1$and T_1) demonstrated consistent, high-order manifestations across all five dimensions of cognitive flexibility during the STEAM-based geometric modeling of natural plants. In the Adaptation dimension, both subjects demonstrated high precision in modifying angular and branching parameters to replicate the organic asymmetry and natural growth habits of target specimens. Subject S_1 calibrated rotation angles to a narrow $\theta = 11^o$ for *Cemara Kipas* (Thuja occidentalis) (Figure 1a) and $\theta = 7^o$ for *Rumput Jepang* (Figure 1b), incorporating color state modifiers (C_0, C_1, C_2, C_3) and nested bracketed branch operators to capture tiered foliage layers. Source triangulation with T_1 confirmed this adaptive competency, as T_1 adjusted the branching angle to $\theta = 20^o$ for the spreading architecture of *Adas Hutan* (Figure 1c) and fine-tuned it to $\theta = 11^o$ for the dense fronds of *Pakis Jepang* (Figure 1d).

Regarding Selective Focus, both S_1 and T_1 successfully abstracted primary skeletal branching hierarchies into formal grammatical symbols while filtering out non-essen-

tial microscopic botanical details. Both subjects structured their models around a central stem path by assigning generative growth states to variable X and forward translation to symbol F, utilizing push/pop stack brackets ([…]) to organize multi-tiered lateral sub-branches without being hindered by foliage irregularities.

In the Strategy Flexibility dimension, both subjects demonstrated an ability to formulate non-standard production rules and explore diverse axiom structures. Subject S_1 utilized distinct starting axioms (Axiom X for Cemara Kipas and Axiom FX for *Rumput Jepang*) and applied simultaneous production rules ($F = C_0$ FF and $F = -F$) alongside multi-turn operators ([++++F−X++X]). Similarly, T_1 embedded nested branch commands directly into the rewriting rule ($F = C_1$ FFF[−++FFX] for *Adas Hutan* and $F = C_0$FFF [C_1 ++FF] for *Pakis Jepang*) and generated asymmetric turns ([− − − C_2 X+X]).

In the Strategy Adjustment dimensions, when initial renders did not match the natural specimen density, both S_1 and T_1 dynamically modified intermediate grammar strings rather than abandoning their chosen approach. Subject S_1 iteratively shifted branch angles by increments of 1° to 2° and introduced color state tags (C_1, C_2) to clearly differentiate new shoots from mature stems. Subject T_1 altered stack nesting depths and adjusted rotational signs (+ and −) to eliminate unintended branch overlap, demonstrating continuous heuristic problem-solving within the digital simulator.

Finally, in the Strategy Assessment dimension, both subjects critically evaluated the visual fidelity and geometric proportions of their digital outputs by regulating recursion depth. Subject S_1 advanced the recursion to iteration 7 (n = 7) for both *Cemara Kipas* (Figure 1a) and *Rumput Jepang* (Figure 1b) to achieve sufficient visual density. Corroborating this evaluation, T_1 selectively maintained iteration 4 (n = 4) for *Adas Hutan* (Figure 1c) to preserve open branch clarity and escalated to iteration 8 (n = 8) for *Pakis Jepang* (Figure 1d) to render dense foliage without graphical distortion.

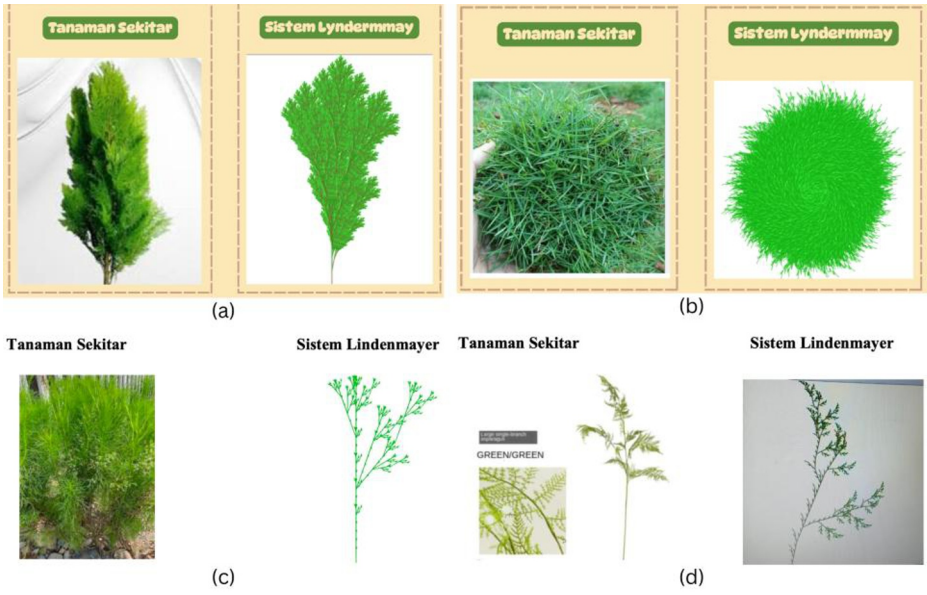


Fig. 1. STEAM modeling artifacts generated by prospective teachers with low mathematics anxiety: (a) real specimen and digital L-System model of *Cemara Kipas* by S_1 ($\theta = 11^o, n = 7$); (b) real specimen and digital L-System model of *Rumput Jepang* by S_1 ($\theta = 7^o, n = 7$); (c) real specimen and digital L-System model of *Adas Hutan* by T_1 ($\theta = 20^o, n = 4$); and (d) real specimen and digital L-System model of *Pakis Jepang* by T_1 ($\theta = 11^o, n = 8$).

3.3 Cognitive Flexibility Profiles of the High Mathematics Anxiety Group (S_2 and T_2)

In sharp contrast to the low anxiety cohort, the artifact analysis of prospective mathematics teachers in the high mathematics anxiety group (S_2 and T_2) revealed pronounced cognitive constraints across all five evaluated dimensions. In the Adaptation dimension, both subjects exhibited parameter rigidity, adhering strictly to uniform rotation angles and standard branching heuristics regardless of the natural morphological differences of the target specimens. Subject S_2 applied nearly identical angular parameters ($\theta = 22^o$ for *Pohon Pinus,* Figure 2a, and $\theta = 26^o$ for *Pohon Rindang,* Figure 2b) and maintained a fixed bilateral branching template ([+X] [−X]). Source triangulation with T_2 corroborated this rigid pattern, as T_2 utilized an identical rotation angle of $\theta = 25^o$ for both the slender needle-like plant (Figure 2c) and the expansive canopy of the fruit tree (Figure 2d).

Regarding Selective Focus, while both S_2 and T_2 recognized basic vertical growth axes, they encountered persistent difficulties in abstracting complex asymmetric branching structures. Subject S_2 produced an upright, tapered fractal structure for *Pohon Rindang* (Figure 2b) that failed to capture the wide, rounded lateral canopy of the real tree, indicating an oversimplified focus on vertical branching at the expense of horizontal spread. Similarly, T_2 abstracted tree branches into basic symmetrical splits ([+Y] [−Y] [++Y] [−Y]), resulting in sparse, disconnected line segments that lacked the morphological character of the original dense specimens (Figure 2d).

In the Strategy Flexibility dimension, both high anxiety subjects demonstrated a reluctance to explore diverse production grammars, relying heavily on repetitive single-variable replacement rules. Rather than exploring varied axioms or introducing multi-rule rewriting mechanisms, S_2 relied on conservative variations of the default branching rule (X = C_1 F[+X] [−X] …). Corroborating this observation, T_2 employed short, non-nested symmetrical rules across both specimens (F = FF[+F] [−F] F[+A] [−A] with A = F[+F] [−F] [++F] [−−F] F for the needle-like plant, and X = FFFFF[+Y] [−Y] with Y=FF[+Y] [−Y] [++Y] [−Y] for the fruit tree) and strictly avoided exploring varied angular values beyond θ = 25°.

In the Strategy Adjustment dimension, both subjects exhibited premature termination of the modeling process when initial outputs showed discrepancies with the real specimens. When the digital output did not adequately reflect natural canopy density, S_2 made only minor alterations to string length rather than adjusting rotation angles or rule structures. Likewise, T_2 made no structural adjustments to production rules, stopping after basic linear configurations.

Finally, in the Strategy Assessment dimension, both subjects exhibited limited critical evaluation regarding the geometric fidelity of their digital outputs relative to real

specimens. Subjects S_2 and T_2 terminated their simulations at low-to-moderate recursion depths (n = 5 for *Pohon Pinus,* Figure 2a; n = 6 for *Pohon Rindang,* Figure 2b; and n = 4 for T_2, Figures 2c and 2d), expressing satisfaction with outputs that exhibited noticeable structural discrepancies from the actual plants. This lack of iterative refinement demonstrates that high mathematics anxiety significantly restricts prospective teachers' cognitive flexibility, manifesting as algorithmic rigidity, template dependency, and reduced willingness to explore complex mathematical representations.

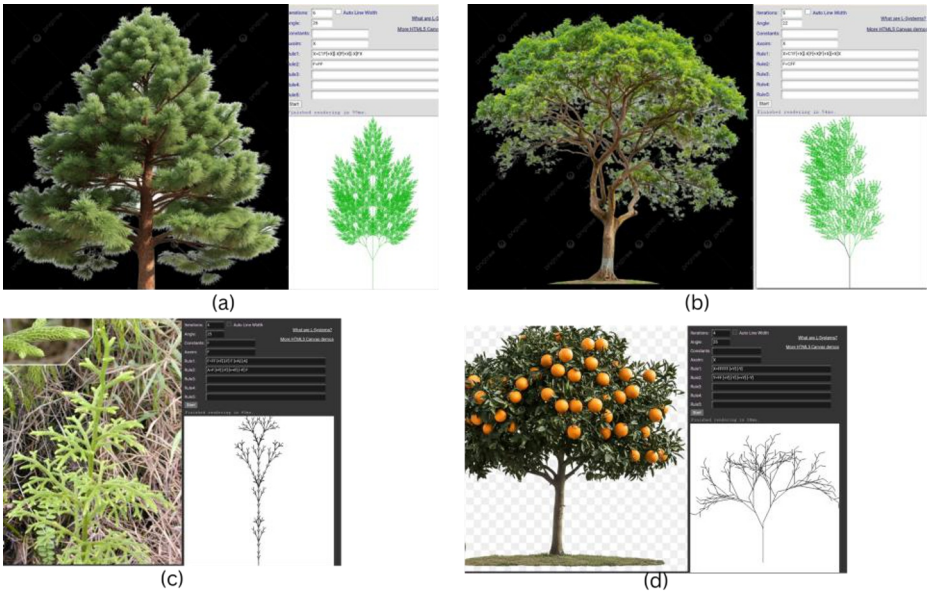


Fig. 2. STEAM modeling artifacts generated by prospective teachers with high mathematics anxiety: (a) real specimen and digital L-System model of *pohon pinus* by S_2 ($\theta = 26^o, n = 6$); (b) real specimen and digital L-System model of *pohon rindang* by S_2 ($\theta = 22^o, n = 5$); (c) real specimen and digital L-System model 1 by T_2 ($\theta = 25^o, n = 4$); and (d) real specimen and digital L-System model 2 by T_2 ($\theta = 25^o, n = 4$);

3.4 Discussion

The empirical findings of this study highlight significant qualitative divergences in how prospective mathematics teachers demonstrate cognitive flexibility during STEAM-based nature geometry exploration, contingent upon their mathematics anxiety levels [1], [10], [11]. Across the five evaluated dimensions (Adaptation, Selective Focus, Strategy Flexibility, Strategy Assessment, and Strategy Adjustment) the low mathematics anxiety group (S_1 and T_1) consistently exhibited robust cognitive flexibility, whereas the high anxiety group (S_2 and T_2) displayed marked algorithmic rigidity and constrained heuristic exploration [6], [8], [9].

A prominent finding from this study is the apparent paradox between students' generalized disposition and their actual domain-specific performance [6], [7], [14]. Although all participating subjects initially reported low general cognitive flexibility dispositions on the Martin and Rubin CFS instrument [6], prospective teachers with low mathematics anxiety demonstrated sophisticated recursive problem-solving behaviors [4], [14]. This discrepancy corroborates previous arguments that generalized self-report scales primarily capture broad psychological perceptions, which do not always represent situated mathematical performance when mediated by interactive digital tools [7], [8], [14]. The dynamic, immediate visual feedback afforded by the web-based Lindenmayer System generator functioned as an effective cognitive scaffold [1], [2], [4], empowering low-anxiety students to externalize mental models, experiment with multi-turn parameters, and execute iterative rule adjustments fearlessly [4], [8], [9].

Conversely, the performance constraints observed in the high mathematics anxiety group provide strong empirical support for the cognitive load and affective-interference theories [10], [11], [13]. As articulated by Juniati and Budayasa, elevated mathematics anxiety occupies and depletes essential working memory capacity, thereby restricting a student's mental bandwidth for processing complex, multi-variable mathematical relationships [11], [13]. In the context of geometric L-System modeling, this cognitive depletion manifested as "template fixation" [8], [9], wherein high-anxiety students adhered rigidly to basic symmetrical branching grammars ([+X] [−X]) and avoided adjusting default angular parameters despite noticeable visual disparities with the real plant specimens [4], [8], [11]. Their premature termination of recursion depth and reluctance to modify production rules reflect an affective avoidance mechanism aimed at minimizing mental distress and perceived failure [10], [11].

These insights bear direct pedagogical implications for mathematics teacher education [1], [3], [9]. Integrating interdisciplinary STEAM exploration through fractal geometry and computational grammars provides a fertile environment for cultivating prospective teachers' adaptive expertise and geometric problem-solving competencies [1], [3], [4]. However, as highlighted by contemporary educational research, pedagogical technology alone cannot bridge performance gaps if affective inhibitors remain unaddressed [2], [11]. Creating supportive, low-stakes mathematical modeling environments that systematically mitigate mathematics anxiety is crucial to empower prospective teachers to explore, evaluate, and dynamically adjust mathematical strategies in technology-rich settings [8], [9], [11].

4 Conclusion

This study demonstrates that prospective mathematics teachers' cognitive flexibility during STEAM-based nature geometry exploration using Lindenmayer Systems is fundamentally differentiated by their mathematics anxiety levels. Across the five evaluated dimensions (Adaptation, Selective Focus, Strategy Flexibility, Strategy Assessment, and Strategy Adjustment) prospective teachers with low mathematics anxiety exhibited high-order cognitive flexibility, characterized by refined parameter adaptations, complex multi-rule grammatical formulations, and critical iterative adjustments enabled by

real-time visual feedback from the web-based simulator. In sharp contrast, prospective teachers with high mathematics anxiety demonstrated pronounced cognitive constraints, manifesting as template rigidity, parameter fixation, and premature termination of exploratory adjustments due to emotional avoidance mechanisms. Furthermore, this study highlights a critical insight: low general self-reported cognitive flexibility dispositions on standardized scales do not inherently restrict domain-specific mathematical performance, provided that affective anxiety remains low and students are scaffolded by interactive digital technologies. Consequently, mathematics teacher education programs must not only design exploratory, interdisciplinary STEAM modeling tasks but also systematically foster supportive, low-anxiety instructional environments to optimize prospective teachers' technological-mathematical adaptive expertise.

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