GLOBAL JOURNAL OF MATHEMATICS EDUCATION
https://journal.insasi.com/index.php/gjme/en

Analyzing the Mathematical Thinking Flexibility of Pre-Service Mathematics Teachers in Solving Quadratic Inequalities

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Article Info

Keywords:

Mathematical thinking flexibility
Procedural strategies
Mathematical representations
Quadratic inequalities

ABSTRACT

This study aimed to analyze the mathematical thinking flexibility of pre-service mathematics teachers in solving quadratic inequalities, identify the strategies they employed, and explore the factors contributing to the dominance of procedural approaches. The study adopted a mixed methods approach using an explanatory sequential design. The participants consisted of 22 undergraduate students enrolled in a Real Analysis course in a Mathematics Education program. Data were collected through a mathematical problem-solving test and semi-structured interviews. Quantitative data were analyzed descriptively, while qualitative data were analyzed using the Miles, Huberman, and Saldaña interactive model. The findings revealed that all participants (100%) relied exclusively on the interval testing method to solve the given problems. No participants employed alternative strategies, such as factor sign analysis, graphical representation, completing the square, or function property analysis. Furthermore, all participants used only symbolic-algebraic representations and did not demonstrate key indicators of mathematical thinking flexibility, including the ability to generate multiple solution strategies, explain relationships among different strategies, and evaluate the effectiveness of the strategies used. Interview findings indicated that the predominance of procedural approaches was influenced by prior learning experiences, the belief that interval testing is the only correct method, and limited opportunities to explore diverse mathematical representations. These findings suggest that obtaining correct answers does not necessarily reflect an adequate level of mathematical thinking flexibility.

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1. INTRODUCTION

One of the primary goals of mathematics education is to develop students' mathematical thinking flexibility, enabling them to select, compare, and apply appropriate strategies when solving mathematical problems (Moma, 2017). Mathematical thinking flexibility extends beyond the ability to obtain correct answers; it also encompasses the ability to understand the relationships among different strategies, evaluate the efficiency of a particular method, and meaningfully transition between multiple mathematical representations (Febrianty et al., 2024; Star & Newton, 2009). In the context of pre-service mathematics teacher education, this competency is particularly important because teachers are expected not only to solve mathematical problems correctly but also to explain mathematical concepts through multiple approaches that accommodate students' diverse ways of thinking (Dosinaeng et al., 2021).

Nevertheless, numerous studies have shown that pre-service mathematics teachers continue to rely heavily on routine procedures acquired through previous learning experiences when confronted with mathematical problems (Nugroho & Dwijayanti, 2019). Although procedural knowledge enables students to produce accurate solutions efficiently, an overreliance on procedural approaches without sufficient conceptual understanding may limit their ability to construct mathematical arguments, establish connections among mathematical concepts, and generate equivalent alternative solution strategies (Aminullah, 2025; Rittle-Johnson et al., 2015). This issue is of particular concern in university-level mathematics education, where students are expected to develop formal reasoning and mathematical proof skills.

In advanced mathematics, particularly in Real Analysis courses, students are expected to transition from computational mathematical activities to more formal, deductive, and justification-based mathematical reasoning (Perbowo & Pradipta, 2017). Tall (1991) argued that the development of advanced mathematical thinking is characterized by the ability to perceive mathematical objects through multiple representations and interconnected conceptual structures (Andri, 2012). Therefore, students enrolled in Real Analysis should not only be capable of applying algorithmic solution procedures but also of constructing mathematical arguments through algebraic, graphical, logical, and analytical approaches.

One mathematical context that provides considerable potential for investigating students' mathematical thinking flexibility is the solution of quadratic inequalities. From a mathematical perspective, quadratic inequalities can be solved using several equivalent strategies, including interval testing, factor sign analysis, graphical interpretation of quadratic functions, completing the square, the use of absolute values, and function property analysis (Putri et al., 2023). The availability of these multiple solution strategies makes quadratic inequalities an appropriate context for examining how students conceptualize mathematical objects and the extent to which they can generate different yet mathematically consistent solution approaches (Sigalingging & Siregar, 2025; Yuniati et al., 2022).

The ability to employ multiple solution strategies is closely associated with mathematical representation skills (Ta'ifah, 2019). According to Duval (2006), profound mathematical understanding depends not only on mastering a single form of representation but also on the ability to transform and coordinate among multiple representations. Individuals with strong conceptual understanding are able to connect symbolic, visual, graphical, verbal, and formal representations throughout the problem-solving process. Conversely, dependence on a single representation often reflects limitations in conceptual understanding and mathematical thinking flexibility (Fatqurhohman & Susetyo, 2022; Rahmawati et al., 2017).

Recent studies have also demonstrated that the use of multiple mathematical representations contributes positively to students' conceptual understanding, problem-solving ability, and confidence in learning mathematics (Putra et al., 2023; Sirajuddin et al., 2020). However, most existing studies have focused primarily on the effectiveness of representation-based instruction or the development of problem-solving skills in general (Gufron et al., 2025; Nizaruddin et al., 2017; Widyawati et al., 2024). Research specifically investigating the mathematical thinking flexibility of pre-service mathematics teachers within advanced mathematics contexts, particularly Real Analysis, remains relatively limited. Moreover, few studies have examined how students generate and relate multiple solution strategies for mathematical problems that are conceptually simple yet rich in representational possibilities.

Nevertheless, previous studies consistently indicate that pre-service mathematics teachers still tend to rely on routine procedures acquired through prior learning experiences when solving mathematical problems. Although procedural knowledge enables students to obtain correct answers efficiently, an excessive dependence on procedural approaches without adequate conceptual understanding may restrict their ability to construct mathematical arguments, establish conceptual connections, and generate equivalent alternative solution strategies (Rittle-Johnson et al., 2021). This issue deserves particular attention in university mathematics education, where students are expected to develop formal reasoning and mathematical proof skills.

In advanced mathematics, particularly in Real Analysis courses, students are expected to progress from computational mathematical activities to reasoning that is more formal, deductive, and grounded in mathematical justification. Tall (1991) argued that the development of advanced mathematical thinking is characterized by the ability to perceive mathematical objects through multiple representations and interconnected conceptual structures. Therefore, students studying Real Analysis should not only be capable of applying algorithmic solution procedures but also of constructing mathematical arguments using algebraic, graphical, logical, and analytical approaches.

One mathematical context that offers considerable potential for investigating students' mathematical thinking flexibility is the solution of quadratic inequalities. Mathematically, quadratic inequalities can be solved using several equivalent strategies, including interval testing, factor sign analysis, graphical interpretation of quadratic functions, completing the square, the use of absolute values, and function property analysis. The availability of these alternative strategies makes quadratic inequalities an appropriate context for examining how students conceptualize mathematical objects and the extent to which they are able to generate different yet mathematically equivalent solution approaches.

The ability to employ multiple solution strategies is closely related to mathematical representation skills. According to Duval (2006), profound mathematical understanding depends not only on mastering a particular representation but also on the ability to transform and coordinate among multiple representations. Individuals who possess strong conceptual understanding are able to connect symbolic, visual, graphical, verbal, and formal representations throughout the problem-solving process. In contrast, reliance on a single representation often indicates limitations in conceptual understanding and mathematical thinking flexibility.

Recent studies have also shown that the use of multiple mathematical representations positively contributes to students' conceptual understanding, problem-solving ability, and confidence in learning mathematics (Ayyıldız Altınbaş et al., 2025; Fitria et al., 2025). However, most existing studies have focused primarily on the effectiveness of representation-based instruction or on developing problem-solving skills in general. Research specifically investigating the mathematical thinking flexibility of pre-service mathematics teachers in advanced mathematics contexts, particularly Real Analysis, remains relatively scarce. Furthermore, few studies have examined how students generate and relate multiple solution strategies when solving problems that are conceptually simple yet rich in representational possibilities.

Preliminary observations of pre-service mathematics teachers enrolled in a Real Analysis course revealed that all students solved quadratic inequality problems using the standard procedure of determining the roots of the corresponding quadratic equation followed by interval testing. Although this strategy produced correct solutions, none of the students proposed alternative approaches, such as factor sign analysis based on multiplication properties, graphical interpretation of quadratic functions, algebraic transformation through completing the square, or arguments based on function properties. These findings suggest that students' problem solving was dominated by the application of familiar procedures rather than by an exploration of the conceptual relationships underlying the mathematical objects involved. This phenomenon is particularly noteworthy because the given problems offer multiple mathematically equivalent representations and solution pathways.

These findings indicate a tendency toward procedural thinking that may hinder the development of students' mathematical thinking flexibility. As future mathematics teachers studying Real Analysis, students are expected to establish connections among mathematical concepts, utilize multiple mathematical representations, and construct diverse yet logically justifiable mathematical arguments. The inability to generate more than one solution strategy for a relatively simple problem may indicate that the transition from procedural knowledge to conceptual understanding and advanced mathematical thinking has not yet developed optimally.

Based on these considerations, this study aims to analyze the mathematical thinking flexibility of pre-service mathematics teachers in solving quadratic inequalities in a Real Analysis course. Specifically, the study seeks to (1) identify the solution strategies employed by the students, (2) analyze their mathematical thinking flexibility based on the diversity of strategies and representations they use, and (3) explore the factors contributing to the dominance of procedural strategies in problem solving. The findings are expected to contribute to the improvement of

Real Analysis instruction by promoting stronger conceptual understanding, richer representational competence, and the development of advanced mathematical thinking among pre-service mathematics teachers.

2. METHOD

This study employed a mixed methods approach using an explanatory sequential design. This design was selected because the study aimed not only to identify the solution strategies employed by students through quantitative analysis but also to obtain a deeper understanding of the characteristics of the mathematical thinking flexibility underlying those strategies. In the first phase, quantitative data were collected and analyzed to identify the range of solution strategies used by the participants. The second phase involved qualitative data collection through in-depth interviews to further explain and interpret the quantitative findings.

The study was conducted in the Mathematics Education Study Program at Universitas Sembilanbelas November Kolaka during the second semester of the 2025/2026 academic year. The participants consisted of all 22 students enrolled in the Real Analysis course. Since all students participated in the written test, a total sampling technique was employed. Subsequently, three students were purposively selected for semi-structured interviews to represent the characteristics of the responses identified in the written test.

The research instruments consisted of a mathematical problem-solving test and a semi-structured interview protocol. The problem-solving test comprised a single open-ended question designed to elicit multiple solution strategies. Students were asked to determine the solution set of the quadratic inequality ($x^2 + x > 2$). In addition to finding the solution set, they were instructed to describe all possible strategies they could use to solve the problem and to explain the reasoning underlying each step of their solution. The problem was selected because it allows several mathematically equivalent solution approaches, including interval testing, factor sign analysis, graphical interpretation of quadratic functions, completing the square, the use of absolute values, and function property analysis.

During the data collection process, all participants first completed the written problem-solving test individually. Their responses were then analyzed to identify the solution strategies employed and the mathematical representations used. Based on this analysis, three participants were selected for follow-up interviews to explore the reasons for their choice of strategies, their conceptual understanding, and their ability to generate or explain alternative solution approaches.

Quantitative data were analyzed descriptively by calculating the frequency and percentage of each solution strategy identified in the students' responses. The quantitative findings were used to describe the overall patterns of students' approaches to solving quadratic inequalities. The interview data were subsequently analyzed qualitatively using the interactive model proposed by Miles, Huberman, and Saldaña, which consists of data condensation, data display, and conclusion drawing. During the data condensation stage, interview transcripts were coded according to themes related to mathematical thinking flexibility. The data display stage involved organizing the findings into tables and narrative descriptions illustrating students' patterns of mathematical thinking. Finally, conclusions were drawn to characterize the mathematical thinking flexibility demonstrated by the participants.

The analysis of mathematical thinking flexibility was based on the framework developed by Star and Newton (2009), which includes three indicators: (1) the ability to generate more than one valid solution strategy, (2) the ability to explain the relationships among the strategies used, and (3) the ability to select or evaluate the most appropriate strategy according to the characteristics of the problem. In addition, the analysis of mathematical representations was guided by Duval's (2006) theory of representation, which emphasizes the importance of coordinating and transforming among multiple representations in developing mathematical understanding.

To ensure the trustworthiness of the findings, several validation strategies were employed, including methodological triangulation, source triangulation, and member checking. Methodological triangulation was achieved by comparing data obtained from the written test and the interviews. Source triangulation involved discussing the analysis with two mathematics education lecturers who have expertise in Real Analysis and mathematics education. Furthermore, the interview interpretations were confirmed with the participants through member checking to ensure that the researchers' interpretations accurately reflected the participants' intended meanings.

3. RESULTS AND DISCUSSION

3.1. Results

This study involved 22 undergraduate students enrolled in the Mathematics Education program who were taking the Real Analysis course. The students were given an open-ended problem requiring them to determine the solution set of the following quadratic inequality::

$$x^2 - 2x > 3$$

In addition to determining the solution set, students were asked to write down all possible strategies they could use to solve the problem and provide mathematical justifications for each step. The analysis focused on the solution strategies employed, the mathematical representations used, the level of mathematical thinking flexibility demonstrated, and the interview data collected from three selected participants.

Solution Strategies Used by the Students

Analysis of the written responses revealed that all students employed the same strategy to solve the given problem. They first transformed the inequality into:

$$x^2 - 2x - 3 > 0$$

The quadratic expression was then factored as:

$$(x+1)(x-3) > 0$$

Next, the students determined the critical points, $x = -1$and $x = 3$, and performed interval testing over the intervals $(-\infty, -1)$, $(-1,3)$, and $(3, \infty)$. Based on the sign analysis of each interval, they concluded that the solution set was

$$(-\infty, -1) \cup (3, \infty).$$

The distribution of the solution strategies is presented in **Table 1**.

Tabel 1. Strategi Penyelesaian yang Digunakan Mahasiswa

Solution Strategy	Number of Students	Percentage
Interval testing	22	100%
Sign analysis of factors	0	0%
Graphical interpretation of the quadratic function	0	0%
Completing the square	0	0%
Absolute value approach	0	0%
Functional property analysis	0	0%

Table 1 shows that every student relied exclusively on the interval testing procedure. No student employed an alternative strategy or combined multiple solution approaches.

Mathematical Representations Used by the Students

The analysis of mathematical representations indicated that all students relied on symbolic-algebraic representations. None used graphical representations to illustrate the position of the quadratic function relative to the x-axis, nor did they employ analytical representations to explain the properties of the quadratic function involved in the problem.

The distribution of mathematical representations is presented in Table 2.

Table 2. Mathematical Representations Used by the Students

Representation Type	Number of Students	Percentage
Symbolic–algebraic	22	100%
Graphical	0	0%
Analytical	0	0%
Verbal argumentation	2	9,09%

Although two students included brief verbal explanations in their written responses, these merely described the sequence of procedural steps and did not provide mathematical reasoning beyond the interval testing method.

Students' Mathematical Thinking Flexibility

Mathematical thinking flexibility was analyzed using three indicators adapted from Star and Newton (2009): (1) the ability to generate more than one valid solution strategy, (2) the ability to explain the relationships among different strategies, and (3) the ability to evaluate or select the most appropriate strategy. The results are summarized in **Table 3**.

Table 3. Achievement of the Mathematical Thinking Flexibility Indicators

Indicator	Number of Students Meeting the Indicator	Percentage
Generated more than one valid strategy	0	0%
Explained relationships among strategies	0	0%
Evaluated or selected the most appropriate strategy	0	0%

Table 3 indicates that none of the students satisfied any of the three indicators of mathematical thinking flexibility examined in this study. Every student relied on a single solution strategy and demonstrated neither the ability to generate alternative approaches nor the ability to compare the effectiveness of different strategies.

Furthermore, no student connected the algebraic solution with the graphical representation of the quadratic function or with the property that a product is positive when both factors are positive or both are negative. These findings suggest that the students' problem-solving approach was predominantly procedural and did not involve the exploration of multiple mathematical representations.

Factors Underlying the Dominance of Procedural Strategies

To gain deeper insight into these findings, semi-structured interviews were conducted with three students selected based on the completeness of their written responses and their mathematical communication skills.

The interviews revealed that all participants regarded interval testing as the standard procedure for solving quadratic inequalities.

Student S1 stated:

"Since high school, inequalities like this have always been solved by finding the roots and then applying interval testing. I don't know any other method."

Student S2 commented:

"I think this method is already the most appropriate one, so I never considered looking for another approach."

Meanwhile, Student S3 remarked:

"I've never tried using graphs to solve problems like this."

When asked about the possibility of using the graph of the quadratic function to determine the solution region, all participants experienced difficulty connecting the algebraic form with its graphical representation. They were also unable to explain the solution based on the property that the product of two factors is positive when both factors have the same sign, either both positive or both negative.

The interview findings identified three main factors underlying the dominance of procedural strategies among the students: (1) a long-standing habit of using interval testing since secondary school, (2) the belief that interval testing is the only correct method for solving quadratic inequalities, and (3) limited experience in exploring multiple mathematical representations and mathematically equivalent solution strategies.

3.2. Discussion

The findings indicate that all participants employed the same strategy to solve the quadratic inequality, namely factorization followed by interval testing. Moreover, no student used an alternative solution strategy or any mathematical representation other than symbolic-algebraic representation. These findings suggest that problem solving was dominated by the application of previously learned procedures and did not reflect the level of mathematical thinking flexibility expected of students who have completed a Real Analysis course.

Dominance of Procedural Knowledge in Solving Quadratic Inequalities

The exclusive use of the interval testing method by all participants indicates that procedural knowledge remains the primary basis for solving mathematical problems. The students were able to execute the algorithmic steps correctly, beginning with factoring the quadratic expression, determining its zeros, and performing interval testing to obtain the solution set. However, successfully arriving at the correct answer does not necessarily indicate an adequate conceptual understanding of the underlying mathematical structure.

According to Rittle-Johnson et al. (2015), procedural knowledge and conceptual knowledge are two interrelated components of mathematics learning. Procedural knowledge enables individuals to solve problems by applying a sequence of known steps, whereas conceptual knowledge involves understanding the relationships among mathematical ideas and the underlying rationale for those procedures. In the present study, although the students demonstrated strong procedural competence, they were unable to explain why the procedure worked or how the same problem could be solved using alternative approaches.

These findings suggest that obtaining the correct solution does not necessarily reflect a deep conceptual understanding of quadratic inequalities. This issue is particularly important because the participants were prospective mathematics teachers who are expected to explain mathematical concepts through multiple approaches and representations in their future classrooms.

Low Levels of Mathematical Thinking Flexibility

One of the principal findings of this study is that none of the students were able to generate more than one valid solution strategy. Likewise, no participant was able to explain the relationships among different strategies or evaluate the potential use of alternative approaches. Based on the indicators adapted from Star and Newton (2009), these results indicate that the students demonstrated a low level of mathematical thinking flexibility.

Star and Newton (2009) argued that mathematical thinking flexibility is characterized by the ability to generate multiple solution strategies, understand the relationships among those strategies, and select the most appropriate strategy according to the characteristics of a given problem. In this study, however, students relied exclusively on a single familiar strategy without considering other valid alternatives. Consequently, their problem-solving process resembled the application of a memorized algorithm rather than an activity of mathematical exploration.

This phenomenon also suggests that students tend to perceive mathematical problems as having only one correct solution procedure. Such a perspective may hinder the development of higher-order thinking because students are not encouraged to explore relationships among mathematical ideas or to search for strategies that are more efficient or conceptually meaningful.

The interview findings further support these results. All participants stated that interval testing had been the standard method they learned since secondary school and that they were unaware of any alternative approaches. This finding suggests that prior learning experiences contributed to the development of a procedural habit of thinking centered on a single solution method.

Limited Ability to Transform Mathematical Representations

Another important finding is the absence of graphical and analytical representations in the students' solutions, despite the fact that the given quadratic inequality can be represented in several mathematically equivalent forms.

The inequality $x^2 - 2x > 3$can be solved using at least three different graphical representations. The first approach is to sketch the graph of $y = x^2 - 2x$and identify the region where the graph lies above the line $y = 3$. The second approach is to rewrite the inequality as $x^2 > 2x + 3$and compare the graphs of $y = x^2$and $y = 2x + 3$. The third approach is to transform the inequality into $x^2 - 2x - 3 > 0$and determine the region where the graph of $y = x^2 - 2x - 3$lies above the x-axis. Although these three representations yield the same solution set, each reflects a different mathematical perspective on the problem.

The students' inability to utilize these representations indicates limitations in their ability to transform mathematical representations. According to Raymond Duval (2006), deep mathematical understanding is characterized by the ability to coordinate and transform among different semiotic representation registers. Individuals with a solid conceptual understanding are able not only to operate within a single representation but also to move flexibly between symbolic, graphical, verbal, and visual representations without losing the underlying mathematical meaning.

In the present study, the students operated exclusively within the symbolic-algebraic register. Although they successfully manipulated algebraic symbols, they did not demonstrate the ability to connect these symbols with corresponding visual representations. This finding indicates that their understanding of quadratic inequalities remained localized to a particular procedural approach rather than developing into an integrated conceptual understanding.

This phenomenon can be interpreted as a form of **representation rigidity**, namely the tendency to rely repeatedly on a single representation even when other equally valid representations are available for solving the problem. Such rigidity may hinder prospective mathematics teachers' ability to explain mathematical concepts to students who possess diverse ways of thinking and different representational preferences.

Implications for Real Analysis Instruction

The findings of this study have important implications for Real Analysis instruction in mathematics teacher education programs. Fundamentally, a Real Analysis course is intended not only to develop students' symbolic manipulation skills but also to foster reasoning, proof construction, generalization, and a deep understanding of mathematical structures.

David Tall (1991) argued that the development of advanced mathematical thinking is characterized by the ability to view a mathematical object from multiple interconnected perspectives. In the present study, however, the students did not exhibit this characteristic because they remained dependent on a single previously learned procedure. As a result, the potential of the given problem to facilitate exploration of the relationships among functions, graphs, inequalities, and algebraic properties was not fully realized.

Therefore, Real Analysis instruction should be designed to engage students in problems that can be solved through multiple approaches. Instructors should emphasize not only the correctness of the final answer but also encourage students to compare alternative strategies, evaluate the efficiency of different approaches, and connect relevant mathematical representations. Learning activities such as multiple-solution tasks, strategy comparison discussions, and graphical representation explorations may effectively promote students' mathematical thinking flexibility.

Overall, the findings demonstrate that although the students were able to obtain the correct solution, their problem-solving processes remained dominated by a single procedural approach and did not reflect the level of mathematical thinking flexibility expected of prospective mathematics teachers. Consequently, instructional approaches that emphasize the exploration of multiple solution strategies and mathematical representations are essential for preparing future mathematics teachers.

4. CONCLUSION

This study aimed to analyze the mathematical thinking flexibility of prospective mathematics teachers in solving quadratic inequalities within a Real Analysis course. The findings revealed that all participants employed the same solution strategy, namely the interval testing method. No alternative strategies, such as sign analysis of factors, graphical representation, completing the square, or functional property analysis, were observed. Furthermore, the students' mathematical representations were exclusively symbolic-algebraic, with no attempt to utilize other mathematically equivalent representations.

Based on the mathematical thinking flexibility indicators adopted in this study, none of the students were able to generate more than one valid solution strategy, explain the relationships among different strategies, or evaluate the most appropriate strategy for the problem. These findings indicate that the students exhibited a low level of mathematical thinking flexibility, and that their problem-solving processes were dominated by the application of familiar procedural methods. The interview results further revealed that this procedural dominance was influenced by three main factors: long-standing experience with the interval testing method since secondary school, the belief that it is the only correct approach to solving quadratic inequalities, and limited opportunities to explore multiple mathematical representations and equivalent solution strategies.

The findings demonstrate that the ability to obtain the correct answer does not necessarily imply the ability to understand a mathematical problem through multiple representations and solution approaches. Therefore, Real Analysis instruction should provide greater opportunities for students to explore alternative solution strategies, compare different mathematical representations, and develop greater mathematical thinking flexibility as an essential component of advanced mathematical thinking in prospective mathematics teachers.

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