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STRUCTURED MATHEMATICAL THINKING: EVALUATING POLYA'S PROBLEM-SOLVING APPROACH IN EXPONENT MULTIPLICATION AND DIVISION

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ABSTRACT

This study investigates the effectiveness of Polya's four-step problem-solving approach in improving Grade 7 students' understanding of exponent multiplication and division. Exponent operations are fundamental in algebra. However, many students struggle to interpret problem structures, apply exponent rules correctly, and verify their solutions. A quasi-experimental one-group pretest–posttest design was employed with 32 junior secondary students at Pibool Uppatham School, Bangkok, Thailand. The instructional intervention integrated Polya's stages of understanding the problem, planning, executing, and reviewing into guided classroom activities. Data were collected using a ten-item test, an analytic scoring rubric, and an error analysis framework. Results revealed a statistically significant improvement in students' performance from pretest to posttest, with a large effect size. Students demonstrated a clearer understanding of exponent expressions, more accurate application of exponent laws, and greater consistency in monitoring their solutions. Error analysis indicated a reduction in common error patterns, including misinterpretation of exponent structure and incorrect application of exponent laws. These results indicate that Polya's formalized planning for problem solving consolidates not only conceptual knowledge but also procedural fluency in exponent reasoning. The study emphasizes the importance of explicit scaffolding in supporting organized mathematical thinking in algebra.

INTRODUCTION

Mathematical problem solving is widely recognized as a central component of numeracy development, as it requires students to interpret quantitative situations, apply symbolic representations, and justify solution strategies (Ningsih & Hidayati, 2022). Within the scope of numeracy education, problem solving extends beyond procedural calculation and involves logical reasoning, structured thinking, and reflective evaluation. Research published in Journal Numeracy has emphasized that numeracy literacy is closely associated with students' logical mathematical thinking, suggesting that structured reasoning processes play a crucial role in strengthening learners' ability to solve mathematical tasks effectively (Pratiwi et al., 2024). These findings reinforce the view that instructional approaches in mathematics classrooms should explicitly support students in organizing and monitoring their reasoning.

A widely used heuristic for mathematical problem solving is Polya's four-stage approach, in which learners interpret the task, select a strategy, implement that strategy, and then review the reasonableness of the solution (Polya, 1962). The framework provides a systematic structure that helps learners navigate complex tasks in a deliberate manner.

(Source: Created by the author)

Figure 1. The Four Stages of Polya's Problem-Solving Process.

Figure 1 summarizes the sequence of problem-solving actions adapted for the present intervention, beginning with problem interpretation and ending with reflective checking of the solution.

Recent empirical studies indicate that Polya's approach can enhance students' mathematical performance and promote clearer explanation of reasoning (Gulam & Arenas, 2024; Jahudin & Siew, 2024). A meta-analysis by Wahab et al. (2024) further confirms that heuristic strategies inspired by Polya's model are positively associated with improvements in mathematical problem-solving achievement. Despite these promising results, many studies examine general problem-solving ability without focusing on specific algebraic content areas that present persistent conceptual challenges for middle school students.

The theoretical implications of Polya's framework become evident when examined in light of metacognitive regulation theory. Problem solving in mathematics requires learners to plan how they will go about the task, monitor their progress, and check if the answer is correct.

These regulatory processes align closely with Polya's stages. Understanding the problem reflects planning. Carrying out the plan involves monitoring. Looking back corresponds to evaluation and self-checking. Research on mathematical reasoning demonstrates that structured reflection enhances students' written explanations and sensemaking, particularly when learners are encouraged to justify their procedures and verify their results (Hughes et al., 2024; Nurtamam & Jannah, 2025). Within numeracy contexts, studies have also shown that differences in students' cognitive processes influence how effectively they organize and apply mathematical reasoning when solving algebraic problems (Sa'adah et al., 2025). These findings suggest that explicit scaffolding through structured problem-solving stages may strengthen metacognitive awareness and reduce common reasoning errors.

In addition to metacognition, algebraic reasoning development provides an important theoretical foundation for this study. Algebraic reasoning involves recognizing symbolic structure, interpreting relationships between variables, and applying transformation rules meaningfully (Biza, 2019). Exponent multiplication and division represent a foundational component of algebraic thinking because they require students to coordinate base–exponent relationships and apply product and quotient rules accurately. However, research indicates that students frequently misunderstand exponentiation, sometimes treating it as repeated multiplication in all contexts or misapplying exponent laws when combining terms (Avitzur, 2012; Ulusoy, 2019). Subsequent studies indicate that recurrent dimensional errors in exponential expressions arise from weak structural comprehension and inadequate oversight on the symbolic representation (Eccius-Wellmann, 2012; Şenay, 2024). These trends emphasize the importance of an instructional focus that gives balanced attention to both conceptual understanding and procedural accuracy.

Although Polya's framework has been implemented in diverse mathematical domains, including algebra and digital learning environments (Ayala et al., 2024; Jahudin & Siew, 2024), empirical evidence regarding its focused application to exponent operations at the lower secondary level remains limited. Prior studies typically report overall improvements in problem-solving scores but provide less detailed analysis of how students interpret symbolic exponent structures or how specific types of errors change following structured instruction. Research in Journal Numeracy further indicates that students' approaches to mathematical tasks are influenced not only by cognitive ability but also by how instructional environments guide their reasoning strategies (Putra, 2024). Moreover, investigations integrating higher-order thinking skills within numeracy instruction suggest that structured learning designs can improve analytical reasoning when tasks are aligned with explicit cognitive scaffolding (Asriati, 2025). These insights support the argument that structured frameworks such as Polya's model may be particularly beneficial when applied to algebraic topics that demand careful symbolic reasoning.

Given the foundational role of exponent operations in later algebraic learning, examining structured problem-solving instruction in this specific content area is important. Exponents serve as a gateway to more advanced mathematical topics, including polynomial expressions and scientific notation. When misconceptions remain unaddressed at the middle school level, students may encounter compounded difficulties in subsequent coursework. By integrating Polya's systematic stages with explicit attention to algebraic structure and metacognitive monitoring, instruction may help students develop clearer reasoning patterns and reduce common procedural mistakes.

The objective of this study is to examine the effectiveness of Polya's four-step problem-solving framework in teaching multiplication and division of exponents to Grade 7 students. The study investigates whether structured problem-solving instruction improves students' performance and reduces common errors in exponent operations. To address this objective, a quasi-experimental one-group pretest–posttest design was employed to evaluate changes in students' performance following the instructional intervention.

Specifically, this study addresses three research questions. First, it examines whether instruction based on Polya's four-step problem-solving framework leads to a statistically significant improvement in Grade 7 students' performance on exponent multiplication and division tasks. Second, it investigates whether the instructional intervention reduces common error patterns in exponent operations, including misinterpretation of exponent structure, incorrect application of exponent laws, and lack of verification of solutions. Third, it analyzes how students' written responses reflect changes in structured reasoning and metacognitive monitoring after participating in Polya-based instruction.

Despite the growing body of research supporting Polya's problem-solving framework, several limitations remain in the literature. Although prior studies have shown that problem-solving instruction can improve mathematics achievement, less is known about how such instruction supports students' reasoning in particular algebraic domains, especially exponent operations. In particular, limited attention has been given to students' understanding of symbolic structure in exponent multiplication and division. Previous research often focuses on achievement scores. It rarely examines the types of reasoning errors students make or how structured guidance may help reduce these errors.

This gap is important because exponent operations form a key foundation of algebraic reasoning in secondary mathematics. Students frequently misunderstand exponent rules and symbolic relationships. These misconceptions can persist and affect later learning in algebra.

This study examines the use of Polya's four-step problem-solving framework in teaching exponent multiplication and division to Grade 7 students. The study focuses on students' learning gains after the instructional intervention. It also analyzes patterns of errors in students' responses. These analyses provide clearer evidence of how structured problem-solving instruction supports students' understanding of exponent operations. The approach also helps explain how students apply exponent rules more accurately. The findings contribute to numeracy research by highlighting the role of structured problem-solving scaffolds in developing algebraic reasoning. The results also suggest that such instruction can support students' metacognitive monitoring during mathematical problem solving.

METHODOLOGY

The study used a quasi-experimental pre-intervention and post-intervention format with a single intact class. The design was used to examine the effectiveness of Polya's four-step problem-solving approach in teaching exponent multiplication and division to Grade 7 students. Quantitative data from the pretest and posttest were used to determine whether students' performance improved after the instructional intervention. To address the second research question, an error analysis was conducted to identify changes in common error patterns in exponent operations. In addition, students' written responses were analyzed to examine changes in structured reasoning and metacognitive monitoring. The intervention was implemented in a naturally existing classroom where random assignment was not feasible.

Before the lessons began, students were given a pretest designed to capture their baseline understanding of exponent concepts and procedures. The pretest measured students' prior knowledge before the instructional intervention. After the instructional sequence, students completed a posttest to measure learning gains. The intervention incorporated Polya's four stages in classroom instruction. These stages included understanding the problem, devising a plan, carrying out the plan, and reviewing the solution. Each stage was implemented through guided classroom activities. In addition to statistical analysis, an error analysis was conducted on students' posttest responses. This analysis aimed to identify common patterns of misunderstanding in exponent problem solving. Before conducting inferential analysis, statistical assumptions were examined. The normality of the score distribution was tested using the Shapiro–Wilk test. The variance between pretest and posttest scores was also examined. This procedure ensured that parametric analysis was appropriate for the data.

The study used a one-group pretest and posttest design to examine instructional effects in an authentic classroom setting. This design allowed the researchers to observe changes in students' performance after the intervention. However, the absence of a control group may limit internal validity. For this reason, the findings should be interpreted with caution. The results should be viewed as exploratory evidence on the effectiveness of structured problem-solving instruction.

The main components of the methodology are summarized in Table 1. The table presents the research design, characteristics of the sample, variables used in the study, data collection procedures, and statistical analyses applied in the research.

Table 1. Research Design and Experimental Procedure

Aspect	Details
Research Design	Quasi-experimental (One-group pretest–posttest design)
Sample	32 Grade 7 students
Independent Variable	Polya's Problem-Solving Framework
Dependent Variable	Mathematical problem-solving ability in exponent operations
Data Collection Methods	Pretest and Posttest, Error Analysis
Statistical Analysis	Descriptive statistics (Mean, Standard Deviation), Normality test (Shapiro–Wilk), Variance comparison, Paired-sample t-test, Effect size (Cohen's d)

Participants

The sample consisted of 32 Grade 7 students at a public lower secondary school in Thailand during the second semester of the 2024 academic year. The sample was selected through convenience sampling based on class availability. All participants had previously received basic instruction on exponent concepts but had not been exposed to Polya-based problem-solving instruction.

Instruments

The research instrument consisted of a researcher-developed test designed to assess students' understanding of exponent operations. The test was reviewed by three mathematics education experts to ensure alignment with the learning objectives, and its content validity was confirmed through expert judgment (Cañeda et al., 2024; Kartono & Sulhadi, 2019). After revisions based on their feedback, the instrument was piloted with a group of students who shared similar characteristics with the study sample. The reliability of the test was established using an internal consistency estimate. The internal consistency reliability of the instrument, calculated using Cronbach's alpha, was .82, indicating acceptable reliability for research purposes (Oloruntegbe et al., 2010; Rufina, 2015). An analytic scoring rubric was employed to assess students' written responses, and an error analysis framework was used to categorize common patterns of mistakes in exponent problem-solving.

Table 2. Error Analysis in Student Problem-Solving

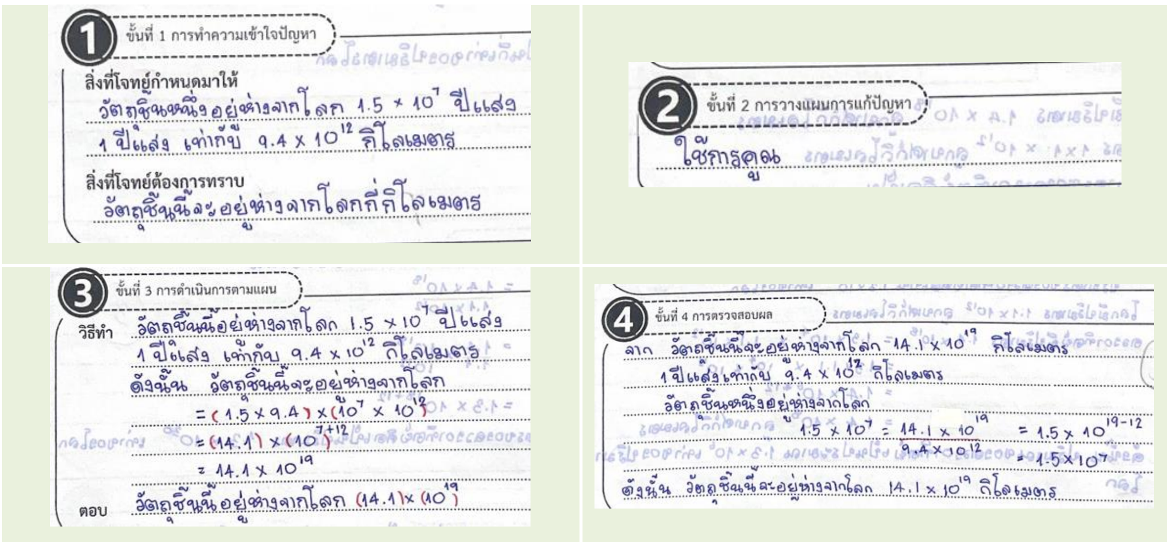
Error Type	Description	Example	Possible Cause	Recommendation
Misinterpretation of problem statement	Students misunderstood the problem structure.	Misreading exponent rules.	Unfamiliar with exponent notation	Explicit teaching with visual examples.
Incorrect application of exponent rules	Students applied exponent laws incorrectly.	$(2^3)^2 = 2^5$ instead of 2^6	Confusion between power and multiplication rules.	Guided practice with step-by-step breakdown.
Calculation errors	Computational mistakes in operations.	$3^2 + 3^3 = 3^5$ instead of $9 + 27 = 36$	Inaccurate arithmetic execution.	Encourage students to verify calculations.
Lack of checking final answer	Students did not check their final answer	Answering $2^0 = 0$ instead of 1	Lack of metacognitive reflection.	Encourage the looking back strategy

Intervention Procedure

The intervention was carried out across four class periods of approximately fifty minutes each and was organized in line with Polya's problem-solving approach. At the beginning of each lesson, students spent time making sense of the exponent problems by discussing what the expressions represented and identifying the information needed for a solution. During the lesson, they brainstormed different approaches to completing the tasks and discussed which exponent rules or operations would apply. Then they attempted to answer the problems, with help from the teacher if they needed clarification or assistance. At the end of every class, students revisited their solutions to confirm that their answers were reasonable and to identify patterns or errors by solving the problem in an alternative way. As the lessons were taught by a classroom teacher, the researcher was present for all sessions of instruction to ensure close adherence of instructional activities to the intended format.

Data Collection

Data for the study were gathered at several points throughout the intervention. Students completed a pretest before the instructional intervention and a posttest after the four Polya-based lessons. During the series of lessons that followed, additional written work was collected as students applied exponent rules and attempted problem-solving tasks. All written responses from both the pretest and posttest, as well as work produced during the lessons, were retained and later examined to identify patterns of errors related to exponent reasoning. Figure 2 provides student work samples showing the use of Polya's four-step problem-solving framework in action regarding exponent operations. Each example illustrates a specific stage of the process, highlighting structured reasoning, appropriate applications, and common errors. The figure highlights how students think about their mathematical reasoning, and the multiple layers of their conceptual understanding.



(Source: Created by the author)

Figure 2. Examples of Student Work Illustrating Polya's Four-Step Problem-Solving Process in Exponent Problems.

The examples of student work presented in Figure 2 were originally written in Thai. English translations are provided to support international readers below.

Step 1: Understanding the Problem

Given information: An object is located 1.5×10^{7} light years away from Earth. One light year is equal to 9.4×10^{12} kilometers.

What needs to be determined:

How many kilometers away is the object from Earth?

Step 2: Devising a Plan

Use multiplication.

Step 3: Carrying Out the Plan

Solution: The object is located 1.5×10^{7} light years away from Earth. One light year is equal to 9.4×10^{12} kilometers. Therefore, the distance of the object from Earth is

$$
\begin{aligned}
&= (1.5\times9.4)\times(10^{7}\times10^{12}) \\
&= (14.1)\times(10^{7+12}) \\
&= 14.1\times10^{19}
\end{aligned}
$$

Answer: The object is 14.1×10^{19} kilometers away from Earth.

Step 4: Checking the Result

From the calculation, the object is 14.1×10^{19} kilometers away from Earth.

One light year is equal to 9.4×10^{12} kilometers.

The distance of the object from Earth can be checked as follows:

$$
\begin{aligned}
\frac{14.1\times10^{19}}{9.4\times10^{12}} &= 1.5\times10^{19-12} \\
&= 1.5\times10^{7}
\end{aligned}
$$

Therefore, the result is consistent.

Conclusion: The object is 14.1×10^{19} kilometers away from Earth.

Data Analysis

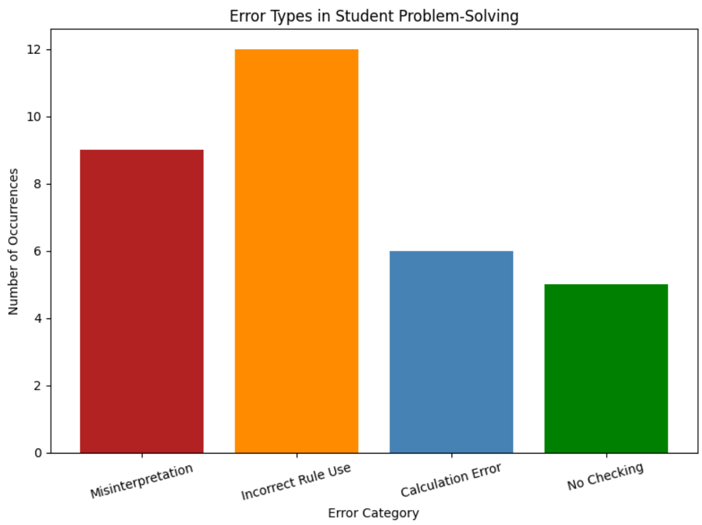
Means and standard deviations were computed as descriptive statistics to summarize students' performance. A paired-sample t-test was conducted to compare pretest and posttest scores and assess whether the observed improvement was statistically significant. Cohen's d was utilized to calculate the effect size, an estimate of the intervention effect magnitude. Prior to conducting the paired-sample t-test, the normality of the data distribution was examined using the Shapiro–Wilk test.

Ethical Considerations

Ethical standards were followed throughout all phases of the study. Participants' confidentiality was protected through the use of coded identifiers, and all data were stored securely. Students participated in the study voluntarily and did not lose any academic standing if they chose not to participate.

RESULTS AND DISCUSSION

The results are presented according to the three research questions of the study. First, the comparison between pretest and posttest scores showed that the instructional intervention improved students' understanding of exponent multiplication and division. Students demonstrated higher performance after participating in Polya-based instruction. The statistical results are presented in Table 3. Second, the analysis of students' responses revealed several common error patterns in exponent operations. The most frequent error was the incorrect use of exponent rules. This was followed by misinterpretation of exponent structure and calculation errors. These findings indicate that students often reverse or misapply exponent laws when solving problems. The distribution of these error patterns is presented in Figure 3.



(Source: Created by the author)

Figure 3. Distribution of Error Types in Student Exponent Problem-Solving

Figure 3 presents the pattern of error categories identified in the students' post-intervention responses. The most common error (37.5% of all errors) was due to the incorrect use of rules. Misinterpretation was next (28.1%), followed by calculation errors (18.8%). The least common category at 15.6% was lack of checking.

These categories relate to the error classification framework shown in Table 2. The quantitative distribution visualized in Figure 3 offers empirical support for the descriptive patterns described in the table. The results demonstrate that students still struggle to correctly apply exponent rules and interpret symbolic expressions accurately. This pattern highlights the need for explicit problem-solving support to strengthen conceptual understanding and procedural competence.

The average posttest score (M = 36.66, SD = 13.54) was higher than the average pretest score (M = 24.72, SD = 12.98) as found in Table 3. This improvement was statistically significant according to a paired-sample t-test, $t(31) = 5.87$, $p < .001$. The effect size analysis obtained a large magnitude of improvement (Cohen's d = 1.04), which attests that the instructional intervention had a substantial impact on students' understanding of exponent operations.

Table 3. Paired-Sample t-Test Comparing Pretest and Posttest Scores (n = 32)

Test	N	Mean	SD	t-value (df)	p-value
Pretest	32	24.72	12.98		
Posttest	32	36.66	13.54	5.87 (31)	< .001

Note. A paired-sample t-test was conducted to compare pretest and posttest scores.

To further examine the magnitude of the observed improvement, effect size was calculated. The results are presented in Table 4.

Table 4. Effect Size (Cohen's d) for the Pretest–Posttest Comparison

Comparison	Effect Size (Cohen's d)	Interpretation
Pretest vs Posttest	1.04	Large effect

Note. Cohen's d was calculated using the standard deviation of the difference scores.

The results show a significant improvement in students' understanding of exponent operations after the intervention. Posttest scores increased compared with pretest scores. Students demonstrated better conceptual understanding of exponent rules. Their procedural accuracy also improved. In addition, students monitored their solutions more carefully. Computational errors occurred less frequently. These results suggest that explicit stepwise guidance supported students in structuring their reasoning and managing exponent tasks more systematically.

The improvement may be explained by the structured guidance provided through Polya's problem-solving stages. These stages guide students to analyze the problem carefully. Students are encouraged to choose appropriate strategies. They are also asked to review their solutions. This process supports more deliberate thinking. It also reduces the tendency to apply rules without reflection. As a result, students may develop stronger metacognitive awareness during problem solving. However, the level of improvement differed among students. Some students showed greater progress than others. Differences in prior knowledge may have influenced these outcomes. Students' readiness to learn may also have affected how they benefited from the intervention. Some students may need additional support. Continued guidance can help them develop more structured reasoning strategies.

This observed improvement in students' performance is consistent with previous research demonstrating that structured problem-solving approaches lead to stronger conceptual understanding and procedural fluency (Schoenfeld, 1992). Despite limitations such as its single-group design, the findings provide support for the view that explicit problem-solving instruction improves students' confidence and helps them avoid common mistakes with exponents.

These findings align with the more recent studies showing that having explicit guidance in both planning and execution phases improves students' mathematical reasoning while reducing common errors (Hughes et al., 2024; Nurtamam & Jannah, 2025). Collectively, this evidence strengthens the argument of well-scaffolded problem-solving routines for learning multi-step symbolic procedures like those involved in exponent operations.

This study, apart from its theoretical contributions also provides practical implications for classroom instruction. Polya's framework provides teachers with a clear structure for lesson planning that supports students in articulating their reasoning and verifying solutions (Syahfitri & Wandini, 2023). Rather than relying solely on memorized rules, students benefited from structured, step-by-step reasoning, consistent with evidence that organized thinking routines foster flexible and adaptive mathematical reasoning (Flynn et al., 2023).

These improvements may occur because Polya's framework encourages students to reflect on their reasoning and verify their solutions. Such metacognitive processes support students in identifying mistakes and adjusting their strategies during problem solving. Previous studies have also reported that structured problem-solving instruction can improve students' reasoning and higher-order thinking skills in mathematics learning (Gradini et al., 2024).

Although the results are encouraging, several limitations should be acknowledged. Polya's framework, while widely applicable, has been described as relatively general and may require adaptation depending on content and learner characteristics (Schoenfeld, 2014). The present study focused on exponent operations within a single classroom context.

Future research should explore the use of Polya's method in other domains of mathematics, including geometry or calculus and with students from a wider variety of backgrounds. It further indicates that future work needs to investigate how structured problem-solving scaffolding can be adapted to better support individual learners and transfer across mathematical topics.

CONCLUSION

The study explored the use of Polya's four-step problem-solving method in teaching Grade 7 students exponent multiplication and division. Results showed a statistically significant improvement in students' performance when comparing pretest and posttest with a large effect size. Students showed more effective interpretation of problem structure, more accurate application of exponent rules and more systematic verification of solutions.

The scaffolded approach of understanding the problem, developing a plan, executing, and reviewing, apparently helped students organize their reasoning and avoid common pitfalls. Although the study was conducted in a single classroom context, the findings suggest that explicit scaffolding can improve conceptual understanding alongside procedural fluency in exponent operations.

Although the study is limited because it was confined to a single classroom setting, it provides additional empirical evidence in favor of embedding structured problem-solving routines into algebra lessons. Polya's framework provides a useful instructional model that may help students work toward clearer reasoning mathematically and increased accuracy with symbolic tasks.

IMPLICATIONS AND RECOMMENDATIONS

The findings of this study offer practical implications for teaching exponent multiplication and division at the junior secondary level. This improvement indicates that

Polya's four-step method can serve as a practical guide for classroom instruction. The clearly-defined phases of understanding the problem, planning, executing and reviewing seem to help students structure their reasoning more consistently and to analyze their work afterward.

This should prompt teachers to explicitly model these stages within the scope of everyday instruction. A focus on structured reflection and guided practice may contribute to minimizing common errors while reinforcing conceptual understanding. Instruction may also focus on helping students articulate the structure of exponent expressions and represent relationships visually to reinforce meaning.

Further research should investigate whether similar improvements are found when Polya's framework is applied to other algebra topics. Studies with larger sample sizes and comparison groups would provide stronger evidence for the effectiveness of structured problem-solving instruction in mathematics classrooms.

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