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# The Effect of Self-Explanation Learning Strategies on Students' Understanding of Mathematical Concepts

Subhan Ajiz Awalludin[1*], Fahmi Sahab[2], Rattikan Saelim[3]

[1,2]Universitas Muhammadiyah Prof DR. HAMKA, Indonesia
[3]Department of Mathematics and Computer Science, Prince of Songkla University, Thailand

*Corresponding author: psu5720320705@gmail.com

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**Abstract**

This study investigates whether a structured self-explanation strategy improves secondary students' conceptual understanding of geometric transformations. Employing a quasi-experimental nonequivalent posttest-only control group design, the research sampled two intact eleventh-grade classes from a public high school. The experimental class received worksheet-embedded prompts guiding them through four phases of self-explanation, whereas the control class experienced conventional instruction. Assumption checks confirmed normality and homogeneity, and an independent-samples t-test compared posttest performance. Students taught with self-explanation achieved higher scores on a five-item open-ended assessment of conceptual understanding than their peers in the control condition. The between-group difference was statistically significant and accompanied by a large effect size (ES ≈ 0.83), indicating meaningful practical gains. Qualitative interpretation of score patterns suggests that explanation prompts facilitated integration across symbolic, graphical, and spatial representations and reduced common misconceptions in transformation tasks. These results align with prior evidence that metacognitive scaffolds deepen conceptual learning and support transfer beyond taught procedures. The findings imply that brief, structured self-explanation can be feasibly integrated into routine lessons to enhance conceptual outcomes. Future research should explore retention over time, effects across diverse topics, and the comparative benefits of alternative metacognitive supports.

Keywords: Conceptual understanding; Geometric transformations; Mathematics education; Metacognitive scaffolding; Self-explanation

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## 1. Introduction

Mathematics plays a fundamental role in shaping students' cognitive development, particularly in fostering their abilities to reason logically, think critically, and solve problems creatively. As such, mathematics is not only a central component of educational curricula worldwide but also a subject that underpins success in science, technology, engineering, and mathematics (STEM) disciplines (Rittle-Johnson et al., 2017; Hafizah et al., 2025). In this context, the ability to understand mathematical concepts becomes crucial. Conceptual understanding, as defined by the National Council of Teachers of Mathematics (NCTM, 2014), refers to the comprehension of mathematical ideas, the relationships between them, and the ability to apply these ideas effectively in varied contexts. Numerous studies have emphasised that conceptual understanding contributes significantly to students' long-term retention of knowledge and their ability to transfer learning to unfamiliar problems (Star, 2005; Booth et al., 2017; Kania et al., 2024).

Despite its recognised importance, research consistently reports that students across different educational levels exhibit limited conceptual understanding of mathematics (Papadopoulos & Frank, 2020; Nguyen et al., 2022). Such findings highlight a persistent challenge in mathematics education: while students may successfully perform procedures, they often lack insight into the underlying concepts. This gap between procedural fluency and conceptual comprehension can hinder students' mathematical development and their ability to engage meaningfully with advanced content. Recent assessments and classroom observations reveal that traditional instructional approaches tend to overemphasize procedural mastery at the expense of conceptual understanding, leading to superficial learning outcomes (Baroody et al., 2007).

This issue presents a critical pedagogical problem: how can educators effectively foster deep mathematical understanding in their students? Several instructional strategies have been proposed to address this challenge, including inquiry-based learning, problem-based learning, and metacognitive scaffolding (Hiebert & Grouws, 2007; Koedinger et al., 2012; Afiyanti et al., 2025). Among these, metacognitive strategies have gained increasing attention for their potential to enhance students' reflective thinking and active engagement in the learning process. In particular, the self-explanation learning strategy has emerged as a promising approach that encourages learners to generate their own explanations during problem-solving, thereby deepening their understanding and promoting knowledge integration (Rittle-Johnson et al., 2020; Angraini et al., 2024).

Self-explanation refers to the process by which students produce explanations for themselves to make sense of new information. This strategy facilitates learning by encouraging students to articulate their reasoning, make inferences, and connect new knowledge with prior understanding (Lombrozo, 2006; Agustito et al., 2023; Supriyadi et al., 2024). Through this process, students can identify gaps in their knowledge, resolve misconceptions, and reinforce conceptual structures. Empirical studies have demonstrated that self-explanation enhances learning outcomes in various domains, including mathematics, science, and computer programming (Van der Graaf et al., 2022; Alhassan, 2017; Hayu & Angraini, 2024; Kania, et al., 2024). Notably, its effectiveness has been observed in both novice and advanced learners, suggesting its broad applicability across educational contexts.

In mathematics education specifically, self-explanation has been linked to improved conceptual understanding and problem-solving performance. Research by Chi et al. (1994) found that students who engaged in self-explanation while studying worked examples outperformed their peers on transfer problems. More recent studies have replicated and extended these findings, indicating that self-explanation supports the acquisition of flexible and transferable mathematical knowledge (Booth et al., 2017; Rittle-Johnson et al., 2017). Moreover, integrating self-explanation into instructional design has been shown to foster metacognitive awareness and encourage active participation in learning tasks (Lazonder & Harmsen, 2016).

Despite the growing body of evidence supporting self-explanation, its implementation in secondary mathematics education remains limited. Several studies have focused on university students or specialized contexts, leaving a gap in our understanding of how self-explanation strategies function in typical high school classrooms, particularly in geometry topics that require high levels of abstraction (Nguyen et al., 2022). Geometry, and specifically the topic of geometric transformation, often presents conceptual difficulties for students due to its visual and spatial nature. Instructional strategies that promote visualization and conceptual engagement, such as self-explanation, may therefore be particularly beneficial in this area.

A closer examination of the literature reveals that while self-explanation has been applied in various learning environments, few studies have explicitly explored its effects on students' conceptual understanding of geometric transformations in high school settings. Furthermore, there is a scarcity of research employing rigorous experimental designs to evaluate its impact in real-world classrooms. This gap underscores the need for empirical studies that investigate the effectiveness of self-explanation strategies within the specific context of secondary mathematics education, using methodologically sound approaches and valid assessment instruments (Van der Graaf et al., 2022).

Accordingly, the present study aims to investigate the effect of self-explanation learning strategies on the conceptual understanding of geometric transformation among eleventh-grade students in a public high school setting. This study contributes to the existing literature by providing empirical evidence from a quasi-experimental design, thereby addressing a notable gap in current research. The novelty of this study lies in its application of self-explanation strategies to a geometry topic at the secondary level, using a controlled classroom setting with validated instruments. By examining whether and to what extent self-explanation facilitates conceptual learning in geometry, the study offers pedagogical insights that may inform instructional practices and curriculum development. Ultimately, the findings may support educators in designing learning environments that promote deep, meaningful understanding of mathematical concepts.

## 2. Methods

This study utilized a quantitative approach through a quasi-experimental design known as the nonequivalent posttest-only control group design. This design is widely used to assess causal relationships in educational interventions when random assignment at the individual level is not feasible (Shadish et al., 2002). The objective was to investigate the effect of self-explanation learning strategies on students' conceptual understanding of geometric transformation. The study was conducted at a public senior high school in Tangerang, Indonesia. The research design is summarised in Table 1.

**Table 1 - Research Design**

| Class | Treatment | Test |
|---|---|---|
| E | XE | Y |
| K | XK | Y |

Information:
E = Experimental Class,
K = Control Class,
XE = Experimental Treatment (Self-Explanation Strategy),
XK = Conventional Learning, and
Y = Posttest on Conceptual Understanding

The population consisted of 144 eleventh-grade students from four parallel social science classes. The topic covered was geometric transformation, known for requiring abstract and spatial reasoning skills (Nguyen et al., 2022). Cluster random sampling was applied to select two classes from the population that had been confirmed to meet the assumptions of normality and homogeneity. Class XI B (36 students) served as the experimental group, while Class XI A (36 students) was assigned as the control group.

The independent variable in this study was the instructional strategy—self-explanation for the experimental group and conventional teacher-centered instruction for the control group. The dependent variable was students' conceptual understanding of geometric transformation. This construct was assessed using a test instrument consisting of five open-ended essay questions. The questions were aligned with the indicators of conceptual understanding proposed by the National Council of Teachers of Mathematics (NCTM, 2014), focusing on students' ability to interpret, represent, and apply geometric transformation concepts accurately.

Content validity of the instrument was established through expert review, and item analysis confirmed that all five questions were valid. Reliability was measured using Cronbach's alpha, and the instrument yielded a coefficient above 0.70, confirming high internal consistency (Tavakol & Dennick, 2011). Before the intervention, both groups were compared using their scores on a mathematics test from a previous topic (linear equations with two variables) to ensure baseline equivalence. Statistical analysis confirmed that no significant difference existed between the groups. The experimental group received instruction based on a structured self-explanation model, which was implemented through student worksheets. The stages of self-explanation included: monitoring comprehension, paraphrasing problems in their own words, bridging inferences with prior knowledge, and elaborating multiple problem-solving strategies. This approach aligns with research highlighting the metacognitive and conceptual benefits of self-generated explanations (Lombrozo, 2006; Van der Graaf et al., 2022).

Following the instructional period, statistical procedures were prepared to analyze the data collected. The Lilliefors test was selected to assess normality of posttest data at a significance level of $\alpha = 0.05$. The homogeneity of variance between groups was tested using the Fisher test. Based on the results of these preliminary tests, the data analysis was designed to proceed using parametric methods. To determine whether a significant difference existed between the experimental and control groups, an independent-samples t-test was planned. The null hypothesis proposed no difference in conceptual understanding between the two groups. The significance level was set at $\alpha = 0.05$. To assess the magnitude of the instructional effect, the effect size (ES) was calculated using formula (1):

$$ES = \frac{\bar{X}e - \bar{X}c}{Sc} \tag{1}$$

Information:

ES : Effect size

$\bar{X}e$ : The average posttest class count experiment

$\bar{X}c$ : Average posttest class count control

$Sc$ : Standard deviation of the class posttest Control

The criteria for effect size according to Sugiyono (Zakiyatun, et al, 2017) are:

$ES < 0{,}2$: Low

$0{,}2 \leq ES < 0{,}8$: Medium

$ES \geq 0{,}8$: High

This methodological framework ensured rigorous planning and robust analysis to evaluate the impact of self-explanation learning strategies. It combined validated instruments, controlled classroom conditions, and appropriate inferential statistics to support internal and external validity. The findings from the implementation of this method are presented in the subsequent Results and Discussion section.

## 3. Results and Discussion

This section presents the empirical findings from the quasi-experimental implementation of the self-explanation learning strategy and integrates those results with a theoretically grounded interpretation. Consistent with standards for quantitative studies in mathematics education, the reporting begins with preliminary equivalence checks, followed by posttest performance, assumption testing, and effect-size estimation, and culminates with a critical discussion situated within the extant literature (Shadish et al., 2002; NCTM, 2014; Rittle-Johnson et al., 2017).

The preliminary equivalence analysis was conducted to ensure that the experimental and control classes were comparable before the intervention. Using archival scores from a unit test on linear equations with two variables, inferential statistics indicated no statistically significant difference between the two groups at baseline. This outcome supports the validity of attributing subsequent posttest differences to the instructional treatment rather than to pre-existing disparities, which is a key requirement for quasi-experimental inference in intact classroom settings (Shadish et al., 2002; Fraenkel et al., 2019).

Following the instructional period, students completed a posttest assessing conceptual understanding of geometric transformations through five open-ended items aligned with established indicators of understanding. Descriptive statistics revealed a consistent advantage for the experimental class taught with self-explanation. The experimental group attained a higher mean, median, and mode than the control group, alongside comparable dispersion. These descriptive trends foreshadowed the inferential results and are consistent with prior studies where metacognitive prompting elevated conceptual performance in secondary mathematics (Chi et al., 1994; Rittle-Johnson et al., 2020; Van der Graaf et al., 2022).

**Table 2 - Posttest Score Summary for Experimental and Control Groups.**

| Statistic | Experimental | Control |
|---|---|---|
| Maximum | 100 | 90 |

| Statistic | Experimental | Control |
|---|---|---|
| Minimum | 55 | 40 |
| Mean | 77 | 66 |
| Median | 75 | 65 |
| Mode | 85 | 70 |
| SD | 13.3 | 12.7 |

Note; Scores reflect students' performance on a five-item open-ended assessment of conceptual understanding of geometric transformations.

Prior to conducting parametric comparisons, the assumptions of normality and homogeneity of variance were evaluated on the posttest scores. The Lilliefors test indicated that both the experimental and control distributions did not deviate significantly from normality at $\alpha = 0.05$, satisfying the requirement for t-testing in each group. The Fisher test corroborated the assumption of homoscedasticity, as the observed variance ratio fell below the critical threshold at the same significance level. Meeting these assumptions enables a valid interpretation of between-group differences via independent-samples t-tests and aligns with best practices in design-based educational research (Shadish et al., 2002; Fraenkel et al., 2019).

The primary inferential analysis used an independent-samples t-test to compare posttest means. The test produced a statistically significant difference favoring the experimental group ($t_{count} = 3.2361$, $t_{table} = 1.6702$, $\alpha = 0.05$), leading to rejection of the null hypothesis of no difference. In practical terms, students who learned with structured self-explanation outperformed peers taught by conventional methods on measures of conceptual understanding. This finding converges with a substantial body of evidence demonstrating the efficacy of eliciting learners' explanations to themselves while studying worked examples and solving problems (Chi et al., 1994; Booth et al., 2017; Rittle-Johnson et al., 2020).

To gauge the magnitude of the treatment effect, the effect size was computed using the control group's standard deviation as the denominator, consistent with the study's analytic plan. The effect-size formula was:

$$\text{Effect size (ES): } ES = (\bar{X}_e - \bar{X}_c) / S_c$$

where $\bar{X}_e$ denotes the experimental group's mean posttest score, $\bar{X}_c$ denotes the control group's mean posttest score, and $S_c$ denotes the control group's posttest standard deviation. Substituting the observed values yielded $ES \approx 0.833$, which is conventionally interpreted as a large effect and, in the present context, indicates a practically meaningful improvement in conceptual understanding attributable to self-explanation. The magnitude aligns with theoretical accounts that self-explanation triggers knowledge integration, inference generation, and error monitoring, mechanisms known to support robust, transferable knowledge structures (Lombrozo, 2006; Rittle-Johnson et al., 2017; Van der Graaf et al., 2022).

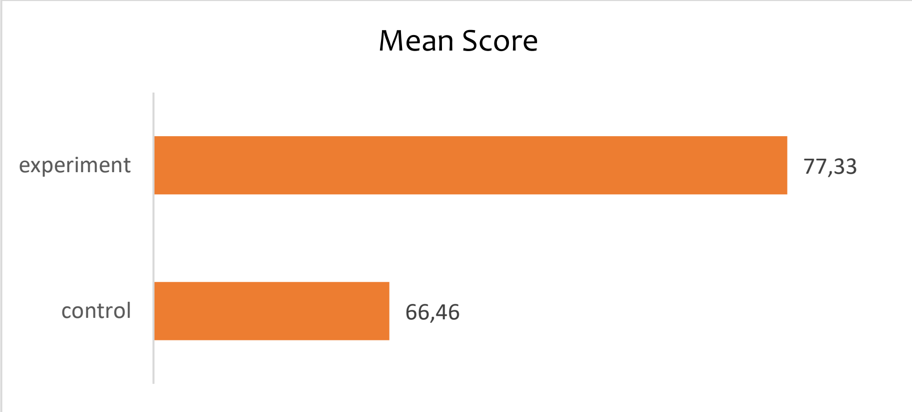


**Figure 1** Mean Scores Conceptual Understanding in Experimental and Control Groups

Figure 2contrasts the mean posttest scores of the experimental and control classes, illustrating the advantage associated with the self-explanation condition (Mean_exp = 77, 33; Mean_ctrl = 66, 46). The visual difference complements the statistical analyses reported above.Interpreting these outcomes within the broader literature helps clarify why the intervention yielded substantial gains. Self-explanation is understood to foster metacognitive regulation whereby learners actively track their comprehension, identify gaps, and seek to resolve inconsistencies by linking new information with prior knowledge. Such processes reduce superficial, procedure-bound performance and shift learners toward coherent conceptual schemas, which are essential for flexible problem solving in mathematics (NCTM, 2014; Rittle-Johnson et al., 2017). Prior experimental and classroom-based studies similarly report that prompting learners to generate explanations—especially when paired with structured materials such as worksheets or worked examples—leads to deeper encoding and better transfer (Chi et al., 1994; Booth et al., 2017; Rittle-Johnson et al., 2020).

The topic focus on geometric transformations provides an informative testbed for explanation-based learning. Transformations require coordination of multiple representations—algebraic rules, coordinate mappings, and visual/spatial reasoning—rendering them susceptible to misconceptions and fragmentary knowledge. In this study, self-explanation likely encouraged students to reconcile these representations, for example by paraphrasing problem statements, mapping symbolic rules to coordinate actions, and justifying equivalences across solution paths. Such bridging inferences and elaborations are central to the mechanisms proposed in the self-explanation literature and align with reports of reduced misconceptions and improved representational fluency in geometry (Nguyen et al., 2022; Van der Graaf et al., 2022).

The methodological rigor of the research design strengthens confidence in the findings. Although intact classes were used, baseline equivalence was established statistically, and assumption checks supported the choice of parametric inference. The measurement instrument underwent content validation and demonstrated acceptable internal consistency, which increases the reliability of the observed gains (Tavakol & Dennick, 2011). These methodological elements accord with recommendations for quasi-experimental evaluations in authentic classroom settings and mitigate common validity threats such as selection bias and instrumentation (Shadish et al., 2002; Fraenkel et al., 2019).

From a practical perspective, the results carry implications for instruction and curriculum design. Integrating brief, structured self-explanation prompts into existing lessons appears to offer a high-leverage, low-cost means of improving conceptual outcomes. Because the prompts were embedded in worksheets that segmented tasks into monitoring, paraphrasing, bridging, and elaboration phases, teachers can feasibly adopt the approach without substantial restructuring of instructional time. Moreover, prior meta-analytic evidence suggests that guided forms of inquiry or explanation outperform unguided discovery, underscoring the importance of scaffolding in metacognitive interventions (Lazonder & Harmsen, 2016). The present findings reinforce that scaffolding through self-explanation can be successfully operationalized in routine secondary mathematics lessons.

Limitations provide avenues for cautious interpretation and future research. The quasi-experimental nature of the design precludes strong causal claims beyond the sampled classes, and the reliance on a single topic—geometric transformation—limits generalizability across mathematical domains. The assessment focused on open-ended items; while aligned with conceptual indicators, additional measures such as transfer tasks, delayed tests, or think-aloud protocols could enrich understanding of mechanisms. Future studies might compare self-explanation with other metacognitive supports, examine dosage effects, or explore heterogeneous impacts across student proficiency levels, building on the adaptive expertise framework in mathematics learning (Rittle-Johnson et al., 2017; Booth et al., 2017).

In summary, the combined results and discussion indicate that self-explanation produced statistically significant and practically substantial gains in students' conceptual understanding of geometric transformations. The evidence dovetails with theoretical and empirical literature on explanation-based learning and metacognition, thereby strengthening the case for its inclusion in secondary mathematics instruction. By engaging students in articulating and refining their own reasoning, the approach advances the curricular goal of developing durable, transferable conceptual knowledge in mathematics (NCTM, 2014; Rittle-Johnson et al., 2020).

## 4. Conclusions

This study demonstrates that integrating a structured self-explanation strategy into secondary mathematics lessons yields meaningful gains in students' conceptual understanding of geometric transformations. Students who engaged in staged self-explanation—monitoring comprehension, paraphrasing, bridging inferences, and elaborating solution paths—outperformed peers who experienced conventional instruction, with a statistically significant difference on posttest measures and a large practical impact (ES ≈ 0.83). The results indicate that prompting learners to generate and refine their own explanations supports knowledge integration across multiple representations and reduces reliance on rote procedures. Pedagogically, the approach is low-cost and scalable because it can be embedded in routine worksheets and aligned with existing curricular goals. Theoretically, the findings add to the growing body of evidence that metacognitive scaffolds promote durable, transferable conceptual knowledge in mathematics. Future studies should examine longitudinal retention, differential effects by prior achievement, and comparative efficacy against other metacognitive supports across additional mathematical domains. Extending the design to include transfer tasks and delayed posttests would further clarify the mechanisms by which self-explanation enhances conceptual understanding and how these benefits generalize to novel problems.

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## Conflict of Interest

The authors declare that there are no conflicts of interest among the authors or with respect to the research, authorship, and publication of this article.

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