



A meta-analysis study: Does the open-ended approach to learning mathematics have an effect on students' high-level mathematical thinking abilities?

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Abstract

The objective of this study is to comprehensively examine the impact of an open-ended instructional approach on students' high-order mathematical thinking skills. The study utilized meta-analysis, using a dataset consisting of 63 scientific papers that contained experimental research findings. Publication bias testing was conducted on 36 papers in 5 iterations, resulting in the identification of 30 publications that fulfilled the intended conditions. The analytical results indicated that, on average, the open-ended approach had a significant impact on students' high-order mathematical thinking skills, falling inside the category of adequate. According to the educational level, it was discovered that the open-ended approach had a consistent impact across all levels of education, ranging from elementary school to university. Additionally, there was no variation in the extent of the impact between different levels of education. The impact of the open-ended approach on high-order mathematical thinking skills is highly significant in both small and large classrooms, with no obvious distinction between the two. According to the mathematics material, the open-ended approach has a highly significant effect size in enhancing high-order mathematical thinking skills. The findings of this study validate that the open-ended approach is critical in enhancing students' high-order mathematical thinking skills at all educational levels, and is not influenced by the quantity of students in a class.

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Introduction

During the 21st century, the study of high-order thinking skills (HOTS) received significant interest from researchers (Dima et al., 2021). The extensive research on students' high-level thinking skills is evident from the large number of publications available. For instance, a search on the Education Resources Information Center (ERIC) resulted in 1,119 articles, accessed on 7 May 2024 with the keyword “*high order thinking skills*”. In addition, a search on Google Scholar was conducted with the same keyword on ERIC with a time span of 2000–2023, resulting in 38,200 articles accessed on May 7, 2024. The information about these publications was obtained by using the Vos Viewer application generating Figure 1 below that provides an overview of articles on high-order thinking skills. The analysis included filters of 1000 publications and was not limited to the year of publication.

Figure 1 illustrates the extensive research conducted on high-order thinking skills (HOTS). The complex structure of the network visualization of these images represents extensive research on HOTS. Regarding to the year of publication, it is evident that researchers utilized the word “mathematical thinking” more frequently in 2012, however in 2020, the term “HOTS” was more prevalent among researchers. The extensive research on high-order thinking skills has resulted in the establishment of seven study clusters: mathematical thinking, higher-order thinking skills, mathematical thinking skills, mathematical reasoning ability, creative thinking, students' high-order thinking skills, and mathematical critical thinking skills.

The extensive study on high-order thinking skills has led to the recommendation that these skills are crucial

for 21st-century learning (Hobri et al., 2018; Schulz & Patrick, 2016). Hence, the latest educational reform in Indonesia, emphasizes the development of high-order thinking skills (Dima et al., 2021; Kemdikbud, 2016). Furthermore, the importance of enhancing students' high-order thinking skills in mathematics education has been emphasized (Sa'dijah et al., 2021). Therefore, developing students' aptitude for high-order thinking skills is essential in mathematics education.

There are various definitions for high-order thinking skills (Schulz & FitzPatrick, 2016). The formulation of the definitions can be interpreted from the perspectives of philosophy and psychology, involving the exploration of thinking processes at both basic and advanced levels. This includes examining the interplay between critical thinking and problem-solving (Lewis & Smith, 2009), as well as the application of these thinking processes to complex situations with multiple variables (Arif, 2019). Considering the dimensions of thinking skills, high-order thinking skills are linked to transfer, critical thinking, reasoning, reflective thinking, science process skills, and problem-solving skills. From a cognitive perspective, high-order thinking skill encompasses the processes of analysis, evaluation, and creation (Brookhart, 2010; Dima et al., 2021; Pratama & Retnawati, 2018). Regarding the level of knowledge, high-order thinking skills are associated with conceptual, procedural, and metacognitive knowledge (Anderson & Krathwohl, 2021; Pratama & Retnawati, 2018). Therefore, research on high-order thinking skills usually encompasses a broad and complex meaning.

The integration of higher-order thinking skills in the mathematics curriculum at schools (Rubin & Rajakaruna, 2014) leads to modifications in educational standards. The majority of states in the United States have implemented new requirements for teachers to prioritize

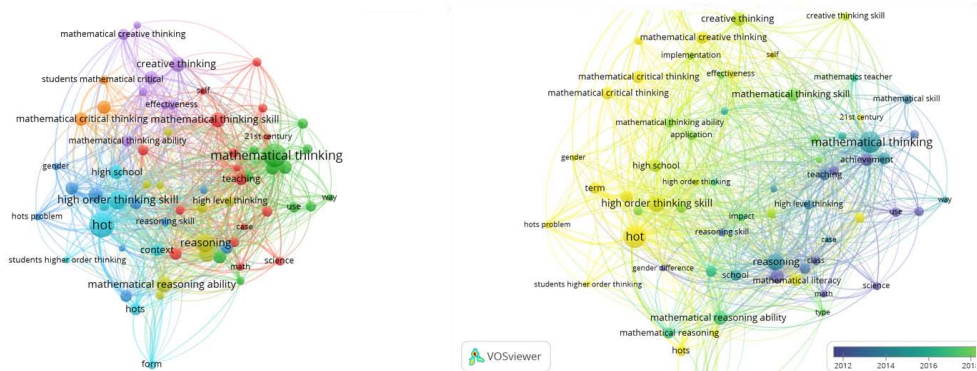


Figure 1 Publication of high-order thinking skills research articles

the teaching of higher-order thinking abilities (Common Core State Standards Initiative, 2015). Extensive research has been conducted to promote the development of high-order thinking skills, which has become a subsequent reference for policymaking, such as in the case of Japanese Mathematics Education. Adopting an open-ended approach to studying mathematics helps to enhance students' high-order thinking skills, particularly in the context of mathematics education (Nohda, 2000), where the open-ended assignments serve as examples of completing high-order thinking processes (Baker, 1993).

Experimental study has shown that the open-ended method improves high-order thinking. Previous studies have revealed a wide range of contribution values, or have yet to pinpoint the precise influence. This research aims to measure the influence's size and direction (Ellis, 2010). Therefore, measurements are needed to compare groups or define the link between two factors, such as an open-ended approach and students' high-order thinking skills. The measurement is effect size (Ellis, 2010). Cohen (1988) defines effect size to quantify a treatment's effects. It is essential for interpreting study findings. Therefore, the effect size of the open-ended method on high-level mathematical thinking skills is important.

Experimental research on students' high-order mathematical thinking skills using an open-ended approach can be analyzed from various viewpoints. According to Erdem and Akyol (2024), the quality of the learning process affects students' academic abilities at various levels of education which has been increasingly emphasized in recent years. Therefore, it is important to analyze evaluations of open-ended research findings that need to be studied based on educational level, mathematics learning material, and class size.

Piaget and Bruner's theories explain how students' thinking capacities improve with instruction. Despite Piaget and Bruner's distinct approaches to thinking growth, their stages bear similarities (Huda & Sudarwono, 2023). Student traits vary by age and cognitive stage. Last-year primary school kids can categorize items but not abstract problems. Students in grades 7 and 8 can learn deductive problem-solving. Analyzing observational patterns helps them draw conclusions (Marinda, 2020). High school pupils are more open, affable, and extraverted (Basti et al., 2022). These distinctions will affect how teachers develop learning environments and how students construct understanding. It emphasizes students' views of classroom learning (Wilson, 2006). The open-ended approach to mathematics teaching may vary, but it can improve pupils' high-order thinking skills.

Competency measurement in mathematics education

research is linked to the study of mathematical content and high-order thinking skills. This measurement aims to assess high-level mathematical thinking skills (Sumarmo et al., 2019). Consequently, the development of this measurement is a fundamental aspect of learning mathematics (Sa'dijah et al., 2021). The National Council of Teacher Mathematics (NCTM) categorizes school mathematics into distinct groups, including numbers and operations, algebra, geometry, measurement, and data analysis and probability (NCTM, 2000). Therefore, it is imperative to investigate the impact of the open-ended approach on the development of high-order mathematical thinking skills using a specific group of school mathematics materials.

Researchers usually use school courses for experimental mathematics education research. Indonesian Minister of Education Regulation Number 17 of 2017 governs classroom size. According to this regulation, elementary, junior, and senior high schools have varying minimum enrollments. Researchers have not consistently linked class size to student learning. Grace and Oluwatoyin (2016) found a high association between class size and student learning results, with both being unsatisfactory. In contrast, Olurotimi and Nike (2021) claim that large classes harm students' attitudes and academic understanding. They reduce teacher-student interaction, motivation, learning achievement, and student commitment (Ayanwoye, 2023). Wang and Calvano (2022) discovered that large courses inhibit interaction and diminish student happiness. Teachers also prefer smaller classes over larger ones. In larger classes, assessments are more challenging (Yelkpiieri et al., 2012). In contrast, smaller classes encourage student participation. These conflicting findings suggest that meta-analysis research should examine students' high-order thinking skills in an open-ended manner. According to Ellis (2010), this method is better for evaluating study results' generality, a key comparative step. The study benefits education policymakers and practitioners (Regional Educational Laboratory West, 2021).

Meta-analysis is a methodical process of reviewing research studies that examine specific effects. It involves combining the results of independent studies to estimate the overall impact on a population (Ellis, 2010). Consequently, it generates comprehensive knowledge by minimizing the distorting effects of primary studies (Juandi & Tamur, 2020). The research methodology employed for quantitative meta-analysis is meta-aggregation and synthesis. This approach enables the summarization of prior research results to address research inquiries (Lewin, 2008). The results of this meta-

analysis provide confirmation of the contribution of the open-ended approach in improving high-level thinking skills in mathematics lessons, so that practitioners, especially teachers, have confidence in implementing it. At what level of education is this open-ended approach appropriate to be applied in mathematics learning?

Methodology

This study examines how open-ended learning affects students' reasoning, problem-solving, communication, connection, creativity, and critical thinking. The control group and pre- and post-test experiments produced secondary data. Theses, dissertations, and national and international journals also publish research findings. We heavily advise and test theses and dissertations. We also provide guidance on potential scientific publications. Journal managers rigorously scrutinize publications. This data source meets scientific technique standards. Data came from Google Search, Google Scholar, ERIC, Garuda, Find Free PDFs of Scientific Articles, EBSCO, and ResearchGate. Researchers set exclusion criteria to find a primary study with experimental research methods (such as pre-post tests and a control group), middle-to high-school students, and the full text available. Studies must be published between 2000 and 2022. The scientist stated that the primary study employs experimental research with a control group design to investigate inclusion and exclusion. Before and after the study, researchers measure average, standard deviation, and non-multivariate analysis. The inclusion-exclusion procedure involves researchers. The second researcher corroborated the first researcher's inclusion-exclusion method after reviewing search results. The third researcher used the second researcher's validation results to run a comprehensive meta-analysis (CMA) on the manuscript.

The process of identifying the papers analyzed in this research using Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Juandi & Tamur, 2020) involves the following steps. Figure 2's inclusion-exclusion approach yielded 36 research findings, including paper data that met criteria. The research findings were divided into four categories: elementary (1–6), middle (7–9), high (10–12), and postsecondary. Influence size depends on elementary, middle, high, and university education. Class size criteria: 30. Small sample sizes are less than 30, and large ones are over 30. It meets the central limit hypothesis (Alwi, 2012). The class size criteria are divided into two groups:

$n < 30$ (small sample) and $n > 30$ (big sample). Following NCTM (2000) standards, educational mathematics encompasses numbers and operations, algebra, geometry, measurement, probability, and statistics. This study also studied the open-ended approach's impact on students' high-order mathematical thinking, scored holistically and categorized by educational level (4 groups), class size (2 groups), and mathematics subject (5 groups).

All data analysis was carried out using the Comprehensive Meta-Analysis (CMA) application, as it is widely recognized and frequently employed for conducting meta-analysis computations. According to Schmidt and Hunter (as cited in Juandi & Tamur, 2020), the effect size is classified descriptively. For values between -0.15 and 0.14, there is no significant effect size. For values between 0.15 and 0.39, the classification is Slightly Significant. For values between 0.40 and 0.74, the classification is moderate. The range between 0.75 to 1.09 is considered significant. The value between 1.10 and 1.44 is classified as very significant. While greater than 1.45 is excellent.

-0.15–0.14	: Not Significant
0.15–0.39	: Slightly Significant
0.40–0.74	: Moderately Significant
0.75–1.09	: Significant
1.10–1.44	: Very Significant
> 1.45	: Excellent

After statistical effect size testing, we used inference analysis to assess the study's overall effect size value. During the study, this analysis examined education levels, class sizes, and mathematical materials. Hypothesis testing always uses .05. In this study, we reject the hypothesis if the p -value falls below .05.

Results and Discussion

Based on the researchers' analysis, 36 articles have been identified that fulfill the specified criteria. Before conducting further research, all eligible papers were tested for publication bias using funnel plots and trim and fill tests. Figure 3 below displays the results of the funnel plot test for the effect size.

Figure 3 shows that while most effect sizes are around the funnel's top, several fall outside the interval estimator's range. Thus, a publication bias test with Trim and Fill is required to meet publication bias assumptions. We used Trim and Fill to calculate the results of the publication bias test on 36 papers over 5 iterations. After analysis, 30 studies met publication bias criteria. Table 1 contains this information about trim and fill publication

bias test.

The table above illustrates that the number of publications that are necessary to be discarded on the left and right sides is 0 (zero). This indicates that 30 publications have been found to meet the analysis requirement. The aforementioned computation was reinforced by applying Rosenthal's Fail-Safe N test to thirty publications to assess the publications' resistance to publication bias. The results of the publication bias test calculations can be seen in Figure 4 below.

From Figure 4, an N value of 2049 is obtained, which shows that it is necessary to publish as many as 2,049 so that the probability value of the rejection of the hypothesis is zero more than 0.000. As is also known, according to Rosenthal (1979), a meta-analysis study

does not have publication bias if the Fail-Safe result N is more than $5k + 10$ or can be written as, where $N/(5k+10) > 1$, k is representative of a number of studies. Based on the formula, with $N = 2049$ and $k = 30$ obtained.

$$\frac{N}{(5K + 10)} = \frac{2094}{(5(30) + 10)} = \frac{2094}{160} = 13,0875 > 1$$

From the results of the calculation above, it can be concluded that there is no publication bias. All tests have been conducted and all of them show results that there is no publication bias in this meta-analysis study. Thus, no research is missing or needs to be added to the analysis due to publication bias.

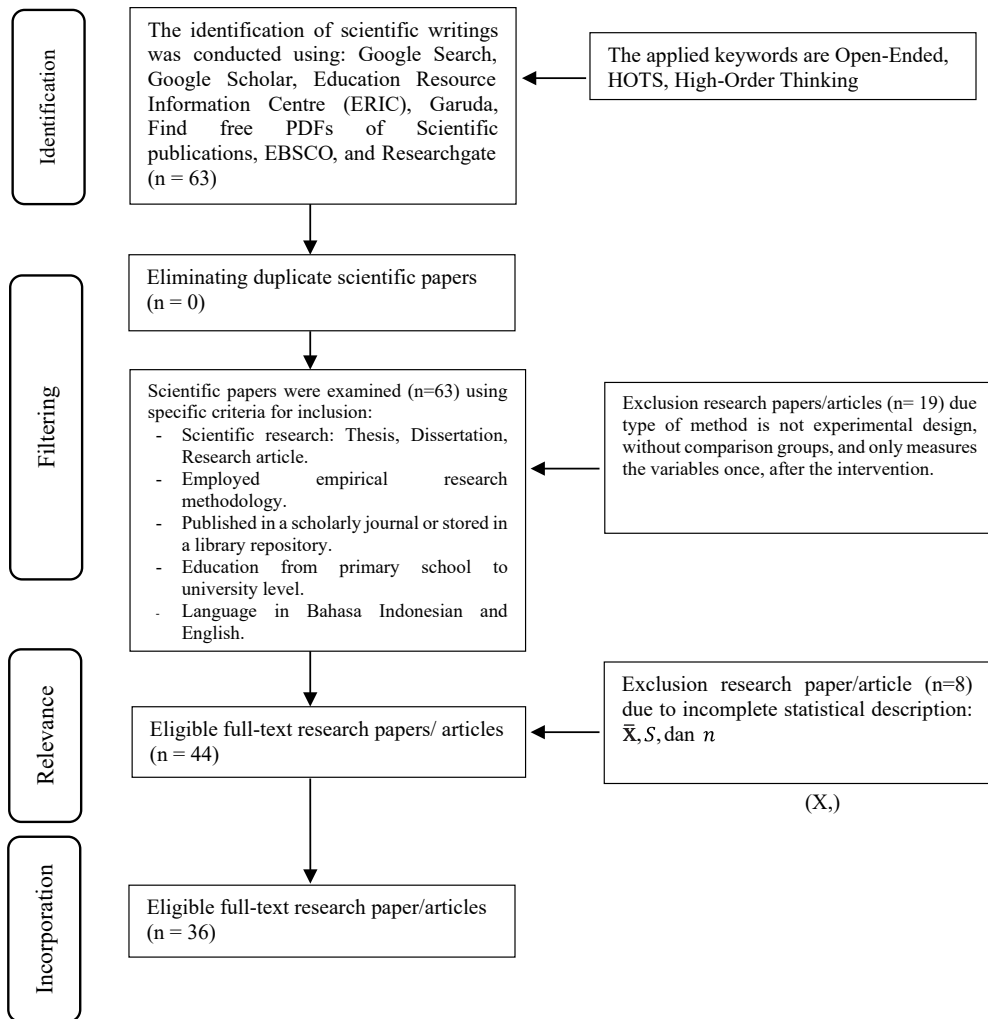


Figure 2 Sequential phases in Prisma's Publication selection process

Descriptive statistics from 30 eligible scientific publications were used for the first statistical analysis. Figure 4 displays the findings from descriptive calculations of the effect size. Based on this figure, the open-ended approach’s average effect size on students’ high-order mathematical thinking skills is 0.680, falling within the moderately significant criteria Schmidt and Hunter (as cited in Juandi & Tamur, 2020). The value of 1.644 was the greatest effect size and 0.110 was the smallest. Aside from that, three or four studies have an effect size with a p value less than .05. This indicates that the open-ended approach from the three studies does not significantly contribute to high-order thinking skills.

Figure 5 presents the average and individual effect size of each publication included in this study. As shown in Figure 5, the effect sizes vary considerably across the 30 studies, with most clustering around the mean

of 0.680. A small number of studies fall below the significance threshold, suggesting inconsistency in the contribution of the open-ended approach across different research contexts.

Publication heterogeneity testing was conducted first to verify the inference drawn from the effect size found above. This test is required to identify the model—the random effect model or the fixed effect model—that is applied in the analysis. Table 2 presents the results of the heterogeneity test from the 30 publications analyzed, including the Q statistic value, degrees of freedom (df), and p value used to determine the appropriate estimation model.

As shown in Table 2, the Q -value of 73.151 and a p -value of .000 both reject the null hypothesis. The p -value for .000 is less than 0.05 when $\alpha = .05$ is used. This indicates that each study possessed a distinct

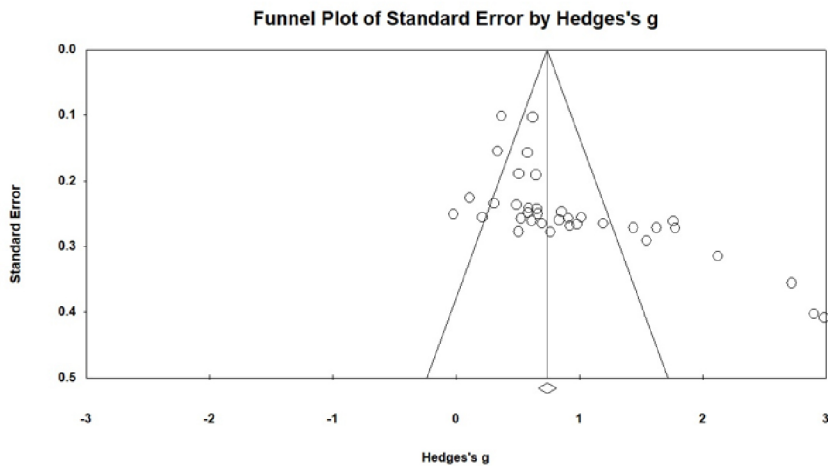


Figure 3 The distribution of effect sizes based on the funnel plot

Classic fail-safe N

Z-value for observed studies	16.48875
P-value for observed studies	0.00000
Alpha	0.05000
Tails	2.00000
Z for alpha	1.95996
Number of observed studies	30.00000
Number of missing studies that would bring p-value to > alpha	2094.00000

Edit

Figure 4 Calculation’s result of fail-safe N

	Studies Trimmed		Random Effects			Q value
	Left	Right	Point Estimate	Lower Limit	Upper Limit	
Observed values			0.65992	0.58695	0.73290	108.72758
Adjusted values	0	0	0.73283	0.66311	0.80255	153.70805

Model	Other heterogeneity statistics				
	Number Studies	Q-value	df (Q)	p-value	I-Squared
Fixed	30	73.151	29	.00	60.356
Random	30				



impact size that shaped its overall influence. Due to effect size variability, a random effects model was used for estimated model analysis. This estimation approach estimates equivalent but not identical population effect sizes. Typically, the distribution of population impact size revolves around the mean and standard deviation. This study's first analysis examines the open-ended study's overall effect size on students' high-order mathematical thinking.

Table 3 The significance test of effect size of open-ended approach

Model	<i>N</i>	z-value	<i>p</i> -value	Effect size and 95% Confidence Interval				
				Hedge's <i>g</i>	SE	Variant	Lower	Upper
Random	30	10.565	.000	0.673	0.064	0.004	0.554	0.806

Based on the parameters of educational level, sample size, and research materials, the effect size of the open-ended approach on students' high-level mathematical thinking was determined in the subsequent analysis. The goal of this analysis is to highlight how the open-ended approach helps to advance higher-order thinking. Table 4 below shows the outcomes of processing the effect size data for each category.

Each educational level's effect size has a significance value below .01. Additionally, the comparison of impact sizes across levels indicates a significant level of .387. This suggests that the open-ended method has a similar impact on high-order thinking skills at elementary, junior high, high school, and university levels. All educational levels can use the open-ended approach to foster high-order mathematical thinking, according to these findings. The open-ended approach to high-order thinking skills demonstrated a significant effect size (p -value = .000) for both small and big sample sizes, according to sample size effect size analysis. However, comparing their impact sizes shows a significant difference (p -value = .037). Thus, while the open-ended approach's effect size matters in both large and small classes, the two have different consequences. We must address class size because the open-ended approach is optimal for developing high-order mathematical thinking skills.

Algebra, geometry, numbers, and unrecorded groups were the experiment's materials criterion. The descriptive analysis reveals that researchers most often choose algebra and geometry groups for investigation. The researcher usually has this option, or the study depends

Table 4 The effect size of study's characteristics

Study's Characteristics	Category	N	Hedge's	Test of null (2-Tail)		Heterogeneity		
				z-value	p-value	Qb	Df(Q)	p-value
Education Level	Elementary	2	0.590	3.230	.001	3.029	3	.387
	Middle	21	0.666	14.107	.000			
	High	4	0.847	6.160	.000			
	University	3	0.659	3.988	.000			
Sample Size	30 or less than	10	0.780	9.143	.000	4.333	1	.037
	31 or more	20	0.628	13.525	.000			
Materials	Algebra	11	0.600	11.357	.000	14.059	3	.003
	Geometry	11	0.542	6.946	.000			
	Number	1	0.982	3.686	.000			
	Unknown	7	0.934	9.243	.000			

on learning materials. All four research groups' impact sizes are extremely significant, as shown by their 0.000 *p*-values. When we compare the effect size results between materials, we find a significant difference (*p*-value = .003). These findings suggest that while all subjects can be taught open-endedly to develop high-order mathematical thinking skills, students must pay close attention to the mathematical content to benefit.

This meta-analysis' high effect size suggests that an integrated, open-ended approach encourages students to freely think about problem-solving techniques, generate multiple solutions, and evaluate their validity to improve their high-order thinking skills. Students can use HOTs in conjunction with learning strategies to enhance their creativity and achieve success (Heong et al., 2019). Students can also solve real-world problems using their unique high-order thinking talents (Payadnya, 2019; Widiartana, 2018). Open-ended problems often have numerous correct answers that lead to the same result and raise unsolved questions. Brookhart (2010) lists these high-order cognitive talents for problem-solving. Thus, learning objectives must help students identify and resolve academic and personal challenges (Brookhart, 2010). The cognitive tension in the open-ended approach to high-order mathematical thinking skills makes effect size important. Cognitive conflict during learning improves math performance (Marhami et al., 2022). We use HOTs during learning and evaluation. Unfortunately, teachers often teach and test low-order thinking skills instead of high-order (Bjorklund, 2008).

These two types of data show that open-ended mathematics instruction is effective at all levels of education, including elementary, junior high, high school, and university levels, in developing high-order mathematical thinking skills. Mental growth does not restrict thinking talents (Rajendran, 2008). High-order

thinking skills in every learning process can assist students in becoming more conscious of their thoughts and improve learning and cognitive progress (Saido et al., 2015). Thus, education should emphasize high-order skills (Kurniawati, 2019). It should be incorporated into the mathematics curriculum to help students think critically (Butkowski et al., 1994) and in education policies and developments to encourage academics to study higher-order thinking skills. The results of the study on class size in open-ended learning support the findings of multiple prior studies (Grace & Oluwatoyin, 2016), which suggest that reducing large class sizes in secondary schools is the best way to mitigate the negative effects (Olurotimi & Nike, 2021). Thus, the government needs to assign more instructors, construct more educational institutions with equivalent facilities, and admit students according to the size of the rooms and other resources (Ayanwoye, 2023).

The mathematics resources have a significant impact on students' high-level mathematical reasoning. Open-ended approaches in any field can enhance high-order mathematical reasoning. Scientific methods and problem-solving assist students in the development of high-level reasoning abilities in the field of science. It can assist them in the formation of scientific knowledge, norms, hypotheses, and theories. Rajendran (2010) asserts that open-ended mathematics can facilitate students' abstracting, applying, synthesizing, validating, and making patterns. It is said that looking at context can help with analytical and evaluative thinking (Malalina et al., 2024), math content, and how Geogebra is used (Wijaya, 2017). Problems with reflective thinking in real numbers can be solved with the help of methodical and analytical assignments (Zachariades, et al., 2013).

Context and open-ended math tasks help students improve high-order thinking skills when learning varied

content (Malalina et al., 2024). Environmental context helps students build connections between formal and factual information, especially when teaching fractions (Malalina et al., 2017) and number patterns (Susanta et al., 2023). Therefore, learning must include open-ended contextual tasks (Malalina et al., 2024). More crucially, the curriculum paper must identify the subject matter's suitable thinking levels, teaching and learning activities, and assessments that should give the intended results. Rajendran (2010) asserts that the curriculum incorporates higher-order thinking, proving that thinking extends beyond high-order mental growth. Conversely, many homes and school learning activities entail thinking. This means schools should emphasize this cognitive process.

Open-ended math learning greatly impacts students' higher-level thinking. The effect size is moderate, at 0.680 (Juandi & Tamur, 2020). Several open-ended studies with small or negative effect sizes affect the effect size value: J044 (-0.0245) looks at the critical thinking of junior high school students, J027 (0.11) looks at their logical thinking, J034 (0.217) looks at their problem-solving, J036 (0.312) looks at their reasoning, and J012 (0.370) looks at how smooth they are. The open-ended approach may not have made much of a difference because teachers aren't well prepared (Beyaztaş & Senemoğlu, 2015; Irawan & Surya, 2017), students do not like math homework (Becker & Shimada, 1997), and they do not really care about answering unusual questions (Kurniawan et al., 2023) among other things. Study habits, gender, and playmates can affect pupils' ability (Jiyed et al., 2022; Owusu & Cobbold, 2020). Thus, when teachers use an open-ended approach to studying mathematics, they must grasp its properties to create learning materials. Teachers can also consider non-cognitive factors such as learning preparedness, motivation, and contextual factors at home and among peers (Lüdeke & Zúñiga, 2017).

Conclusions and Recommendation

Open-ended strategies typically improve students' higher-order mathematical reasoning, according to one study. Testing results are consistent across educational levels, class sizes, and math resources. The analysis shows a large influence (0.680). The open-ended strategy considerably affects students' mathematical reasoning, according to the study's educational level groups. All degrees of open-ended mathematics training improve students' higher-order mathematical reasoning. Comparing large and small class sizes showed that open-

ended approaches promoted higher-order thinking in both cases. We found no significant differences between class sizes. School math curriculum includes algebra, geometry, and numerical operations. Another group missed cataloging experimental supplies. Our top algebra and geometry resources came from four groups. The four open-ended approach experiment materials have a large effect size, according to impact size analysis. Open-ended lessons boost higher-order thinking. The research recommendations confirm that the open-ended approach works for teaching mathematics in elementary, junior high, high school, and university. Open-ended assignments help teach and assess comprehension. The open-ended approach works in primary, secondary, and higher education. Instructional tools must include lesson plans, activities with complete solutions, and explicit criteria for various student responses.

Conflict of Interest

The authors declare no conflict of interest.

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