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Examining the Effect of Problem-Based Learning Approach on Learners` Mathematical Creativity: A Meta-Analysis

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Abstract

Problem-based learning (PBL) is linked to developing learners` creative thinking in mathematics. This process-oriented approach capitalizes on using problems to stimulate learning through independent and collaborative investigations. This meta-analysis looked at the effectiveness of using PBL to influence mathematical creativity. Fifteen results from 13 studies were analyzed in which a medium effect (g=0.580) was computed using the random effects model. Further, the analysis of heterogeneity statistics suggests conducting a subgroup analysis in which only the strategy used in the comparison group and educational level, among the identified characteristics, moderates the effect of PBL on mathematical creativity. Future research should expand geographically to encompass a more diverse educational landscape and include a broader demographic to validate the efficacy of PBL across different age groups and cultural contexts.

Introduction

The dawn of a new age requires skills that capacitate people to thrive. This set of skills is summarized as 21st-century skills, specifically life skills, emphasizing critical thinking, creativity, collaboration, and communication. As one of its major concerns, creativity is taking new ideas and generating appropriate and high-quality products (Wright, 2010). It lies at the center of growth and innovation in many human endeavors. Thus, it warrants an increasing interest in policymakers worldwide that shifted creativity as a topic from the periphery to the core of debate (Newton & Newton, 2014). Creativity is part of mathematics education and necessary for performing mathematical assignments (Ayllón et al. 2016). Mathematical Creativity (MC) is a domain-specific subset of creativity that has amassed an increasing interest and activity in recent years (Akgul & Kaveci, 2016). In 1970, Laylock described mathematical creativity as the ability to analyze a given problem from multiple perspectives, identify patterns, differences, and similarities, produce multiple ideas, and choose an appropriate method to deal with unfamiliar mathematical situations. Mathematical creative thinking is essential for academic achievement and later workplace success (Sari et al., 2023). The application of creative math instruction in the mathematics classroom positively affects math achievement among students. A creative mathematics lesson stimulates students' thought processes, encourages them to discover new information, and increases academic achievement. Furthermore, teaching mathematics creatively fosters students' positive attitudes toward mathematics (Tok, 2015). The effect of cultivating mathematical creativity among students shows readiness to take up new tasks, initiate new ideas related to classroom work and mathematical projects, and adapt quickly to changes in procedures

(Hamid & Kamarudin, 2020).

Students can improve their creative mathematical thinking by practicing math problems (Masitoh, 2019). Problems are often used as springboards prior to presentations of mathematical concepts of the discourse. Creativity or creative ability is associated with equitable thinking, suggesting that teaching creativity in schools (by incorporating creative skills, strategies, and problem-solving into curricula) may increase equitable thinking on a larger scale (Luria et al., 2017). It is one of the motivations for the Problem-based learning (PBL) approach. PBL is a learning approach that requires learners to study the subject matter while solving problems to facilitate learning (Hmelo-Silver, 2004).). A student-centered paradigm cultivates activeness and learning motivation, problem-solving abilities, and breadth of knowledge as the foundation for in-depth comprehension and problem-solving (Ali, 2019). It consists of five major steps: student preparation, problem orientation, investigation, presentation, and evaluation. Over the years, there has been an increase in the implementation of PBL in education since it has considerably affected students' creative mathematical thinking (Juandi & Tamur, 2021). This educational approach emphasizes real-world problems, encouraging students to explore and solve them collaboratively. As a result, students develop deeper understanding and critical thinking skills, enhancing their ability to think creatively in mathematical contexts. The shift towards PBL reflects a broader recognition of the need to prepare students for complex problem-solving in this dynamic world (Li, 2022).

To establish the effectiveness of the problem-based learning approach on learners` mathematical creativity, a meta-analysis was conducted to answer the following questions:

1. What is the overall effect size of using PBL on learners` mathematical creativity?
2. Is there a significant difference between the effect sizes of the studies according to the;
    a. period the study was conducted,
    b. the strategy used in the comparison group,
    c. level of education and
    d. sample size?

Method

Research Design

This study made use of meta-analysis as its research design. Meta-analysis is a process used to systematically synthesize or combine the data of single, independent studies, applying statistical techniques to calculate an overall or "absolute" effect (Amlung, 2023). It does not simply pool data from smaller studies to achieve a larger sample size. It uses well-recognized, systematic procedures to account for discrepancies in sample size, study design, and outcomes (treatment effects). Furthermore, it assesses the sensitivity of their conclusions to their systematic review protocol (i.e., study selection and statistical analysis).

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Framework was employed to identify and select studies in this meta-analysis. This framework ensures a thorough and transparent process by providing a structured approach to the literature review (Anghelescu, 2023). It includes guidelines for searching, screening, and reporting studies, which helps minimize bias and enhance the reliability of the findings.

Search Protocol

The studies in this report were found using Harzing's Publish or Perish version 8 software and the AnimoSearch library of De La Salle University. The researcher runs a series of searches from online databases Crossref, Google Scholar, OpenAlex, Scopus, Semantic Scholar, and PubMed. Further, additional articles using the Google search engine were considered. The following keywords were used in searching for the articles; "Problem-based learning," "PBL," "Mathematical Creativity," and "Creative Thinking in Mathematics."

Inclusion and Exclusion Criteria

A meta-analysis of published studies was conducted to examine the effect of the problem-based learning approach on students' mathematical creativity. The titles, abstracts, and contents of the included studies were evaluated based on the five criteria listed below.

1. The study must explicitly use a problem-based learning approach as its treatment in a mathematics class.
2. The study measured learners' mathematical creativity or creative thinking in mathematics.
3. The study employed either quasi-experimental or experimental research designs.
4. The study supplied the statistical data necessary to calculate the effect size (e.g., sample size, mean, standard deviation, t-test value, mean difference)
5. The paper must be written in English and featured in a peer-reviewed journal or conference proceedings between January 2017 and June 2023.

Studies that did not meet the following criteria were excluded from the analysis. The researcher alone inspected the results from the different databases along the set parameters.

Identification and Selection of Studies for Inclusion

The initial stage of identifying and choosing the studies for inclusion in the meta-analysis involves searching in Crossref, Google Scholar, OpenAlex, Scopus, Semantic Scholar, and PubMed databases using the previously indicated key phrases. Other online materials were also reviewed upon search using the AnimoSearch. A total of 2047 studies were collected and screened against the inclusion criteria using titles, keywords, and abstracts. The remaining 2041 studies were included after inspection for duplication. This screening process was performed by visual inspection after the database searches were compiled in a single sheet of MS Excel. A total of 64 studies remained after the screening process. At the same time, 189 were excluded for having no English translation, 1759 were excluded due to the inappropriateness of key terms in the title, and 29 were excluded after a careful review of the abstracts. The remaining 64 studies entered the second phase of identifying and selecting the studies, which entailed a full paper review. Out of the 64 papers, only 24 passed the screening for eligibility. After reviewing the full-text articles, 11 studies were removed from the meta-analysis due to a lack of quantitative data that will be used in the subsequent analysis. Aside from that, the studies have insufficient statistical information, and those with no comparison group were likewise discarded. After the two phases of reviews, only 13 studies remained to move forward in the meta-analysis. It is, however, essential to point out that 2 of these 13 studies used three groups in their analyses; thus, the researcher opted to use those two studies twice in the analysis. The first comparison was between problem-based learning and the positive intervention used in the comparison group, while the second comparison was with problem-based learning and the conventional approach. For this reason, the succeeding analyses would have 15 individual results, which were extracted only from the 13 papers. Figure 1 shows the identification and selection of studies in this meta-analysis.

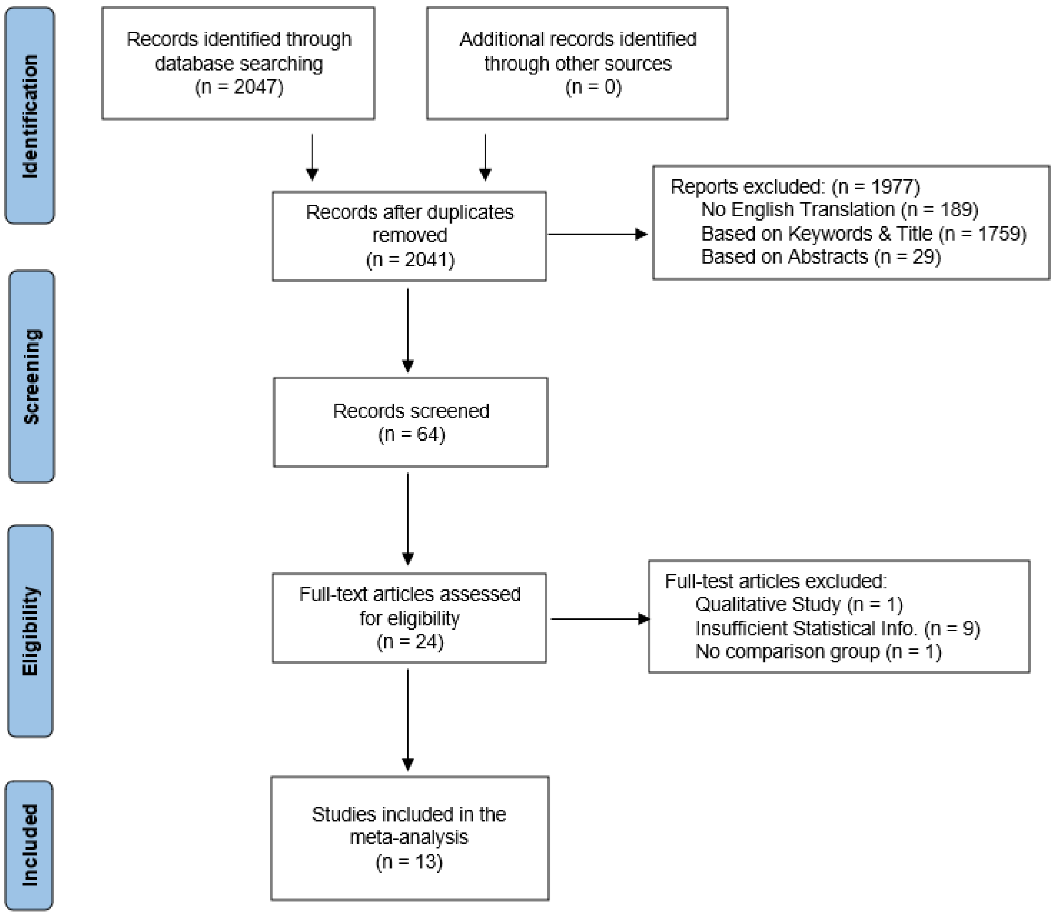

Figure 1. Flow Diagram for the Article Selection

Coding Procedures

The data collected from the screened journals were coded using the following: (a) study identification (author's last name and year of publication); (b) learners' grade level; (c) period the study was conducted; (d) study`s location; (e) approach used in the experimental/comparison group; (f) outcome measure characteristics which are sample sizes, means, and standard deviations.

Effect Size Calculation and Data Analysis

The analysis for this study was carried out using the Comprehensive Meta-Analysis (CMA) of Borenstein et al.

(2022). Effect size (Hedge's g) was used to compute the extent of the effectiveness of the PBL strategy employed. Hedges' g is the standardized mean difference equal to the difference between the mean values of experimental and comparison groups divided by the standard deviation. It is a more accurate version of Cohen's d, which corrects bias in small sample studies without affecting larger samples (Hedges & Olkin, 2014). The means, standard deviations, sample sizes, computed t-test value, and mean difference were used to compute the effect size. The random effects model was used after the initial analysis of the heterogeneity statistics. The computed Q-value was 153.093 with 14 degrees of freedom $p < 0.001$. These statistics implied that the true effect size differs in all the included studies. Thus, the studies in the analysis are assumed to be a random sample from a universe of potential studies.

Results

Descriptive Results

Out of the 2047 papers initially retrieved from the literature search, only thirteen studies, with fifteen identified results, met the set inclusion criteria for meta-analysis. In terms of education level, the majority of the studies were conducted in secondary institutions (60%), while the remaining 40% were at the tertiary level. Of the fifteen, 14 (93%) were conducted in Indonesia, while only 1 study (7%) was in Pakistan. The researcher decided to classify the studies according to the period they were conducted. The COVID-19 pandemic affected the humanities, and the education sector is no exception (Schleicher, 2020). Thus, it was decided to separate studies conducted before the pandemic and during the health crisis. Sixty percent (60%) of the recorded results were conducted before, and the remaining 40% during the pandemic. Regarding research design, 7% used the experimental set-up, while 93% used a quasi-experiment. Out of these 93% percent, four results explicitly reported that they had non-equivalent groups of participants.

In line with the strategies used in the experimental group, most studies (53%) used collaborative PBL. However, in these reviewed articles, the authors did not explicitly mention it in their reports, which is why the researcher deduced this strategy based on the information available. The remaining 47% was divided into seven studies employing cooperative learning, problem-solving, the Maastricht approach, open-ended worksheets, mathematical habits of the mind, the scientific approach, and SIDIA software-assisted instruction. Positive control has been practiced in educational research as an essential element of research ethics. Thus, this meta-analysis included reports that used positive interventions in their comparison groups. Six studies, each with 7%, used Think-Pair-Share cooperative learning, scientific approach without worksheets, cooperative learning jigsaw type, project-based learning STEM, aptitude treatment interaction, and problem-posing approach. The remaining 60% explicitly mentioned the use of the conventional approach to teaching.

The total number of learners from the studies included in this meta-analysis is $N = n_1 + n_2 = 1308$, where $n_1 = 665$ for the treatment group (i.e., all learners instructed through PBL) and $n_2 = 643$ for the comparison group. As the effect size computation is affected by the size of the groups, the researcher decided to categorize each study according to the number of participants in their respective groups. This action resulted in 53% of the studies having at least 30 participants in each group and the remaining 47% having fewer than 30 participants.

Overall Effect Size of PBL

Computations for the analysis were facilitated using Comprehensive Meta-Analysis Version 4 (Borenstein et al., 2022). The effect size index is the standardized difference in means (g), and the random-effects model was employed. The 15 reports in the analysis are assumed to be a random sample from a universe of potential studies, and this analysis will be used to make an inference to that universe (Borenstein, 2019; Borenstein et al., 2010; Borenstein et al., 2021; Hedges & Vevea, 1998). Table 1 presents the overall effect size and other relevant statistics.

Table 1. Overall Effect Size

	K	ES	SE	Variance	95% CI		Z	p	Heterogeneity				Between study		Prediction Interval	
					Lower	Upper			Q	df	P	i^2	τ	τ^2	Lower	Upper
Fixed	15	0.521	0.058	0.003	0.408	0.633	9.050	0.000	153.093	14	0.000	90.855	0.713	0.509	-1.019	2.178
Random	15	0.580	0.196	0.038	0.196	0.964	2.960	0.003								

The mean effect size is 0.580, with a 95% confidence interval of 0.196 to 0.964. The Z-value tests the null hypothesis that the mean effect size is zero. The Z-value is 2.960 with p = 0.003. Using a 0.050 criterion alpha, the null hypothesis was rejected. Thus, it was concluded that the mean effect size is not precisely zero in the universe of populations comparable to those in the analysis. The I-squared statistic is 90.855%, which tells us that some 90.855% of the variance in observed effects reflects variance in true effects rather than sampling error. The results warrant further investigation to determine sources of variability.

Tau-squared, the variance of true effect sizes, is 0.509 in g units. Tau, the standard deviation of true effect sizes, is 0.713 in g units. Suppose we assume the true effects are normally distributed (in g units). In that case, we can estimate that the prediction interval is -1.019 to 2.178.

Table 2 below presents each study's computed effect size. Five studies reported a large effect size [i.e., Risnawati et al., (2018), Noviyani et al., (2021)-B, Miliyawati & Herman, (2019), Hasanah et al., (2020), and Putra et al., (2021)]. It is important to note that all the effect sizes here were highly significant. The five studies here all used conventional learning in the comparison group. Concerning moderate effect size, four studies fall under this category. These were the studies of Masitoh (2019), Habeahan and Siagian (2021), Purba and Sinaga (2019), and Ahmad and Gunawan (2019). The second and third studies used positive interventions for the comparison group, while the first and last studies employed conventional learning. It is also imperative to report that all four reported significant effect sizes.

On the other hand, only the study of Amir et al. (2018) reported small effect sizes, while Masitoh & Prasetyawan (2019) and Astuti (2021)-B reported weak effect sizes. All these effect sizes were not significantly different with zero effect. Thus, the effect of the PBL approach on the treatment group was not significantly different from the effect of using other approaches in the comparison group. There were also studies reporting negative effect sizes. These are the studies of Noviyani et al. (2021)-A, Maskur et al. (2020), and Astuti (2021)-A. The first study reported a non-significant effect size, while the remaining two reported otherwise. The studies of Maskur et al. (2020) and Astuti (2021)-A reported significant effect sizes.

Table 2. Study`s Effect Sizes

Study Label	ES	SE	Variance	95% CI		Z	p
				Lower	*Upper*		
Habeahan & Siagian (2021)	0.741	0.273	0.074	0.206	1.275	2.716	0.007
Masitoh (2019)	0.909	0.286	0.082	0.348	1.469	3.178	0.001
Masitoh & Prasetyawan (2019)	0.193	0.225	0.051	-0.248	0.633	0.858	0.391
Amir et al. (2018)	0.377	0.257	0.066	-0.127	0.881	1.466	0.143
Purba & Sinaga (2019)	0.703	0.332	0.110	0.052	1.354	2.118	0.034
Ahmad & Gunawan (2019)	0.612	0.285	0.081	0.054	1.171	2.148	0.032
Risnawati et al. (2018)	1.106	0.144	0.021	0.824	1.389	7.681	0.000
Noviyani et al. (2021)-A	-0.231	0.294	0.086	-0.807	0.345	-0.785	0.433
Noviyani et al. (2021)-B	1.300	0.327	0.107	0.659	1.941	3.973	0.000
Miliyawati & Herman (2019)	1.291	0.181	0.033	0.936	1.646	7.125	0.000
Maskur et al. (2020)	-1.240	0.274	0.075	-1.778	-0.703	-4.520	0.000
Astuti (2021)-A	-0.299	0.149	0.022	-0.591	-0.008	-2.011	0.044
Astuti (2021)-B	0.178	0.156	0.024	-0.129	0.484	1.137	0.256
Hasanah et al. (2020)	1.340	0.283	0.080	0.786	1.894	4.739	0.000
Putra et al. (2021)	1.872	0.335	0.113	1.214	2.529	5.580	0.000
Pooled	0.580	0.196	0.038	0.196	0.964	2.960	0.003
Prediction Interval	0.580			-1.019	2.178		

Subgroup Analysis

The researcher grouped the studies according to the period they were conducted, the strategy used in the comparison group, educational level, and sample size. This grouping served as the characteristics identified for the subgroup analysis. Conducting subgroup analysis based on specific characteristics can provide valuable insights and enhance the validity of research findings. One approach was to group studies according to the period they were conducted, such as before and during COVID-19. It allowed the researcher to examine how external factors, such as the pandemic, influenced educational outcomes. The pandemic caused significant disruptions and adaptations in teaching methods, learning environments, and student experiences (Zhukov et al., 2023), which could differentially impact the results of studies conducted in these distinct periods.

Another important aspect is analyzing the strategy used in the comparison group. Comparing conventional strategy with all other strategies is essential for understanding the relative effectiveness of the former compared to the latter (Ganzon, 2023). This distinction helped isolate the impact of different pedagogical strategies and provided clearer insights into which methods might be more effective under various conditions.

Furthermore, considering the educational level, such as secondary versus tertiary education, acknowledges that students at different stages of their educational journey may respond differently to instructional strategies. Secondary and tertiary learners differ in cognitive development, learning needs, and educational goals, making it crucial to assess how educational interventions perform across these distinct levels (Olsen, 2017).

Lastly, subgroup analysis based on sample size, distinguishing between studies with fewer than 30 and those with at least 30 learners, addresses concerns about the reliability and generalizability of findings. Smaller sample sizes might lead to less stable and less generalizable results due to higher variability and potential biases (Nundy et al., 2022). By comparing studies with different sample sizes, the researcher evaluated the robustness of the findings and ensured that sample size limitations did not overly influence the conclusions drawn.

A common among study variance component across subgroups was combined using a random effects model to facilitate the statistical analysis. Tests for subgroup differences based on random-effect models may be preferable to those based on fixed-effect models due to the high risk of false-positive results when comparing subgroups in a fixed-effect model (Shahn, 2023). Table 3 summarizes the results of the subgroup analysis.

Table 3. Subgroup Analysis Results

Characteristic	Group	No. of Studies	Effect Size	Test of Null (2-tail)		Heterogeneity		
				Z	*p*	*Q*	*df*	*P*
Period	Pre-pandemic	9	0.599	2.166	0.030	0.018	1	0.894
	Pandemic	6	0.614	1.888	0.059			
Strategy Used in the Comparison Group	Conventional	9	0.977	4.990	0.000	10.663	1	0.001
	Others	6	-0.037	-0.153	0.879			
Level of Education	Secondary	9	0.919	4.510	0.000	6.971	1	0.008
	Tertiary	6	0.079	0.324	0.746			
Sample Size	Less than 30	7	0.836	2.830	0.005	1.354	1	0.244
	At least 30	8	0.374	1.409	0.159			

Firstly, the analysis of research characteristics in Table 3 shows that studies classified based on the period it was conducted were not significantly heterogeneous ($Q=0.018$, $P>0.05$). It implies that there was insufficient evidence to claim that studies conducted before the pandemic did not yield different effect sizes than those conducted during the health crisis. Nevertheless, pre-pandemic studies yielded a significant effect size ($g=0.599$, $p< 0.05$). The result suggests that using the PBL approach had a moderate effect size on learners' creative thinking. In contrast, studies conducted during the pandemic reported a moderate effect size that is not statistically significantly different from zero ($g=0.614$, $p>0.05$).

Concerning the second characteristic (i.e., the strategy used for the comparison group), the computed Q-value is 10.633 with a P-value of 0.001. These heterogeneity statistics suggest that the conventional approach, compared with other approaches reported in the reviewed studies, does matter. Studies where the PBL approach was compared to conventional learning showed different effect sizes compared to studies that used positive intervention in their comparison groups. Additionally, studies that used the conventional approach for the comparison group reported a combined significant effect size of g=0.977 (p<0.05). In contrast, the other subgroup reported an effect size of g=-0.037 (p>0.05), which is not statistically different from having no effect.

When the studies were classified based on educational level, two subgroups were identified –secondary and tertiary. The reported heterogeneity statistics for this characteristic suggest a significant difference in the effect sizes of each level (Q=6.971, P<0.05). There is enough evidence to support that the educational level is a moderating variable on the effect size of the PBL approach on learners` mathematical creativity. The nine studies for the secondary level resulted in a combined effect size of g=0.919. This effect size is moderate and significantly different from no effect (p<0.01). For the tertiary level, a weak effect size was observed at g=0.079, which is not statistically significant from zero.

For categorizing the studies based on the number of participants in each group of the experiments, the heterogeneity statistics are Q=1.354 and P=0.244. These statistics suggest that insufficient evidence supports the claim that the effect size for studies with small and sufficiently large sample sizes differs. However, it is noteworthy that studies with sample sizes less than 30 reported a moderate effect size (g=0.836), which is statistically significant at p<0.05. In contrast, studies involving sample sizes of at least 30 participants yield a non-significant small effect size (g=0.374, p>0.05.)

Publication Bias

Publication bias arises when the analysis is systematically unrepresentative of completed studies. Meta-analysis has been touted as providing a more accurate assessment of research literature than traditional narrative reviews; however, if the sample of studies retrieved for review is biased, the validity of the results of a meta-analytic review is threatened, regardless of how systematic and exhaustive it is in other respect (Egger et al., 2022). Figure 2 below presents the Funnel Plot of the standard error of hedge`s g.

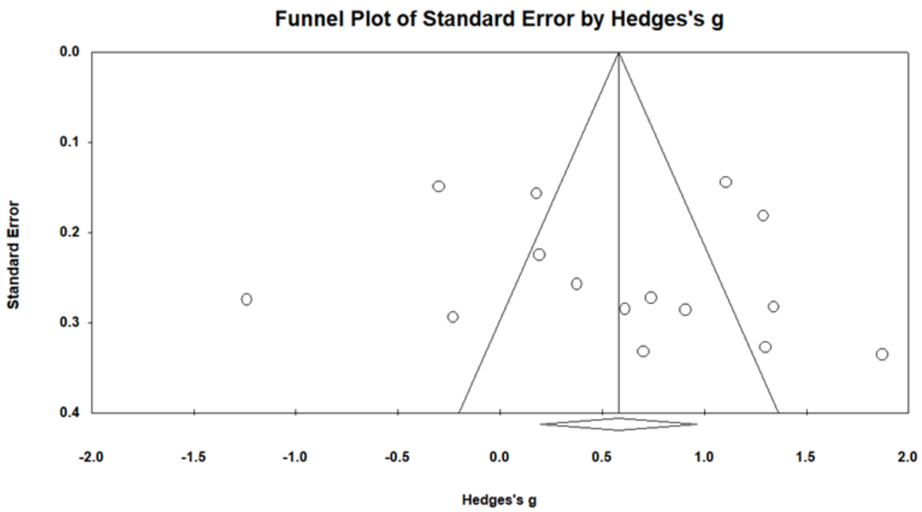

Figure 2. Funnel Plot

The funnel plot shows that the distribution of the effect sizes is asymmetrical with respect to the perpendicular line associated with the mean effect. Rank correlation and regression tests were applied to check for publication bias. In this case, Kendall's tau b (corrected for ties, if any) is 0.152, with a 1-tailed p-value (recommended) of 0.214 or a 2-tailed p-value of 0.429 (based on continuity-corrected normal approximation). The non-significance of the estimated correlation suggests that bias was not detected. However, this does not directly address the implications of the bias. A non-significant correlation may be attributable to low statistical power; thus, it cannot be interpreted as proof that bias is absent. Hence, Egger`s test of tests was used. This approach may have some advantages over the rank correlation method. In certain situations, this may be a more effective test. In addition, this approach can be expanded to include several predictor variables, allowing us to simultaneously evaluate the impact of multiple variables, including sample size, on the treatment effect. In this case, the intercept is 1.457, 95% confidence interval (-4.848, 7.763), with t=0.499, df=13. The 1-tailed p-value (recommended) is 0.313, and the 2-tailed p-value is 0.626, which are both greater than 0.05, thus suggesting that bias was absent.

This meta-analysis incorporates data from 15 studies with the computed Classic fail-safe N of 449. This implies that it would need to locate and include 449 'null' studies for the combined 2-tailed p-value to exceed 0.10. Further, the Orwin fail-safe N is 776, suggesting that we must locate 766 studies with mean hedges' g of 0 to bring the combined hedges' g under 0.01.

Discussion

Problem-based learning (PBL) is a pedagogical approach where students learn by actively engaging in real-world and personally meaningful tasks. It has gained recognition and has been an attractive option for promoting creative thinking in mathematics (Rézio et al., 2022; Hidayah & Dwijanto, 2023). PBL emphasizes the process of learning acquisition, making it an effective strategy for developing students' mathematical creative thinking abilities (Masitoh, 2019).

A meta-analysis was conducted to evaluate the overall effect size of PBL on creative thinking in mathematics. This systematic review synthesized 15 studies and found an overall effect size of 0.580, suggesting that PBL has a moderate positive impact on learners' mathematical creativity. According to Cohen et al. (2002), an effect size of this magnitude indicates a meaningful and moderate influence on educational outcomes. This result is consistent with the findings of Yunita et al. (2020), who synthesized results from 19 studies in Indonesia, concluding that PBL significantly enhances students' mathematical creative thinking.

Several factors contribute to the effectiveness of PBL in fostering creative thinking. Firstly, PBL uses problems as the starting point for learning, encouraging students to engage in problem-solving activities that require creative and critical thinking (Sartika et al., 2023). This method compels students to delve deeply into problems, explore multiple solutions, and apply their mathematical knowledge in novel ways (Hmelo-Silver & Eberbach, 2011). Such engagement is crucial for developing creative thinking skills, as it promotes flexibility, originality, and the ability to see connections between different concepts (Jonassen, 2011). PBL also supports a learner-centered environment where students take ownership of their learning process (Nurlaelah, 2023). This autonomy and responsibility in learning can lead to higher motivation and engagement, further enhancing creative thinking (Savery, 2015). Research by Barrows (1996) highlights that the iterative process of hypothesizing, testing, and refining solutions in PBL helps students develop robust problem-solving skills, which are directly linked to creative thinking. In addition, the collaborative nature of PBL allows students to work in groups, facilitating the exchange of diverse ideas and perspectives. This collaboration is instrumental in nurturing creativity, as it exposes students to different viewpoints and encourages the synthesis of new ideas (Susetyarini et al., 2022). Collaboration in PBL not only enhances creative thinking but also builds critical social and communication skills essential for holistic educational development (Sajidan et al., 2022).

The findings from this meta-analysis acknowledge the value of PBL in enhancing mathematical creativity. PBL cultivates essential cognitive skills crucial for academic and real-world success by engaging students in meaningful problem-solving activities. These results underscore the importance of incorporating PBL into the mathematics curriculum to foster a more creative and innovative learning environment.

The heterogeneity analysis, indicated by an I-squared statistic of 90.86%, reveals substantial variability among the included studies, necessitating a subgroup analysis to identify potential sources of this heterogeneity (Borenstein et al., 2009). The researcher identified four key variables for subgroup analysis: study period, strategy used in the comparison group, educational level, and sample sizes. Among these, the strategy used in the comparison group and educational level were significant sources of heterogeneity, with $Q = 10.663$, $p < 0.05$, and $Q = 6.971$, $p < 0.05$, respectively.

Studies comparing PBL with conventional learning strategies yielded a moderate and statistically significant effect size ($g = 0.977$, $p < 0.01$), underscoring the efficacy of PBL in enhancing mathematical creativity over conventional strategies. This finding aligns with research indicating that PBL fosters a more profound understanding and application of knowledge through active problem-solving and critical thinking (Hmelo-Silver & Eberbach, 2011; Savery, 2015; Biruni et al., 2023). Conversely, studies employing positive interventions in the comparison group reported a negative aggregate effect size, which was not statistically significant ($g = -0.037$, $p > 0.05$). It implies that the nature of the intervention in the comparison group significantly influences the effectiveness of PBL, with the conventional strategy being less conducive to fostering mathematical creativity than other innovative teaching strategies.

The educational level of participants also emerged as a significant factor. Studies involving secondary students reported a moderate combined effect size ($g = 0.919$, $p < 0.01$), indicating that PBL significantly enhances mathematical creativity at this educational level. This finding is consistent with previous research suggesting that secondary education is critical for developing creative thinking skills (Henriksen et al., 2017; Bracci, 2022). In contrast, studies with tertiary-level participants showed a weak and statistically non-significant effect size ($g = 0.079$, $p > 0.05$). This contradicts findings by Yunita et al. (2020), who reported no significant difference across educational levels. These contrasting results highlight the need for further investigation into how educational level moderates the effectiveness of PBL, suggesting that different pedagogical approaches may be needed for different educational stages.

In terms of the study period, the analysis revealed that it was not a significant source of heterogeneity. Both pre-pandemic and pandemic studies reported moderate effect sizes, with pre-pandemic studies showing a significant combined effect size ($g = 0.599$, $p < 0.05$) and pandemic studies showing a non-significant combined effect size ($g = 0.614$, $p > 0.05$). It suggests that the effectiveness of PBL in enhancing mathematical creativity was not significantly impacted by the disruptions caused by the COVID-19 pandemic. This finding contrasts with some reports that educational disruptions during the pandemic negatively affected learning outcomes (Feng et al., 2021). The consistency in the effectiveness of PBL before and during the pandemic underscores its robustness as an educational approach. On a similar note, the sample size did not significantly moderate the effect of PBL on mathematical creativity. However, studies with smaller sample sizes reported a significant moderate effect ($g = 0.836$, $p < 0.05$), while those with larger sample sizes reported a smaller, non-significant effect ($g = 0.374$, $p > 0.05$). This observation aligns with Yunita et al. (2020), who found no significant differences between different sample size groups. It suggests that while smaller studies might show more pronounced effects due to less variability and more controlled environments, the overall impact of PBL remains consistent across varying sample sizes.

In summary, the subgroup analyses reveal that the strategy used in the comparison group and educational level significantly influence the effectiveness of PBL in enhancing mathematical creativity. These findings underscore the importance of contextual factors in educational research and suggest areas for further investigation, particularly regarding the role of educational level and specific strategies used in comparison groups.

Conclusion

This paper reviewed studies linking the PBL approach with mathematical creativity. Using the PRISMA framework, 13 papers with 15 identified results were scrutinized for meta-analysis. The overall effect size reflects the moderate effect of the PBL approach on students' mathematical creativity. This result adds credibility to using PBL as a practical approach to improving creative thinking in mathematics. A subgroup analysis was also conducted, which showed that the strategy used in the comparison group affected the effect of PBL. Studies comparing PBL with the conventional approach report larger effect sizes than those using positive interventions in the comparison groups. Furthermore, it also showed that educational level relates to that effect and that high school learners benefit the most in the PBL.

Limitations

The fifteen results included in this meta-analysis are relatively small. However, the result can be considered valid upon analyzing the publication bias. The restrictions set for the selection criteria lead to difficulty in looking for empirical studies involving the effectiveness of PBL on mathematical creativity. The concentration of studies was from a single country, which may also affect the results. Lastly, other variables that might influence the effectiveness of PBL on mathematical creativity must also be studied. These may include the treatment duration of the implementation and some pertinent demographic information about the participants. These variables were not included in the analysis.

Recommendations

Considering the moderate effect of Problem-Based Learning (PBL) on enhancing mathematical creativity, as demonstrated by this meta-analysis, future research should expand geographically to encompass a more diverse educational landscape and include a broader demographic to validate the efficacy of PBL across different age groups and cultural contexts. Recognizing the limitations due to the narrow scope of variables and the concentration of studies within a single country, subsequent studies are urged to investigate the impact of variables such as the duration of PBL implementation and specific demographic characteristics of participants. A comparative analysis involving various instructional strategies could further elucidate PBL's unique contributions to mathematical creativity.

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