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Enhancing Creative Thinking in Physics Education: A Systematic Review and Meta-Analysis

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Abstract: *Creative thinking is a critical skill in physics education that enables students to develop effective problem-solving. This study aims to explore various interventions and their effects on enhancing creative thinking skills in physics education through a systematic review and meta-analysis. A keyword search across Scopus and ERIC identified 22 studies that met the criteria and were selected for analysis. The meta-analysis findings indicate that interventions implemented in physics learning significantly enhance creative thinking skills, with a very strong effect size. Among the types of interventions, instructional models demonstrated the largest effect size, highlighting their potential to foster creative thinking. Moderator analysis revealed significant variations across countries of study, sample size, intervention duration, and the physics topics involved. However, no significant differences were found for moderators such as publication type, education level, types of interventions applied, and instruments measuring creative thinking. These findings emphasise the importance of designing and adapting teaching strategies to enhance creative thinking skills in physics learning. This study contributes to strengthening the evidence for integrating creative thinking into physics education to meet the demands of the 21st century.*

Keywords: *creative thinking, instructional strategies, intervention effectiveness, meta-analysis, physics education, systematic review*

Meningkatkan Kemampuan Berpikir Kreatif dalam Pendidikan Fisika: Sebuah Tinjauan Sistematis dan Meta Analisis

Abstrak: Berpikir kreatif merupakan keterampilan krusial dalam pendidikan fisika yang memungkinkan peserta didik mengembangkan kemampuan pemecahan masalah secara efektif. Penelitian ini bertujuan untuk menelaah berbagai intervensi serta pengaruhnya terhadap peningkatan keterampilan berpikir kreatif dalam pendidikan fisika melalui tinjauan sistematis dan meta-analisis. Kata kunci pada basis data Scopus dan ERIC, diperoleh total 22 studi yang memenuhi kriteria untuk dianalisis. Temuan meta-analisis menunjukkan bahwa intervensi yang diterapkan dalam pembelajaran fisika secara signifikan meningkatkan keterampilan berpikir kreatif, dengan ukuran efek yang sangat kuat. Di antara jenis intervensi yang ditinjau, model pembelajaran memberikan ukuran efek tertinggi, menegaskan potensi model pengajaran inovatif dalam mendorong pengembangan berpikir kreatif. Analisis moderator mengungkapkan adanya variasi signifikan berdasarkan negara penelitian, ukuran sampel, durasi intervensi, serta topik fisika yang dipelajari. Namun, tidak ditemukan perbedaan signifikan pada moderator seperti jenis publikasi, jenjang pendidikan, jenis intervensi yang diterapkan, maupun instrumen pengukuran berpikir kreatif. Temuan ini menekankan pentingnya merancang dan menyesuaikan strategi pembelajaran untuk meningkatkan keterampilan berpikir kreatif dalam pembelajaran fisika. Studi ini berkontribusi dalam memperkuat bukti mengenai pentingnya integrasi strategi berpikir kreatif dalam pendidikan fisika untuk menjawab tuntutan pembelajaran abad ke-21.

Kata kunci: berpikir kreatif, efektivitas intervensi, meta-analisis, pendidikan fisika, strategi pembelajaran, tinjauan sistematis

INTRODUCTION

Education today must prepare students to tackle the increasingly complex challenges of the 21st century. It is essential for students to be equipped with 21st-century skills, often referred to as the 6Cs, which include critical thinking, creativity, collaboration, communication (Haryani et al., 2024; Vebriani et al., 2024), character building, and citizenship (Davies et al., 2017). Creative thinking is an essential 21st-century skill that educators should cultivate to address the growing complexity of contemporary challenges (Rizal et al., 2024a), and a critical ability that individuals of all ages need to develop (Nurjanah et al., 2024). Education that focuses on creative thinking skills is crucial for 21st-century individuals.

Creative thinking plays a crucial role in student success in physics education. Physics, as a complex subject (Pals et al., 2023), requires effective problem-solving abilities (Gok, 2010; Ince, 2018). The problem-solving process involves organising ways of thinking and actions to achieve specific goals, which is closely related to creativity (Ince, 2018). Creative thinking not only helps students solve physics problems but also improves their academic performance (Hai et al., 2023). The lack of exploration and development of students' creative thinking leads to difficulties in learning physics and low physics learning outcomes (Batlolona & Diantoro, 2023). Therefore, fostering creative thinking in the physics subject should be a primary focus in physics teaching strategies.

Creative thinking has diverse definitions and involves complex abilities. It includes generating innovative ideas, solving problems, and developing new methods to address specific challenges (Samaniego et al., 2024). Key abilities in creative thinking include originality, fluency, flexibility, and elaboration (Samaniego et al., 2024). Creativity refers to conditions that involve novelty and relevance (Heinze, 2013; Samaniego et al., 2024). In the context of creativity, it is important to understand whether it is an individual or group trait and whether it is a characteristic of a process or an outcome (Ritson, 2021). Creativity in the literature is considered an individual property (Ritson, 2021). Creative thinking is a complex ability that encompasses originality, fluency, flexibility, and elaboration, involving an innovative process that generates new and beneficial ideas, both individually and collectively.

Creative thinking is viewed as a developing process that can be nurtured through various experiences and challenges (Zaremohzzabieh et al., 2024). Creativity is not merely an innate trait, but a skill that can be honed through deliberate practice (Zaremohzzabieh et al., 2024). The view of creativity as a transferable ability has led to the development of educational strategies designed to cultivate creative thinking across various disciplines (Samaniego et al., 2024). Students need guidance to understand the importance of creative thinking as a vital life skill for navigating change and new challenges (Asrizal et al., 2024). Therefore, educators and researchers are responsible for developing tools that foster students' creativity in the future (Rahimi & Shute, 2021). Creative thinking, as a skill that can be developed, is essential for educators and researchers to develop approaches and tools that support its growth across various disciplines, including physics education.

Research on the development of creative thinking skills in physics is highly relevant, as evidenced by the literature. Thus, this study was conducted as a systematic review and meta-analysis to explore the initiatives undertaken by physics educators and researchers to enhance students' creative thinking abilities. By analysing previous empirical studies, this study aims to identify the most effective interventions for enhancing creative thinking skills in physics education. The findings of this study are expected to provide educators, researchers, and educational professionals with valuable insights into optimal strategies to support the development of creative thinking in physics students.

Literature reviews and meta-analyses on the development of creative thinking in physics education are still relatively limited. Most previous studies have focused on other fields, such as the characteristics of creative thinking in arts and design education(Samaniego et al., 2024), educational technology interventions (Zaremohzzabieh et al., 2024), and the impact of collaborative learning on metacognitive skills and creative thinking in biology education (Ramdani et al., 2022). In science, meta-analyses have been conducted to investigate the effectiveness of interventions on scientific creativity (Bi et al., 2020)). In physics, previous meta-analyses have examined the influence of project-based learning models on students' creative thinking abilities (Rohmatika et al., 2024). However, studies specifically comparing various instructional interventions and exploring the impact of moderator variables, such as publication type, education level, intervention type, and intervention duration, remain scarce.

Thus, this study aims to synthesise previous research to generalise the effectiveness of various instructional interventions in enhancing students' creative thinking abilities in physics. Using a meta-analysis approach, this research will identify the extent of interventions' impact, which interventions are most effective, and the role of moderator variables in influencing students' creative thinking skills. The results of this study are expected to provide a solid foundation for developing more effective physics teaching strategies that nurture students' creative thinking skills. By addressing the research gaps identified above, this study formulates the following Research Questions (RQs) to guide the meta-analysis.

RQ1 : What learning interventions can develop students' creative thinking in physics education?

RQ2 : Which learning interventions have the most significant impact on enhancing creative thinking skills in physics education?

RQ3 : How do moderator variables, such as publication type, country, sample size, educational level, and intervention duration, affect the effectiveness of interventions aimed at enhancing creative thinking in physics education?

METHOD

This study employs a systematic literature review and meta-analysis method. A systematic literature review is essential for identifying research priorities and understanding initial conceptual frameworks for future studies (Higgins et al., 2019). It refines and clarifies the information gathered (Ilma et al., 2023). The goal of meta-analysis is to synthesise quantitative information from multiple studies (Garzón & Acevedo, 2019). This meta-analysis estimates the Effect Size (ES) of various physics interventions on students' creative thinking abilities, using Cohen's d. The importance of conducting meta-analysis lies in its ability to resolve conflicting findings across studies (Zaremohzzabieh et al., 2024).

Search Strategy

The process of searching and reviewing articles took place in October and November 2024. The first step was identifying keywords for searching databases. The keywords used were "creative thinking" OR "creativity" AND "physics". The databases used for this study include Scopus, ERIC, and Google Scholar.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria guided the selection of articles for this study. The first inclusion criterion required that articles be published in online scholarly journals or as

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international conference papers, excluding books, book reviews, theses, and dissertations. The second inclusion criterion specified that articles should be published between January 2014 and November 2024. This study focuses on the novelty of research findings, so articles published before January 2014 were excluded, as were those published after November 2024, as they were still under editorial review at the time of article screening. The fourth inclusion criterion is that articles must be written in English; non-English articles are excluded. The fifth criterion is that the articles must examine the impact of interventions on enhancing creative thinking in physics education. Articles on unrelated topics were excluded. The sixth criterion is that the study must be empirical, including both experimental and control groups. Non-experimental studies or those with only one treatment group were excluded. The seventh criterion is that articles must provide the required quantitative data, including sample sizes, mean scores, and standard deviations for both the control and experimental groups. If studies do not report standard deviations but provide alternative data such as t-values, F-values, and p-values, they were still included. Articles lacking the necessary quantitative information were excluded. A summary of the inclusion and exclusion criteria is presented in Table 1.

Table 1. Inclusion and Exclusion Criteria

Inclusion Criteria (IN)	Exclusion Criteria (EX)
IN1: journal article and conference paper	EX1: book, book review, thesis, dissertation
IN2: publication range from January 2014 to November 2024	EX2: publications prior to January 2014 and after November 2024
IN3: open access	EX3: limited access
IN4: written in English	EX4: written in a language other than English
IN5: the topic studied concerns improving students' creative thinking abilities in physics education	EX5: topics unrelated to the development of students' creative thinking abilities in physics education
IN6: experimental empirical research with a control group	EX6: non-experimental research with only one group
IN7: providing data on the sample size, scores, and standard deviation or t, F, and p-values	EX7: not providing the required data

Article Selection Procedure

The procedure for identifying relevant articles in this study follows the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The steps include identification, screening, eligibility, and inclusion (Moher et al., 2009). By performing a keyword search in Scopus and ERIC, 1318 articles were initially identified.

After applying the first, second, third, and fourth exclusion criteria (see Table 1) and removing duplicates, 856 articles were excluded. A total of 462 articles were screened based on their titles, abstracts, and keywords, and 396 were excluded under the fifth and sixth exclusion criteria. Subsequently, 66 articles were reviewed in full, of which 47 were excluded under the seventh exclusion criterion. Ultimately, 19 articles were deemed eligible and included for analysis in this study. The flow of the article selection process is presented in Figure 1.

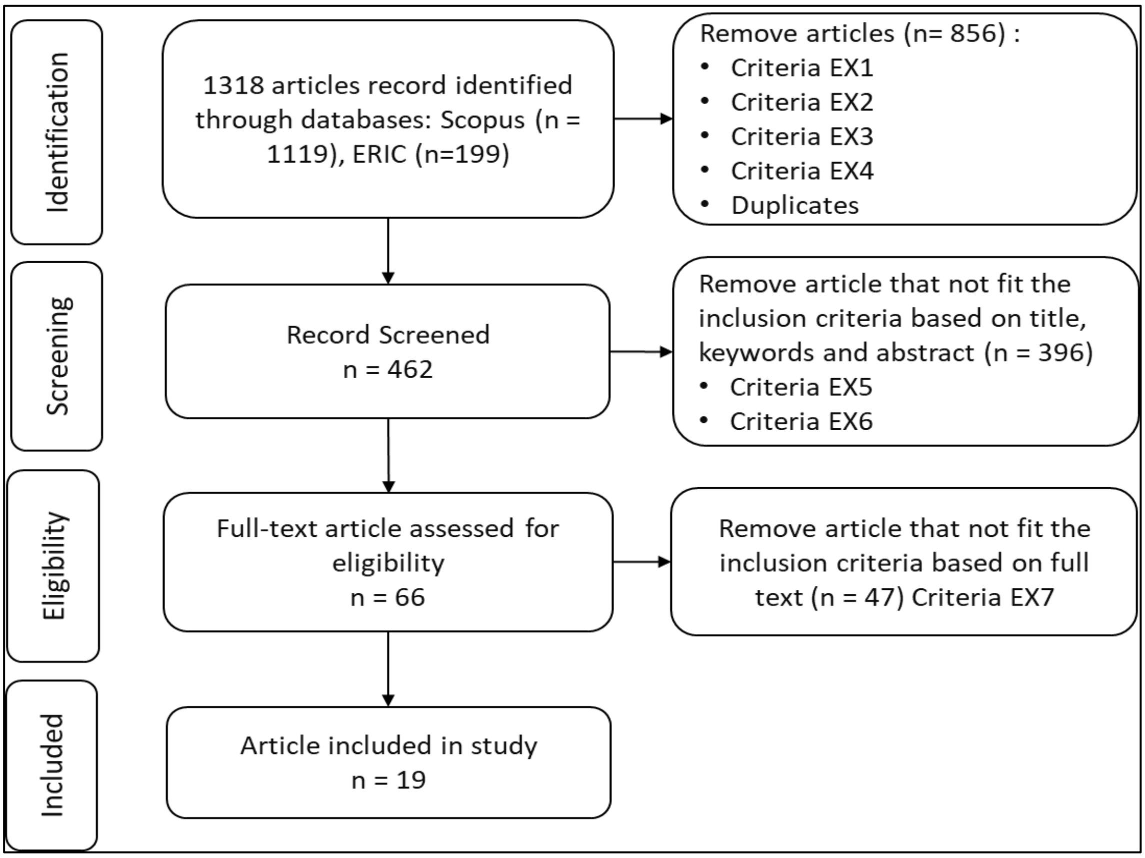

Figure 1. Article Selection Procedure

Moderator Variables

Moderator variables are study characteristics that may influence the outcomes of research findings. Identifying moderators involves examining whether study results vary across different subgroups. The moderator variables used in this study include publication type, the country where the study was conducted, sample size, participant type (educational level), type of intervention, duration of intervention, type of creative thinking instrument, and physics topics addressed.

Study Coding

To ensure the study's objectives are met, the scope was defined through a coding process. This process facilitated comparisons of the characteristics of the articles included in the meta-analysis and the conversion of quantitative data needed to calculate effect sizes. Details of the coding methodology are presented in Table 2.

Table 2. Overview Coding of Study

Identification of the study	Characteristics of the study	Quantitative data of the study
• The first author of study • Publication year	• Publication type • Country • Sample size • Academic level • Intervention type • Intervention duration • Topic in physcs • Instrument type	• **ne**: sample size of the experimental group • **nc**: sample size of the control group • **xe**: mean of the experimental group • **xc**: mean of the control group • **sde**: standard deviation of the experimental group • **sdc**: standard deviation of the control group

Data Analysis

Data analysis was conducted to address the research questions and achieve the study's objectives. To examine physics learning interventions that foster students' creative thinking, this systematic review adopted a qualitative approach, descriptive content analysis (Page et al., 2021). Additionally, to assess the effects of physics learning interventions and their moderator variables on enhancing students' creative thinking abilities, a meta-analytic technique was applied to synthesise the effect sizes of individual studies quantitatively using a random-effects model. The random-effects model accounts for potential variability across studies and provides a more conservative estimate of effect sizes (Zaremohzzabieh et al., 2024).

Effect size calculations were performed in RStudio using the mean, sample size, and standard deviation. For studies lacking standard deviation data, alternative metrics such as F-values, t-values, or p-values were used to compute Cohen's d effect sizes in Microsoft Excel using the following formula. If t-values are available, the following Equation (1).

$$d = \frac{t\sqrt{n_E+n_C}}{n_E n_C} \tag{1}$$

If F-values were provided, Equation (2).

$$d = \frac{\sqrt{F\ (n_E+n_C)}}{n_E n_C} \tag{2}$$

If only p-values were available, they were converted into t-values using Microsoft Excel with the formula =TINV(p-value, df) (Borenstein et al., 2021), where *df* is the degrees of freedom. The resulting t-values were then used in Equation (1) to compute effect sizes. Hedges (1981) noted that *d* is slightly biased. To address this, *d* was further refined into Hedges' *g* by multiplying it by a correction factor J:

$$g = J\ x\ d, with\ J = 1 - \frac{3}{4df - 1} \tag{3}$$

$$df = (n_1 + n_2 - 2) \tag{4}$$

The standard error (SEg) of Hedges' *g* was calculated using:

$$SE_g = \sqrt{v_g} \tag{5}$$

$$v_g = \frac{n_E+n_C}{n_E\ n_C} + \frac{d^2}{2(n_E+n_C)}\ \mathrm{x} J \tag{6}$$

Hedges' *g* was chosen as the effect size measure because it is more accurate for smaller sample sizes. The interpretation of effect sizes follows Cohen (2013), $|g| \leq 0{,}2$, small effect; $0{,}2 \leq |g| \geq 0{,}5$ medium effect; $0{,}5 \leq |g| \geq 0{,}8$ large effect; and $|g| \geq 0{,}8$ very large effect.

Effect sizes and their standard errors obtained through RStudio and Microsoft Excel were merged for further analysis. The combined dataset was analysed using the R packages meta (Balduzzi et al., 2019) and metafor (Viechtbauer, 2010) to compute the overall effect size, conduct moderator variable analyses, and assess publication bias.

Publication bias was assessed using funnel plot analysis and the fail-safe number calculation. Funnel plot symmetry was tested via Egger's regression (Egger et al., 1997), a statistical method for detecting asymmetry indicative of publication bias. Additionally, the fail-safe number was calculated to estimate the number of unpublished studies with nonsignificant effect sizes required to render the overall effect size insignificant (Rosenthal, 1979; Zaremohzzabieh et al., 2024).

The fail-safe number is considered robust if it exceeds the threshold 5k+10, where kkk is the number of studies included in the meta-analysis (Borenstein et al., 2021; Rothstein et al., 2005). A sufficiently large fail-safe number indicates that the existence of

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unpublished studies with nonsignificant effect sizes would not affect the overall conclusions.

RESULT

Data Description

A total of 19 articles meeting the inclusion criteria were identified, encompassing 23 independent studies, as some articles included multiple pairs of experimental and control groups. The included studies were published between 2016 and 2024. Most were conducted in Indonesia, with additional studies from the USA, South Korea, Turkey, and Chile. Sample sizes ranged from 30 to 120 participants per study, with a total of 1287 participants. Thirteen studies reported Torrance Tests of Creative Thinking (TTCT) scores, and several explored aspects such as fluency, flexibility, originality, and elaboration. Detailed data are presented in Table 3.

Table 3. Overview Study Characteristic

Variables	n	%
Publication Type		
Journal	17	77.3
Conference	5	22.7
Country		
Indonesia	15	68.2
USA	4	18.2
Korea	1	4.5
Turkey	1	4.5
Chili	1	4.5
Sample Size		
Small (n≤30)	11	50
Large (n>30)	11	50
Academic Level		
Upper Secondary	12	54.5
Primary	5	22.7
College	4	18.2
Lower Secondary	1	4.5
Intervention Type		
Learning model	8	36.4
Education technology	5	22.7
Teaching material and learning model	5	22.7
Learning integration	3	13.6
Instructional approach	1	4.5
Intervention Duration		
3 weeks	6	27.3
No information	5	22.7
8 weeks	2	9.1
5 meetings	2	9.1
16 weeks	1	4.5
15 weeks	1	4.5
12 weeks	1	4.5
4 meetings	1	4.5
2 weeks (5 meetings)	1	4.5
2 weeks (4 meetings)	1	4.5
1 week (2 meetings)	1	4.5
Topic in Physics		
No information	4	18.2
Other	4	18.2
Force, motion and natural disaster	4	18.2
Force and motion	2	9.1

Variables	n	%
Wave	2	9.1
Computational physics	1	4.5
Pascal law	1	4.5
Global warning	1	4.5
Rectilinear motion	1	4.5
Basic physics	1	4.5
Work, energy, impulse and momentum	1	4.5
Electricity	1	4.5
Work and energy	1	4.5
Fluid	1	4.5
Heat and temperature	1	4.5
Instrument Type		
TTCT	12	54.5
Other	10	45.5

Classification of intervention types

A synthesis of the findings from 22 studies revealed various interventions effective in enhancing creative thinking skills in physics education. The interventions were diverse, encompassing educational models, teaching materials, and instructional approaches. Table 4 presents a synthesis of these 22 studies, classifying the types of interventions that contributed to enhancing students' creative thinking in the physics subject.

Table 4. Interventions to Develop Students' Creative Thinking in Physics

No	Intervention Type	Description
1	Learning model	Quantum flipped learning (Agustini et al., 2022) The generative learning with a cognitive conflict strategy focused on creative thinking (Akmam et al., 2023) STEM-Based 7E learning cycle (Parno et al., 2020) Creative Problem Solving (CPS) and flipped classrooms (S. Rahayu et al., 2022) Creative Problem Solving (CPS)-Local culture (Widyaningtyas et al., 2024) Higher order thinking virtual laboratory (Sapriadil et al., 2019) Open education resources-assisted Problem Based Learning (PBL) (Sedayu et al., 2024) Problem Based Learning (PBL)-blended learning (Syukri et al., 2022)
2	Teaching material and learning model	E-teaching materials-STEM (Asrizal et al., 2022) STEM Smart Physics E-Module (Asrizal et al., 2024) Problem Based Learning-3D thinking maps (Bektiarso et al., 2021) Contextual Teaching and Learning (CTL) based Physics E-module (Desnita et al., 2022) Problem-based multimedia e-books (Zulaikha et al., 2022)
3	Instructional approach	Multiple representation (Guentulle et al., 2024)
4	Education technology	Robotics technology (Koç & Büyük, 2021) Augmented Reality (Wibowo, 2023) Mobile learning using Problem-Based Learning Management System (PBLMS) (Rizal et al., 2024b)
5	Learning integration	Art integration (Ooms et al., 2018) The integrated program combining science and the art of dance (Young-Mi & Hye-Jeon, 2016)

Overall effect of learning interventions on enhancing creative thinking in physics

The combined effect of studies examining the enhancement of students' creative thinking in physics education is presented in the forest plot (Figure 2).

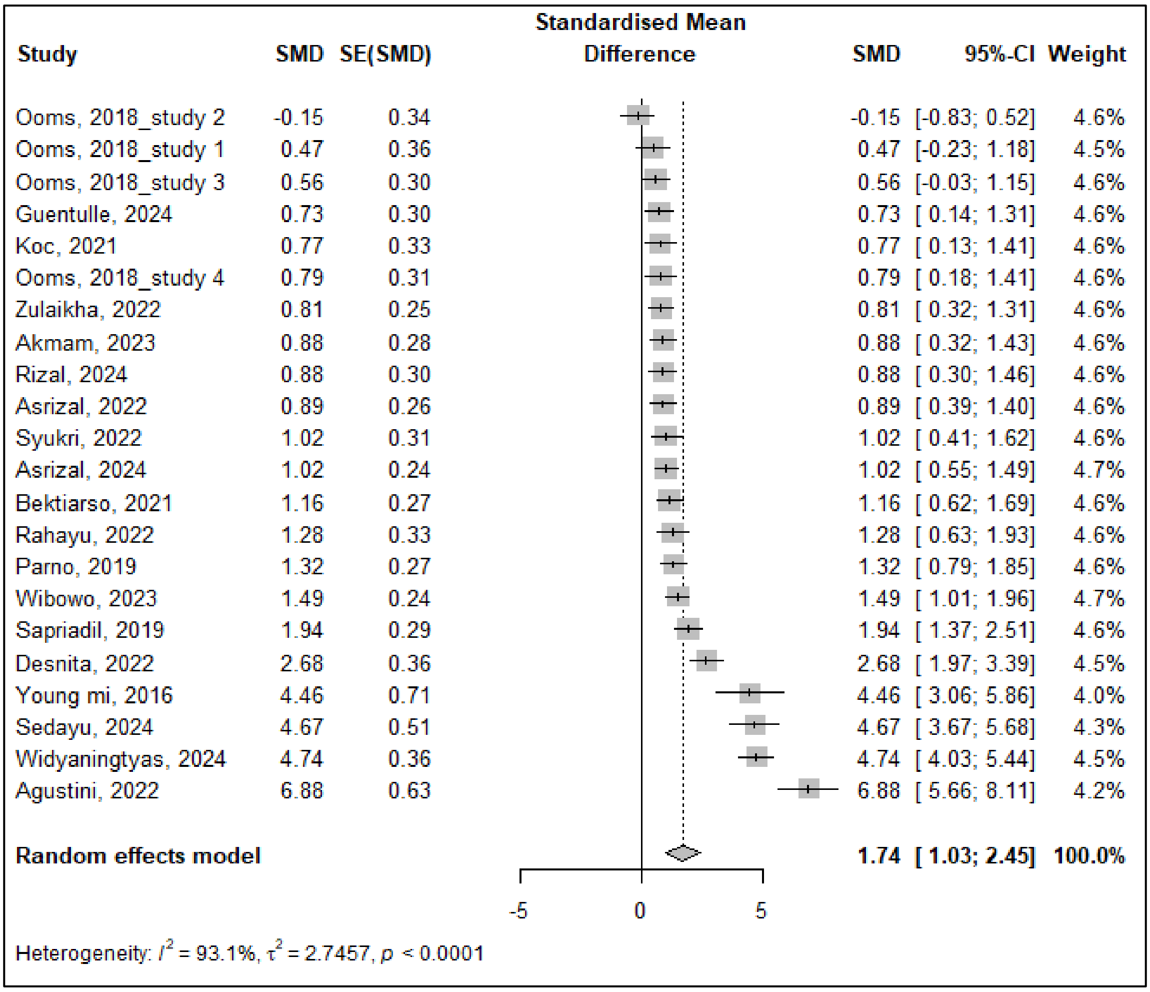

Figure 2. Forest Plot

The random-effects model analysis revealed that the mean effect size across the 22 studies was 1.74 ($p < 0.001$), with a 95% confidence interval of 1.03 to 2.45. This effect size is categorised as strong, indicating that specific learning strategies significantly enhance students' creative thinking in physics education. However, significant heterogeneity was observed among the effect sizes of the 22 studies (Q = 304.69, df = 21, $p < 0.0001$), suggesting substantial variability in effect sizes across studies. This finding highlights the need for further moderator analysis.

Moderator Analysis

Given the variability in effect sizes from the initiatives undertaken by physics educators and researchers, moderator variables were analysed. Nine moderators were examined: publication type, country, sample size, academic level, type of intervention, intervention duration, physics topics, and instrument types used to measure creative thinking. The results are summarised below and illustrated in Figure 3.

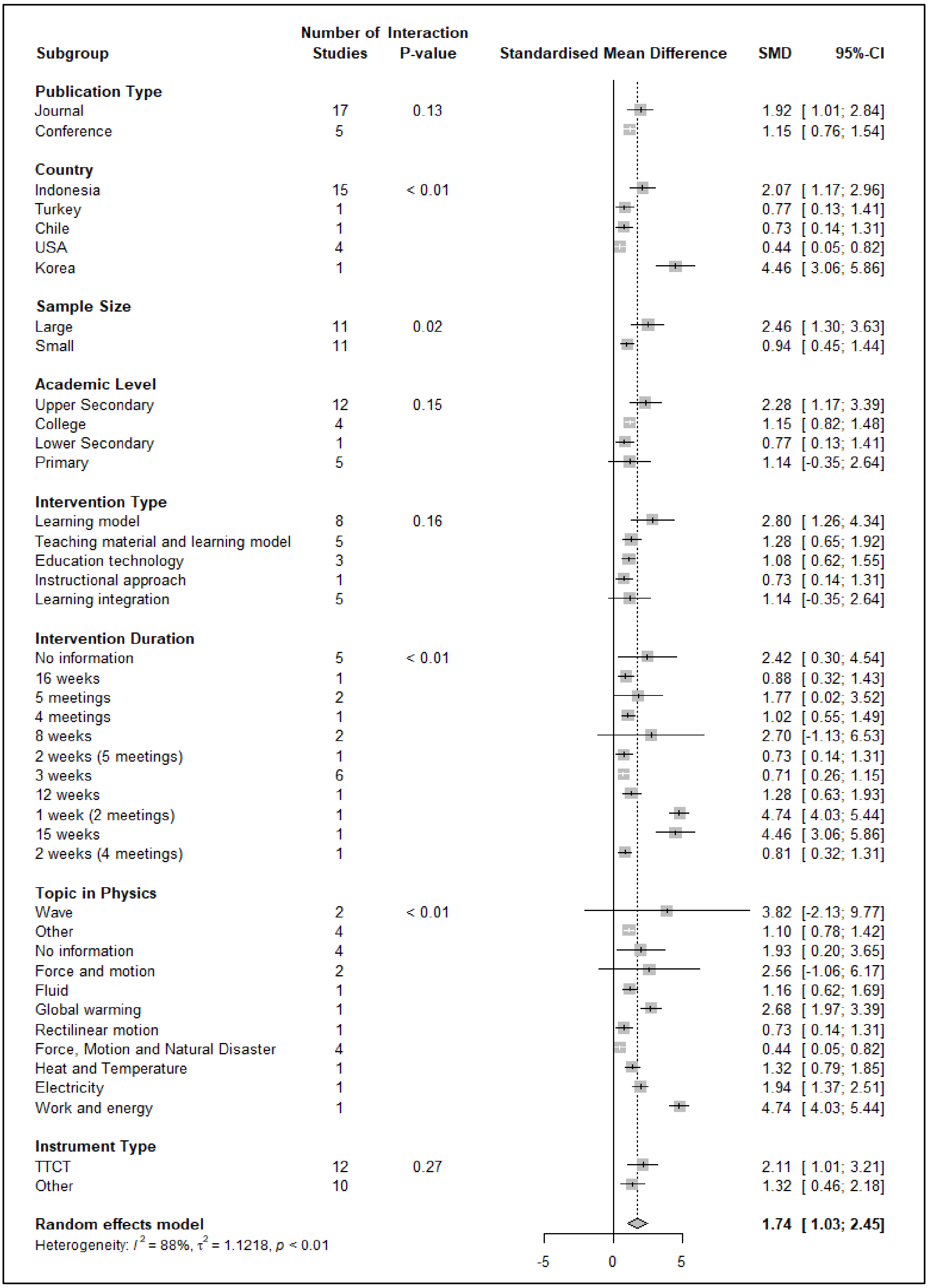

Figure 3. Forest Plot for Moderator Analysis

Type of Publication

The moderator "type of publication" included journal articles and conference papers. Figure 3 shows no significant difference in the average effect size between these groups ($p = 0.13$). However, journal studies (SMD = 1.92, 95% CI [1.01, 2.84]) had a larger effect size compared to conference papers (SMD = 1.15, 95% CI [0.76, 1.54]), suggesting potentially higher methodological quality in journal publications.

Country

A statistically significant difference in effect sizes was observed across countries ($p < 0.01$). The highest effect size was observed in South Korea (SMD = 4.46; 95% CI [3.06, 5.86]), followed by Indonesia (SMD = 2.07; 95% CI [1.17, 2.96]). This result indicates that cultural and educational system differences across countries may impact the effectiveness of interventions in developing students' creative thinking in physics.

Sample Size

Sample sizes were categorised into small ($n \leq 30$) and large ($n > 30$). Significant differences were found ($p = 0.03$), with studies involving larger samples (SMD = 2.46; 95% CI [1.30, 3.63]) exhibiting a much higher effect size than those with smaller samples (SMD = 0.94; 95% CI [0.45, 1.44]).

Academic Level

The academic levels ranged from elementary school to university. Although effect sizes varied, no significant difference was observed based on participants' academic level ($p = 0.16$). The largest effect size was observed at the high school level (SMD = 2.28; 95% CI [1.17, 3.39]), suggesting the potential of high school education to foster creative thinking in physics.

Intervention Type

Interventions were grouped into five categories: instructional models, teaching materials, educational technology, instructional approaches, and integrated learning. While no significant differences were observed across categories ($p = 0.19$), instructional models demonstrated the highest mean effect size (SMD = 4.10; 95% CI [1.24, 6.96]), highlighting the potential of appropriate models to enhance creative thinking in physics.

Intervention Duration

Intervention duration showed significant differences ($p < 0.01$). The largest effect sizes were observed for interventions lasting four weeks (SMD = 4.46; 95% CI [3.06, 5.86]) and three weeks (SMD = 4.74; 95% CI [4.03, 5.44]), underscoring the importance of duration in achieving better outcomes for the development of creative thinking in physics.

Topic in Physics

Significant differences in effectiveness were noted across different physics topics ($p < 0.01$). The largest effect size was observed for waves (SMD = 3.82; 95% CI: [-2.13, 9.77]), followed by fluid dynamics, electricity, and global warming. Topics such as linear motion had smaller effect sizes.

Instrument Type

No significant differences were found based on the type of creative thinking measurement instrument ($p = 0.13$). However, instruments based on the Torrance Tests of Creative Thinking (TTCT) demonstrated larger effects (SMD = 2.11; 95% CI [1.01, 3.21]) compared to others.

Evaluation of Publication Bias

Publication bias was assessed using funnel plots and the fail-safe N method. The funnel plot is presented in Figure 4.

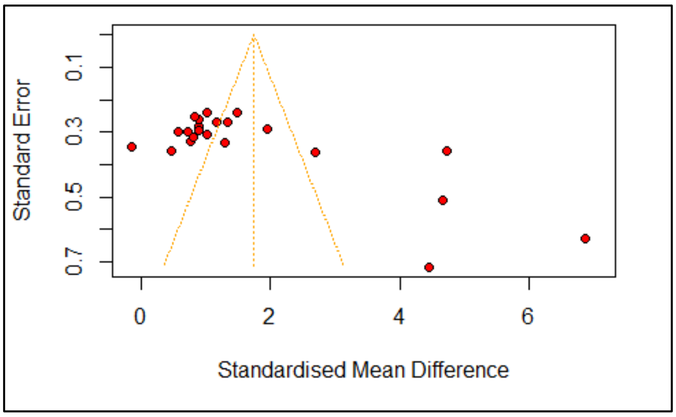

Figure 4. Funnel Plot

If the funnel plot shows a symmetrical distribution, it typically indicates no significant publication bias. If the funnel plot shows asymmetry, such as gaps or a greater distribution on one side, it suggests publication bias. The funnel plot (Figure 4) shows a greater distribution on the right (positive) side, indicating a potential for publication bias. To assess funnel plot balance, an Egger's test was performed.

Egger's test for symmetry revealed t = 3.77, df = 20, $p < 0.0012$, with a bias estimate of 10.7065 (SE = 2.8408), indicating potential publication bias. The fail-safe N calculation using Rosenthal's approach yielded a fail-safe N of 5290, which is well above the threshold of 5k + 10 (where k is the number of studies, calculated as 5 × 22 + 10 = 120). This indicates that the presence of unpublished studies with nonsignificant effect sizes does not compromise the overall conclusions about effect sizes in this study.

DISCUSSION

Interventions and their effectiveness in enhancing creative thinking

Various interventions aimed at fostering students' creative thinking in physics education have demonstrated significant results. Research indicates that approaches such as learning models, innovative teaching materials, instructional strategies, educational technology, and interdisciplinary integration enhance students' creativity, achieving a combined effect size of 1.73, categorised as very strong. Among these, learning models proved the most effective, with the highest effect size of 2.8 (n = 8).

The application of learning models, such as Quantum Flipped Learning, has shown particularly promising outcomes. This model integrates discovery-based learning with active student interaction, leveraging relevant and repetitive contexts to facilitate the development of creative thinking skills (Agustini et al., 2022). Quantum Learning allows students to maximise their potential (Agustini et al., 2022), while flipped learning provides flexibility in learning without spatial or temporal limitations, thereby broadening access to education (Widyaningrum et al., 2020). Specifically, flipped learning has been shown to be effective in physics education, significantly enhancing students' creativity (Rahayu & Kuswanto, 2021).

Beyond Quantum Flipped Learning, other models of teaching, such as the STEM-Based 7E Learning Cycle (Parno et al., 2020) and cognitive conflict-based learning (Akmam et al., 2023), also show efficacy in enhancing creative thinking in physics education.

Research highlights that Problem-Based Learning (PBL) and Creative Problem Solving (CPS) are frequently employed models for developing creative thinking in physics. These results are consistent with the study by Rizal et al. (2024a), which found that learning activities within a PBL-based management system can facilitate the development of creative thinking among prospective physics teachers. In line with this, the research by Ernawati et al. (2023) revealed that PBL with scaffolding effectively improves students' creative thinking skills by encouraging active participation, problem-solving, and idea exchange. Meta-analyses by Erdem (2022) further confirm the significant influence of PBL on students' creative thinking skills. CPS, which emphasises systematic approaches to organising creative ideas (Beda et al., 2020), demonstrates even greater effectiveness than simple PBL (Suciati et al., 2023). These innovative models are effective due to their constructivist nature, fostering collaboration and promoting higher-order reasoning, consistent with Virtanen & Tynjälä's (2019) findings that collaborative, interactive, and constructivist learning environments enhance creativity.

Teaching materials grounded in learning models (g = 1.28, n = 5) also support the development of creative thinking. These materials include STEM-based teaching materials and e-modules (Asrizal et al., 2024, 2022), Contextual Teaching and Learning (CTL) e-modules (Desnita et al., 2022), multimedia e-books, and thinking maps grounded in Problem-Based Learning (Bektiarso et al., 2021; Zulaikha et al., 2022). All teaching materials involve technological or electronic aids. This aligns with the findings of Pebriana et al. (2024), who report that STEM-based e-modules improve students' creative thinking. Interactive multimedia supported by technology enhances creativity in elementary students (Kobsiripat, 2015). Additionally, guided discovery-based physics STEM e-modules improve students' motivation and creative thinking skills (Setiaji et al., 2024), while e-module implementation fosters creative thinking (Sueb et al., 2024). Aligning with this, engaging e–learning–based instructional media stimulates students' attention, supports deeper internalisation and understanding of the material, and, in line with the demands of the Industrial Revolution 4.0 and globalisation, facilitates the development of students' creative thinking (Saputra et al., 2023).

In educational technology, tools such as augmented reality (Wibowo, 2023), robotics (Koç & Büyük, 2021), and mobile learning based on PBL Management Systems (Rizal et al., 2024a) have significantly impacted students' creative thinking in physics (g = 1.08, n = 3). A meta-analysis by Zaremohzzabieh et al. (2024) highlights the role of technology in enhancing fluency, flexibility, and originality in students' creative thinking. Moreover, Badeleh (2019) confirms the positive impact of robotics training on student creativity in physics learning. Further support comes from meta-analyses indicating the positive influence of mobile learning on physics learning outcomes (Abdullah et al., 2024) and the dual impact of augmented reality on learning outcomes (Garzón & Acevedo, 2019) and creativity (Yilmaz & Goktas, 2017).

Integrating physics education with the arts also significantly enhances students' creativity (g = 1.14, n = 5). For instance, combining physics with dance (Young-Mi & Hye-Jeon, 2016) Adopting STEAM approaches (Wilson et al., 2021) boosts creativity and critical thinking. King & McCall (2024) argue that cross-disciplinary approaches provide enriched, relevant learning experiences for 21st-century learners.

Instructional approaches (g = 0.73, n = 1), such as multiple representation-based methods, effectively enhance learning and creative thinking in physics (Guentulle et al., 2024). Research supports the effectiveness of multiple representations in mathematics education as an instructional intervention for enhancing prospective elementary school teachers' creative thinking abilities (Bicer, 2021). Furthermore, the application of multiple representations, combined with the creative problem-solving model, has been shown to improve students' creative thinking skills (Fathonah et al., 2024).

In summary, these interventions collectively underscore their potential to enhance students' creative thinking in physics education, as evidenced by their effectiveness ranking by effect size (see Figure 3): learning models > teaching materials > interdisciplinary learning > educational technology > instructional approaches. The study by Agustini et al. (2022), which employed Quantum Flipped Learning, significantly contributes to the combined effect size, reaffirming the importance of constructivist approaches that foster collaboration, cognitive strategies, and problem-solving in developing creative thinking in physics education.

Effects of moderator variables

This section analyses how variables such as publication type, country, sample size, education level, intervention type, intervention duration, physics topics, and creative thinking instruments moderate intervention effectiveness. Results reveal that moderator variables such as country, sample size, intervention duration, and physics topics significantly affect intervention efficacy, whereas publication type, education level, intervention type, and instruments do not show significant differences.

The moderator variable of the research country's origin influences the effectiveness of interventions designed to enhance creative thinking in physics learning. A previous meta-analysis investigating self-efficacy and mathematical creativity found significant differences by country, with country as a moderator (Herianto et al., 2024). However, this finding contrasts with another meta-analysis on the effects of teaching on students' creative thinking, which reported no significant differences across countries of study (Gürkan & Dolapçioğlu, 2020). Consequently, the role of the country as a moderator lacks substantial support in the literature.

The moderator of sample size affects the effectiveness of interventions in fostering creative thinking in physics. Statistically, sample size significantly impacts research outcomes, with larger samples yielding more stable results and stronger generalisations compared to smaller ones (Tobler, 2024). The duration of intervention also moderates the effectiveness of creative thinking interventions in physics education. Similarly, meta-analyses on the use of educational technology to enhance creative thinking skills highlight that intervention duration plays a crucial role in shaping students' expectations and boosting their resilience (Zaremohzzabieh et al., 2024). The physics topic as a moderator significantly influences the effectiveness of interventions on students' creative thinking. This suggests that physics teaching strategies should consider the subject's characteristics to optimise the development of students' creative thinking abilities.

Research implications and limitations

The findings of this study have significant implications for the future development of physics education. Theoretically, this study aligns with previous literature suggesting that creative thinking can be enhanced through learning approaches that actively engage students in the learning process. Furthermore, the findings regarding the effectiveness of moderator variables open avenues for further research on how specific contexts and conditions may influence the success of learning interventions. This study also makes a significant contribution to understanding how learning interventions can improve students' creative thinking skills in physics education. Moderator variables such as country, intervention duration, and physics topics play a critical role in determining the effectiveness of interventions. The implications of these findings provide guidance for educators, policymakers, and researchers in developing more effective learning programs that meet contemporary educational needs.

However, this study has several limitations. First, although the potential for publication bias is considered negligible based on the fail-safe-N approach, there remains a potential for publication bias as evidenced by the Egger's test results and the symmetry of the Funnel Plot (see Figure 4). McMillan & Schumacher (2010) state that meeting the criteria for random assignment in education is challenging. Additionally, Bi et al. (2020) note that researchers often play multiple roles, such as designing, conducting, and analysing research, which makes it difficult to find studies with low bias risk. This bias can lead to reported effect sizes that are larger than the actual effect sizes. Second, the studies included in this research were selected based on established criteria: only those published in English and available in open access were considered. Future research should include studies in other languages and those with restricted access to provide a broader perspective on the development of creative thinking in physics. Third, despite using international databases such as Scopus and ERIC, the majority of the studies reviewed originated from Indonesia. This may introduce publication bias, as Erdem (2022) highlights, and limit the generalizability of the findings to the context of physics education in other countries. Fourth, this study focused solely on studies indexed in Scopus and ERIC. Future research should expand the search to a broader range of databases to gain a more comprehensive understanding of the development of students' creative thinking in physics.

CONCLUSION

This study reveals that learning interventions focusing on innovative learning models significantly enhance students' creative thinking skills in physics education. Additionally, the implementation of technology-based learning materials such as e-modules and multimedia, as well as teaching approaches like multiple representations, technology-assisted learning, and integrating physics with the arts, positively impacts students' creative thinking in physics.

The findings also underscore the importance of moderator variables, such as country, sample size, intervention duration, and physics topics, in shaping the effectiveness of learning interventions. Variables such as country, intervention duration, and subject-matter characteristics significantly enhance teaching effectiveness. However, other variables, such as publication type, education level, and research instruments, show no significant differences in outcomes. Overall, these findings provide valuable insights for educators, curriculum developers, and researchers in designing learning interventions that effectively enhance students' creative thinking in physics.

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