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The impact of brain science literacy on creative thinking: a meta-analytic study

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Introduction: Creative thinking is essential for developing high-level innovative talents. However, its underlying neuroplastic mechanisms and effective educational interventions remain underexplored.

Methods: This meta-analysis synthesizes data from 35 experimental studies ($N = 14,688$) to examine the effects of brain science literacy on creative thinking and its potential moderators.

Results: The results indicate that brain science literacy has a small but significant positive effect on creative thinking ($g = 0.20$, $p = 0.003$), with stronger effects observed in teaching strategy optimization ($g = 0.32$), student behavioral regulation ($g = 0.37$), and early childhood interventions ($g = 0.70$). The impact on originality ($g = 0.53$) was significantly stronger than on fluency ($g = 0.20$) and the overall creativity score ($g = 0.26$). The intervention effects varied across educational stages, with the most substantial benefits seen in early childhood ($g = 0.70$) and at the university level ($g = 0.30$).

Discussion: These findings suggest that improving brain science literacy can promote neuroplasticity and enhance creative thinking, with varying effects across developmental stages and creative components. The benefits observed in early childhood highlight the critical importance of brain science literacy-informed educational interventions during sensitive periods of cognitive development. This study provides solid empirical support for integrating neuroscience principles into educational practice, offering practical guidance for educational policy and curriculum design. Overall, brain science literacy appears to foster creativity through a dual pathway: neuroplasticity activation and developmental stage adaptation, presenting a focused framework for evidence-based neuroeducational interventions.

KEYWORDS

brain science literacy, creative thinking, moderating effect, neural mechanism, meta-analysis

1 Introduction

The application of brain science in education has increasingly garnered attention at the global policy level, with numerous governments and international organizations launching strategic initiatives to promote the development and practical translation of educational neuroscience. The Organisation for Economic Co-operation and Development (OECD, 2007, 2022), through its “Brain and Learning” project and reports such as Neuroscience and Education, emphasizes the critical role of brain science research in optimizing learning processes, understanding learning difficulties, and designing personalized instructional approaches. Similarly, the U.S. National Science Foundation (National Science Foundation,

2020) has funded multiple education research programs centered on brain-cognition-learning frameworks, advancing learning theories grounded in neural plasticity. China's Outline for Building China into an Education Power (2024–2035) (Central Committee of the Communist Party of China and State Council, 2025) likewise highlights the strategic need to explore novel models for cultivating top-tier innovative talents. Brain science primarily elucidates the relationship between brain development and learning, providing a scientific basis for educational practice. As one of the most cutting-edge disciplines of the twenty-first century, brain science's potential to foster technological innovation and talent development is increasingly recognized.

With ongoing advancements in brain science technologies and their deeper integration into education, brain science literacy—defined as an individual's foundational understanding of brain science concepts, critical cognition, and the ability to apply such knowledge to guide learning and healthy living (Yang et al., 2024)—has emerged as a vital dimension of cognitive scientific literacy for modern learners and educators. In contrast, neuroeducation is a broader interdisciplinary field that integrates neuroscience, psychology, and education to develop evidence-based teaching practices (Howard-Jones, 2014; Im et al., 2018). While brain science literacy supports neuroeducation by providing necessary cognitive tools, the two are not synonymous. Additionally, neuroscience-informed teaching focuses on the practical application of neuroscience findings by educators to optimize teaching strategies (Dubinsky et al., 2019). Without sufficient brain science literacy, the implementation of neuroscience-informed teaching may risk being misguided by common neuromyths. Brain science literacy, as a core competency for future talent development, is not only a critical component of scientific literacy but also foundational for individuals to comprehend brain mechanisms, regulate cognitive processes, and develop higher-order thinking skills. Creative thinking, as a key higher-order cognitive ability, closely relates to brain functions such as executive function, emotional regulation, and associative processing. The essence of educational innovation lies in fostering thinking skills, and creative thinking, as a central element of human cognition, has been identified by major policy bodies including the OECD and the World Economic Forum (2020) as a crucial capability for future education and labor markets.

However, traditional models for cultivating innovative thinking typically rely on teacher-centered, unidirectional knowledge transmission, which has clear limitations in stimulating student initiative and creativity. Recently, educational researchers have begun exploring new approaches that integrate neuroscience literacy into creative thinking development. Unlike traditional factors promoting creativity—such as self-efficacy (Huang and Hu, 2020) or behavioral perception (Cheng et al., 2015)—or instructional innovations like curriculum design (Zhou and Li, 2019) and teaching methods (Huang and Lu, 2025), neuroscience provides an evidence-based neurobiological foundation for innovative education and focuses on the interaction between neuroscience and education, particularly on how teaching impacts learner behavior (Thomas et al., 2019).

With advances in high-tech neuroimaging methods such as functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), research and educational innovation increasingly target the cultivation of future-oriented core competencies. Students are not only beneficiaries of educational

reform but also active agents in understanding, driving, and reflecting on their own learning and development (Olakulehin, 2021). Creativity research has entered a “neuroscience era,” shifting focus from cognitive structures to brain functional networks. Neuroscientific evidence indicates that creative thinking is not an isolated function but the product of coordinated activity across multiple brain regions, particularly involving dynamic interactions among the default mode network, central executive network, and salience network (Beatty et al., 2015). Current neuroscience research on creative thinking mainly concentrates on specific cognitive domains and theoretical applications.

Despite the promising potential of brain science in education, some scholars have noted controversies regarding its practical effectiveness in improving student outcomes following interventions (Cherrier et al., 2020). Consequently, consensus is lacking on whether neuroscience literacy truly benefits the development of students' creative thinking. Existing studies show substantial heterogeneity in intervention approaches, measurement instruments, and research methodologies. The precise mechanisms and moderating factors by which neuroscience literacy influences creative thinking remain insufficiently synthesized, resulting in challenges to establish definitive and instructive conclusions. To bridge the “gap” between neuroscience and education and guard against distortions of scientific facts (Howard-Jones, 2014). This study argues for a comprehensive understanding of the foundational components and cognitive mechanisms of brain science literacy, with a focused examination of its impact on key brain regions underlying creative thinking and the characteristics of effective interventions.

Accordingly, this study employs meta-analytic techniques to systematically review and quantitatively integrate 35 relevant experimental studies, aiming to: (1) elucidate the underlying mechanisms through which neuroscience literacy fosters creative thinking development; (2) analyze the moderating roles of neuroscience intervention types, creativity measurement indices, and methodological features on creative thinking outcomes; and (3) provide evidence-based, feasible recommendations for educational practitioners. The findings are expected to advance the integration of neuroscience and innovative education, thereby furnishing theoretical support and practical guidance for cultivating innovative talents aligned with emerging demands in new quality-driven productivity.

2 Research methods

2.1 Literature search and screening

This study conducted a comprehensive search of both Chinese and English literature published between January 2010 and March 2025, focusing on the relationship between brain science and creative thinking. The Chinese databases searched included China National Knowledge Infrastructure (CNKI), Wanfang Data Knowledge Service Platform, and VIP Chinese Journal Service Platform. The English databases included Springer Link, Web of Science, and IEEE Xplore. Keyword combinations used for the search encompassed terms such as “Brain Science,” “Brain Science Literacy,” “fNIRS,” “Eye Movement,” “Creativity,” “Creative Thinking,” “Creativity Measurement,” and “Divergent Thinking.” Additionally, backward citation tracking was performed on all included articles, relevant reviews, and empirical

studies to ensure comprehensive literature coverage and to avoid omission of pertinent studies.

The retrieved studies were screened based on the following inclusion criteria:

- (1) Empirical studies examining the relationship between brain science and creative thinking, excluding purely theoretical discussions and review articles;
- (2) Complete data availability with clearly reported sample sizes;
- (3) Explicit investigation of the association between brain science and creative thinking, employing experimental or quasi-experimental designs with control and experimental groups; data must include sample sizes, means, standard deviations, or other statistics necessary to calculate effect sizes. Studies solely using structural equation modeling, regression analysis, or other statistical techniques without such data were excluded;
- (4) Duplicate data usage was avoided—if multiple publications used the same dataset, only one was included;
- (5) Studies published within the specified period (2010.1–2025.3), regardless of language or geographic region.

The screening process followed the PRISMA guidelines (Moher et al., 2009) and is illustrated in Figure 1. Ultimately, 35 studies meeting the meta-analysis criteria were included, providing 108 independent effect sizes with a total sample of 14,688 participants.

2.2 Study coding

To quantify the effect of neuroscience literacy interventions on creative thinking and identify potential moderators, included studies were systematically coded across three main dimensions:

- (1) Type of neuroscience literacy intervention: following the classification framework proposed by Yang et al. (2024), interventions were categorized into three groups: (i) Teacher professional development (teaching strategy selection); (ii) Pathways for Literacy Cultivation (early education, innovative teaching models, mentor training); and (iii) Individual student growth (affective attitudes and behavioral performance).

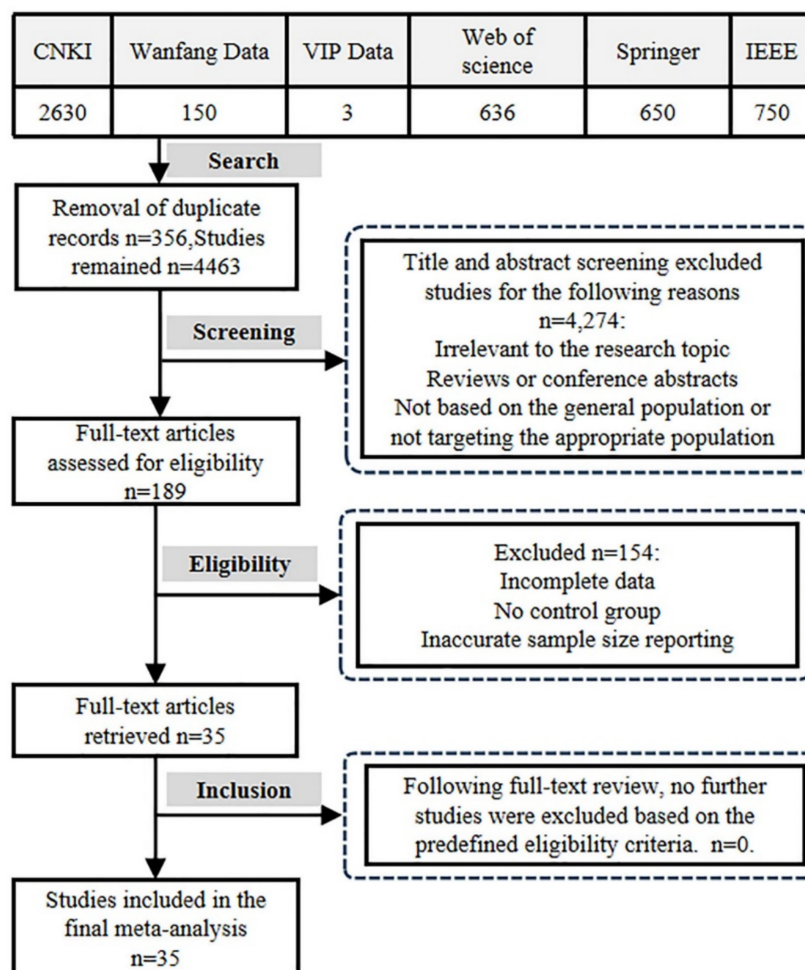


FIGURE 1
Flowchart of literature search and selection process.

- (2) Creative thinking measurement indices: based on [Torrance's \(1972\)](#) structural model of creative thinking, creativity was coded into subdimensions including flexibility, originality, elaboration, and fluency, as well as an aggregated total score.
- (3) Study methodological characteristics: educational stages of the sample populations were coded following [Wang et al. \(2025\)](#), including early childhood, primary, secondary, and university levels. Sample sizes were also recorded.

These three dimensions constitute key moderators in this study and provide the foundation for subsequent heterogeneity and subgroup analyses. Systematic coding of intervention types, creativity dimensions, and Study methodological characteristics allows exploration of their moderating effects on intervention efficacy, thereby offering more explanatory power in elucidating the mechanisms linking brain science literacy and creative thinking.

2.3 Data processing and analysis

This study utilized Comprehensive Meta-Analysis Version 3.0 to analyze the data, following five main steps: First, assessment of publication bias; second, testing for heterogeneity; third, examination of the main effect; fourth, conducting sensitivity analysis; and fifth, analysis of moderating effects. Effect sizes were represented using the standardized mean difference, Hedges' g —a bias-corrected version of Cohen's d ([Vøllestad et al., 2012](#))—to calculate the aggregated results. This effect size served as the measure of the impact of brain science literacy on creative thinking.

3 Results

3.1 Assessment of publication bias

This meta-analysis employed multiple statistical methods to evaluate the presence of publication bias in the overall effect size, including the Fail-safe N (Nfs), Begg's rank correlation test, Egger's linear regression analysis, and the trim-and-fill method for precise adjustment ([Khouri et al., 2013](#)). Although the intercept from Egger's regression was statistically significant (intercept = 1.55), indicating a potential risk of publication bias, the Begg's test yielded a Z value of 1.83 (less than 1.96) and $p = 0.068$ (greater than 0.05), suggesting an acceptable result. The fail-safe N was 1,530, exceeding the threshold of $5 \times 108 + 10 = 550$, meaning that an additional 980 unpublished studies with null results would be required to invalidate the findings of this study. Based on this, the trim-and-fill method was applied to correct for the influence of a small number of studies with potentially inflated effect sizes. As shown in [Figure 2](#), after including 26 imputed studies, the 134 effect sizes were symmetrically distributed around the funnel plot's central axis. Ultimately, 68 effect sizes fell within the funnel, while 66 were at the edges. The pooled results before and after trimming showed no significant changes, indicating the robustness of the meta-analytic findings. In summary, the results of this meta-analysis can be considered reliable within the relevant research field.

3.2 Heterogeneity test

This study assessed the heterogeneity of effect sizes using both the Q statistic and the I^2 index. According to the criteria, when the Q value is significant ($p < 0.05$) and $Q > df(Q)$, and I^2 exceeds 60%, the



FIGURE 2
Funnel plot for publication bias evaluation.

effect sizes are considered to be heterogeneously distributed, warranting the use of a random-effects model; otherwise, a fixed-effects model is applied (Hedges and Olkin, 2014). The heterogeneity test results showed a Q value of 832.90 ($df = 107$, $p < 0.001$), indicating substantial heterogeneity among effect sizes. To address the limitation of the Q test in quantifying heterogeneity magnitude, the I^2 index was also employed. I^2 is commonly used to evaluate the degree of heterogeneity between studies, with values of 25, 50, and 75% typically representing low, moderate, and high heterogeneity, respectively. When the Q statistic is significant and $I^2 \geq 75\%$, strong heterogeneity exists across studies and cannot be ignored. Under such circumstances, applying a random-effects model is more appropriate to better capture the variability among studies. In this study, I^2 was 87.16%, indicating that 87.16% of the variance was attributable to true differences in effect sizes, confirming high heterogeneity among studies and aligning with the Q test findings described above.

3.3 Main effect test

As shown in Table 1, the aggregated results of 35 experimental or quasi-experimental studies examining the effect of brain science literacy on creative thinking ($k = 108$) are presented. After meta-analyzing 134 corrected independent effect sizes, the overall effect size was found to be $g = 0.20$. According to Cohen's classification of effect sizes—very weak ($r < 0.1$), weak ($0.1 \leq r < 0.3$), moderate ($0.3 \leq r < 0.5$), strong ($0.5 \leq r < 0.7$), very strong ($0.7 \leq r < 0.9$), and extremely strong ($r \geq 0.9$) (Cohen, 2013)—this indicates a small but positive effect of brain science literacy on the development of creative thinking. This suggests that integrating brain science literacy into classroom instruction can contribute to fostering students' creative thinking abilities.

3.4 Sensitivity analysis

The heterogeneity test indicated a high level of heterogeneity among the effect sizes of the included studies. Based on the funnel plot and the deviation of effect sizes, this study conducted a sensitivity analysis on the heterogeneous effect sizes of the relationship between brain science literacy and creative thinking using the leave-one-out method (Liu et al., 2020). Using the “one study removed” function in CMA 3.0, the analysis showed that after excluding any single study, the effect size between brain science literacy and creative thinking consistently ranged from 0.17 to 0.21, remaining within the confidence interval of the main analysis with a consistent direction and small fluctuation. These results indicate good robustness of the findings.

3.5 Moderating effects on creative thinking

Moderator variables were introduced at the research design stage to investigate the specific conditions under which the dependent variable (Y) is influenced by the independent variable (X). In this study, creative thinking indicators, types of brain science literacy interventions, and educational stages were selected as moderator variables, with the aim of analyzing the differential effects of brain science literacy on students' creative thinking across various moderating conditions, as shown in Table 2. It is important to note that certain moderator variables, such as teacher professional development, were underrepresented in the original dataset, potentially limiting the generalizability of the corresponding findings. This limitation warrants further investigation in future research.

3.5.1 Moderating effect of brain science literacy intervention types

As shown in Table 2, the between-group heterogeneity test for the moderating effect of brain science literacy intervention types yielded $Q = 18.25$, $p = 0.003 < 0.05$, indicating significant differences in the effects of brain science literacy on creative thinking across different types of interventions. Specifically, early childhood education ($g = 0.70$, $p = 0.006$), innovative educational models ($g = 0.45$, $p = 0.026$), teaching strategy selection ($g = 0.32$, $p = 0.012$), and student behavioral regulation ($g = 0.37$, $p = 0.016$) all demonstrated statistically significant positive effects. Among these, early childhood education ($g = 0.70$) exhibited the strongest impact on the development of creative thinking, suggesting that the integration of brain science literacy during the early stages of education is particularly effective in fostering students' creative potential. While other intervention types also showed positive effects, their impact was comparatively smaller. Certain intervention types did not produce statistically significant effects ($p > 0.05$). These findings underscore the importance of implementing brain science literacy interventions during the early developmental period to maximize the promotion of creative thinking skills, while also providing nuanced insights into the varying effectiveness of different educational strategies.

3.5.2 Moderating effect of measurement indicators on creative thinking outcomes

The results of the moderation effect analysis (see Table 2) indicate that the type of creative thinking measurement significantly influences the observed effects of brain science literacy interventions ($Q = 14.19$, $p = 0.007 < 0.05$). Specifically, the effect sizes for different measurement indicators were as follows: originality ($g = 0.53$, $p = 0.001$), composite total score ($g = 0.26$, $p = 0.013$), and fluency ($g = 0.20$, $p = 0.025$), all of which demonstrated statistically significant positive effects. Among these, originality exhibited the

TABLE 1 The pooled effect size and heterogeneity test results.

Effect model	k	g	95% CI		Two-tailed Test		Heterogeneity test			
			Lower limit	Upper limit	Z	P	Q	df	p (two-tailed)	I^2
Random effects model	108	0.20	0.05	0.24	2.99	0.003	16.21	2	0.000	87.16

TABLE 2 Analysis of the moderating impact of brain science literacy on students' creativity development (random effects model).

Dimension	Moderator variable	Effect size and 95% confidence interval					Test and null		Test of heterogeneity	
		<i>n</i>	<i>g</i>	SE	Lower limit	Upper limit	<i>Z</i>	<i>P</i>	<i>Q</i>	<i>P</i>
Research method characteristics	Educational stage								11.51	0.021
	Early childhood	9	0.70	0.25	0.21	1.20	2.77	0.006		
	Primary school	11	0.13	0.12	−0.11	0.37	1.05	0.292		
	Secondary school	29	−0.02	0.10	−0.22	0.19	−0.16	0.876		
	University	54	0.30	0.08	0.15	0.46	3.78	0.000		
	Other	5	−0.05	0.22	−0.48	0.38	−0.22	0.825		
	Sample size								2.69	0.261
	<50	31	0.30	0.16	0.11	0.50	3.05	0.002		
	50–100	49	0.20	0.10	0.02	0.38	2.14	0.032		
	>100	28	0.11	0.03	−0.02	0.24	1.61	0.106		
Types of brain science literacy interventions	Student development								4.72	0.030
	Student behavioral Regulation	20	0.37	0.15	0.07	0.67	2.40	0.016		
	Learning emotions and attitudes	14	−0.04	0.11	−0.26	0.18	−0.37	0.709		
	Pathways for literacy cultivation								10.87	0.004
	Early childhood education	9	0.70	0.25	0.21	1.20	2.77	0.006		
	Innovative teaching models	11	0.45	0.20	0.05	0.84	2.23	0.026		
	Trainer development	35	−0.02	0.08	−0.17	0.14	−0.20	0.844		
	Teacher professional development									
	Instructional strategy selection	19	0.32	0.13	0.07	0.57	2.52	0.012		
Creative thinking measurement indicators	Indicators								14.19	0.007
	Elaboration	13	−0.03	0.09	−0.20	0.15	−0.29	0.775		
	Fluency	30	0.20	0.01	0.03	0.38	2.24	0.025		
	Flexibility	14	−0.08	0.12	−0.31	0.16	−0.62	0.533		
	Originality	19	0.53	0.16	0.21	0.85	3.26	0.001		
	Total score	32	0.26	0.11	0.05	0.47	2.47	0.013		

largest effect size ($g = 0.53$), suggesting that it is the most sensitive indicator for capturing the changes brought about by brain science literacy interventions and plays a more substantial role in promoting students' creative thinking development. This finding indicates that brain science literacy interventions are particularly effective in enhancing students' ability to generate novel and unique ideas. In contrast, the interventions did not yield significant effects on elaboration, flexibility, dimensions ($p > 0.05$). The moderating effects for other outcome variables were also not statistically significant.

3.5.3 Moderating effect of research methodological characteristics on creative thinking outcomes

In this study, the samples were categorized based on participants' educational stages: early childhood, primary school, secondary school, university, and others. The between-group effect yielded a Q -value of 11.51 ($p = 0.021 < 0.05$), indicating that the educational stage significantly moderates the impact of brain science literacy interventions on creative thinking outcomes. Specifically, the effect sizes across stages were as follows: early childhood ($g = 0.70, p = 0.006$)

and university ($g = 0.30, p = 0.000$). These findings indicate that brain science literacy is more readily absorbed and translated into creative thinking abilities during early developmental stages or when learners possess stronger autonomous learning capacities. In contrast, the intervention effects at the primary and secondary school levels were comparatively weaker, which may suggest that teaching strategies or research methodologies at these stages are relatively fixed or may require further optimization.

Additionally, this study classified the included samples into three groups based on sample size to examine whether sample size moderates the effect of brain science literacy interventions on creative thinking outcomes. A heterogeneity test was conducted, and the results are presented in Table 2. All observed effect sizes were greater than zero, indicating a consistent positive impact of brain science literacy on creative thinking outcomes. The heterogeneity test yielded non-significant results ($p = 0.26 > 0.05$), suggesting that the size of the sample did not significantly influence the effectiveness of brain science literacy interventions within creative thinking curricula. These findings demonstrate that the positive effect of brain science literacy on creative thinking remains stable regardless of whether the study employed a small or large sample size.

4 Discussion

This study, through a meta-analysis integrating 35 empirical studies, revealed the facilitating effects of brain science literacy on creative thinking and its underlying neurocognitive mechanisms, while identifying key moderating factors such as measurement indicators and developmental stage differences. The following discussion is organized across three dimensions: instructional strategy adjustment, student behavioral enhancement, and educational stage adaptation.

4.1 Neurocognitive mechanisms of the impact of brain science literacy on creative thinking

4.1.1 Teacher-level mechanism: it is essential to activate the synergistic interaction between the prefrontal cortex and the default mode network

The findings demonstrate that brain science literacy exerts a small yet positive effect on creative thinking ($g = 0.20$), potentially attributable to its optimization of the coordination between the prefrontal cortex and the default mode network (Beatty et al., 2015). Teachers equipped with brain science literacy are capable of adjusting instructional strategies based on neuroscientific principles ($g = 0.32$), more effectively allocating attentional resources and designing divergent thinking-oriented classroom activities (Immordino-Yang and Damasio, 2007).

Empirical evidence indicates that such instructional adjustments enhance the efficiency of dorsolateral prefrontal cortex activation for attentional control, while reducing inappropriate suppression of the default mode network, thereby providing a more favorable neural foundation for students' creative thinking. Additionally, Torrijos-Muelas et al. (2021) emphasized that neuroscience knowledge helps teachers to identify and avoid common neuromyths, such as the "10%

brain usage" misconception, thus improving the scientific rigor of instructional design.

4.1.2 Student-level mechanism: enhancement of cognitive flexibility in behavioral regulation

In classroom practice, interventions incorporating brain science literacy significantly improved students' behavioral regulation ($g = 0.37$). Instructional methods such as task-driven and cooperative learning were shown to activate the prefrontal cortex, thereby facilitating knowledge transfer and divergent thinking (Beatty et al., 2015). Moreover, case studies and preliminary empirical findings suggest that neurofeedback-based personalized learning recommendations can provide real-time emotional regulation, assist students in the optimal allocation of working memory, and offer fine-tuned learning adjustments tailored to students' individual cognitive and psychological profiles.

These strategies further enhance students' self-efficacy (Huang and Hu, 2020), increasing their willingness to attempt novel problem-solving approaches and effectively improving their ability to handle challenges (Quitadamo et al., 2008) and their academic planning competencies (Zhou, 2023).

4.1.3 Educational stage differences: intervention timing based on neural development

The effectiveness of interventions varies significantly across educational stages ($Q = 11.51, p = 0.021$).

Early childhood ($g = 0.70$): the most significant intervention effects were observed in early childhood, likely due to the heightened neural plasticity associated with the critical period of synaptic pruning (Richards and Conte, 2020). Knudsen (2004) systematically described the mechanisms of synaptic pruning and experience-driven synaptic stabilization during critical periods, underscoring the profound impact of early interventions on neural structures. Bahrnick and Lickliter (2012) further proposed that multisensory stimulation in early childhood (e.g., cross-modal tasks involving tactile and visual processing, selective attention training) promotes myelination in the corpus callosum and association cortices, establishing a neural foundation for creative thinking. Early intervention emphasizes implementation during the critical periods of brain development in children, as the early childhood stage is characterized by heightened neural plasticity. This period is regarded as a "window of opportunity" for neurodevelopment and represents the stage with the greatest potential for educational intervention (Albay and Eisma, 2025). Empirical studies emphasize the importance of sensory-rich, socially interactive, and cognitively challenging environments in this stage. Educational practices should prioritize the design of exploratory and creative scenarios, employing gamified tasks, social interaction, and emotional scaffolding to holistically support the development of cognitive, emotional, and social skills.

Primary and secondary education: current empirical studies indicate that intervention effects at the primary and secondary levels are not statistically significant ($p > 0.05$), warranting further exploration. Although these stages are widely regarded as critical for the rapid development of students' creative potential, the existing evidence suggests that interventions during this period have limited practical efficacy. Schleicher (2023) argued that this may be closely related to the standardized curricula and exam-oriented learning environments prevalent in current educational systems. Traditional

classrooms, typically dominated by teacher-led instruction and correct-answer-driven tasks, provide minimal opportunities for student autonomy and open-ended expression. Swan (2017) pointed out that standardized assessments constrain teaching to prescribed content, fostering a fast-paced, superficial, and fact-focused pedagogy that does not support or cultivate critical thinking. Nahar (2023) further noted that the dominance of standardized testing compels teachers to prioritize test performance, reducing time for innovative teaching and limiting the integration of critical and creative thinking training. Even when teachers possess neuroscience literacy, they often face significant systemic constraints from curriculum evaluation frameworks, instructional pacing requirements, and parental expectations, which collectively impede the effective implementation of intervention content. Preliminary literature suggests that integrating neuroscience literacy with gamified learning and project-based pedagogy (Al-Barakat et al., 2025; Drake et al., 2025) may offer viable solutions. Future studies should prioritize the exploration of brain science literacy strategies for designing contextualized, collaborative, and appropriately challenging learning tasks tailored to the developmental characteristics of students at this stage.

Higher education ($g = 0.30$): although the intervention effect in higher education is less pronounced than in early childhood, it remains meaningful. This stage primarily relies on the fine-tuned remodeling of white matter tracts, such as the superior longitudinal fasciculus (Chen et al., 2025). Sampaio-Baptista et al. (2013) and Sampaio-Baptista and Johansen-Berg (2017) demonstrated through DTI and immunohistochemical studies that significant white matter plasticity persists during the university years. While students at this stage are nearing neurological maturity, interdisciplinary learning and complex problem-solving tasks can still effectively activate the frontoparietal network, supporting abstract reasoning and cognitive reframing (Lunov, 2024). Brain science literacy-informed instructional designs incorporating multisensory input, cross-disciplinary integration, and visual learning tools can assist university students in overcoming cognitive fixation and further advancing their creative potential.

4.2 Neurofunctional differentiation across creative thinking dimensions

The moderating effects across different creative thinking measures were found to be statistically significant ($Q = 14.19$, $p = 0.007$), suggesting functional specificity within neural systems in response to brain science literacy interventions.

Originality ($g = 0.53$): originality exhibited the most substantial improvement, indicating that neuroscience-based interventions are particularly effective in enhancing the ability to generate novel and original ideas. This effect is likely linked to the synergistic activation of the prefrontal cortex and the default mode network (Beatty et al., 2015). Originality, as the most breakthrough-oriented dimension of creative thinking, signifies an individual's propensity to transcend conventional pathways and generate novel, unique solutions. Accordingly, future intervention designs should particularly focus on stimulating internal associative processes and strengthening cognitive flexibility and divergent thinking.

Fluency ($g = 0.20$) and combined creativity scores ($g = 0.26$): although the effect sizes for fluency and overall creativity scores were

smaller compared to originality, both demonstrated statistically significant improvements. Prior studies have indicated that fluency is primarily dependent on the working memory buffer capacity of the prefrontal cortex (Adiastuty et al., 2020), suggesting that brain science literacy interventions not only ignite creative ideation but also improve the efficiency of information processing and the fluidity of cognitive output. These findings underscore the importance of selecting appropriate measurement indicators based on specific educational objectives. For example, if the primary goal is to cultivate breakthrough innovation capabilities, originality-focused assessments and tasks that activate the default mode network should be emphasized. Conversely, if the aim is to strengthen rapid associative thinking, fluency-based measures should be prioritized, alongside instructional strategies that enhance working memory compatibility.

In summary, diversified interventions targeting brain science literacy not only facilitate the dissemination of neuroscientific knowledge to both teachers and students but also promote its seamless integration into creative instructional practices. Through the deep synergy between scientific theory and educational application, teachers can design developmentally appropriate, tailored intervention strategies based on students' cognitive levels and educational stages. Such an approach fosters a more profound understanding and practical competence in applying neuroscience principles within educational settings for both educators and learners.

4.3 Research limitations and implications

4.3.1 Research limitations

This study, based on a meta-analytic approach, systematically synthesized empirical evidence on the effects of brain science literacy interventions on students' creative thinking, thereby identifying multiple intervention pathways and their moderating mechanisms. Nevertheless, several limitations remain, which may affect the explanatory power and generalizability of the results:

- (1) Some of the studies included in the analysis did not provide detailed information regarding critical factors such as the duration of the brain science literacy intervention, regional context, or educational stage. The absence of systematic descriptions of intervention dosage, implementation environments, and key intervention components restricts the study's ability to offer in-depth explanations of intervention pathways and limits the applicability of personalized recommendations to specific educational settings.
- (2) Although Begg's test and fail-safe N indicate the robustness of the findings, Egger's regression suggests the potential presence of small-sample bias. Future research should prioritize the design and implementation of large-scale, multi-center, high-quality randomized controlled trials to further enhance statistical power and minimize the impact of potential biases on the conclusions.
- (3) Studies focusing on teacher professional development account for only 11% (4 out of 35) of the included research, leading to insufficient statistical power in evaluating the moderating effect of this dimension. Teachers, as the key disseminators of neuroscience literacy interventions, play a pivotal mediating role in fostering students' creativity through improvements in

their professional competence. Teachers, as the key disseminators of brain science literacy interventions, play a pivotal mediating role in fostering students' creativity through improvements in their professional competence. However, research explicitly the pathways through which teachers' brain science literacy influences students' creativity via instructional practices remains scarce, limiting a comprehensive understanding of the underlying mechanisms of the interventions.

- (4) Although the sample included in this study covered regions such as Mainland China, Taiwan, Jordan, the Philippines, Indonesia, Mexico, and certain areas of Spain, the research is still predominantly concentrated in Asia. Moreover, most Asian samples focused on developing countries in East and Southeast Asia, indicating a degree of geographical bias. While a limited number of studies from the Americas (Mexico) and Europe (Spain) contributed to the regional diversity of this analysis, the existing evidence remains largely centered in specific cultural, educational, and resource contexts. In particular, there is a notable lack of studies validating these findings within educational systems in North America, Africa, Northern Europe, and regions where less commonly spoken languages dominate. Given the substantial differences in educational systems, cultural backgrounds, and teaching practices across countries and regions, the current findings face uncertainty regarding their generalizability and cross-cultural applicability, thus limiting their potential for broader educational implementation.

4.3.2 Research implications

In light of the above findings, advancing the understanding of brain science literacy interventions requires meta-analyses that incorporate larger, more diverse, and more comprehensively reported datasets. Only through such efforts can the underlying mechanisms of these interventions be more rigorously elucidated, thereby enhancing the scientific validity and practical applicability of the conclusions. Based on this study, several targeted recommendations and implications are proposed for future research and educational practice concerning the integration of brain science literacy and creative thinking:

4.3.2.1 Align educational systems with neurodevelopmental stages to support adaptive cultivation

The development of creative thinking follows a distinct stage-specific trajectory. Primary school represents a critical period for shaping personality and fostering creative dispositions. At this stage, it is essential to prioritize the nurturing and stimulation of students' creative potential. The secondary school years serve as a key transitional phase from concrete, image-based thinking to abstract, logical reasoning, during which creative thinking gradually matures and solidifies. Guided by neuroscience literacy, secondary education should increasingly focus on cultivating students' higher-order thinking and cognitive flexibility. It is recommended that primary education incorporate multi-sensory stimulation—such as visual, auditory, and interactive experiences—to enrich learning environments. Open-ended, exploratory tasks should

be employed to activate neural connections and promote associative and imaginative thinking. In secondary education, neuroscience-informed strategies such as spaced learning, mind mapping, and emotional regulation training should be emphasized to optimize memory retention, improve abstract reasoning, and develop students' metacognitive skills in both learning and creativity.

4.3.2.2 Strengthen teachers' brain science literacy to facilitate personalized instruction

Teachers are central to the effective translation of brain science literacy into classroom practice. Their knowledge structures, pedagogical beliefs, and professional competencies directly influence whether neuroscience principles can be successfully transformed into teaching strategies that enhance students' creativity. This study highlights the significant role of brain science literacy in promoting innovative teaching models and early childhood education. It is therefore essential to systematically strengthen teachers' understanding of brain development, cognitive processing, and the neural mechanisms of creativity. Comprehensive training in brain science literacy should cover key topics such as neuroplasticity, working memory, and the interplay between emotion and cognition. Teachers should also be encouraged to design personalized, differentiated instructional activities, including varied learning pathways, optional assignments, and interest-based group projects. Such practices support students' individual cognitive profiles and learning rhythms, encouraging autonomous exploration. This approach enables the development of highly individualized, creativity-supportive learning environments that move beyond rigid, one-size-fits-all instructional models.

4.3.2.3 Innovate multimodal blended learning to activate whole-brain synergistic creativity

Neuroscience emphasizes the critical role of multi-sensory, multi-channel coordination in fostering creative thinking. Effectively integrating online personalized learning with offline collaborative and experiential practices can significantly stimulate multi-sensory perception and multimodal thinking in students. Blended learning models that seamlessly combine online and offline components provide opportunities for students to engage in personalized information retrieval, critical evaluation, and knowledge reconstruction online, thereby enhancing critical and convergent thinking. Concurrently, collaborative, project-based, and immersive offline learning experiences can stimulate divergent thinking and activate brain regions associated with abstract, multi-dimensional processing, facilitating the generation of original ideas. The integration of online and offline instructional strategies allows for a more comprehensive promotion of students' creative expression, the expansion of imagination, and the development of sophisticated problem-solving abilities.

5 Conclusion

This meta-analysis demonstrates that teachers equipped with brain science literacy and capable of applying it to classroom instructional design can effectively promote the development of

students' creative thinking, with particularly strong improvements observed in originality. Furthermore, the study reveals that various moderating factors—such as the type of brain science literacy intervention (e.g., early childhood education, innovative instructional models), dimensions of creativity measurement, and educational stage—exert significant influences on intervention outcomes. These findings suggest that future intervention designs should emphasize precise alignment between intervention types and target populations. The results not only uncover the potential mechanisms through which brain science literacy interventions foster creative thinking but also offer empirically grounded pathways and practical recommendations for educators.

Although this study systematically synthesized and quantified the overall effects of neuroscience literacy interventions, several limitations remain. These include a geographically limited sample distribution, potential small-sample biases, insufficient reporting of key intervention elements, and the possible restriction of generalizability due to differences in educational systems. Notably, the existing evidence is predominantly derived from educational contexts characterized by examination-oriented frameworks and highly standardized curricula. The applicability of these findings to decentralized management systems, project-based learning environments, and diversified curriculum structures requires further empirical validation. Given these considerations, future research should prioritize empirical investigations across diverse cultural contexts, educational governance models, and broader educational systems. In light of this, future research should prioritize empirical investigations across diverse cultural contexts, varying educational governance models, and broader educational systems. Particular attention should be given to the detailed reporting of intervention components, the expansion of sample sizes, and the accumulation of empirical data on teacher-mediated pathways. Additionally, sustained attention is needed to examine the long-term effects of interventions on the different dimensions of students' creative thinking, in order to advance the practical application and validation of brain science literacy within diverse educational settings.

Author contributions

QP: Conceptualization, Visualization, Investigation, Writing – original draft, Data curation, Software. YM: Writing – review & editing, Resources, Validation, Funding acquisition, Supervision. LZ: Supervision, Validation, Data curation, Formal analysis, Writing – review & editing. RZ: Data curation, Validation, Writing – review & editing, Supervision, Investigation, Software, Formal analysis.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that Gen AI was used in the creation of this manuscript. During the preparation of this work the authors used DeepL in order to edit English language of individual sentences and words. After using this, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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