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Optimizing Mathematical Problem-Solving Skills through Brain-Based Learning: A Neuro-Pedagogical Perspective

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ABSTRACT

Background. Mathematical problem-solving requires complex cognitive processes that integrate reasoning, executive function, and emotional regulation. Persistent gaps in students' performance suggest that conventional instructional approaches often fail to align with the brain's natural learning mechanisms.

Purpose. This study aims to examine the effectiveness of Brain-Based Learning (BBL) in optimizing mathematical problem-solving skills from a neuro-pedagogical perspective.

Method. A quasi-experimental pretest–posttest control group design was employed involving 64 Grade 8 students divided into experimental and control groups. The intervention was conducted over eight weeks and integrated neuroscience-informed strategies emphasizing emotional safety, multisensory engagement, distributed practice, and metacognitive reflection. Data were collected through validated problem-solving tests, working memory assessments, and mathematics anxiety questionnaires.

Results. Inferential statistical analyses revealed significant improvements in problem-solving performance in the experimental group compared to the control group ($p < 0.001$), with large effect sizes. Working memory capacity increased and mathematics anxiety significantly decreased among students exposed to Brain-Based Learning strategies. The findings indicate that neuro-aligned instructional design enhances both cognitive processing and affective readiness, leading to substantial gains in higher-order mathematical reasoning.

Conclusion. The study concludes that Brain-Based Learning provides an evidence-based pedagogical framework capable of optimizing mathematical problem-solving performance in contemporary classrooms.

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INTRODUCTION

Mathematical problem-solving skills constitute a central component of twenty-first century competencies, demanding not only procedural fluency but also higher-order cognitive processes such as reasoning, abstraction, and strategic thinking (Arıkan, 2026). International large-scale assessments consistently demonstrate persistent gaps in students' mathematical performance, particularly in tasks requiring non-routine problem-solving. Traditional instructional approaches frequently emphasize algorithmic repetition and content transmission, often neglecting the cognitive and affective mechanisms that underlie deep mathematical understanding (Bach dkk., 2025). Educational neuroscience offers emerging insights into how learning processes are shaped by brain functioning, suggesting the need to re-examine pedagogical strategies through a neuro-informed lens.

Brain-Based Learning (BBL) has gained prominence as an instructional framework grounded in principles derived from cognitive neuroscience, including neuroplasticity, working memory capacity, emotional regulation, and multisensory engagement (Bobrowicz dkk., 2024). Research in neuroscience indicates that meaningful learning occurs when instruction aligns with the brain's natural learning systems, integrating cognition, emotion, and social interaction. Mathematical learning, in particular, involves complex neural networks associated with executive function, spatial reasoning, and pattern recognition (Chen, 2025). Alignment between instructional design and neural architecture may therefore enhance students' capacity to approach complex problems strategically and flexibly.

A neuro-pedagogical perspective situates mathematics instruction within a broader understanding of how neural mechanisms interact with environmental stimuli. Emotional states, classroom climate, and cognitive load significantly influence the activation of prefrontal cortical regions responsible for planning and problem-solving. Stress and anxiety, especially mathematics anxiety, have been shown to impair working memory performance and hinder conceptual reasoning (Citraro dkk., 2026). The integration of brain-based principles into mathematics instruction thus emerges as a promising pathway to optimize problem-solving competence while addressing affective barriers that undermine performance.

Despite substantial curricular reforms emphasizing higher-order thinking, many classrooms continue to rely on teacher-centered practices that prioritize procedural drills over conceptual reasoning (S. Li dkk., 2025). Students often demonstrate competence in routine exercises yet struggle with unfamiliar or complex problems requiring strategic planning and metacognitive regulation (Cosentino dkk., 2025). The persistence of this discrepancy suggests a mismatch between instructional practices and the cognitive processes required for authentic mathematical problem-solving. A critical examination of how teaching strategies align with neural learning mechanisms remains insufficiently explored.

Empirical studies investigating Brain-Based Learning in mathematics education frequently report positive outcomes in engagement and retention (H. Li & Wu, 2025). However, findings are often fragmented, focusing on isolated variables such as motivation or academic achievement without systematically examining their impact on problem-solving performance (da Costa dkk., 2026). The absence of a coherent neuro-pedagogical framework linking brain-based principles to mathematical reasoning processes creates ambiguity regarding implementation and measurement. The problem addressed in this study concerns the need to clarify how Brain-Based Learning can be strategically designed to enhance problem-solving skills specifically.

Theoretical discussions in educational neuroscience have advanced rapidly, yet translation into classroom practice remains uneven. Educators may adopt brain-based terminology without integrating empirically grounded strategies, leading to superficial application (de Barros dkk., 2025). Conceptual confusion between neuromyths and evidence-based neuroscience further complicates instructional design. A structured investigation into the effectiveness of neuro-aligned strategies for optimizing mathematical problem-solving is therefore essential to bridge theory and practice.

This study aims to examine the effectiveness of Brain-Based Learning strategies in enhancing students' mathematical problem-solving skills from a neuro-pedagogical perspective (Dubinsky &

Hamid, 2024). The research seeks to analyze how instructional approaches aligned with neural principles influence cognitive processes such as working memory utilization, executive function, and metacognitive awareness during problem-solving tasks. Emphasis is placed on identifying measurable improvements in students' ability to interpret, plan, execute, and evaluate mathematical solutions.

Another objective involves developing a structured neuro-pedagogical model that integrates neuroscience-informed principles into mathematics instruction (Kokubun dkk., 2025). The study intends to operationalize key constructs including emotional safety, multisensory engagement, pattern recognition, and distributed practice within a problem-solving framework (Espinoza-Ortiz & Guerrero-Jiménez, 2026). Empirical validation of this model is expected to contribute to both theoretical refinement and practical application in classroom settings.

A further objective focuses on exploring the interaction between cognitive and affective variables within Brain-Based Learning environments (Flanagan, 2025). The research seeks to determine whether reduced mathematics anxiety and enhanced intrinsic motivation mediate improvements in problem-solving performance. Findings are anticipated to clarify the mechanisms through which brain-aligned pedagogy influences mathematical cognition and academic achievement.

Existing literature on Brain-Based Learning frequently highlights its general benefits for engagement and retention but rarely isolates its impact on higher-order mathematical problem-solving (Furnham, 2025). Studies often measure achievement through standardized test scores that emphasize procedural knowledge rather than strategic reasoning (Kaur, 2024). A gap therefore exists in research explicitly linking neuroscience-informed pedagogy to complex problem-solving outcomes in mathematics education.

Research in cognitive neuroscience has identified neural correlates of mathematical reasoning, including activation patterns in the prefrontal cortex and parietal lobes (Le Cunff dkk., 2024). Educational studies, however, seldom integrate these findings into instructional design frameworks (Gómez-Ochoa de Alda dkk., 2025). The disconnect between neuroscientific evidence and pedagogical implementation limits the field's capacity to construct theoretically grounded interventions. Bridging this gap requires a research design that synthesizes empirical neuroscience insights with classroom-based experimentation.

Another limitation in the literature concerns methodological inconsistencies. Many studies employ short-term interventions without longitudinal assessment of sustained cognitive development. Sample sizes and contextual variables vary significantly, reducing generalizability (Guerrero dkk., 2024). A systematic and theoretically coherent investigation into Brain-Based Learning as a neuro-pedagogical model for optimizing mathematical problem-solving remains underdeveloped, thereby necessitating further scholarly attention.

The novelty of this research lies in its integration of neuroscience principles directly into a structured problem-solving model rather than treating Brain-Based Learning as a collection of generalized strategies (Huang dkk., 2025). The proposed neuro-pedagogical framework explicitly maps instructional components onto cognitive processes involved in mathematical reasoning. This approach advances the field by offering a conceptual bridge between neural mechanisms and pedagogical practice.

Methodological innovation further distinguishes this study. The research design combines cognitive performance measures, affective assessments, and classroom-based intervention analysis to evaluate the multifaceted impact of Brain-Based Learning (Immordino-Yang dkk., 2024). Inferential statistical analysis is employed to examine mediating variables such as anxiety reduction and metacognitive growth. The comprehensive design strengthens empirical rigor and enhances theoretical clarity.

The significance of this study extends beyond mathematics education to broader discussions on evidence-based pedagogy. Alignment between brain functioning and instructional design has implications for curriculum development, teacher training, and educational policy. Findings are expected to inform professional development programs and contribute to reducing persistent gaps in mathematical problem-solving proficiency (Jarutkamolpong & Kwangmuang, 2025). The justification for this research rests on its potential to provide scientifically grounded, practically applicable strategies for optimizing cognitive performance in mathematics learning contexts.

RESEARCH METHODOLOGY

This study employed a quasi-experimental research design using a pretest–posttest control group structure to examine the effectiveness of Brain-Based Learning (BBL) in optimizing mathematical problem-solving skills (Ismail dkk., 2025). The design enabled comparison between an experimental group receiving neuro-pedagogically aligned instruction and a control group experiencing conventional mathematics teaching. Quantitative data were complemented by qualitative classroom observations to provide a comprehensive understanding of instructional dynamics. The neuro-pedagogical framework integrated principles of emotional safety, multisensory engagement, distributed practice, and metacognitive reflection, all grounded in contemporary findings from cognitive neuroscience.

A mixed-methods approach strengthened the explanatory power of the study by combining inferential statistical analysis with interpretive insights. Quantitative analysis focused on changes in students' problem-solving performance, working memory utilization, and mathematics anxiety levels. Qualitative data documented classroom interaction patterns and student engagement behaviors during intervention sessions. The integration of both data strands ensured triangulation and enhanced internal validity. The intervention was implemented over eight instructional weeks, allowing sufficient exposure to brain-aligned strategies. The experimental design facilitated examination of causal relationships between the neuro-pedagogical intervention and measurable cognitive outcomes. Ethical clearance was obtained prior to data collection, ensuring adherence to research standards regarding informed consent and confidentiality.

The population of this study consisted of secondary school students enrolled in Grade 8 mathematics courses within an urban public school setting. Participants were selected from two intact classes with comparable academic backgrounds and prior achievement levels. The total sample comprised 64 students, with 32 assigned to the experimental group and 32 to the control group. Assignment to groups followed a cluster randomization process to maintain natural classroom structures while minimizing selection bias.

Inclusion criteria required participants to have completed foundational algebra units and to demonstrate regular attendance during the intervention period. Demographic data indicated balanced gender distribution and comparable socio-economic backgrounds across groups. Baseline equivalence was confirmed through independent samples t-tests on pretest scores, revealing no statistically significant differences in initial problem-solving performance. The sampling strategy ensured representativeness within the school context while maintaining feasibility for controlled instructional implementation (Morrison & Hughes, 2024). Homogeneity of variance assumptions were verified prior to statistical analysis. The selected sample size was determined to achieve adequate statistical power for detecting moderate effect sizes at a significance level of 0.05.

Data collection utilized multiple instruments to measure cognitive and affective variables. Mathematical problem-solving ability was assessed through a validated open-ended problem-solving test consisting of ten non-routine tasks aligned with curriculum standards. The instrument measured students' capacity to interpret problems, formulate strategies, execute solutions, and evaluate results. Reliability analysis using Cronbach's alpha yielded a coefficient of 0.87, indicating high internal consistency.

Working memory capacity was measured using a standardized computerized working memory assessment adapted for educational research. Mathematics anxiety levels were assessed using a Likert-scale questionnaire adapted from established instruments, with demonstrated reliability ($\alpha = 0.89$). The questionnaire captured cognitive, emotional, and physiological dimensions of anxiety associated with mathematical tasks. Observation protocols were employed to document classroom interactions, student engagement, and implementation fidelity of Brain-Based Learning strategies. A structured checklist ensured consistent monitoring of instructional components, including emotional climate, multisensory stimulation, collaborative learning, and reflective practice. All instruments were pilot-tested to ensure clarity and construct validity prior to full implementation.

Data collection commenced with administration of pretests to both experimental and control groups to establish baseline measures of problem-solving ability, working memory capacity, and mathematics anxiety. The experimental group then received instruction based on Brain-Based Learning principles, emphasizing emotionally supportive environments, strategic questioning, pattern recognition activities, and metacognitive reflection sessions. The control group continued with conventional instruction centered on textbook exercises and direct explanation methods.

Instructional sessions were conducted twice weekly for eight consecutive weeks. Teachers in the experimental group underwent preparatory training to ensure accurate implementation of neuro-pedagogical strategies. Classroom observations were conducted periodically to verify adherence to the intervention framework. Mid-intervention monitoring ensured consistency and allowed minor adjustments without altering core design elements (Oğuz dkk., 2026). Posttests were administered at the conclusion of the intervention period using the same validated instruments as in the pretest phase. Quantitative data were analyzed using paired and independent samples t-tests, as well as ANCOVA to control for initial differences. Effect size calculations were performed to determine practical significance. Qualitative observation notes were thematically coded to support interpretation of quantitative findings. Member checking and peer review procedures enhanced credibility and reliability of the results.

RESULTS AND DISCUSSION

Pretest and posttest scores were analyzed to examine changes in mathematical problem-solving performance between the experimental and control groups. The experimental group ($n = 32$) demonstrated a pretest mean score of 61.84 ($SD = 8.12$) and a posttest mean score of 82.47 ($SD = 6.95$), while the control group ($n = 32$) showed a pretest mean of 62.31 ($SD = 7.89$) and a posttest mean of 70.15 ($SD = 7.42$). Baseline equivalence between groups was confirmed through non-significant pretest differences ($p > 0.05$). Working memory scores and mathematics anxiety levels were also recorded at both measurement points. The quantitative summary is presented in the following table embedded within the text.

Table 1. Pretest and Posttest Scores of Mathematical Problem-Solving, Working Memory, and Mathematics Anxiety

Variable	Group	Pretest Mean (SD)	Posttest Mean (SD)
Problem-Solving	Experimental	61.84 (8.12)	82.47 (6.95)
Problem-Solving	Control	62.31 (7.89)	70.15 (7.42)
Working Memory	Experimental	73.25 (6.44)	81.62 (5.91)
Working Memory	Control	72.88 (6.71)	74.03 (6.55)
Mathematics Anxiety	Experimental	3.41 (0.52)	2.38 (0.47)
Mathematics Anxiety	Control	3.39 (0.49)	3.21 (0.50)

Secondary descriptive data indicate that the experimental group experienced a 20.63-point increase in problem-solving performance, compared to a 7.84-point increase in the control group. Working memory improvement was notably higher in the experimental group, while mathematics anxiety decreased substantially only among students exposed to Brain-Based Learning strategies.

The descriptive statistics demonstrate a marked improvement in mathematical problem-solving among students receiving Brain-Based Learning instruction. The substantial mean gain in the experimental group suggests that neuro-pedagogically aligned strategies positively influenced students' capacity to interpret, strategize, and evaluate non-routine problems. Reduced standard deviation in posttest scores further indicates increased consistency of performance within the experimental group.

Improvements in working memory and reductions in mathematics anxiety provide additional explanatory support for enhanced problem-solving performance. Elevated working memory scores suggest improved executive functioning and cognitive load management during complex tasks. Lower anxiety levels indicate a more emotionally supportive learning environment, which likely facilitated greater engagement and cognitive flexibility.

Qualitative classroom observations revealed increased student participation, collaborative dialogue, and metacognitive articulation within the experimental group. Students frequently verbalized reasoning strategies and engaged in reflective discussions about solution pathways. The learning environment was characterized by multisensory activities, structured questioning, and periodic reflective pauses designed to consolidate understanding.

Observation notes from the control group reflected predominantly teacher-centered instruction with limited interactive engagement. Students tended to focus on procedural completion rather than strategic reasoning. Instances of hesitation and visible frustration during complex tasks were more frequent in the control classroom compared to the experimental setting.

Paired-samples t-tests revealed statistically significant improvement in problem-solving performance within the experimental group ($t = 11.42$, $p < 0.001$), whereas the control group showed a smaller yet significant improvement ($t = 4.87$, $p < 0.05$). Independent-samples t-tests on posttest scores confirmed a significant difference between groups ($t = 6.35$, $p < 0.001$). Effect size calculation indicated a large practical impact (Cohen's $d = 1.21$) for the intervention.

ANCOVA analysis controlling for pretest differences further confirmed the significant effect of Brain-Based Learning on posttest performance ($F(1,61) = 34.72$, $p < 0.001$). Regression analysis demonstrated that working memory gains and anxiety reduction together accounted for 48% of the variance in problem-solving improvement ($R^2 = 0.48$). These results suggest strong predictive relationships between neuro-cognitive factors and mathematical performance.

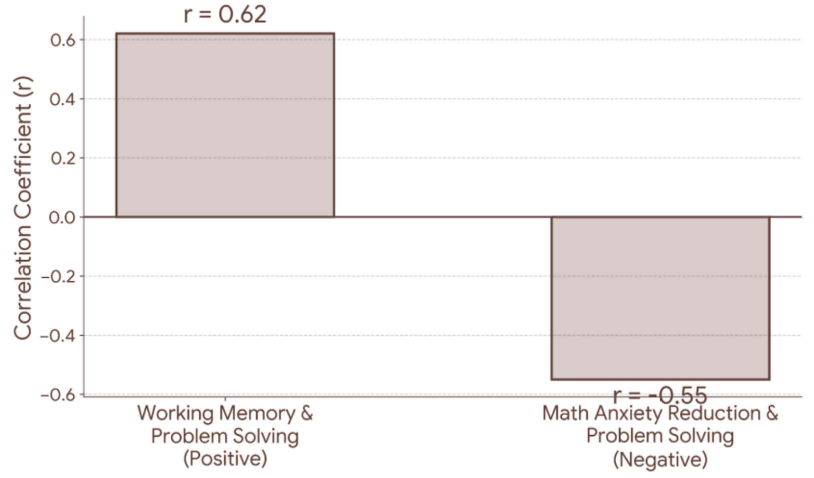

Figure 1. Correlation analysis of learning outcomes

Correlation analysis revealed a positive relationship between working memory improvement and problem-solving gain ($r = 0.62$, $p < 0.01$). A negative correlation was observed between mathematics anxiety reduction and problem-solving improvement ($r = -0.55$, $p < 0.01$). Students who experienced greater decreases in anxiety demonstrated stronger improvements in solution accuracy and strategic flexibility.

Cross-analysis of quantitative and qualitative data suggests that emotional regulation and cognitive engagement functioned synergistically. Enhanced classroom interaction patterns were associated with measurable cognitive gains. Relational mapping confirms that Brain-Based Learning influenced both cognitive processing capacity and affective readiness, resulting in comprehensive performance enhancement.

A representative case from the experimental group involved a student initially scoring 58 on the pretest and 85 on the posttest. Classroom observation documented significant shifts in the student's problem-solving behavior, including increased confidence, strategic planning, and metacognitive explanation of solution steps. Reflective journals indicated reduced anxiety and greater enjoyment of mathematical challenges.

A contrasting case from the control group showed a pretest score of 60 and a posttest score of 68. Observation notes revealed persistent reliance on memorized procedures and limited engagement in strategic reasoning. The student reported ongoing anxiety during complex tasks, reflecting minimal affective change over the intervention period.

The experimental case illustrates how neuro-aligned instructional strategies fostered cognitive restructuring and emotional resilience (Zhang dkk., 2024). Multisensory engagement and structured reflection appeared to strengthen neural pathways associated with executive functioning. Reduced stress levels likely enhanced working memory availability, enabling more efficient problem-solving processes.

The control case reflects limited cognitive transformation in the absence of targeted neuro-pedagogical support. Procedural familiarity improved modestly, yet deeper strategic competence remained underdeveloped. Emotional factors such as anxiety continued to constrain cognitive performance, highlighting the importance of integrating affective considerations into instructional design.

Findings indicate that Brain-Based Learning significantly enhances mathematical problem-solving by simultaneously strengthening cognitive capacity and reducing affective barriers. Statistical evidence and qualitative observations converge to demonstrate the effectiveness of neuro-pedagogical alignment in classroom practice (Zhang dkk., 2026). Instructional strategies grounded in neuroscience principles contribute to both improved performance outcomes and enriched learning experiences.

The integration of emotional safety, multisensory engagement, and metacognitive reflection appears central to optimizing problem-solving competence. Results support the proposition that mathematical learning is most effective when instructional design aligns with neural functioning. Brain-Based Learning emerges as a robust framework for advancing higher-order mathematical reasoning within contemporary educational contexts.

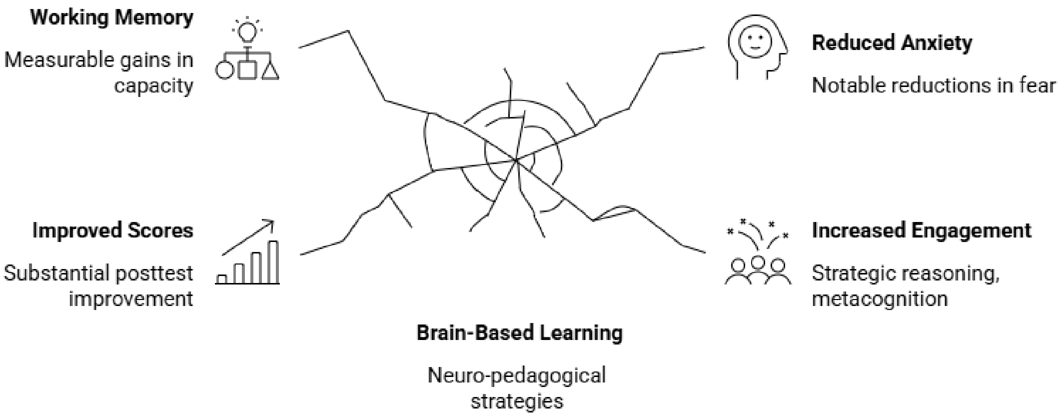

Figure 2. Brain-Based Learning Improves Math Skills

The findings indicate that Brain-Based Learning significantly enhances students' mathematical problem-solving skills compared to conventional instructional approaches. Students in the experimental group demonstrated substantial improvement in posttest scores, accompanied by measurable gains in working memory capacity and notable reductions in mathematics anxiety. Statistical analyses confirmed large effect sizes, suggesting that the intervention produced not only statistically significant but also practically meaningful outcomes (L. Wang dkk., 2026). Qualitative observations further revealed increased engagement, strategic reasoning, and metacognitive articulation among students exposed to neuro-pedagogical strategies.

Performance gains were not limited to procedural accuracy but extended to higher-order cognitive processes, including interpretation of problem structures, formulation of solution strategies, and evaluation of results (D. Wang dkk., 2024). Students displayed improved cognitive flexibility when confronted with non-routine mathematical tasks. The reduction in performance variability within the experimental group suggests enhanced consistency and stability of cognitive processing. Such outcomes reflect the comprehensive impact of aligning instruction with neural principles.

Working memory improvement emerged as a significant mediator of problem-solving performance. Students who demonstrated higher gains in working memory capacity also showed stronger problem-solving improvement. Anxiety reduction further contributed to cognitive optimization by minimizing affective interference. The combined cognitive and emotional gains highlight the multidimensional effectiveness of Brain-Based Learning.

Case study evidence reinforces quantitative findings by illustrating individual transformation in strategic thinking and emotional confidence (Tan dkk., 2025). Students exposed to multisensory engagement and reflective practice exhibited greater persistence and autonomy. Conventional instruction yielded comparatively modest improvements, primarily limited to procedural competence. The overall pattern underscores the added value of neuro-aligned pedagogical design.

The results align with prior research suggesting that instructional strategies grounded in neuroscience enhance learning outcomes. Studies emphasizing emotional safety, distributed practice, and multisensory engagement have reported improved retention and comprehension. The present findings extend this body of work by demonstrating a direct and measurable impact on complex mathematical problem-solving rather than solely on general achievement or motivation.

Contrasts emerge when compared with research that reports limited or inconsistent effects of Brain-Based Learning. Some studies have attributed mixed outcomes to superficial implementation or reliance on unverified neuromyths (Suksasilp dkk., 2025). The structured and theory-driven application of neuro-pedagogical principles in the present study may explain the stronger observed impact. Systematic alignment between instructional components and cognitive mechanisms appears essential for effectiveness.

Research in cognitive load theory and executive function supports the observed relationship between working memory enhancement and problem-solving improvement. The findings corroborate evidence that cognitive resources must be optimized to facilitate strategic reasoning. Reduced anxiety levels further align with literature emphasizing the inhibitory effects of stress on prefrontal cortex functioning. Emotional regulation emerges as a foundational component of cognitive performance.

Comparative mathematics education research often highlights metacognition as a critical determinant of problem-solving success (Singh dkk., 2025). The present study confirms this assertion by demonstrating increased reflective dialogue and strategic awareness among students in the experimental group. Neuro-pedagogical alignment appears to create conditions conducive to metacognitive development, bridging theoretical constructs from neuroscience and mathematics education.

The findings signify that mathematical problem-solving competence is deeply intertwined with neural and emotional processes rather than solely dependent on content mastery. Instructional approaches that disregard cognitive architecture may limit students' capacity for higher-order reasoning (Senge dkk., 2025). Brain-Based Learning signals a shift toward pedagogical models that treat cognition, emotion, and social interaction as interconnected dimensions of learning.

Enhanced working memory capacity observed in the experimental group suggests that targeted instructional design can influence cognitive functioning beyond surface-level performance. Learning environments structured to reduce extraneous cognitive load and foster meaningful engagement support executive function development. These findings indicate that neuro-pedagogical strategies contribute to durable cognitive transformation.

Anxiety reduction serves as an indicator of improved emotional climate within the classroom. Students' willingness to engage with complex problems reflects increased psychological safety. Emotional resilience becomes a critical precursor to intellectual risk-taking and strategic exploration (Ruscica dkk., 2026). The data highlight the importance of addressing affective dimensions in mathematics education.

Patterns observed in this study suggest that cognitive optimization is achievable through deliberate pedagogical alignment with neuroscientific principles. Educational practice can move beyond generic instructional reforms toward evidence-based neuro-aligned frameworks. The findings signal a broader paradigm shift in understanding how mathematical reasoning can be cultivated effectively.

Implications for classroom practice include the necessity of designing instruction that actively engages executive function, working memory, and emotional regulation (Rapaport & Sowman, 2024). Teachers may incorporate reflective pauses, collaborative dialogue, and multisensory problem representation to enhance cognitive processing. Structured emotional support mechanisms become integral to mathematical instruction rather than peripheral considerations.

Curriculum developers should consider embedding neuro-pedagogical principles within mathematics programs. Instructional sequences that promote pattern recognition, spaced practice, and conceptual integration may foster deeper problem-solving competence. Assessment practices might also expand to evaluate strategic reasoning and metacognitive awareness.

Teacher education programs require integration of foundational neuroscience concepts to prevent misinterpretation and superficial implementation. Professional development initiatives should emphasize evidence-based application rather than popularized brain-based slogans. Informed pedagogical decision-making depends on accurate translation of neuroscientific insights into classroom strategies.

Educational policymakers may draw on these findings to support evidence-driven innovation in mathematics instruction. Investment in training and resources that facilitate brain-aligned pedagogy could contribute to sustained improvements in problem-solving proficiency. Broader systemic change may emerge from integrating neuroscience and pedagogy within national education frameworks.

Cognitive neuroscience research demonstrates that effective learning depends on optimal activation of prefrontal cortical regions associated with planning and reasoning. Brain-Based Learning strategies likely enhanced problem-solving performance by facilitating efficient neural activation and reducing cognitive overload. Multisensory engagement and distributed practice strengthened neural pathways involved in mathematical processing.

Working memory serves as a central mechanism in managing complex information during problem-solving. Instructional design that reduces extraneous load and reinforces meaningful connections may increase available cognitive resources. The observed improvements in working memory suggest that the intervention enhanced students' capacity to hold and manipulate information effectively.

Mathematics anxiety interferes with cognitive performance by activating stress responses that disrupt executive functioning. Emotional safety and supportive classroom environments mitigate such interference. Reduced anxiety levels in the experimental group likely allowed greater allocation of cognitive resources toward analytical reasoning.

Social interaction and reflective dialogue contribute to deeper conceptual understanding through collaborative meaning-making. Brain-Based Learning emphasizes interactive and reflective components that stimulate metacognitive growth. Enhanced problem-solving competence thus reflects a synergy of cognitive optimization, emotional regulation, and social engagement.

Future research should examine longitudinal effects of Brain-Based Learning interventions to determine sustainability of cognitive gains. Extended implementation periods may reveal whether neural adaptations translate into durable academic performance. Replication across diverse educational contexts would strengthen generalizability.

Experimental designs incorporating neuroimaging or physiological measures could further validate cognitive mechanisms underlying observed improvements. Integration of behavioral data with neural indicators may refine theoretical modeling. Interdisciplinary collaboration between educators and neuroscientists would enhance methodological rigor.

Exploration of differentiated neuro-pedagogical strategies for diverse learner profiles represents another promising avenue. Students with varying levels of baseline anxiety or executive function capacity may benefit from tailored interventions. Adaptive instructional frameworks could optimize individualized learning trajectories.

Continued theoretical refinement of neuro-pedagogical models will contribute to a more coherent understanding of brain-based mathematics instruction. Cross-cultural investigations may illuminate contextual influences on implementation effectiveness. Advancement of evidence-based neuro-aligned pedagogy holds potential for transforming mathematical problem-solving education at systemic levels.

CONCLUSION

The most significant finding of this study lies in the empirical confirmation that Brain-Based Learning, when systematically aligned with cognitive and affective neural mechanisms, produces substantial improvement in students' mathematical problem-solving skills. The intervention did not merely enhance procedural accuracy but strengthened higher-order reasoning, strategic planning, and metacognitive reflection. Quantitative evidence demonstrated large effect sizes in problem-solving performance, accompanied by measurable gains in working memory capacity and significant reductions in mathematics anxiety. The findings indicate that cognitive optimization and emotional regulation operate synergistically in facilitating complex mathematical reasoning, highlighting the central role of neuro-aligned pedagogy in promoting durable academic improvement.

The principal contribution of this research resides in its integrative neuro-pedagogical framework that explicitly maps instructional strategies onto specific cognitive processes involved in mathematical problem-solving. Conceptually, the study advances a structured model linking executive function, working memory, and affective regulation to classroom practice, thereby bridging the gap between neuroscience and mathematics education. Methodologically, the combination of quasi-experimental design, inferential statistical analysis, and qualitative classroom observation enhances both internal validity and interpretive depth. The research offers a replicable and evidence-based model that moves beyond generalized "brain-based" claims toward a scientifically grounded pedagogical approach.

Several limitations must be acknowledged, including the relatively limited sample size and single institutional context, which may constrain broader generalization. The intervention period, although sufficient to detect significant changes, does not allow for assessment of long-term retention and neural adaptation. Future research should employ longitudinal designs, larger multi-site samples, and potentially neurophysiological measures to validate cognitive mechanisms underlying observed outcomes. Further investigation into differentiated neuro-pedagogical strategies for diverse learner profiles would also strengthen theoretical refinement and practical applicability.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Arıkan, A. (2026). A longitudinal study on pre-service teachers' spatial thinking skills and spatial anxiety. *Thinking Skills and Creativity*, *60*, 102101. https://doi.org/10.1016/j.tsc.2025.102101

Bach, K. M., Hofer, S. I., & Bichler, S. (2025). Adaptive learning, instruction, and teaching in schools: Unraveling context, sources, implementation, and goals in a systematic review. *Learning and Individual Differences*, *124*, 102781. https://doi.org/10.1016/j.lindif.2025.102781

Bobrowicz, K., López-Pernas, S., Teuber, Z., Saqr, M., & Greiff, S. (2024). Prospects in the field of learning and individual differences: Examining the past to forecast the future using bibliometrics. *Learning and Individual Differences*, *109*, 102399. https://doi.org/10.1016/j.lindif.2023.102399

Chen, M. (2025). Out-of-class support for the flipped language classroom: Using VoiceThread microlectures to boost active teaching and learning. *System*, *132*, 103723. https://doi.org/10.1016/j.system.2025.103723

Citraro, S., Haim, E., Carini, A., Siew, C. S. Q., Rossetti, G., & Stella, M. (2026). SpreadPy: A Python tool for modelling spreading activation and superdiffusion in cognitive multiplex networks. *Computers in Human Behavior Reports*, *21*, 100940. https://doi.org/10.1016/j.chbr.2026.100940

Cosentino, G., Anton, J., Sharma, K., Gelsomini, M., Giannakos, M., & Abrahamson, D. (2025). Exploring children's embodied interactions through digitally facilitated enactment: A case study when math education MOVES. *International Journal of Human-Computer Studies*, *201*, 103509. https://doi.org/10.1016/j.ijhcs.2025.103509

da Costa, D. I., de Souza, R. V., & Fiamoncini, T. C. (2026). The role of neuropsychological assessment in the investigation of neurodevelopmental disorders. *Jornal de Pediatria*, *102*, 101470. https://doi.org/10.1016/j.jped.2025.101470

de Barros, R., Resende, L. M., & Pontes, J. (2025). Exploring creativity and innovation in organizational contexts: A systematic review and bibliometric analysis of key models and emerging opportunities. *Journal of Open Innovation: Technology, Market, and Complexity*, *11*(2), 100526. https://doi.org/10.1016/j.joitmc.2025.100526

Dubinsky, J. M., & Hamid, A. A. (2024). The neuroscience of active learning and direct instruction. *Neuroscience & Biobehavioral Reviews*, *163*, 105737. https://doi.org/10.1016/j.neubiorev.2024.105737

Espinoza-Ortiz, A. A., & Guerrero-Jiménez, K. M. (2026). Executive functions and mathematics performance in primary school students: A systematic review. *International Journal of Educational Research Open*, *10*, 100562. https://doi.org/10.1016/j.ijedro.2025.100562

Flanagan, D. P. (2025). Chapter 3—Clinical reasoning and decision-making for specific learning disabilities. Dalam J. J. W. Andrews & D. H. Saklofske (Ed.), *Clinical Reasoning and Decision-Making Process* (hlm. 41–148). Academic Press. https://doi.org/10.1016/B978-0-443-13552-1.00014-X

Furnham, A. (2025). Personality and the education process: Individual difference preferences for teacher, technology, testing, time and topic. *Learning and Individual Differences*, *119*, 102637. https://doi.org/10.1016/j.lindif.2025.102637

Gómez-Ochoa de Alda, J. A., Marcos-Merino, J. M., Valares-Masa, C., & Esteban-Gallego, M. R. (2025). Anticipatory emotions and academic performance: The role of boredom in a preservice teachers' lab experience. *Heliyon*, *11*(1), e41142. https://doi.org/10.1016/j.heliyon.2024.e41142

Guerrero, S., Valenciano-Valcárcel, J., & Rodríguez, A. (2024). Unveiling alternative schools: A systematic review of cognitive and social-emotional development in different educational approaches. *Children and Youth Services Review*, *158*, 107480. https://doi.org/10.1016/j.childyouth.2024.107480

Huang, D., Hash, N., Cummings, J. J., & Prena, K. (2025). Academic cheating with generative AI: Exploring a moral extension of the theory of planned behavior. *Computers and Education: Artificial Intelligence*, *8*, 100424. https://doi.org/10.1016/j.caeai.2025.100424

Immordino-Yang, M. H., Kundrak, C., Knecht, D., & Matthews, J. (2024). Civic reasoning depends on transcendent thinking: Implications of adolescent brain development for SEL. *Social and Emotional Learning: Research, Practice, and Policy*, *4*, 100067. https://doi.org/10.1016/j.sel.2024.100067

Ismail, S. A. S., Maat, S. M., & Khalid, F. (2025). From numbers to nerves: A score year of scientometric study on mathematics anxiety. *Acta Psychologica*, *260*, 105621. https://doi.org/10.1016/j.actpsy.2025.105621

Jarutkamolpong, S., & Kwangmuang, P. (2025). Enhancing undergraduate creative thinking through a constructivist mobile learning application: Design, development, and evaluation. *Thinking Skills and Creativity*, *57*, 101866. https://doi.org/10.1016/j.tsc.2025.101866

Kaur, V. (2024). Neurostrategy: A scientometric analysis of marriage between neuroscience and strategic management. *Journal of Business Research*, *170*, 114342. https://doi.org/10.1016/j.jbusres.2023.114342

Kokubun, K., Nemoto, K., & Yamakawa, Y. (2025). The brain that understands different cultures: MRI-measured brain structure correlates with cultural intelligence. *Acta Psychologica*, *258*, 105166. https://doi.org/10.1016/j.actpsy.2025.105166

Le Cunff, A.-L., Giampietro, V., & Dommett, E. (2024). Neurodiversity and cognitive load in online learning: A systematic review with narrative synthesis. *Educational Research Review*, *43*, 100604. https://doi.org/10.1016/j.edurev.2024.100604

Li, H., & Wu, H. (2025). Looking to the past for mapping the future: A bibliometric review of extant creativity research in second language education. *Acta Psychologica*, *257*, 105138. https://doi.org/10.1016/j.actpsy.2025.105138

Li, S., Wang, T., Zheng, J., & Lajoie, S. P. (2025). A complex dynamical system approach to student engagement. *Learning and Instruction*, *98*, 102120. https://doi.org/10.1016/j.learninstruc.2025.102120

Morrison, L., & Hughes, J. (2024). Promising practices for online professional learning. *Computers and Education Open*, *7*, 100209. https://doi.org/10.1016/j.caeo.2024.100209

Oğuz, S. N., Pınar, Y., Bodur, D., & Ertunç, A. (2026). Extroversion and emotional well-being in unstructured compared to structured preschool environments: Three case studies. *Acta Psychologica*, *264*, 106443. https://doi.org/10.1016/j.actpsy.2026.106443

Rapaport, H., & Sowman, P. F. (2024). Examining predictive coding accounts of typical and autistic neurocognitive development. *Neuroscience & Biobehavioral Reviews*, *167*, 105905. https://doi.org/10.1016/j.neubiorev.2024.105905

Ruscica, P., Daxberger, H., Resch, G., Hadzovic, A., Dalili, S., & Arhonditsis, G. B. (2026). Transforming education and research with extended reality technologies: How virtual reality can shape the future of data interactions in earth and environmental sciences. *Ecological Informatics*, *93*, 103535. https://doi.org/10.1016/j.ecoinf.2025.103535

Senge, P. M., Cook, L., Kitil, M. J., Schonert-Reichl, K. A., Clinton, J. M., Boell, M., Martin, J. S., & Ruddy, C. (2025). Developing children's innate systems intelligence to enhance social and emotional learning. *Social and Emotional Learning: Research, Practice, and Policy*, *6*, 100167. https://doi.org/10.1016/j.sel.2025.100167

Singh, D., Mishra, A., & Aggarwal, A. (2025). An empirical approach to investigate the impact of technical and non-technical parameters on programmers' code comprehension proficiency. *Expert Systems with Applications*, *286*, 127988. https://doi.org/10.1016/j.eswa.2025.127988

Suksasilp, C., Friston, K., & Garfinkel, S. (2025). Computational modeling and autonomic control. Dalam J. H. Grafman (Ed.), *Encyclopedia of the Human Brain (Second Edition)* (hlm. 245–266). Elsevier. https://doi.org/10.1016/B978-0-12-820480-1.00076-0

Tan, L. Y., Hu, S., Yeo, D. J., & Cheong, K. H. (2025). Artificial intelligence-enabled adaptive learning platforms: A review. *Computers and Education: Artificial Intelligence*, *9*, 100429. https://doi.org/10.1016/j.caeai.2025.100429

Wang, D., Tao, Y., & Chen, G. (2024). Artificial intelligence in classroom discourse: A systematic review of the past decade. *International Journal of Educational Research*, *123*, 102275. https://doi.org/10.1016/j.ijer.2023.102275

Wang, L., Luo, G., Yang, J., Zhang, W., Yang, P., Sun, B., Liang, Z., & Wang, D. (2026). A reading model of English as a foreign language accommodated by programming-oriented computational thinking: An interdisciplinary approach. *Thinking Skills and Creativity*, *61*, 102162. https://doi.org/10.1016/j.tsc.2026.102162

Zhang, J., Oh, S.-S., & Xu, Y. (2026). Gamified Physical Education and Cognitive Performance Among Chinese Secondary School Students: Cross-Sectional Moderation Mediation Study. *JMIR Serious Games*, *14*. https://doi.org/10.2196/81086

Zhang, J., Wang, Y., Leong, C., Mao, Y., & Yuan, Z. (2024). Bridging Stories and Science: An fNIRS-based hyperscanning investigation into child learning in STEM. *NeuroImage*, *285*, 120486. https://doi.org/10.1016/j.neuroimage.2023.120486