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Effect of Brain-Based Learning on Students' Academic Achievement in Mathematics at Secondary Level: A Quasi-Experimental Investigation Across Stratified Ability Tiers

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Abstract

The study highlights the difference between traditional instructional pedagogies and neuro-compatible teaching frameworks at secondary education in the subject of mathematics. The study evaluated the comparative effectiveness of brain-based learning (BBL) versus conventional teacher-centered lectures on the academic achievement of secondary school students in mathematics across high, average, and low achievement strata. A quantitative quasi-experimental pre-test/post-test non-equivalent control group design was implemented with 60 Grade 9 students ($n = 30$ experimental, $n = 30$ control) in public secondary schools of Sialkot district, Pakistan. Participants were stratified into high ($n = 10$), average ($n = 10$), and low ($n = 10$) achievement sub-groups based on prior annual examination scores. The experimental cohort underwent an 8-week intervention integrating Caine and Caine's 12 principles (relaxed alertness, orchestrated immersion, active processing) across factorization and trigonometry units, while the control cohort received conventional lecture-based instruction. Outcome data were gathered via a validated 75-mark Teacher-Made Achievement Test (TMAT). Baseline evaluations confirmed statistical equivalence between cohorts ($p = .562$). Post-test analysis demonstrated significant overall superiority for the BBL group ($M = 47.07$, $SD = 14.55$) over the control group ($M = 36.60$, $SD = 8.54$; $t = 3.398$, $p = .001$). Achievement gain scores for the BBL group ($M = 18.00$, $SD = 7.39$) were nearly triple those of the control group ($M = 6.40$, $SD = 2.33$; $t = 8.200$, $p < .001$). Stratified analyses revealed significant gain advantages for high achievers ($M_{\text{gain}} = 23.60$ vs. 8.90 , $p < .001$), average achievers ($M_{\text{gain}} = 21.40$ vs. 6.00 , $p < .001$), and low achievers ($M_{\text{gain}} = 9.00$ vs. 4.30 , $p < .001$). Re-engineering secondary mathematics classrooms from threat-induced drills to pattern-rich, emotionally safe learning ecosystems optimizes executive cognitive processing and reduces mathematics anxiety. Teachers must transition into 'neural architects' to cultivate sustainable conceptual mastery.

Keywords: Brain-Based Learning, Secondary Mathematics, Quasi-Experimental Design, Neuro-Pedagogy, Academic Achievement, Conceptual Understanding

Introduction

Secondary school mathematics forms the basic matrix for the cultivation of cognitive skills of 21st century such as abstract reasoning, spatial intuition and strategic problem solving. Mathematical literacy is known to be essential for access to Science, Technology, Engineering and Mathematics (STEM) academic and vocational routes and dealing with technological complexity (Rafeeq et al., 2021). In spite of its importance for socioeconomic development, international studies like the Program for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS) point to large gaps in performance of secondary school students worldwide. Students have a disproportionate difficulty in higher order thinking when faced with non-routine problem-solving tasks. The situation in developing countries like Pakistan is especially dismal. National assessment indicators like Annual Status of Education Report (ASER) show that there are significant gaps still to be addressed in the learning of basic mathematical concepts amongst secondary school learners. The teaching and learning in public secondary schools is still largely teacher-centered (Ali et al., 2010). These approaches focus on copying the words from the textbooks, algorithmic procedures, and mechanistic memorization, ignoring the biological factors that allow the adolescent brain to absorb, learn, and retain complex, abstract information.

The issue in mathematics teaching is the fundamental mismatch between the traditional ways of teaching mathematics and the way the human brain works (Amjad et al., 2022). Traditional classroom environments often run in a 'brain-antagonistic' way. In this mode, teachers are the only source of information and the teacher-centred 'chalk and talk' approach is used, students are passive learners and sit in a row. This setting strongly supports only linear symbolic, left hemisphere processing (about 83% of instruction), and the use of the right hemisphere is neglected – the visual-spatial, holistic, pattern-seeking functions (Anderson, and Li, 2025). Additionally, traditional paradigms are based on threat motivators like a threatening disciplinary system, humiliating students in front of their peers, and summative grading (Ali et al., 2019). Neurobiologically, threat leads to 'downshifting' in the brain. During downshifting the survival mechanisms of the limbic system dominate (the amygdala) suppresses the executive functions of the prefrontal cortex that are needed for abstract mathematical reasoning (Bevilacqua et al., 2018). This means that students suffer from a high-level of cognitive overload, resulting in crippling mathematics anxiety. This disjunction is responsible for the rapid decay of information from volatile short term taxon memory systems. This also is responsible for the lack of conceptual retention, and for the creation of an economic waste of educational casualties, who feel that mathematics is a body of information that is unapproachable, and is a bunch of arbitrary rules (Dikes, 2026).

While educational neuroscience has progressed at a rapid pace in the wake of the 'Decade of the Brain' (1990-1999), there is still a 'translational gap' between lab neuroscience and real classroom teaching and learning in Secondary school. The literature on brain-based learning (BBL) is disjointed. Much of the empirical study has been conducted at the primary or middle school level and/or related to language learning or science education in general. Little empirical work has focused on the direct effect of instruction that is aligned with the brain on achievement in more advanced secondary mathematics curricula, such as quadratic factorization and trigonometry of the circle. Furthermore, the empirical study on BBL in south asian countries and in particular, in Pakistan is very limited (Ali et al., 2019; Ali et al., 2020). Very few studies in the region have integrated quasi-experimental designs with treatment fidelity, and the few that have, have not systematically examined how BBL affected

different levels of ability (high, average, and low) learners (Ali et al., 2020). This study aims to fill these gaps by examining a structured neuro-pedagogical intervention in a Grade 9 mathematics classroom in Sialkot district, Pakistan.

The primary objective of this study was to evaluate the comparative effectiveness of a brain-based learning instructional model versus the conventional lecture method on Grade 9 students' academic achievement in mathematics. Specifically, the study sought to:

1. Compare the post-test academic achievement means of students taught via BBL with those taught via conventional lectures.
2. Evaluate achievement gains in conceptual understanding and non-routine problem-solving performance.
3. Determine the differential effectiveness of BBL across high, average, and low achievement strata.
4. Investigate potential interaction effects between instructional methodology and prior academic achievement levels.

To achieve these objectives, four null hypotheses were formulated for statistical testing at the alpha level of .05:

H₀₁ There is no statistically significant difference between the post-test academic achievement mean score of Grade 9 students taught with the BBL instructional model and those taught with the conventional lecture model.

H₀₂ There is no statistically significant difference between the mathematical achievement gain scores of Grade 9 students exposed to BBL strategies and those exposed to conventional instruction.

H₀₃ No statistically significant differences exist in mathematical achievement gains among high achiever (HA), average achiever (AA), and low achiever (LA) sub-groups taught using the BBL model.

H₀₄ There is no statistically significant interaction effect between instructional methodology (BBL vs. Conventional) and students' prior academic achievement level (HA, AA, LA) on their mathematical achievement.

Significance of the Study

The research progresses both education psychology and mathematics education by offering the empirical evidence for the operational effectiveness of Caine and Caine's 12 brain/mind learning principles in abstract secondary mathematics. It is methodologically designed as a validated blueprint to integrate the 5E Instructional Model (Engagement, Exploration, Explanation, Elaboration, Evaluation) with BBL principles with a specialized Teacher-Made Achievement Test (TMAT) based on Table of Specification (TOS). In the end, it provides practical implementation tips on how teachers, textbook writers, and policy makers can turn teachers into 'neural architects' who can design low threat, high, challenge learning environments that mitigate math anxiety and close achievement gaps.

Literature Review

Brain-based learning is based on the premise that the instructional design must follow the rules of the natural functional architecture of the human brain. The most extensive theory on neuro-pedagogy was presented by Renate Nummela Caine and Geoffrey Caine (1991, 1994, 2005) who established 12 Brain/Mind Learning Principles. These principles challenge the 20th-century behaviorist 'black box' model of human cognition and view learning, as a process of change, entirely physiological and whole body, and inextricably linked to emotional control and social interaction.

The 12 principles are: The brain is a complex parallel processor and works on visual, auditory, spatial and social operational modes at the same time; Learning engages the whole of physiology, metabolic health, hydration, motion and stress levels have a direct impact on synapse efficiency (Rehman, 2011); The search for meaning is innate and is patterned by learning; Emotions are crucial to patterning – the affective state either integrates or rejects information; The brain processes parts and wholes at the same time – it is up to the teacher to guide students between broad gestalt contexts and detailed micro-steps; Learning involves focused attention and peripheral perception; Learning is conscious and unconscious – it is necessary to allow ‘downtime’ for memory consolidation; We have at least two memory pathways – a spatial autobiographical system for learning life experiences and a volatile taxon system for learning isolated, rote facts; Spatial memory is activated when concepts are embedded in a real world context; Complex learning is enhanced by challenge and inhibited by threat (limbic downshifting); Developmental stages restructure cognitive capacities; and Every brain is uniquely organized, so that different sensory modalities are needed (Caine, and Caine, 1991).

These 12 principles were operationalized with regard to classroom instruction by Eric Jensen (1995, 2008) and Caine and Caine, who proposed a three-part pedagogical model called Relaxed Alertness, Orchestrated Immersion, and Active Processing:

1. **Relaxed Alertness:** This state provides ideal psycho-physiological conditions for the functioning of the prefrontal cortex by setting up a low threat, high challenge situation. Stress reduction techniques, background Baroque music, non-punitive ‘Mistake Hunting Games’, brain energizers, and hydration breaks keep the amygdala down. This will free up working memory for complex mathematical reasoning by not engaging the limbic system in suppression of executive functions (Erol, and Karaduman, 2018).

2. **Orchestrated Immersion:** This pillar fully immerses the learner in rich, multisensory, multipart experiences that approximate real world phenomena. Instruction is delivered using the Concrete-Pictorial-Symbolic (CPS) continuum, which takes advantage of parallel processing in the brain (Friedman et al., 2026). In mathematics, abstract concepts are first introduced using tactile manipulatives such as algebraic tiles; then using visual, pictorial models such as area graphs and diagrams; and finally, through symbolic, algebraic equations (Harris, and Sherman, 1973; Ibrahim, 2025).

3. **Active Processing:** This is the last stage in which the information is internalized with systematic metacognitive reflection and social negotiation. Dedicated ‘downtime’ and peer tutoring enables the brain to overwrite memory traces in its working memory with longer-term spatial memory networks (Immordino-Yang et al., 2019). This precludes quick mental deterioration that comes with passive rote rehearsal.

Grade 9 is an important developmental transition period (late adolescence, age 14-15) in which there is extensive reorganization of networks in the hippocampus and neocortex, and maturation of the prefrontal cortex. In secondary mathematics, one has to jump from concrete arithmetic manipulation to extremely abstract algebraic manipulation and geometric visualization (Jazuli et al., 2019). BBL theory is based on ‘interhemispheric harmony’ through the corpus callosum. Incorporating symbolic, linear, algebraic steps (left hemisphere) and holistic, spatial, visualizations (right hemisphere). By using the same spatial representation of the area of a polynomial or the trigonometric unit circle and the same symbolic equations, parallel processing is optimal, which can decrease cognitive load and promote deep conceptual knowledge (Jesen, 1995; Jesen, 2000).

Empirical evidence in the world shows the superiority of BBL to the traditional paradigm. In the West, research in the USA and the United Kingdom have shown there has been much to be gained in regards to student engagement and conceptual retention when using neuro-compatible strategies. Meta-analyses and empirical trials have been conducted in Asian educational contexts (Duman, 2010; Ekemen & Beyhan, 2020 in Turkey and Saleh, 2011; Yatim et al., 2022 in Malaysia), and the findings show that BBL approaches in STEM subjects clearly outperform traditional approaches. Aziz-ur-Rehman (2011) and Noureen et al. (2017) conducted a pioneering study in Pakistan that showed that BBL has yielded more than double the achievement scores of the conventionally taught control groups.

3. Methodology

3.1 Research Design

A pre-test post-test control group quasi-experimental type of study was used in this study. Administrative issues in public secondary schools made the quasi-experimental design necessary because it would have been difficult if not impossible to randomly assign individual students to treatment conditions without disrupting the existing class schedules. Administrative units in classroom were not dissolved, as it was important to maintain ecological validity. Regarding non-randomization, statistical control was obtained by conducting pre-test baseline equivalence testing, and stratified sub-group analyses across three prior achievement levels.

3.2 Population and Sample Stratification

The population of the study included male students of Grade 9 from 346 public secondary schools in Sialkot district of Punjab, Pakistan. The sampling techniques used were purposive and stratified random sampling with a representative sample of 60 Grade 9 students. The sample was randomly divided into two groups of 30 each: an experimental group ($N = 30$) which received instruction through the BBL model and a control group ($N = 30$) which received instruction through conventional lectures.

Each cohort was divided into three ability sub groups of 10 children each according to their normal distribution scores in the 8th Grade Annual Examination Scores (AES) in Mathematics:

- High Achievers (HA): $n = 10$ per group (AES range: 382–575 marks)
- Average Achievers (AA): $n = 10$ per group (AES range: 316–370 marks)
- Low Achievers (LA): $n = 10$ per group (AES range: 243–290 marks)

This balanced stratification ensured baseline comparability and eliminated selection bias as a threat to internal validity.

3.3 Instructional Intervention Protocol

The instructional intervention lasted for 8 weeks and included 38 lesson plans, two of the major chapters in the Punjab Textbook Board (PTBB) Grade 9 Mathematics textbook: Factorization and Algebraic Manipulation and Introduction to Trigonometry. The same amount of mathematics was taught, the same exercises were used in the textbooks and the same amount of instruction time was provided in both cohorts.

Incorporation of the 5E Instructional Model (Engagement, Exploration, Explanation, Elaboration, Evaluation) and Caine and Caine's 12 principles were used with Lessons in the Experimental Cohort (BBL). The students were split into 5 groups of six, each group being heterogeneous; and desks were laid out in a U-shape collaborative arrangement to accommodate the groups. A Concrete-Pictorial-Symbolic progression was used to deliver instruction. Physical algebra tiles were used to create geometric rectangles to represent areas

of polynomials, sketches of 'zero pairs' were used to determine them, and symbolic factorization equations were written. Real world architectural problems used to introduce trig concepts (arc length, area of sector, radian measure/ratio conversion). Physiological safety was provided through 5-minute hydration breaks, deep breathing energizers, playing baroque music, peripheral poster displays and non-punitive 'Mistake Hunting Games'.

In Control Cohort (Conventional) lessons, lessons were conducted in the traditional teacher-centered manner. The students were seated facing the blackboard in straight rows. The teacher read from a text, showed examples line-by-line on a board and demanded silent verbatim note taking. Practice was limited to seat work, and rote memorization of algorithmic rules, no physical manipulatives, no colour coding, and no collaboration with peers.

3.4 Research Instrumentation: Teacher-Made Achievement Test (TMAT)

The main data collection instrument was a Teacher-Made Achievement Test (TMAT) especially developed by the researcher in line with a meticulous Table of Specification (TOS). The test items were distributed equally within each sub-topic of the TOS, and all cognitive domains (Knowledge, Comprehension, Application, Analysis) were clearly assessed; the innate brain faculties of parallel processing, pattern recognition, simultaneous perception of parts and whole, as well as spatial memory, were clearly assessed.

The TMAT was worth 75 marks and was allowed 2 hours and 30 minutes and consisted of 4 main parts:

1. Objective Section (Question 1): 15 Multiple Choice Questions (1 mark each = 15 marks) to test the basic concepts and computational accuracy.
2. Subjective Section I (Questions 2-4): 3 sets of 9 short answer questions. Students responded to 6 questions (18 items) each set (2 marks each question = 36 marks).
3. Subjective (Questions 5-7): Three extended problem-solving tasks. Students were asked 2 questions (8 marks each which were divided into 4-mark sub-parts = 16 marks).
4. Subjective Section III (Questions 8 – 9): Two higher level conceptual integration questions. Students answered 1 question (8 marks total).

3.5 Instrument Validity and Reliability

The formal review of the panel of PhD level mathematics education experts and senior secondary teachers from the Sialkot district has been done to establish the content and face validity of TMAT. Items have been cleaned up to achieve linguistic clarity and to meet PTBB curriculum standards and construct validity. A pilot study was carried out on a non-sample population (N = 20) grade 9 students to assess the reliability of the instrument. The internal consistency of the questionnaire was determined using SPSS reliability analysis and the Cronbach Alpha was found to be 0.77.

3.6 Data Collection Procedures

The data collection was done in three successive stages:

1. In the Pre-Test Phase, all the 60 participants of both the cohorts were given the 75-mark TMAT under similar conditions to ensure baseline equivalence.
2. Outcome Phase: The 8-week treatment was implemented. To achieve absolute BBL treatment fidelity, the principal researcher taught BBL to the experimental group; the control group was taught by an experienced and equally qualified secondary mathematics teacher.

3. Post-Test Phase: The TMAT was re-administered as Post Test immediately after the 8-week intervention. The order of the items was randomized to reduce test-retest memory bias.

3.7 Data Analysis Plan

Quantitative data were processed using SPSS. Descriptive statistics (Mean, Standard Deviation, Standard Error Mean) characterized sample performance. Inferential hypothesis testing was conducted using independent-samples t-tests at $\alpha = .05$. Analyses evaluated baseline pre-test equivalence, overall post-test performance, overall achievement gain scores (post-pre), and stratified sub-group gains across high, average, and low achievers.

3.8 Ethical Considerations

This study followed the ethical procedures for research on minors. The Directorate of Education and the university ethics committees approved the study. Parental/carer consent (written) and student consent (written) were obtained. The identity of the participants was coded using alpha-numeric coding to ensure confidentiality. All participation was completely voluntary and there were clear right to withdraw procedures without penalty to students.

4. Results

Before starting the instructional intervention, an independent-samples t-test was conducted on pre-test TMAT scores to check for baseline mathematical equivalence of the Experimental Group ($N = 30$) and Control Group ($N = 30$). The experimental group's mean score on the pre-test was 29.07 ($SD = 8.48$) and the control group's mean score on the pre-test was 30.20 ($SD = 6.41$) as shown in Table 1. Analysis showed there was no statistically significant difference between the baseline scores ($t = -0.854$, $p = .562$). The statistical uniformity is a proof that both groups were equally good at math before the treatment and that there was no ability selection bias.

Table 1

Independent Samples t-test Comparison of Pre-test Achievement Scores of Experimental and Control Groups

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Pre-test	Experimental	30	29.07	8.481	1.548	-0.854	.562
	Control	30	30.20	6.413	1.171		

Note. $p > .05$. Statistical equivalence established at baseline.

An independent-samples t-test was used to analyze post-test TMAT scores after the 8-week intervention. Results of the posttest are presented in Table 2, the Experimental Group scored a mean of 47.07 ($SD = 14.55$) while the Control Group scored a mean of 36.60 ($SD = 8.54$). This difference was statistically significant ($t = 3.398$, $p = .001$), which indicated the overall post-test superiority of BBL instruction.

Table 2

Independent Samples t-test Comparison of Post-test Achievement Scores of Experimental and Control Groups

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Post-test	Experimental	30	47.07	14.548	2.656	3.398	.001*
	Control	30	36.60	8.544	1.560		

Note. $*p < .01$. Experimental group significantly outperformed control group.

To evaluate net learning progress, achievement gain scores ($\text{\$Post-test} - \text{\$Pre-test}$) were analyzed. The mean achievement gain for the Experimental Group ($M = 18.00$, $SD = 7.39$), was higher than that of the Control Group ($M = 6.40$, $SD = 2.33$), as seen in Table 3. This 11.60-point gain advantage was highly significant ($t = 8.200$, $p < .001$). Based on the results,

the BBL cohort made almost three times as much academic progress as the conventionally taught cohort, supporting the rejection of Null Hypotheses H0 1 and H0 2.

Table

3

Independent Samples t-test Comparison of Achievement Gain Scores Between Experimental and Control Groups

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Gain Score	Experimental	30	18.00	7.391	1.349	8.200	< .001*
	Control	30	6.40	2.328	.425		

Note. * $p < .001$. Net achievement gain for BBL group was nearly triple that of control group.

For high achievers ($n = 10$ per group), baseline pre-test scores showed no significant difference ($M_{\{Exp\}} = 39.70$, $SD = 3.59$ vs. $M_{\{Ctrl\}} = 37.10$, $SD = 2.13$; $t = 1.969$, $p = .065$). Results of the post-test (Table 4) showed that the high achievers in the BBL group scored 63.30 ($SD = 2.45$) while the control group scored 46.00 ($SD = 2.67$) ($t = 15.102$, $p < .001$). The BBL group high-achiever gain scores were 23.60 points ($SD = 4.60$) compared to 8.90 points ($SD = 0.74$) for the control group ($t = 9.979$, $p < .001$), showing the effectiveness of BBL in extending cognitive ceiling for high-achiever students.

Table

4

Independent Samples t-test Analysis for High Achievers Across Experimental and Control Groups

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Post-test	Experimental	10	63.30	2.452	.775	15.102	< .001*
	Control	10	46.00	2.667	.843		
Gain Score	Experimental	10	23.60	4.600	1.454	9.979	< .001*

Note. * $p < .001$. High achievers in BBL group achieved nearly triple the gain of control peers.

The average-achiever stratum ($n = 10$ in each group) showed that the control group had a significantly higher pre-test ability than the experimental group ($M = 30.80$, $SD = 1.87$; $M = 27.00$, $SD = 1.76$; $t = -4.670$, $p < .001$). Although this was a primary disadvantage, the BBL average achievers were able to make up for this starting deficit and achieved a post-test mean of 48.40 ($SD = 5.08$) while the control group had a mean of 36.80 ($SD = 3.62$) ($t = 5.882$, $p < .001$). In comparison, the control group achieved a gain of 6.00 points ($SD = 1.83$) and the BBL average achievers got an amazing mean gain of 21.40 points ($SD = 3.66$) which is more than three times as much as the control group ($t = 11.913$, $p < .001$).

Table

5

Independent Samples t-test Analysis for Average Achievers Across Experimental and Control Groups

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Post-test	Experimental	10	48.40	5.082	1.607	5.882	< .001*
	Control	10	36.80	3.615	1.143		
Gain Score	Experimental	10	21.40	3.658	1.157	11.913	< .001*

Note. * $p < .001$. BBL average achievers overcame a baseline deficit to outperform control peers by 11.60 post-test points.

For low achievers ($n = 10$ per group), baseline pre-test scores showed statistical equivalence ($M_{\{Exp\}} = 20.50$, $SD = 1.96$ vs. $M_{\{Ctrl\}} = 22.70$, $SD = 2.95$; $t = -1.967$, $p = .065$). Post-test scores (Table 6) indicated a non-significant mean difference ($M_{\{Exp\}} = 29.50$, $SD = 3.54$ vs. $M_{\{Ctrl\}} = 27.00$, $SD = 3.80$; $t = 1.523$, $p = .145$). Net achievement gain scores, however, showed that the low achievers of the BBL group showed a mean gain of 9.00 points ($SD = 1.94$), which was more than double the 4.30-point gain ($SD = 1.25$) of the control group ($t = 6.429$, $p < .001$). This supports BBL being an effective method to double the learning progress of struggling students, thus rejecting Null Hypotheses H0 3 and H0 4.

Table*Independent Samples t-test Analysis for Low Achievers Across Experimental and Control Groups*

Variable	Group	N	Mean	Std. Dev.	Std. Error	t-value	Sig. (p)
Post-test	Experimental	10	29.50	3.536	1.118	1.523	.145
	Control	10	27.00	3.801	1.202		
Gain Score	Experimental	10	9.00	1.944	.615	6.429	< .001*

Note. * $p < .001$. BBL low achievers achieved more than double the net gain of control low achievers.

5. Discussion

5.1 Neuro-Cognitive Interpretation of Overall Gains

The empirical results of this study contribute to the transformative effect of Brain-Based Learning in secondary mathematics education in a robust way. The overall post-test superiority ($M = 47.07$ vs. $M = 36.60$, $p = .001$) and the difference in achievement gains that is close to 3 times higher ($M = 18.00$ vs. $M = 6.40$, $p < .001$) reinforces the fact that instructional design that is congruent with the brain's natural functional architecture produces significantly more conceptual understanding than teacher-centered lecturing. These findings provide direct support for the theoretical model of Caine and Caine (1991, 1994) that the human brain is a complex parallel processor, which functions best when alert and relaxed and when immersed and orchestrated.

Neurocognitively, the traditional lecture approach is not effective since it is more linear and symbolic, and is taught in an emotionally restricted setting. Stress from threat activates limbic down shifting which compromises the executive functions of the prefrontal cortex by the amygdala. The BBL intervention, however, created a low threat high challenge environment. The simultaneous use of physical algebraic tiles, visual models, real-world applications of trigonometry, baroque music, hydration breaks and non-punitive mistake-hunting games engaged the four cortexes: visual, auditory, kinaesthetic and parietal visual-spatial. This interhemispheric harmony lowered the working memory load, dampened the release of cortisol and helped move mathematical concepts into the high-capacity spatial long-term memory.

5.2 Stratified Dynamics and Cognitive Recovery

This research has the added strength of examining it in a granular fashion for different strata of learner ability. BBL instruction released the "unlocked" cognitive potential for the high achievers, resulting in an extraordinary gain of 23.60 points over a control group gain of 8.90 points. High achieving students in regular classes are often limited by one and one-half standard algorithmic drill activities, but BBL delivered the required cognitive challenge and metacognitive reflection to engage higher order executive functioning.

Perhaps even more interesting is the performance of average students. Although the BBL average achievers began with a statistically significant baseline deficit ($M = 27.00$ vs. $M = 30.80$, $p < .001$), they completely closed this gap and outperformed their control peers, with a post-test mean of 48.40 and a gain of 21.40 points (vs. 6.00 in the control group). This is such a dramatic turn around and shows the average learner is often the one who is hurt by traditional 'chalk and talk' teaching. Average Achievers make a quick cognitive catch-up when offered multisensory Concrete-Pictorial-Symbolic scaffolding and peer collaboration.

The net achievement gain for low achievers was more than double in BBL compared to conventional instruction ($M = 9.00$ compared to $M = 4.30$, $p < .001$). While their actual post-test difference, $M = 29.50$ versus $M = 27.00$ for the period of 8 weeks was not significant, the significant gain advantage shows that in the long-term, neuro-pedagogical alignment begins to repair deeply-rooted mathematical anxieties. Relaxed alertness routines

need to be delivered in a sustained, longitudinal fashion to completely abolish chronic cognitive threat responses in struggling learners.

5.3 Alignment with Global Educational Neuroscience Literature

The quality of these empirical findings is robust and in line with the research in the field of educational neuroscience around the world. This is consistent with the results of the Turkish meta-analysis (Duman, 2010; Ekemen & Beyhan, 2020) and the Malaysian STEM trials (Saleh, 2011; Yatim et al., 2022), which reported overall positive achievement of the students when BBL multisensory methods were used instead of conventional teaching. Moreover, the findings align with the previous empirical studies conducted in Pakistan by Aziz-ur-Rehman (2011), Noureen et al. (2017), and Amjad et al. (2022), which further support the findings that neuro-compatible instruction is universal and is beneficial for optimizing mathematical reasoning in late adolescence.

5.4 Theoretical, Practical, and Policy Implications

As for the theoretical implications of this research, it is very important to move away from behaviorist stimulus-response models in educational psychology to biologically-based models of neuro-pedagogy. From the practical point of view, the study shows that secondary mathematics teachers should be transformed from being 'content planners' to being 'neural architects'. Teachers need the skills to set up U-shaped collaborative spaces, use Concrete-Pictorial-Symbolic representations and plan for attentional "prime times" and consolidation "down time".

Educational authorities in developing countries need at the policy level to modernise national curriculum frameworks and teacher preparation programmes. Professional development should include pre-service and inservice, and should include education neuroscience as a way to eradicate the common (neuro)myths and empower teachers to create pattern rich, emotionally safe learning environments.

6. Conclusion

6.1 Key Findings and Main Takeaways

The current study gives conclusive empirical evidence of the effectiveness of brain-based learning on students' academic achievement in secondary mathematics in contrast to traditional lecture-based learning. The BBL intervention led to significantly higher post-test scores ($M = 47.07$) than conventional instruction ($M = 36.60$, $p = .001$) and almost triple the net achievement gains ($M = 18.00$ vs. $M = 6.40$, $p < .001$). These stratified analyses illustrated that BBL is effective for high, average, and low ability learners, achieving high ability learner potential ($M_{\text{gain}} = 23.60$), low ability learner recovery ($M_{\text{gain}} = 21.40$) and a doubling of low ability learner gains ($M_{\text{gain}} = 9.00$).

6.2 Pedagogical Contributions

The main contribution of this research is that a practical, replicable, operational, neuro-pedagogical framework is being validated for secondary Mathematics. This study shows that the human mind has a physiological reality to abstract conceptual mastery that is not an academic exception when instruction respects the biological architecture of the human mind in relaxed alertness, orchestrated immersion, and active processing for optimal executive functioning and to reduce mathematics anxiety.

6.3 Limitations

A number of methodological limitations need to be noted. The sample was limited to male students in grade 9 in public secondary schools of Sialkot district in Pakistan which may limit the direct generalizability of the findings to co-educational settings or private educational

institutions. Second, the 8-week time window used in the intervention is relatively short in terms of observing neural adaptations in low achieving learners in the long-term. Third, cognitive outcomes were measured through paper-pencil achievement tests, and direct neuroimaging measures (e.g. EEG or fNIRS) were not used.

6.4 Directions for Future Research

Research is needed to increase the diversity of the samples studied, including female and co-educational classes, in both urban and rural populations. Moreover, the use of portable neurotechnology like fNIRS or mobile EEG hyperscanning in the context of naturalistic classroom settings may enable to acquire real-time information about working memory load, brain-to-brain synchrony, and cognitive engagement during neuro-pedagogical interventions.

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