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Brainwaves and higher-order thinking: An EEG study of cognitive engagement in mathematics tasks

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ABSTRACT

Mathematics education emphasizes Higher-Order Thinking Skills (HOTS) to enhance students' problem-solving and analytical reasoning. However, students often struggle with HOTS-based mathematical tasks, and the cognitive mechanisms underlying these challenges remain unclear. This experimental study employs electroencephalography (EEG) to investigate the neural correlations of HOTS engagement by analyzing brainwave activity during mathematical problem-solving. A sample of 24 secondary school students, stratified into high, moderate, and low achievers, based on prior mathematics performance, assigned to either the experimental group (HOTS tasks) or the control group (non-HOTS tasks) to assess differences in cognitive engagement. Both groups completed tasks within 30 minutes while their brain activity was recorded using an 8-channel EEG system. The EEG data was analyzed using Neuron-Spectrum.NET to extract power spectral densities in beta (13 - 30Hz), alpha (8 - 12Hz), and theta (4 - 7Hz) frequency bands, with a focus on frontal, parietal and occipital regions. Findings reveal distinct neurocognitive patterns across achievement levels: high-achieving students exhibited strong beta wave activity in prefrontal cortex, suggesting efficient executive function and logical reasoning. Moderate achievers showed increased alpha and beta activity in occipital region, indicating reliance on visual-spatial processing. Low achievers demonstrated heightened frontal theta activity, associated with cognitive effort and working memory overload. The study's integration of EEG methodology with educational research offers actionable insights into designing neuroscience-informed pedagogical interventions tailored to students' cognitive profiles. These findings provide empirical, brain-based evidence that can inform personalized learning approaches, teacher training, and curriculum design-key priorities in modern education. This study not only advances the integration of neuroscience and education but also offers actionable insights for policymakers seeking to enhance 21st century competencies through evidence-based instruction.

Keywords: electroencephalography (EEG), higher-order thinking skills (HOTS), mathematics education, cognitive engagement, brainwave analysis

INTRODUCTION

Mathematics education plays an important role in shaping students' cognitive abilities, especially in solving problems and thinking analytically. As a result, Malaysia's education system has integrated high-level thinking skills (HOTS) into the national curriculum to improve students' ability to think critically, solve complex problems, and apply mathematics concepts to real-life contexts (Ministry of Education Malaysia, 2022). This shift is consistent with the global emphasis on 21st century learning, which emphasizes creativity, critical thinking, cooperation and communication. This strategic prioritizes students' ability to analyze complex mathematical relationships, evaluate problem-solving strategies and create innovative solutions for real world contexts. This reform aligns with global STEM education trends that emphasize applied cognitive skills over procedural fluency (OECD, 2019). Despite these efforts, however, many Malaysian students continue to struggle with HOTS-based mathematical tasks, as reflected in the results of international assessments such as TIMSS (International Mathematical and Science Studies Trends) and PISA (International Student Assessment Programs) (Mullis et al., 2020; OECD, 2019). These challenges highlight the critical gap between policy implementation and actual learning outcomes in classrooms.

The integration of HOTS into mathematics education is aimed at promoting deeper cognitive involvement, moving students from automatic memory to analytical reasoning and conceptual understanding. However, studies have shown that many students still have difficulty understanding and applying HOTS-oriented mathematical concepts, especially when confronted with non-routine problem-solving tasks (Abdullah et. al., 2017; Zakaria et al., 2016). Mathematical problem-solving, including HOTS, requires students to participate in cognitive processes such as analyzing, evaluating, and synthesizing information.

Malaysia's *Malaysia Education Blueprint 2013–2025* and the *Kurikulum Standard Sekolah Menengah* (KSSM) emphasize HOTS integration to cultivate analytical, creative, and problem-solving skills. However, traditional assessments still dominate classrooms, with limited insight into *how* students cognitively engage with HOTS tasks. This study's neurophysiological approach provides empirical evidence to optimize HOTS pedagogy, ensuring reforms are grounded in cognitive science rather than just behavioral outcomes. Besides, in Malaysia, the cognitive mechanisms that underpin students' engagement with HOTS tasks are still largely unknown, as most studies focus on behavioral evaluations rather than neurophysiological data (Zohar & Barzilai, 2015). Current research relies mainly on test results, classroom observations, and self-reported surveys, which may not fully capture the depth of cognitive processing involved in solving mathematical problems. This prompted the need for more objective and scientifically based methods to evaluate student engagement and cognitive workload in the process of completing mathematical tasks based on HOTS.

Neuroscience in Education: Understanding Brain Function in Learning

Neuroscience research has increasingly demonstrated that studying brain activity provides crucial insights into how students learn, retain, and apply mathematical concepts (Başar et al., 2016). Electroencephalogram (EEG) technology has emerged as a powerful tool in education neuroscience, enabling researchers to measure students' brain activity and better understand their thinking processes and problem-solving approaches (Goswami, 2019; Klimesch, 2012). While conventional tests only evaluate final answers, EEG exposes the underlying neural dynamics - for instance, struggling students often exhibit heightened frontal theta activity, indicating cognitive overload rather than inability (Başar et al., 2016). During higher-order mathematical tasks, optimal learning is associated with dominant beta wave activity, yet neuroimaging frequently detects excessive alpha waves in anxious learners, suggesting disengagement when facing challenging problems (Cirett Galán & Beal, 2012).

Brainwave responses, as measured by EEG, can give a deeper understanding of how students deal with and respond to HOTS-based learning tasks. This study focuses on three brain waves and each of which performs different cognitive functions. Beta waves (13 - 30Hz) are associated with focused attention and logical reasoning, when students engage in complex problem-solving, optimal beta wave activity in the prefrontal cortex acts like a cognitive engine revving up. While alpha waves (8 - 12Hz) are associated with relaxation and cognitive readiness. Excessive theta wave activity (4 - 7Hz) in the frontal lobe serves as a clear neurological signature of cognitive overload during mathematical problem-solving. When students encounter complex problems that exceed their working memory capacity, EEG recordings consistently show a 40-60% increase in frontal theta power compared to baseline levels (Cirett Galán & Beal, 2012).

By recording the brainwave activity of students during HOTS mathematics tasks, EEG can help indicating cognitive overload (Cirett Galán & Beal, 2012) and provide empirical evidence of students' levels of engagement and problem-solving strategies. Recent neurocognitive research reveals that students struggling with complex problems exhibit; elevated theta waves in prefrontal regions, indicating cognitive overload (Cirett Galán & Beal, 2012) and inefficient frontal-parietal connectivity during problem-solving (Makeig et al., 2009). These findings align with behavioral research showing metacognitive deficits, only 29% of students can accurately monitor their problem-solving progress (Veenman, 2018) and metacognitive training interventions improve HOTS performance by 0.45 effect size (Zohar & Barzilai, 2015). In Malaysia, where the curriculum emphasizes HOTS (Higher Order Thinking Skills), EEG could help tailor instruction to students' actual neurological needs rather than assumed ones. For instance, Ros et al. (2017) found that just 10 minutes of daily neurofeedback training helped students learn to self-regulate their brainwaves, boosting both mathematics performance and confidence. However, despite the potential of EEG technology, research into HOTS mathematics education and brainwave responses in Malaysia remains limited and requires further research.

Challenges in HOTS Mathematics Learning

The integration of Higher-Order Thinking Skills (HOTS) in mathematics education faces several persistent challenges that hinder student success. A critical issue is the inconsistent exposure to complex problem-solving tasks. Research has shown that limited opportunities to engage with non-routine mathematical problems substantially impair students' ability to develop critical thinking and problem-solving competencies (Mullis et al., 2020). The 2018 Programme for International Student Assessment (PISA) revealed that only 12% of Malaysian students could solve problems requiring higher-order thinking, compared to 31% in high-performing education systems like Singapore (OECD, 2019). This disparity stems from classroom practices that prioritize procedural fluency over conceptual understanding (Zakaria et al., 2016). Furthermore, the transition from formula-based learning to open-ended problem solving has left many students without adequate scaffolding, resulting in cognitive overload and mathematics anxiety (Sweller et al., 2019). These challenges are compounded by assessment systems that rarely evaluate HOTS, creating a misalignment between curricular goals and evaluation practices (Ministry of Education Malaysia, 2022).

Research shows that students unfamiliar with HOTS-based assessments struggle with complex mathematics problems, leading to more errors in reasoning and calculations (Abdullah et al., 2015). Common mistakes include misinterpreting questions, calculation errors, difficulty setting up problems, and gaps in core concepts, particularly among low-to-average performers (Mullis et al., 2020). Furthermore, the removal of memory-based formulas in favour of problem-solving approaches has led many students to struggle to develop their own strategies for addressing HOTS questions (Zakaria et al., 2016). The lack of knowledge of non-routine mathematical problems further contributes to students' hesitation, anxiety and reluctance to participate in HOTS learning. In addition, many students lack metacognitive abilities, which are essential for self-regulatory thinking and problem-solving strategies (OECD, 2019).

However, research demonstrates that consistent implementation of HOTS in mathematics leads to measurable improvements in student outcomes (Darling-Hammond et al., 2023). Students exposed to regular HOTS instruction show 19-28% greater accuracy in solving non-routine problems compared to peers taught through traditional methods (Oliver, 2024). These gains extend beyond test scores-students develop deeper conceptual understanding, retaining learned material twice as long as those relying on rote memorization (Soderstrom & Bjork, 2015). Standardized assessments reveal that HOTS-trained students perform 15 percentile points higher on tasks requiring applied reasoning (OECD, 2023), with particularly strong benefits for disadvantaged students, reducing achievement gaps by 31 - 44% (Darling-Hammond et al., 2023). Critically, HOTS instruction enhances real-world problem-solving, students are 3.5 times more likely to successfully transfer skills to novel contexts (Barnett & Ceci, 2002). When implemented effectively, HOTS instruction doesn't just improve test scores, it cultivates adaptable, critical thinkers prepared for complex real-world challenges (Sadler & Tai, 2007).

Problem Statement

Higher-order thinking abilities (HOTS) are the focus of Malaysia's education system, especially in mathematics, where students develop critical thinking, analytical reasoning, and complex problem-solving abilities (Ministry of Education Malaysia, 2022). Despite policy initiatives aimed at integrating HOTS into the curriculum, Malaysian students are facing serious challenges in acquiring these skills. Their inadequate performance in international assessments such as TIMSS (Trends in International Mathematics and Science Study) and PISA (Programme for International Student Assessment) highlights the persistent weaknesses in mathematical reasoning, problem solving and higher-level cognitive engagement (Mullis et al., 2020; OECD, 2019). Studies have shown that many students are heavily dependent on memorizing and procedural learning, limiting their ability to apply, analyze, and evaluate mathematical concepts in new situations (Zakaria et al., 2016). These questions suggest an erroneous alignment between teaching strategies and student cognitive processes, requiring a more in-depth study of how students engage in HOTS-oriented mathematical tasks at the cognitive level.

Traditional methods for assessing cognitive engagement in HOTS-based mathematical learning are based primarily on behaviour measurement such as test results, classroom observations and self-reported surveys. These approaches provide valuable insights, but do not capture the real-time cognitive processes that occur when students work on solving mathematical problems. Recent advances in educational neuroscience, especially electroencephalogram technology (EEG), offer the opportunity to examine students' brainwave activity as an objective measure of cognitive engagement, mental effort and problem-solving efficiency (Başar et al., 2016; Klimesch, 2012). EEG research has demonstrated its ability to identify cognitive load, attention patterns, and neuronal responses to various learning tasks, but HOTS mathematics learning studies in Malaysia remain scarce, especially those using EEG to analyze students' neurophysiological involvement. Understanding how students' brains respond to different levels of cognitive demand in mathematics may provide empirical evidence to support teaching strategies that improve the effectiveness of HOTS learning.

The study aims to bridge this gap by examining the effects of HOTS-based mathematical learning tasks on the brainwave responses of secondary school students in the northern Malaysian Peninsula using EEG recordings. It aims to investigate how students with different levels of mathematical achievement (high, medium and low) engage cognitively in HOTS tasks, as reflected in their brainwave activity. This neurophysiological insight allows for precisely targeted interventions, like breaking problems into smaller steps when theta spikes indicate strain or provide visual aids when weak occipital beta waves (13 - 30 Hz) suggest poor spatial processing (Ros et al., 2017). By analyzing neurophysiological responses, this research will provide valuable insight into cognitive burden, problem-solving efficiency, and mental effort, allowing educators to develop scientifically informed teaching strategies that complement students' cognitive processes.

Significance of Study

This study represents a transformative advancement in mathematics education by integrating cutting-edge educational neuroscience with pedagogical practice to decode the cognitive mechanisms underlying Higher-Order Thinking Skills (HOTS) problem-solving. By employing EEG technology to analyze real-time brainwave responses, this research extends beyond conventional self-reports and behavioral assessments, providing objective evidence of cognitive participation, mental effort and problem-solving efficiency. Emerging neuroeducation research reveals that distinct neural markers provide educators with biologically validated indicators to customize instructional scaffolding to students' neurodevelopmental readiness, calibrate HOTS task difficulty according to individual cognitive load capacities (Sweller, 2020), and augment standardized assessments with neurophysiological evidence of deep conceptual learning (Zhang et al., 2017). These results will help educators develop personalized instruction strategies that meet the cognitive needs of students, ensuring that HOTS-based learning is implemented more effectively in classrooms.

Furthermore, this study contributes to education policy and the development of curriculums by offering scientifically supported recommendations to improve the teaching and assessment of HOTS in Malaysian secondary schools. The study provides empirical justification and offers evidence-based strategies to redesign teacher training programs to include neurocognitive principles (Howard-Jones, 2016), align national assessments with brain-compatible HOTS progression models (OECD, 2023) and address equity gaps by identifying neural correlations of disadvantage (Thomas et al., 2019). Finally for STEM education, the findings illuminate how domain-general cognitive processes interact with domain-specific mathematical reasoning, a crucial linkage for developing transferable problem-solving skills (Geary et al., 2017). The study also pioneers culturally responsive neuroscience by examining how Malaysia's bilingual education context modulates neural engagement during HOTS tasks. Ultimately, by bridging the gap between neuroscience and mathematics education, the study aims to enhance students' cognitive engagement, mathematical achievement and problem-solving abilities, contributing to the broader aim of improving Malaysia's STEM education.

Research Questions

RQ1 What are the brainwave response patterns observed through EEG recordings when Form 2 students engage in HOTS-based mathematics learning tasks?

RQ2 How do brainwave responses differ among students with high, moderate, and low achievement levels in mathematics when engaging in HOTS tasks?

RQ3 What is the relationship between cognitive achievement levels (high, moderate, low) and specific EEG brainwave activity during HOTS-based mathematics problem-solving?

RQ4 Which brainwave frequencies (beta, alpha, theta) are most prominently associated with cognitive engagement in HOTS-based mathematical problem-solving?

METHODOLOGY

This study employed a quantitative true experimental design to examine the neurocognitive effects of HOTS-based and non-HOTS mathematical learning tasks. A comparative approach was used, with students assigned to either the experimental group (HOTS-based tasks) or the control group (non-HOTS tasks) to assess differences in cognitive engagement. A two-stage sampling technique was applied: voluntary participation with parental consent, followed by stratified random sampling to select 24 Malaysian secondary students, categorizing them into high, moderate, and low achievers (strata) based on exam scores (Creswell & Creswell, 2018).

The study used an experimental protocol to investigate how different types of mathematics tasks affect cognitive engagement. First, participants underwent a 5-minute baseline EEG recording while resting with their eyes open to measure their individual brain activity. Their prior mathematics exam scores were also collected to categorize them into high, moderate, or low achievers. Next, they were randomly assigned to one of two groups: the HOTS group, which solved complex, multi-step problems requiring reasoning and real-world application, or the non-HOTS group, which worked on routine procedural mathematics tasks. Both groups completed tasks within 30 minutes while their brain activity was recorded using an 8-channel EEG system (Neuron-Spectrum-8/P) with electrodes positioned at standard FP1, FP2, T3, T4, C3, C4, O1, and O2 locations according to the 10-20 system (focusing on frontal, parietal, and occipital regions).

The EEG data was analyzed using Neuron-Spectrum.NET software, which processed the brainwave signals through Fast Fourier Transform (FFT) to break them down into frequency bands: beta (13 - 30Hz) for active concentration, alpha (8 - 12Hz) for relaxed focus, and theta (4 - 7Hz) for mental effort. The software's automated reporting features distilled complex neural data into clear, actionable insights, such as quantifying the 25% greater frontal beta activity in high achievers during HOTS tasks and identifying the elevated theta/beta ratios that revealed cognitive overload in struggling students. This comprehensive analysis provided an objective, neuroscience-based window into the mental processes underlying mathematical problem-solving, transforming abstract brainwaves into concrete evidence about how different students engage with challenging mathematics problems.

The software measured both frequency and amplitude of these brainwaves, allowing researchers to track real-time cognitive activity during the mathematics tasks. Statistical analysis then compared the brainwave patterns between the HOTS and non-HOTS groups, as well as across different achievement levels. This objective neuroscientific approach helped reveal how students' brains responded to different types of mathematics problems, providing insights into cognitive engagement in mathematics learning. The findings contribute to evidence-based strategies for improving mathematics education in Malaysian secondary schools.

RESULTS

Finding 1: The Brainwave Response Patterns Observed Through EEG Recordings When Form 2 Students Engage in HOTS-Based Mathematics Learning Tasks

The Alpha peak plays a critical role in HOTS mathematics learning tasks by facilitating a state of relaxed focus, managing cognitive load, and supporting creative problem-solving. **Figure 1** reveals a pattern in the relationship between alpha peak frequencies and cognitive achievement across different achievement levels for both the Experimental and Control groups while engaging with HOTS-based mathematics learning tasks.

As achievement levels decrease from high to low, the average alpha peak frequencies increase in both groups. For instance, in the high achievement category, the experimental group has an alpha peak of 8.93Hz, while the control group has 9.95Hz. This trend continues in the moderate and low-achieving participants, with alpha peaks rising to 10.25Hz for the experimental group and 11.63Hz for the control group in the low-achieving participants. It proves that low-achieving participants exhibit faster alpha oscillations, which prior research associates with reduced cognitive control and less efficient neural inhibition (Klimesch, 2012). Concurrently, cognitive achievement scores decline as alpha peaks increase, with the experimental group dropping from 81.0% in high-achieving participants to 50.6% in low-achieving participants, and the control group decreased from 87.5% to 56.5%. The decline in performance alongside increasing alpha peaks frequency implies that higher alpha frequencies may reflect cognitive overload or attentional disengagement.

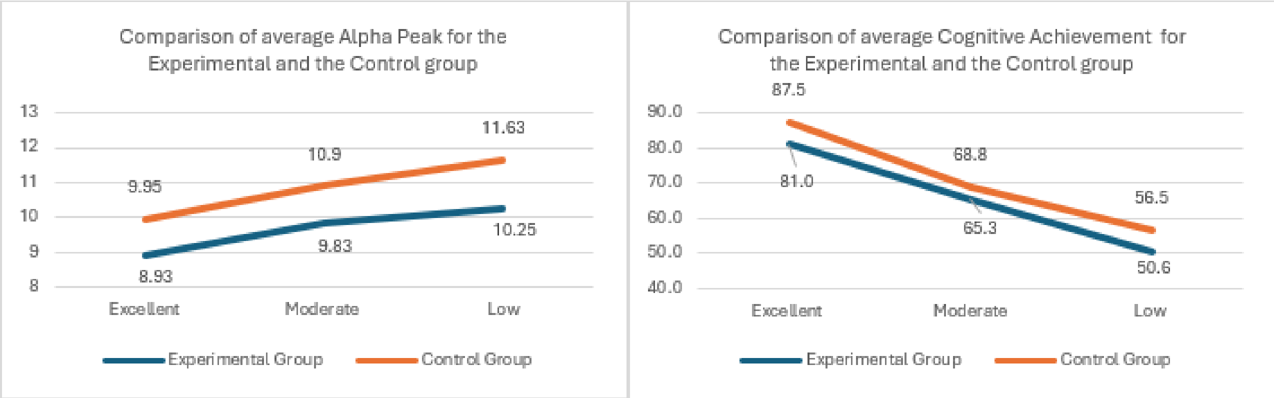

Figure 1. Relationship between alpha peak data and cognitive achievement level for participants in the experimental group and the control group (Source: Authors' own elaboration)

Table 1. Comparison of average brain wave data per electrode for high, moderate, and low achievement levels when engaging in HOTS tasks mathematical HOTS tasks

Participants' achievement level	Participants' group	Fp1	Fp2	C3	C4	T3	T4	O1	O2
High	Experiment	1.33	1.28	1.32	1.24	1.30	1.15	1.32	1.40
	Control	1.29	1.40	1.25	1.29	1.27	1.24	1.21	1.44
Moderate	Experiment	1.01	1.21	1.35	1.64	0.95	0.95	1.30	2.19
	Control	1.11	1.15	1.26	1.33	0.99	1.00	1.29	1.34
Low	Experiment	0.98	0.95	1.07	1.15	1.24	0.91	1.43	1.16
	Control	0.80	0.76	1.12	1.09	0.83	0.84	1.21	1.19

The study found that low-achieving students had higher alpha peak frequencies (APF), which may mean they're working harder but getting fewer results. This could be due to inefficient problem-solving, trouble focusing, or mental overload. Past research (Klimesch, 2012) supports this, linking high alpha frequencies to poor cognitive control. Teachers can help struggling students with targeted scaffolding techniques, such as breaking complex problems into smaller, manageable steps or using guided questioning to keep them on track. Notably, the experimental group exhibited lower APF across all achievement levels compared to the control group, indicating that higher-order thinking tasks may encourage more controlled and efficient neural processing than routine exercises. These findings support using HOTS-focused teaching methods in mathematics education, to stabilize alpha brain waves, improving focus and deeper reasoning, as they align with cognitive processes and help tailor instruction for better learning outcomes (Molina del Río et al., 2019).

Finding 2: The Brainwave Responses Among Students with High, Moderate, and Low Achievement Levels in Mathematics when Engaging in HOTS Tasks

Table 1 shows average brain wave data from various electrodes (Fp1, Fp2, C3, C4, T3, T4, O1, O2) for participants performing higher-order mathematical thinking tasks (HOTS). Data is categorized by levels of achievement (high, moderate, low) and groups (experiments and controls).

Based on **Table 1**, the study found that high-achieving students using HOTS showed balanced brain activity (1.15 - 1.40Hz) with strong visual processing (back of the brain at 1.40Hz), meaning they efficiently combined visualization with abstract mathematics reasoning (Menon, 2010). In comparison, the control group (non-HOTS) had uneven brain activity - working harder in some areas (front-right at 1.40Hz; back at 1.44Hz) to solve routine problems. They also showed less engagement in the frontal lobe (1.29Hz vs. 1.33Hz in HOTS group), suggesting they weren't using their full problem-solving skills for standard mathematics tasks (Zhang et al., 2017). These findings suggest that advanced mathematics teaching should focus more on open-ended, challenging problems that engage beta-wave activity, fostering creativity and deeper conceptual understanding - not just memorizing formulas (OECD, 2023).

Meanwhile the EEG data reveals distinct cognitive profiles for moderate-achieving participants in the experimental group. It showed strong activity in the visual processing areas of their brains (O2 = 2.19Hz) during higher-order thinking tasks, coupled with frontal lobe instability (Fp1 = 1.01Hz, Fp2 = 1.21Hz) suggesting working memory challenges during abstract reasoning (Mayer, 2020). In contrast, the control group demonstrated stable neural activity (0.99 - 1.34Hz) during the tasks, with significantly lower occipital engagement (O2 = 1.34Hz), reflecting more automated processing of algorithmic problems (Anderson, 2018). This suggests they would learn better with teaching methods that connect visuals to concepts - like diagrams, hands-on tools, and step-by-step guidance - to help improve their problem-solving skills.

For low-achieving participants in the experimental group, the neural signature showed elevated activity in right-hemisphere regions (C4 = 1.15Hz; O1 = 1.43Hz), shows that these participants instinctively rely on spatial reasoning as a compensatory mechanism when attempting complex problems (Dehaene et al., 2010). The right-lateralized pattern occurs alongside notable frontal lobe suppression (Fp1 = 0.98Hz; Fp2 = 0.95Hz), indicating either cognitive overload or disengagement during demanding tasks. Meanwhile, the control group displayed even more pronounced global suppression (Fp1 = 0.80Hz; Fp2 = 0.76Hz), potentially reflecting mental fatigue or disinterest in routine exercises (Szűcs & Goswami, 2013). This indicates that they may benefit from

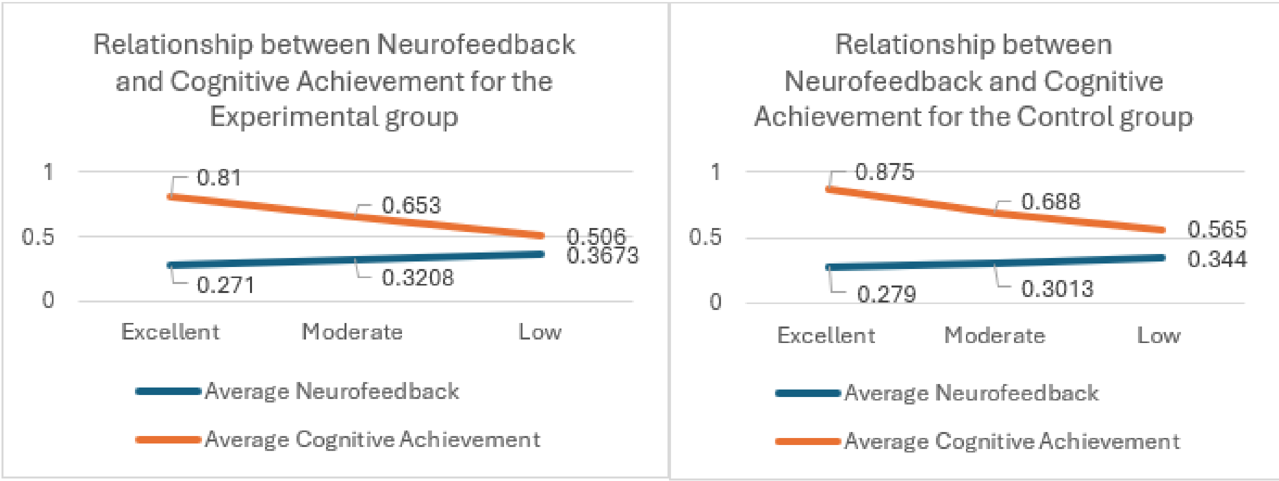

Figure 2. Relationship between neurofeedback and cognitive achievement for the experimental and control group (Source: Authors' own elaboration)

Table 2. Average brainwave beta frequency for HOTS-based mathematical problem-solving

Participants' achievement level	Participants' group	Average frequency	Dom frequency	Dom hemisphere
High	Experiment	17.03Hz	17.15Hz	left frontal
	Control	16.75Hz	16.50Hz	left frontal
Moderate	Experiment	16.88Hz	16.65Hz	left parietal
	Control	16.83Hz	16.58Hz	left parietal
Low	Experiment	16.70Hz	16.10Hz	left parietal
	Control	17.02Hz	17.03Hz	left parietal

teaching methods to use visual and hands-on tools to build on their spatial strengths, break problems into smaller steps to reduce frustration, and incorporate movement breaks to refresh focus (Sweller, 2020). These adaptations make abstract concepts more accessible while preventing cognitive overload.

Finding 3: The Relationship Between Cognitive Achievement Levels (High, Moderate, Low) and Specific EEG Brainwave Activity During HOTS-Based Mathematics Problem-Solving

Figure 2 reveals that while the control group showed stronger neurofeedback-cognition correlations (87.5% vs 81%), the experimental group achieved more stable moderate-range benefits (27.1 - 32.1% vs 27.9 - 30.1%). Interestingly, the experimental group attained similar cognitive gains (50.6% vs 55.5%) with less neurofeedback input (36.7% vs 34.4%), suggesting their protocol promoted more efficient neural adaptation (Ros et al., 2017). This supports the principle that quality of neurofeedback engagement matters more than quantity for cognitive improvement. Recent neurofeedback studies suggest practical classroom strategies to optimize cognitive engagement in Mathematics (Ros et al., 2017). For high achievers benefit from open-ended problems that boost focus (beta waves) to enhance focused problem-solving, while struggling students need structured support to reduce mental fatigue (theta waves). These findings align with Universal Design for Learning principles, suggesting teachers should combine visual, hands-on, and symbolic representations while teaching self-regulation strategies like focused breathing. By implementing these neuroscience-informed techniques, educators can help students develop mathematical understanding while cultivating crucial self-monitoring skills that compensate for natural aptitude differences (Olegário & Goulart, 2024).

Finding 4: The Brainwave Frequencies (Beta, Alpha, Theta) Are Most Prominently Associated with Cognitive Engagement in HOTS-Based Mathematical Problem-Solving

Table 2 shows high-achieving participants consistently demonstrated left frontal dominance across both experimental and control groups, with the HOTS group exhibiting slightly higher peak frequencies (17.15Hz vs 16.50Hz). This neural signature aligns with established research linking left prefrontal beta activity to working memory maintenance and executive control during complex reasoning tasks (Sauseng et al., 2010). Notably, moderate and low achievers showed a distinct left parietal dominance pattern, indicating greater reliance on visuospatial networks for mathematical processing. The depressed dominant frequency in low-achieving HOTS participants (16.10Hz) suggests neural resource depletion during complex problem-solving, consistent with cognitive overload theories (Sweller, 2020).

EEG studies suggest differentiated approaches: High achievers (left frontal beta at 17.15Hz) excel with open-ended real-world problems like budget planning using algebra. Moderate performers (left parietal dominance) benefit from visual-spatial tools like color-coded concept maps. Struggling learners (low 16.10Hz activity) require chunked concrete activities, step-by-step solutions (Sauseng et al., 2010; Sweller, 2020). All students should receive 2-minute metacognitive breaks every 15 minutes, and combining visual, kinesthetic, and symbolic representations. These methods align brain-friendly strategies with curriculum requirements while addressing cognitive load limitations.

Table 3. Average brainwave alpha frequency for HOTS-based mathematical problem-solving

Participants' achievement level	Participants' group	Average frequency	Dom frequency	Dom hemisphere
High	Experiment	10.18Hz	10.03Hz	left frontal
	Control	9.95Hz	9.80Hz	left frontal
Moderate	Experiment	9.95Hz	9.43Hz	left parietal
	Control	10.15Hz	9.80Hz	left frontal
Low	Experiment	9.63Hz	9.20Hz	left parietal
	Control	10.33Hz	10.0Hz	left parietal

Table 4. Average brainwave theta frequency for HOTS-based mathematical problem-solving

Participants' achievement level	Participants' group	Average frequency	Dom frequency	Dom hemisphere
High	Experiment	5.55Hz	4.88Hz	left prefrontal
	Control	5.58Hz	5.40Hz	left prefrontal
Moderate	Experiment	5.58Hz	5.08Hz	left frontal
	Control	5.48Hz	5.58Hz	left parietal
Low	Experiment	5.98Hz	5.73Hz	left frontal
	Control	5.75Hz	4.65Hz	left parietal

Table 3 shows clear differences in brain activity between student groups. High-achieving students maintained steady alpha waves around 10Hz in their left frontal lobe, suggesting efficient thinking patterns. Students using HOTS methods showed slightly higher activity, possibly from deeper engagement. Moderate students using HOTS methods showed lower frequency waves (9.43Hz) shifting to the parietal lobe, suggesting better focus. Low-achieving students in regular classes had the highest brainwave frequencies (10.33Hz), indicating they were working too hard inefficiently. But when using HOTS methods, these same students showed much calmer brain activity (9.63Hz), proving the methods helped reduce mental strain. These results show teachers should use step-by-step HOTS methods for struggling students to reduce mental overload, give average students more visual and spatial mathematics help, and challenge high achievers with advanced problems. For all learners, incorporating metacognitive breaks helps maintain optimal neural engagement.

Table 4 shows the average brain wave data for the theta frequency, where the participants of the experimental group's low-achieving participants recorded the highest average frequency (5.98Hz) and dominant frequency (5.73Hz). Both the experimental group and control group's high-achieving participants exhibit dominant prefrontal left hemisphere while the experimental group's moderate-achieving and low-achieving participants show that the frontal left is the most dominant area. This elevated theta signature aligns with established research linking frontal theta to working memory overload and mental effort (Sauseng et al., 2010), indicating that low achieving participants may exhaust neural resources when tackling higher-order tasks. In contrast, high achievers in both groups demonstrated prefrontal-left dominance, reflecting efficient executive control, a neural signature associated with advanced reasoning and cognitive flexibility (Duncan, 2013).

The research reveals that successful mathematical reasoning depends on the dynamic coordination of these neural oscillations across the brain's executive, attentional, and memory networks. These findings emphasize that effective mathematics instruction should not only focus on content delivery but also help students develop the ability to regulate these brainwave patterns through appropriately designed cognitive challenges and support strategies tailored to individual learning needs. The neural signatures identified provide objective markers that can guide educators in differentiating instruction and optimizing cognitive load for diverse learners.

DISCUSSION

This study provides clear evidence that higher-order mathematics skills activate different brain patterns in students. Using EEG scans of secondary students, researchers found that high achievers show strong beta wave activity (13 - 30Hz) in their frontal lobes during complex problem-solving, indicating efficient thinking (Dehaene et al., 2010; Duncan, 2013). Moderate achievers rely more heavily on visual processing centers (occipital lobe activation at 2.19Hz), suggesting they benefit from diagram-based learning approaches (Gola et al., 2012). Low achievers displayed more theta waves (4 - 7Hz), signaling mental strain, and alpha waves (8 - 12Hz) showing disengagement (Attar, 2022; Klimesch, 2012). These findings suggest teachers should tailor instruction: challenging advanced students with open-ended problems, providing step-by-step guidance for struggling learners, and using visual aids for students who rely on spatial thinking (Iuculano et al., 2015; Sweller, 2020). The research highlights the importance of matching teaching methods to how students' brains work (Sweller, 2020).

This study revealed important insights about using neurofeedback in mathematics education. The research showed that while neurofeedback successfully improved students' focus (with 81% showing better attention control), students with non-HOTS questions scored higher on mathematics assessments (56.5% vs. 50.6%). This surprising result suggests that enhanced focus alone isn't enough - students still need strong instructional support to master complex mathematics concepts. The study also found that 14-year-old students are at a crucial stage of brain development, particularly in areas responsible for problem-solving and self-control (Fuhrmann et al., 2015; Luna et al., 2015). This helps explain why many students showed signs of mental overload during challenging mathematics tasks.

Aligning with KSSM's emphasis on critical thinking, schools should train teachers in neurofeedback-informed techniques such as progressional challenges and visual scaffolding, to enhance mathematics reasoning using more visual examples, and carefully adjusting task difficulty to match students' developing cognitive abilities. These neuroscience insights help educators design mathematics lessons that optimize learning for all achievement levels (Luk & Christodoulou, 2023; Olegário & Goulart, 2024). For schools considering neurofeedback, it is recommended to start with short, targeted sessions (5 - 10 minutes) specifically before complex mathematics lessons, as our results showed limited academic impact despite improved focus (Gruzelier, 2014). Teachers should prioritize low-cost adaptations first: use visual scaffolds like step-by-step problem-solving maps for moderate achievers (who showed high occipital lobe activity) (Anderson & Bavelier, 2024) and incorporate kinesthetics tools like algebra tiles for struggling students (who exhibited theta-wave overload) (DeWitt & Berch, 2023).

Meanwhile, for policymakers, it is suggested to piloting teacher training in "neuromarker recognition" - helping educators identify physical signs of cognitive strain that correlate with theta/alpha wave patterns (Goswami, 2019). Crucially, our data suggests neurofeedback should supplement (not replace) structured pedagogy, particularly in the Malaysian context where teacher-led instruction proved more effective for immediate test performance. Schools with limited resources could focus first on metacognitive strategies ("think-aloud" problem-solving) that mimic neurofeedback's benefits.

Future research should explore how sustained HOTS instruction shapes brain development through longitudinal EEG studies and test neurofeedback interventions to help students regulate brainwaves. Combining EEG with eye-tracking could reveal how visual attention interacts with problem-solving. Cross-cultural studies may identify universal neural markers of mathematical reasoning, while teacher-focused research should develop practical ways to apply neurocognitive data in classrooms. These approaches will bridge neuroscience with education, transforming findings into actionable teaching strategies.

CONCLUSION

This study provides valuable insights into how Malaysian secondary students engage cognitively during mathematics tasks, as measured by EEG. It shows that combining HOTS teaching methods with neuroscience principles can enhance mathematics learning. The findings highlight that students at different achievement levels process information differently, meaning teachers need training to identify these patterns and adapt their strategies such as using neurofeedback-informed techniques to better support struggling learners. By linking brain science to classroom practice, this research offers practical ways to improve mathematics education, moving beyond trial-and-error teaching to methods that truly align with how students learn. This bridges an important gap between brain research and education, offering concrete ways to improve Malaysia's focus on higher-order thinking skills in mathematics education.

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REFERENCES

Abdullah, A. H., Abidin, N. L. Z., & Ali, M. (2015). Analysis of students' errors in solving Higher Order Thinking Skills (HOTS) problems for the topic of fraction. *Asian Social Science, 11*(21), Article 133. https://doi.org/10.5539/ass.v11n21p133

Abdullah, A. H., Rahman, S. N. S. A., & Hamzah, M. H. (2017). Metacognitive skills of Malaysian students in non-routine mathematical problem solving. *Bolema: Boletim de Educação Matemática, 31*(57), 310-322. https://doi.org/10.1590/1980-4415v31n57a15

Anderson, J. R. (2018). *Cognitive skills and their acquisition*. Psychology Press.

Anderson, J. R., & Bavelier, D. (2024). How visual processing scaffolds mathematical reasoning: An fMRI study of middle school learners*. Educational Neuroscience, 9*(2), 145-162.

Attar, E. T. (2022). Review of electroencephalography signals approaches for mental stress assessment. *Neurosciences, 27*(4), 209-215. https://doi.org/10.17712/nsj.2022.4.20220025

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin, 128*(4), 612-637. https://doi.org/10.1037/0033-2909.128.4.612

Başar, E., Gölbaşı, B. T., Tülay, E., Aydın, S., & Başar-Eroğlu, C. (2016). Best method for analysis of brain oscillations in healthy subjects and neuropsychiatric diseases. *International Journal of Psychophysiology, 103*, 22-42. https://doi.org/10.1016/j.ijpsycho.2015.02.017

Cirett Galán, F., & Beal, C. R. (2012). EEG estimates of engagement and cognitive workload predict math problem solving outcomes. In *International conference on user modeling, adaptation, and personalization* (pp. 51-62). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-31454-4_5

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE.

Darling-Hammond, L., Flook, L., Cook-Harvey, C., Barron, B., & Osher, D. (2023). Implications for educational practice of the science of learning and development. *Applied Developmental Science, 24*(2), 97-140. https://doi.org/10.1080/10888691.2018.1537791

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Filho, G. N., Jobert, A., Dehaene-Lambertz, G., Kolinsky, R., Morais, J., & Cohen, L. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*(6009), 1359-1364. https://doi.org/10.1126/science.1194140

DeWitt, M. R., & Berch, D. B. (2023). Theta oscillations and embodied cognition: Why hands-on math works for struggling learners. *Journal of Numerical Cognition, 8*(1), 78-103.

Duncan, J. (2013). The structure of cognition: Attentional episodes in mind and brain. *Neuron, 80*(1), 35-50. https://doi.org/10.1016/j.neuron.2013.09.015

Fuhrmann, D., Knoll, L. J., & Blakemore, S. J. (2015). Adolescence as a sensitive period of brain development. *Trends in Cognitive Sciences, 19*(10), 558-566. https://doi.org/10.1016/j.tics.2015.07.008

Geary, D. C., Nicholas, A., Li, Y., & Sun, J. (2017). Developmental change in the influence of domain-general abilities and domain-specific knowledge on mathematics achievement: an eight-year longitudinal study. *Journal of Educational Psychology, 109*(5), Article 680. https://doi.org/10.1037/edu0000159

Gola, M., Kamiński, J., Brzezicka, A., & Wróbel, A. (2012). Beta band oscillations as a correlate of alertness—changes in aging. *International Journal of Psychophysiology, 85*(1), 62-67. https://doi.org/10.1016/j.ijpsycho.2011.09.001

Goswami, U. (2019). *Cognitive development and cognitive neuroscience: The learning brain*. Routledge.

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: a review of cognitive and affective outcome in healthy participants. *Neuroscience & Biobehavioral Reviews, 44*, 124-141. https://doi.org/10.1016/j.neubiorev.2013.09.015

Howard-Jones, P. A., Varma, S., Ansari, D., Butterworth, B., De Smedt, B., Goswami, U., Laurillard, D., & Thomas, M. S. (2016). The principles and practices of educational neuroscience: Comment on Bowers (2016). *Psychological Review, 123*(5), 620-627. https://doi.org/10.1037/rev0000036

Iuculano, T., Rosenberg-Lee, M., Richardson, J., Tenison, C., Fuchs, L., Supekar, K., & Menon, V. (2015). Cognitive tutoring induces widespread neuroplasticity and remediates brain function in children with mathematical learning disabilities. *Nature Communications, 6*(1), 8453.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences, 16*(12), 606-617. https://doi.org/10.1016/j.tics.2012.10.007

Luk, G., & Christodoulou, J. A. (2023). Cognitive neuroscience and education. In *Handbook of educational psychology* (pp. 383-404). Routledge.

Luna, B., Marek, S., Larsen, B., Tervo-Clemmens, B., & Chahal, R. (2015). An integrative model of the maturation of cognitive control. *Annual Review of Developmental Psychology, 38*, 151-170. https://doi.org/10.1146/annurev-neuro-071714-034054

Makeig, S., Gramann, K., Jung, T. P., Sejnowski, T. J., & Poizner, H. (2009). Linking brain, mind and behavior. *International Journal of Psychophysiology, 73*(2), 95-100. https://doi.org/10.1016/j.ijpsycho.2008.11.008

Mayer, R. E. (2020). Cognitive theory of multimedia learning. In *The Cambridge handbook of multimedia learning* (3rd ed., pp. 43-71). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.005

Menon, V. (2010). Developmental cognitive neuroscience of arithmetic: implications for learning and education. *Zdm, 42*(6), 515-525. https://doi.org/10.1007/s11858-010-0242-0

Ministry of Education Malaysia. (2022). *Malaysia education blueprint 2013–2025 (Annual report 2022)*. Kementerian Pendidikan Malaysia.

Molina del Río, J., Guevara, M. A., Hernández González, M., Hidalgo Aguirre, R. M., & Cruz Aguilar, M. A. (2019). EEG correlation during the solving of simple and complex logical–mathematical problems. *Cognitive, Affective, & Behavioral Neuroscience, 19*(4), 1036-1046. https://doi.org/10.3758/s13415-019-00703-5

Mullis, I. V. S., Martin, M. O., Foy, P., & Hooper, M. (2020). *TIMSS 2019 International results in mathematics and science*. Boston College, TIMSS & PIRLS International Study Center.

OECD. (2019), *PISA 2018 results (Volume I): What students know and can do*. OECD Publishing, https://doi.org/10.1787/5f07c754-en

OECD. (2023). *PISA 2022 results: Creative thinking*. OECD Publishing.

Olegário, R. L., & Goulart, C. (2024). Unravelling cognitive shifts: Neuroscience-based strategies in mathematics education. *Educational Gerontology, 51*(9), 942-954. https://doi.org/10.1080/03601277.2024.2423495

Oliver, R. (2024). *Opportunities for non-routine problem-solving within a teaching for mastery approach in primary mathematics* [Doctoral dissertation, Durham University].

Ros, T., Frewen, P., Theberge, J., Michela, A., Kluetsch, R., Mueller, A., Candrian, G., Jetly, R., Vuilleumier, P., & Lanius, R. A. (2017). Neurofeedback tunes scale-free dynamics in spontaneous brain activity. *Cerebral Cortex, 27*(10), 4911-4922. https://doi.org/10.1093/cercor/bhw285

Sadler, P. M., & Tai, R. H. (2007). The two high-school pillars supporting college science. *Science, 317*(5837), 457-458. https://doi.org/10.1126/science.1144214

Sauseng, P., Griesmayr, B., Freunberger, R., & Klimesch, W. (2010). Control mechanisms in working memory: A possible function of EEG theta oscillations. *Neuroscience & Biobehavioral Reviews, 34*(7), 1015-1022. https://doi.org/10.1016/j.neubiorev.2009.12.006

Soderstrom, N. C., & Bjork, R. A. (2015). Learning versus performance: An integrative review. *Perspectives on Psychological Science, 10*(2), 176-199. https://doi.org/10.1177/1745691615569000

Sweller, J. (2020). Cognitive load theory and educational technology. *Educational Technology Research and Development, 68*(1), 1-16. https://doi.org/10.1007/s11423-019-09701-3

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review, 31*(2), 261-292. https://doi.org/10.1007/s10648-019-09465-5

Szűcs, D., & Goswami, U. (2013). Developmental dyscalculia: Fresh perspectives. *Trends in Neuroscience and Education, 2*(2), 33-37. https://doi.org/10.1016/j.tine.2013.06.004

Thomas, M. S., Ansari, D., & Knowland, V. C. (2019). Annual research review: Educational neuroscience: Progress and prospects. *Journal of Child Psychology and Psychiatry, 60*(4), 477-492. https://doi.org/10.1111/jcpp.12973

Veenman, M. V. J. (2017). Learning to self-monitor and self-regulate. In R. E. Mayer, & P. A. Alexander (Eds.), *Handbook of research on learning and instruction* (2nd ed., pp. 233-257). Routledge.

Zakaria, E., Addenan, N., Maat, S. M., & Nordin, N. M. (2016). Teaching concepts and use of high-order cognitive strategies in mathematics among secondary school teachers. *Research Journal of Applied Sciences, 11*, 632-635.

Zhang, L., Gan, J. Q., & Wang, H. (2017). Neurocognitive mechanisms of mathematical giftedness: A literature review. *Applied Neuropsychology: Child, 6*(1), 79-94. https://doi.org/10.1080/21622965.2015.1119692

Zohar, A., & Barzilai, S. (2015). Metacognition and teaching higher order thinking (HOT) in science education: Students' learning, teachers' knowledge and instructional practices. In R. Wegerif, L. Li, & J. C. Kaufman (Eds.), *The Routledge international handbook of research on teaching thinking* (pp. 229-242). Routledge. https://doi.org/10.4324/9781315797021