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EEG-BASED ANALYSIS OF NEUROCOGNITIVE ENGAGEMENT DURING HOTS-ORIENTED SCIENCE TASKS AMONG FORM TWO

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ABSTRACT

This study examined the effects of Higher-Order Thinking Skills (HOTS)-based science tasks on academic performance and neurocognitive engagement among Form Two secondary school students in Malaysia. A quasi-experimental post-test control group design was employed involving 30 students assigned to either a HOTS-based science task group or a conventional science task group. Electroencephalography (EEG) was used to measure alpha-wave activity and neurofeedback output during science-learning activities. Data were analyzed using descriptive statistics, independent sample t-tests, and Pearson correlation analysis. The findings indicated that students in the control group achieved slightly higher academic performance scores than students in the HOTS group, although the differences were not statistically significant. EEG findings showed that lower-achieving students demonstrated relatively higher alpha wave frequencies and neurofeedback outputs during task completion. However, these relationships were weak and statistically non-significant. The findings suggest that HOTS-oriented science tasks may increase cognitive demands and mental workload, particularly among students with weaker metacognitive regulation skills. Importantly, elevated alpha wave activity was interpreted with caution as a context-dependent indicator of attentional engagement and mental effort, rather than as evidence of intelligence or hidden cognitive potential. The study highlights the importance of balancing HOTS instruction with appropriate scaffolding and demonstrates the potential of EEG as a supplementary tool for examining students' cognitive engagement during science learning activities.

Keywords: higher-order thinking skills (HOTS), science education, educational neuroscience, electroencephalography (EEG), alpha wave activity, cognitive engagement, secondary school students

INTRODUCTION

In recent years, the integration of Higher-Order Thinking Skills (HOTS) into science education has become a major educational priority in many countries, including Malaysia. HOTS-based instruction emphasizes students' ability to analyze, evaluate, and create knowledge rather than merely recall factual information (Krathwohl, 2002). Within the Malaysian educational context, the Malaysian Education Blueprint 2013–2025 highlights the importance of nurturing critical, creative, and innovative learners capable of solving real-world problems through meaningful learning experiences (Ministry of Education Malaysia, 2013). Consequently, HOTS implementation has increasingly become embedded within the secondary science curriculum and classroom assessment practices.

Despite these curricular reforms, many students continue to struggle when engaging with HOTS-oriented science tasks. Previous studies have shown that students often perform adequately in lower-order tasks involving recall and comprehension but experience difficulty when required to interpret evidence, justify reasoning, and apply scientific concepts in unfamiliar contexts because these tasks demand deeper conceptual understanding, analytical reasoning, and metacognitive regulation (Zohar & Dori, 2003; Brookhart, 2010). This issue appears particularly prominent among lower-achieving students who may lack sufficient metacognitive strategies, conceptual foundations, or self-regulatory skills needed to manage complex problem-solving tasks (Mutlu, 2019).

Several researchers have argued that HOTS instruction contributes positively to scientific reasoning and conceptual understanding when implemented effectively (Brookhart, 2010; Zohar & Dori, 2003). However, findings across the literature remain inconsistent. Some studies report that HOTS-based activities improve critical thinking and inquiry skills, whereas others indicate that cognitively demanding tasks may reduce short-term academic performance when students are insufficiently prepared for higher-order reasoning (Sweller, 1988; Paas & Sweller, 2014). These inconsistencies suggest that HOTS effectiveness may depend not only on task complexity but also on instructional scaffolding, prior knowledge, and students' cognitive regulation abilities.

In Malaysia, HOTS has been incorporated into the Kurikulum Standard Sekolah Menengah (KSSM) as part of broader educational reforms aimed at developing innovative and critical thinkers (Ministry of Education Malaysia, 2013). Nevertheless, the implementation of HOTS in science classrooms remains uneven. Arshad et al. (2018) reported that Malaysian students generally perform better on lower-order questions compared with open-ended analytical tasks requiring reasoning and justification. Similarly, Ahmad et al. (2019) found that some teachers experience difficulties in designing meaningful HOTS-based learning activities due to time constraints, examination pressure, and limited pedagogical preparation.

In practice, HOTS instruction frequently remains examination-oriented rather than inquiry-oriented. Students are often trained to answer structured examination questions rather than engage in authentic scientific problem-solving or reflective reasoning. As a result, low achievement on HOTS-related assessments is frequently interpreted as evidence of weak ability rather than of excessive cognitive load, insufficient scaffolding, or ineffective metacognitive regulation. This limitation highlights the importance of examining not only whether students succeed in HOTS tasks but also how they cognitively engage with them during learning activities.

Science education places substantial cognitive demands on learners because students are expected to process abstract concepts, manipulate visual-spatial representations, and draw logical inferences from evidence simultaneously (Montague, 2007). According to Cognitive Load Theory, learning performance may decline when instructional demands exceed the learner's working memory capacity (Sweller, 1988). Cognitive load may emerge from task complexity itself or from ineffective instructional design that imposes unnecessary mental demands on learners (Paas & Sweller, 2014).

However, not all cognitively demanding learning experiences are necessarily harmful. Some educational researchers argue that appropriately challenging tasks can stimulate deeper conceptual understanding and meaningful learning. Consequently, it is important to distinguish between cognitive load and cognitive engagement, as these constructs are frequently discussed interchangeably despite representing different aspects of learning. Cognitive engagement generally refers to students' psychological investment, attentional focus, and willingness to exert effort during learning activities (Fredricks et al., 2004). In contrast, cognitive load refers to the amount of mental effort imposed on working memory during task processing (Sweller, 1988).

This distinction is particularly important in HOTS-oriented science learning. A student may appear highly engaged while simultaneously experiencing excessive cognitive load that negatively affects task performance. Therefore, poor performance during HOTS activities should not be automatically interpreted as low cognitive ability, as students may be investing substantial mental effort while struggling to regulate attentional and cognitive resources effectively. Such distinctions remain insufficiently explored in many classroom-based HOTS studies.

Metacognitive awareness also influences students' ability to manage cognitively demanding science tasks. Mutlu's (2019) meta-analysis demonstrated that students with stronger metacognitive regulation skills tend to perform better in higher-order problem-solving activities. However, several Malaysian studies suggest that many students receive limited explicit instruction in metacognitive strategies such as planning, monitoring, and self-evaluation during science learning (Arshad et al., 2018). This suggests that difficulties with HOTS tasks may stem not only from limitations in content knowledge but also from insufficient cognitive regulation strategies.

Traditional classroom assessments typically evaluate learning using observable outcomes such as test scores, assignment completion, or examination performance. While these measures provide useful information about student achievement, they do not fully capture the internal cognitive processes that occur during learning activities. As a result, researchers have increasingly explored educational neuroscience approaches to complement conventional educational assessment methods (Ansari et al., 2012).

Educational neuroscience integrates perspectives from cognitive psychology, neuroscience, and education to better understand how students process information during learning activities (Howard-Jones, 2014). Importantly, educational neuroscience does not seek to replace pedagogical or psychological theories. Instead, it provides additional insight into students' attentional regulation, cognitive workload, and task-related mental processing under specific instructional conditions.

One neurophysiological tool that has gained increasing attention in educational research is electroencephalography (EEG), which records electrical activity generated by neural oscillations in the brain. EEG has been widely used to examine attention, mental workload, memory processing, and task engagement during learning activities because it provides real-time monitoring of neural responses (Klimesch, 1999). Compared with other neuroimaging techniques, EEG is relatively practical for classroom-related studies because it is portable, non-invasive, and capable of capturing rapid changes in brain activity during learning tasks.

Among EEG frequency bands, alpha wave activity (8–14 Hz) has received particular attention because of its association with attention regulation, working memory, and cognitive control (Başar & Güntekin, 2012). Nevertheless, the interpretation of alpha wave activity remains debated across the literature. Some studies associate elevated alpha activity with focused internal attention and increased mental effort during cognitively demanding tasks (Klimesch, 1999). In contrast, other studies suggest that heightened alpha synchronization may reflect fatigue, anxiety, stress, attentional fluctuation, or cognitive overload during difficult learning activities (Antonenko et al., 2010).

These contrasting findings indicate that alpha wave activity should not be interpreted simplistically as a direct indicator of intelligence, learning potential, or academic readiness. Instead, alpha activity is better understood as a context-dependent indicator of neurocognitive activation influenced by multiple psychological and environmental factors. This distinction is important because some educational neuroscience studies have overgeneralized EEG findings by equating increased brain activation with superior cognitive capability.

The distinction between neurocognitive activation and neural efficiency is also important in interpreting EEG findings. Neurocognitive activation generally refers to increased physiological activity associated with cognitive processing during task performance. In contrast, neural efficiency refers to the ability to perform cognitive tasks effectively with relatively lower neural resource expenditure (Neubauer & Fink, 2009). Previous studies involving high-performing learners have sometimes reported lower or more stable alpha activity compared with lower-performing learners, suggesting that efficient learners may require fewer cognitive resources to complete similar tasks (Klimesch, 2012). Therefore, higher EEG activation should not automatically be interpreted as evidence of better learning or greater cognitive ability.

Another concept that requires clarification is neurofeedback. In EEG-based educational studies, neurofeedback commonly refers to quantified indicators of brain activity generated during task engagement (Demos, 2005). However, neurofeedback should not be confused with measures of cognitive performance or intelligence. Rather, neurofeedback reflects physiological patterns associated with attentional states, mental effort, and cognitive processing during a specific task context. Furthermore, neurofeedback outputs may be influenced by contextual factors such as emotional stress, fatigue, environmental distraction, anxiety, or task unfamiliarity (Antonenko et al., 2010).

EEG research in educational settings has produced mixed findings regarding the relationship between alpha activity and academic performance. Some studies report that students demonstrating stronger alpha synchronization during cognitively demanding tasks tend to perform better academically because of more efficient attentional regulation (Klimesch, 2012). In contrast, other studies suggest that elevated alpha activity among lower-performing students may reflect increased mental effort, cognitive overload, or inefficient processing strategies rather than higher cognitive capability (Antonenko et al., 2010). These inconsistencies highlight the importance of interpreting EEG indicators cautiously and contextually.

Despite increasing international interest in educational neuroscience, EEG-based studies in Malaysian science education remain relatively limited. Most local HOTS studies continue to rely primarily on surveys, interviews, and academic test scores to evaluate learning outcomes. Although these approaches provide valuable information regarding student achievement and perceptions, they may overlook important aspects of students' task-related cognitive engagement during HOTS-based science learning.

Integrating HOTS instruction with EEG-based monitoring offers an opportunity to better understand how students cognitively manage complex science learning tasks. HOTS frameworks emphasize reasoning, inquiry, and analytical thinking, whereas EEG provides additional insight into students' attentional regulation and mental workload during task performance. Importantly, EEG should not be viewed as replacing traditional educational assessment but rather as complementing behavioral evidence by revealing additional dimensions of cognitive processing during learning.

Several studies have suggested that students may demonstrate substantial neurocognitive activation during difficult learning tasks even when academic performance remains relatively low (Klimesch, 2012). However, interpretations of such findings vary considerably across the literature. Some researchers interpret elevated brain activation as evidence of deeper cognitive engagement, whereas others argue that it may instead reflect inefficient processing, cognitive overload, or attentional instability (Antonenko et al., 2010). This disagreement demonstrates the importance of avoiding deterministic interpretations of EEG findings in educational research.

For example, a student who performs poorly on a HOTS science task may not necessarily lack cognitive ability. Instead, the student may experience excessive cognitive load, limited metacognitive regulation, or difficulty allocating attentional resources effectively during problem solving (Sweller, 1988; Mutlu, 2019). Therefore, combining HOTS-based instruction with EEG monitoring may help researchers better understand the relationship between observable academic performance and students' internal cognitive processing during learning activities.

This study, therefore, seeks to contribute to the growing field of neuroeducation by examining both academic performance and neurocognitive engagement during HOTS-based science learning among Form Two students in Malaysia. Importantly, the study does not treat EEG indicators as direct measures of intelligence, learning potential, or fixed cognitive ability. Instead, alpha wave activity and neurofeedback output are interpreted cautiously as context-dependent indicators of attentional regulation, mental effort, and cognitive workload during task completion.

Specifically, this study addresses the following research questions:

i. What differences exist in science task performance, alpha wave activity, and neurofeedback output between students completing HOTS-based science tasks and those completing conventional science tasks?
ii. What is the relationship between alpha wave frequency, neurofeedback output, and science task performance among Form Two students?
iii. How do science task performance, alpha wave activity, and neurofeedback output differ across high-, moderate-, and low-achieving students during science task completion?

METHODOLOGY

Research Design

This study employed a quasi-experimental post-test control group design to investigate the effects of Higher-Order Thinking Skills (HOTS)-based science tasks on students' academic performance and neurocognitive responses. Although students were randomly assigned to groups, the inclusion of baseline EEG recordings and cognitive profiling aligns the study more closely with a quasi-experimental framework rather than a fully randomized true experimental design (Fraenkel & Wallen, 2009).

The study adopted an educational neuroscience perspective by integrating behavioral performance data with neurophysiological measurements to better understand students' cognitive engagement during science learning activities (Ansari et al., 2012; Howard-Jones, 2014). EEG was used to monitor students' alpha wave activity during science tasks. Alpha activity was interpreted as a context-dependent indicator of attentional engagement and mental workload rather than a direct measure of intelligence or learning potential (Klimesch, 1999; Başar & Güntekin, 2012). Since alpha activity is state-dependent, interpretations were made cautiously, as it may also reflect fatigue, anxiety, stress, attentional fluctuations, or cognitive overload (Antonenko et al., 2010).

Participants

The study involved 30 Form Two students (aged 14 years) from a Malaysian secondary school. Participants were selected through purposive sampling based on accessibility, parental consent, and willingness to participate in EEG-based activities. Due to the exploratory nature of the study and logistical limitations associated with classroom EEG data collection, the sample size was intentionally kept small, consistent with pilot neuroeducation studies (Antonenko et al., 2010; Dikker et al., 2017). Participants were randomly assigned to two groups:

i. Experimental group (n = 15): HOTS-based science tasks
ii. Control group (n = 15): Conventional science tasks

Students were further categorized into high, moderate, and low performance groups based on computerized cognitive assessment scores and baseline academic performance.

Baseline EEG recordings were used only as supplementary contextual information, not as indicators of fixed cognitive ability (Klimesch, 2012).

Cognitive Assessment Tool

A computerized cognitive assessment was developed to evaluate students' scientific reasoning and higher-order thinking performance. The instrument included:

i. Analogical reasoning tasks
ii. Inference-based science questions
iii. Pattern recognition activities
iv. HOTS-oriented mini tasks

The assessment measured analytical reasoning and problem-solving performance rather than intelligence. Content validation was conducted by science education and educational psychology experts to ensure alignment with HOTS constructs in the Malaysian curriculum (Krathwohl, 2002; Brookhart, 2010).

EEG Measurement

Brainwave activity was recorded using an 8-electrode mobile EEG headset and a 12-channel recording system. Recordings focused on alpha wave frequencies (8–14 Hz), particularly within frontal and occipital regions associated with attention and cognitive processing (Klimesch, 1999; Başar, 2012). The Neuron-Spectrum.NET system enabled:

i. Real-time alpha wave monitoring
ii. Neurofeedback percentage estimation
iii. Time-synchronized recordings

In this study, alpha wave frequency refers to EEG-recorded activity associated with attentional engagement and mental workload during task completion, while the neurofeedback output is the percentage-based EEG activation index generated during task performance.
EEG recordings were conducted under controlled classroom conditions to minimise signal artefacts. Alpha activity was interpreted cautiously because variations may reflect attentional focus, cognitive load, fatigue, stress, or inefficient cognitive regulation rather than superior cognitive ability (Antonenko et al., 2010; Paas & Sweller, 2014).

Learning Tasks and Assessments

The HOTS-based tasks required students to analyze scientific situations, justify reasoning, and propose solutions to contextual science problems. In contrast, the conventional tasks emphasized factual recall and direct application of concepts.

All tasks were reviewed by science educators and educational psychology experts to ensure construct validity and curriculum alignment (Brookhart, 2010; Zohar & Dori, 2003).

Group	Task Type	Characteristics
Experimental	HOTS-Based Science Tasks	Analytical, open-ended, problem-solving
Control	Conventional Science Tasks	Recall-based, structured, multiple-choice

Procedure

The study was conducted in three phases:

Phase 1: Baseline Assessment
- Students completed the computerized cognitive assessment
- Baseline EEG recordings were obtained
- Initial academic and neurocognitive data were documented

Phase 2: Instructional Intervention
- The experimental group engaged in HOTS-oriented science activities
- The control group received conventional instruction
- EEG recordings were collected during task completion

Phase 3: Post-Task Assessment
- Both groups completed science assessments
- Final EEG recordings were conducted
- Academic and EEG data were compiled for analysis

Data collection sessions were conducted under standardized classroom conditions to reduce environmental influences on EEG recordings.

Data Analysis

Data were analyzed using descriptive and inferential statistics.

Academic Performance Analysis

Science assessment scores were analyzed using Microsoft Excel and SPSS version 27. Analyses included:
- Mean and standard deviation calculations
- Independent sample t-tests to examine differences between HOTS and conventional groups (Field, 2018)
- Descriptive comparison across achievement levels

EEG Data Analysis

EEG analysis focused on:
- Alpha wave frequencies
- Neurofeedback output
- Patterns of cognitive engagement during task completion

EEG indicators were interpreted as measures of attentional engagement and mental workload rather than direct indicators of intelligence or academic capability (Başar & Güntekin, 2012).

Cross-Analysis

Pearson correlation analysis was conducted to examine relationships between:

- Alpha wave activity
- Neurofeedback output
- Science task performance

Elevated neurocognitive activation was interpreted with caution as possible evidence of increased mental effort, attentional fluctuations, cognitive overload, or inefficient cognitive regulation, rather than higher cognitive potential (Klimesch, 2012).

RESULTS

This section presents the findings in four parts: (i) science task performance, (ii) EEG alpha wave activity, (iii) neurofeedback output, and (iv) cross-analysis between academic performance and neurocognitive engagement. In response to reviewer feedback, both descriptive and inferential statistical analyses were included to strengthen the analytical rigor of the study. Independent sample t-tests and Pearson correlation analyses were conducted using SPSS version 27.

Academic Performance on Science Tasks

Student performance was assessed using post-task science assessments. Table 1 presents the mean scores and standard deviations according to instructional group and achievement level.

Table 1. Science Learning Task Assessment Scores (%)

Achievement Level	Experimental Group (M ± SD)	Control Group (M ± SD)
High	77.2 ± 4.13	80.5 ± 3.84
Moderate	68.8 ± 5.21	70.5 ± 4.76
Low	60.4 ± 6.02	67.2 ± 5.44

An independent sample t-test indicated that the control group achieved slightly higher scores than the experimental group; however, the difference was not statistically significant, $t(28) = -1.84, p > .05$.

Interpretation

Although students in the HOTS group engaged in more analytical and problem-solving activities, their scores did not significantly exceed those of the control group. This suggests that HOTS-oriented tasks may initially increase cognitive demands without producing immediate improvements in academic performance. This finding is consistent with studies indicating that HOTS learning often requires repeated exposure and instructional scaffolding before achievement gains become evident (Arshad et al., 2018; Ahmad et al., 2019).

The findings also support Cognitive Load Theory, which proposes that excessive task complexity without sufficient support may overload students' working memory, particularly among lower-achieving learners (Sweller, 1988; Paas & Sweller, 2014).

EEG Alpha Wave Frequency During Task Completion

Alpha wave frequency data (8–14 Hz) were collected during science task completion to examine students' attentional engagement and mental workload. Table 2 presents the mean alpha frequencies across achievement levels and instructional groups.

Table 2. Alpha Peak Frequency (Hz) During Task Completion

Achievement Level	Experimental Group (M ± SD)	Control Group (M ± SD)
High	9.45 ± 0.71	10.15 ± 0.64
Moderate	10.13 ± 0.66	10.83 ± 0.59
Low	10.73 ± 0.74	11.53 ± 0.69

Independent sample t-test analysis showed no statistically significant difference in alpha wave frequency between groups, $t(28) = -1.52$, $p > .05$. However, descriptive trends indicated that lower-achieving students demonstrated higher alpha frequencies across both instructional conditions.

Interpretation

Low-achieving students exhibited the highest alpha wave frequencies, suggesting increased mental effort or attentional demands during task completion. These findings should be interpreted with caution, as elevated alpha activity does not necessarily indicate superior cognitive ability or learning efficiency. Instead, alpha activity may reflect heightened cognitive workload, attentional fluctuation, fatigue, or compensatory processing during difficult tasks (Klimesch, 1999; Başar & Güntekin, 2012).

The experimental group showed slightly lower alpha frequencies than the control group. One possible explanation is that HOTS tasks imposed greater cognitive complexity, leading to fluctuations in attentional regulation or cognitive fatigue among some learners (Antonenko et al., 2010). High-achieving students maintained relatively stable alpha frequencies across conditions, potentially reflecting more efficient cognitive regulation during task engagement (Klimesch, 2012).

Neurofeedback Output During Science Task Completion

Neurofeedback percentages were used to estimate students' neurocognitive engagement during science learning activities. Table 3 presents the neurofeedback output according to instructional group and achievement level.

Table 3. Neurofeedback Output (%) During Science Task Completion

Achievement Level	Experimental Group (M ± SD)	Control Group (M ± SD)
High	29.73 ± 3.12	31.48 ± 2.96
Moderate	34.18 ± 3.54	36.20 ± 3.28
Low	37.18 ± 3.81	38.40 ± 3.47

Independent sample t-test analysis revealed that differences in neurofeedback output between groups were not statistically significant, $t(28) = -1.27, p > .05$.

Interpretation

Low-achieving students demonstrated the highest neurofeedback readings, indicating increased mental effort and sustained cognitive activation during task performance. However, this elevated neurocognitive engagement did not correspond to higher academic achievement. This finding supports previous research suggesting that neural activation and academic performance do not always align directly, particularly when learners experience cognitive overload or insufficient metacognitive regulation (Antonenko et al., 2010; Mutlu, 2019).

Students in the experimental group showed slightly lower neurofeedback percentages despite engaging in more cognitively demanding HOTS activities. This pattern may reflect cognitive fatigue or more selective allocation of attentional resources during complex problem-solving tasks (Başar, 2012).

Cross-Analysis: Academic Performance and Neurocognitive Engagement

Pearson correlation analysis was conducted to examine the relationship between academic performance, alpha wave activity, and neurofeedback output.

The analysis revealed a weak negative correlation between academic performance and alpha wave activity ($r = -0.32, p > .05$), indicating that students with higher alpha activity tended to demonstrate slightly lower academic performance. Similarly, neurofeedback output showed a weak negative relationship with assessment scores ($r = -0.29, p > .05$). However, these relationships were not statistically significant.

Interpretation

The findings suggest a possible performance–engagement mismatch, whereby students demonstrating higher levels of neurocognitive activation did not necessarily achieve stronger academic outcomes. Importantly, these findings should not be interpreted as evidence of hidden intelligence or untapped cognitive superiority. Rather, they may indicate that some students invested greater mental effort while struggling to manage the cognitive demands of HOTS-oriented tasks.

This interpretation aligns with Cognitive Load Theory and metacognitive learning research, which emphasize that increased mental effort alone does not guarantee successful task performance unless accompanied by effective cognitive regulation and instructional support (Sweller, 1988; Montague, 2007).

The findings also support the potential role of EEG as a supplementary educational tool for understanding students' cognitive engagement during learning activities. However, EEG indicators should be interpreted cautiously and together with behavioral and academic data rather than as standalone measures of student capability (Howard-Jones, 2014; Klimesch, 2012).

DISCUSSION

This study explored the effects of HOTS-based science assessments on academic performance and EEG alpha wave activity among Form Two students. By integrating behavioral and neurophysiological data, the findings provide insights into how students with different achievement levels cognitively engage with complex science tasks. Importantly, the EEG findings in this study were interpreted with caution as context-dependent indicators of attentional engagement and mental workload rather than as direct measures of intelligence or cognitive potential (Howard-Jones, 2014; Klimesch, 2012).

The Cognitive Demands of HOTS Tasks

The lower academic performance observed among students in the HOTS group, particularly among lower-achieving learners, supports concerns that HOTS-oriented tasks may impose substantial cognitive demands when insufficient instructional scaffolding is provided (Sweller, 1988; Paas & Sweller, 2014). HOTS tasks typically require multi-step reasoning, abstraction, interpretation, and evidence-based justification, all of which place pressure on working memory and attentional regulation (Montague, 2007).

Although high-achieving students maintained relatively stable performance across both instructional conditions, moderate- and low-achieving students demonstrated greater difficulty with HOTS-oriented tasks. This finding suggests that cognitively demanding science activities may disproportionately challenge students with weaker metacognitive regulation skills or limited prior conceptual understanding (Mutlu, 2019; Ahmad et al., 2019). Similar findings were reported by Arshad et al. (2018), who argued that HOTS implementation without differentiated support may unintentionally widen achievement differences among learners.

The findings also reinforce the distinction between cognitive engagement and cognitive load. Students may appear highly engaged during HOTS activities while simultaneously experiencing excessive cognitive load that negatively affects performance. Therefore, lower performance among some students should not be automatically interpreted as a lack of effort or ability; it may instead reflect difficulties in managing the cognitive demands of complex science tasks.

Alpha Wave Activity and Neurocognitive Engagement

One notable finding of this study was that lower-achieving students exhibited higher alpha-wave frequencies and neurofeedback outputs during HOTS task completion. However, these findings should not be interpreted as evidence of hidden intelligence, fixed cognitive superiority, or untapped learning potential. Instead, elevated alpha activity may reflect increased mental effort, heightened attentional demands, cognitive overload, or inefficient cognitive regulation during difficult learning activities (Klimesch, 1999; Antonenko et al., 2010).

Previous EEG studies have produced mixed interpretations regarding elevated alpha activity during cognitively demanding tasks. Some researchers associate higher alpha synchronization with focused internal attention and increased cognitive effort (Başar & Güntekin, 2012). In contrast, other studies suggest that elevated alpha activity may emerge when learners experience fatigue, anxiety, stress, or attentional fluctuation under challenging task conditions (Antonenko et al., 2010). The present findings therefore support a cautious and context-specific interpretation of EEG indicators rather than deterministic conclusions regarding student capability.

The weak negative relationship observed between academic performance and alpha activity further suggests that increased neurocognitive activation does not necessarily correspond to stronger academic outcomes. This finding may indicate that some lower-achieving students invested greater mental effort while struggling to regulate cognitive resources effectively during HOTS-oriented tasks.

Neural Efficiency and Cognitive Regulation

Interestingly, high-achieving students demonstrated relatively lower and more stable alpha wave activity across instructional conditions. This pattern may reflect neural efficiency, whereby students perform cognitive tasks effectively while expending fewer cognitive resources (Neubauer & Fink, 2009). Similar findings have been reported in studies suggesting that learners with stronger cognitive strategies often demonstrate more efficient attentional regulation during complex problem-solving tasks (Klimesch, 2012).

In contrast, lower-achieving students demonstrated higher neurofeedback outputs and alpha activity, potentially reflecting increased mental effort or inefficient information processing during HOTS activities. Importantly, higher neurocognitive activation should not be automatically interpreted as better learning performance, as excessive activation may also indicate cognitive overload or difficulty in managing task demands (Antonenko et al., 2010).
These findings highlight the importance of differentiating HOTS instruction according to students' cognitive readiness and metacognitive regulation abilities. Without sufficient scaffolding, cognitively demanding tasks may overwhelm learners who lack effective strategies for organizing and regulating information during problem solving.

Educational Implications

The findings of this study provide several implications for science education and HOTS implementation.

First, HOTS instruction should be implemented progressively with appropriate scaffolding and metacognitive support, particularly for lower-achieving students (Mutlu, 2019). Structured guidance, reflective questioning, and self-monitoring activities may help students manage cognitive load more effectively during higher-order science learning tasks.

Second, the findings suggest that EEG may serve as a supplementary educational tool for examining students' attentional engagement and mental workload during learning activities. However, EEG indicators should not be used as standalone measures of intelligence, ability, or academic potential. Instead, neurophysiological data should be interpreted together with behavioral and academic evidence (Howard-Jones, 2014).

Third, the distinction between cognitive engagement and cognitive overload is particularly important in HOTS-based instruction. Students who demonstrate elevated mental effort may still struggle academically if task complexity exceeds their ability to regulate cognitive resources effectively. Consequently, instructional design should balance cognitive challenge with sufficient support to prevent excessive cognitive overload and disengagement.

Finally, the findings reaffirm that traditional achievement measures alone may not fully capture students' learning experiences during HOTS-oriented science activities. Integrating behavioral and neurophysiological perspectives may provide a more comprehensive understanding of how students cognitively respond to complex learning tasks under different instructional conditions.

CONCLUSION

This study examined the effects of Higher-Order Thinking Skills (HOTS)-based science tasks on academic performance, alpha wave activity, and neurofeedback output among secondary school students in Malaysia. By integrating traditional assessment methods with electroencephalography (EEG) data, the study provided additional insight into students' neurocognitive engagement during HOTS-oriented science learning activities.

The findings indicated that students exposed to HOTS-based tasks did not demonstrate significantly higher academic performance compared with students completing conventional science tasks. In particular, lower-achieving students experienced greater difficulty when engaging with cognitively demanding HOTS activities. These findings support previous research suggesting that HOTS-oriented instruction may increase cognitive demands and mental workload, especially when learners lack sufficient metacognitive regulation skills or instructional scaffolding (Sweller, 1988; Mutlu, 2019).

At the same time, lower-achieving students demonstrated relatively higher alpha wave frequencies and neurofeedback outputs during task completion. However, these findings should be interpreted cautiously because elevated alpha activity does not necessarily indicate higher intelligence, hidden cognitive potential, or fixed learning capacity. Instead, increased neurocognitive activation may reflect greater mental effort, attentional fluctuation, cognitive overload, stress, or inefficient cognitive regulation during difficult learning tasks (Antonenko et al., 2010; Klimesch, 2012).

The study also identified a possible performance–engagement mismatch, whereby students demonstrating higher neurocognitive activation did not necessarily achieve stronger academic outcomes. This finding highlights the importance of distinguishing between cognitive engagement, cognitive load, and academic achievement during HOTS-based learning. Increased mental effort alone may not produce successful performance unless accompanied by effective instructional support, metacognitive regulation, and appropriate task design.

Importantly, the findings suggest that EEG may serve as a supplementary educational tool for examining students' attentional engagement and mental workload during science learning activities. Nevertheless, EEG indicators should not be treated as standalone measures of intelligence, ability, or academic potential. Rather, neurophysiological data should be interpreted together with behavioral and academic evidence to provide a more balanced understanding of students' learning experiences.

This study, therefore, supports several educational implications. HOTS instruction should be implemented progressively with sufficient scaffolding, particularly for lower-achieving students who may struggle with excessive cognitive demands. Additionally, metacognitive strategy training may help students manage attentional resources and cognitive load more effectively during higher-order problem-solving tasks.

Several limitations should also be acknowledged. The study involved a relatively small sample size and focused solely on alpha-wave activity in a short-term instructional context. Consequently, the findings should be interpreted within the exploratory scope of the study and should not be generalized broadly. Future research should involve larger participant samples, longitudinal designs, and additional EEG frequency bands such as beta and theta activity to further examine students' neurocognitive responses during HOTS-oriented science learning.

Overall, the integration of educational neuroscience and science pedagogy offers valuable opportunities to understand how students respond cognitively to complex learning tasks. However, the educational value of EEG lies not in labeling students according to perceived cognitive potential, but in providing additional insight into how learners manage attentional and cognitive demands during meaningful learning experiences**.**

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