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Research Article

Insights into cognitive processes operating during classroom learning

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Attention-based learning tasks of modern classrooms require processing of information in working memory. Not much is known about the cognitive processes operating during these tasks. To gain an understanding of the processes that support cognitive functions like learning, we have monitored the activity of the brain waves emanating from the frontal lobes region of a group of high school students working on a series of conceptually-linked tasks using a commercially available electroencephalographic (EEG) headband. Analysis of the EEG recordings revealed an increase in the relative power of gamma and beta as students worked through the tasks, suggesting that they were adding items in the working memory, retaining them, retrieving and reading them out for either use in the tasks or disposal. Remarkably, a decrease in alpha activity indicated that students seem to be attenuating the inhibition of distracting images retrieved from memory to make a larger pool of words available for solving the word puzzle. Such cognitive processing probably increased the load in the working memory as indicated by reduction in theta activity. Lastly, the students increased wakeful attention and alertness by lowering the delta activity. These results provide new insights into the cognitive functions operating during attention-based classroom learning tasks.

Keywords: Cognition; Attention; Classroom learning; Brain waves; Electroencephalographic

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1. Introduction

The brain plays essential roles in homeostasis by constantly monitoring the external as well as internal stimuli that it receives and formulating appropriate responses (Yin & Yuan, 2015). Such activity is vital for maintaining optimal conditions for proper functioning of the organs of the body to support survival, growth and reproduction. Much of what the brain does is involuntary and does not require our conscious attention. In fact, studies seem to suggest that there may be a limited capacity of the brain reserved for tasks that need conscious attention (Foxe & Snyder, 2011; Neely, 1977; Schneider & Shiffrin, 1977; Schneider & Fisk, 1982).

Explicit learning in classrooms requires students to focus on tasks consciously (Chafee & Crowe, 2017; Eichenbaum, 1999; Reber & Squire, 1994). During such learning, the brain is thought to focus attention on the tasks to accomplish the purpose stated in the task. The brain does this

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very efficiently using two seemingly opposite yet complementary mechanisms. It can enhance engagement with the evidently correct stimuli while simultaneously disengaging or suppressing the processing of stimuli that supposedly supply irrelevant or distracting information (Foxe & Snyder, 2011). Adoption of such a sophisticated dual-mechanism of attention helps process large amounts of information quickly and respond appropriately. This strategy is particularly well suited for modern times where the brain has to sift through information emanating from different sources, identify and suppress irrelevant information while staying focused on processing information relevant to the task at hand. Although the magnitude of attention-seeking distracting information seems to have grown many fold when compared to ancient times, not much is known about how high school students are able to cope with distractions while studying for high stakes exams.

Cognitive functions like learning relying on attention activate specific neural signalling pathways (Oby et al., 2019). The transmission of the information originating from the stimuli; for example, a task requiring interpreting the optimal pH of the enzyme from the graph, in the form of electrical impulses to the different regions of the brain and the associated biochemical reactions during its processing are known to emit brain waves. Six different types of brain waves, namely gamma (γ, 30-80 Hz), beta (β, 13-30 Hz), alpha (α, 8-13 Hz), theta (θ, 3-7 Hz) and delta (δ, 1-3 Hz) are produced by the brain, which can be monitored by using electroencephalographic (EEG) recordings measured by devices (Huang et al., 2020). Importantly, patterns of the EEG recordings of the brain waves have been shown to vary depending on the nature of the cognitive task. For instance, the power of gamma and beta waves has been shown to increase in the EEG during external attention-requiring learning tasks (Baddeley, 2003; Howard et al., 2003; Lundqvist et al., 2018; Schmidt et al., 2019). Similarly, in some studies, the power of delta has been shown to increase while working on tasks involving mental calculations and those requiring 'internal concentration '(Fernández et al., 1995). In contrast, the power of alpha waves is likely to reduce in the EEG while working on cognitive tasks requiring construction of mental imagery (Bollimunta et al., 2011). Similarly, the power of theta waves is likely to reduce as the brain encodes episodic memory or retrieves memory (Brzezicka et al., 2019); although, some studies have reported the opposite (Gärtner et al., 2015; Hsieh & Ranganath, 2014). Thus, monitoring brain wave patterns can potentially provide valuable information on cognitive functions like active learning for deducing whether the learning tasks are suitable for producing the desired learning outcomes.

The current teaching and learning environments are very different from a few decades ago, where the role of the students was to passively listen to the teachers as they spoke. In modern classrooms, students learn actively by constructing their own knowledge (Bruner, 1961; Locke, 1948). Key understandings are developed in a gradual manner through problem solving tasks, exploration and experimentation (Uzun & Sen, 2023; Woods, 1987). Students learn concepts through assimilation and accommodation (Piaget, 2013); constantly refining their mental models as they develop a deeper knowledge of concepts (Gentner & Gentner, 1983). Teachers facilitate cognition through presenting concepts that are linked, but progressively difficult (Vygotsky, 1978). Adequate support in the form of contingent instructions, chunking, pairing, re-teaching, language support, etc is provided to ensure that every student is learning and engaged with the highest quality learning material (Bruner & Bruner, 1966; Skinner, 1974). Thus, tenets of numerous learning theories are visible in modern classrooms, making learning more fun and effective.

The proficiency in use of cognitive skills of high school students is measured in part by an objective marks-based evaluation of their responses to attention-requiring paper-based questions. However, the mechanisms underlying the cognitive processing of information while responding to tasks requiring varying levels of cognitive effort remain largely unknown. In this study, we have designed a series of increasingly complex learning tasks that require the use of cognitive functions like problem solving based on inductive reasoning, resulting in a vigorous stimulation of neural activity. In particular, we wanted to examine the modulation of the brain waves, signifying neural activity, as a function of cognition while working on these tasks. Analysis of the pattern of the brain waves elicited was likely to shed light on the nature of the cognitive processes operating during the task. It is important to know this information for optimizing learning strategies such that all students are utilizing their full cognitive potential for achieving the highest possible learning outcome. Based on this premises, we recruited high school students to study their brain wave patterns as they worked on a series of tasks requiring increasing cognitive effort. The brain wave patterns were recorded using a headband fitted with an EEG recording device as described previously (Huang et al., 2020; Minteer et al., 2019). Analysis of the power of the waves in the EEG recordings in light of the responses to each of the tasks reveal similarities as well as individual differences in cognitive effort. Notably, we found task-specific differences in elicitation of cognitive functions. For instance, a reduction in the power of alpha observed in the EEG for task 5 seems to suggest that the students were attenuating the inhibition of distracting images of words in their minds to make more words available for solving the puzzle. In contrast, an increase in the power of gamma observed as the students worked through conceptually linked tasks suggested that the students were adding items from previous tasks for retention in working memory so that they could be used for the following tasks. The implications of these findings for designing learning tasks are discussed.

2. Materials and Methods

2.1. Participants and Design of the Study

Six high school students from Year 10 class, comprising of equal number of girls and boys, were enrolled for the study (see Table 1). All the procedures related to ethics, including obtaining informed written consent were followed.

Table 1
Design of the study

	Expected time to finish the task	*Total marks*	*Student S1HA*	*Student S2LA*	*Student S3*	*Student S4*	*Student S5*	*Student S6*
Task 1	1 min	6	✓	✓	✓	✓	✓	✓
Task 2	5 min	10	✓	✓	✓	✓	✓	✓
Task 3	10 min	6	✓	✓	✓	✓	✓	✓
Task 4	10 min	4	✓	✓	✓	✓	✓	✓
Task 5	15 min	6	✓	✓	X	X	X	X

Note. ✓ = performed this task; X = did not perform this task; S1HA = High-achieving student; S2LA = Average-achieving student

Four grade-level appropriate learning tasks with increasing complexity, requiring a progressively greater cognitive effort were designed (Supplementary files S1 and S2). All six students attempted these tasks. In addition, two students, a relatively low-achieving student and a high-achieving student, from the same group of six students recruited for the study, were given an additional fifth task (Table 1). The comparison of the performance of these two students under identical conditions was expected to shed light on the differences in cognitive processing by the two students with varying achievement levels.

There was no time limit imposed for the completion of the tasks. However, all the tasks had to be completed in one seating and the tasks had to be done in the order from 1 to 4 or 1 to 5 without any lag between the tasks. As soon as the students finished one task, they had to start working on the next task. The total time expected for the completion of tasks 1 to 4 was 26 minutes. The fifth task was expected to require 15 minutes for completion. Each task was assigned marks and the completed tasks were awarded marks based on the rubric for the grading of the tasks (Table 1).

Several considerations were taken into account while designing the tasks. Firstly, the tasks had to revolve around grade-level exploration of concepts. Secondly, to make them authentic, the tasks had to follow a style similar to the attention-based classroom learning assignments or questions asked in standardized exams. Lastly, the tasks had to be designed such that they built learning gradually with each step leading to the elicitation of a higher order cognitive function. In line with the considerations, the tasks represented the following steps with each step imposing more cognitive demand over the previous (Supplementary files S1 and S2).

Step 1 - Observation of a key phenomenon (Task 1)
Step 2 - Exploration of the phenomenon by re-working it (Task 2)
Step 3 - Application of the learning in familiar situation (Task 3)
Step 4 - Application of the learning in unfamiliar situation to solve a problem (Task 4)

The fifth task that was limited to two out of the six students involved solving a word puzzle called WordleTM. This task represents a modern-day scenario, where the brain attempts cognition in presence of competing distracting information from multiple sources. The fifth task was done online using a laptop with the results being noted down on the paper provided to the students.

Instructions for each task, rubrics and the actual tasks with space for providing written responses were printed on paper (Supplementary files S1 and S2). The students were asked to work on the tasks individually without sharing any information with their peers. The brain wave patterns were recorded as they worked on the tasks. After completion of all the tasks, the students turned in their sheets that contained their written responses to the tasks. These responses were graded based on the rubrics (Table 2 and supplementary files S1 and S2).

2.2. Ethics

Details of the study like purpose, methods, significance and the things that students would do if they agree to participate in the study were discussed in class. Students were informed about the kind of data that would be collected and the data privacy policy was explained to them. A printed copy of this information along with a consent form was given to the students. They were asked to discuss the project with their parents and obtain written consent from them for participation in the study. Participation was voluntary and there were no incentives for participation.

Table 2
Marks scored by students

	Task 1	*Task 2*	*Task 3*	*Task 4*	*Task 5*	*Total marks*
	Marks out of 6	*Marks out of 10*	*Marks out of 6*	*Marks out of 4*	*Marks out of 6*	
Student S1 HA	6	10	6	2	6	30/32
Student S2 LA	6	8	4	0	6	24/32
Student S3	6	8	5	0	ND	20/26
Student S4	6	10	5	0	ND	21/26
Student S5	6	9	4	2	ND	21/26
Student S6	6	9	5	0	ND	20/26

Note. S1HA = High achieving student; S2LA = Average achieving student; ND = Task not done. Only high achieving student (S1HA) and average achieving student (S2LA) was given this task.

2.3. Collection of EEG data

A commercially available headband, BrainLinkTM (Macrotellect, USA), fitted with EEG electrodes linked to a device was used to monitor brain waves according to the manufacturer's instructions. The EEG data was collected in real-time, but remotely, using an App (Basic DetectionTM) synched with the device via Bluetooth. A file was created in the App at the start of each task. The Start and End icons were used to start and end EEG data collection, respectively. The data collected for each task by the App can be retrieved in numerical values and also visualized in the form of graphs. The App provides values for relative power of each wave in terms of percentage of the cumulative power of all waves. Relative changes in the power of each wave can be interpreted from the data (Huang et al., 2020).

2.4. Data Processing

All raw data were processed in MS excel. Bar graphs with error bars representing standard deviation were made in excel. The student's t-test was applied for finding statistically significant differences between pairs of data at the $p < 0.05$ level.

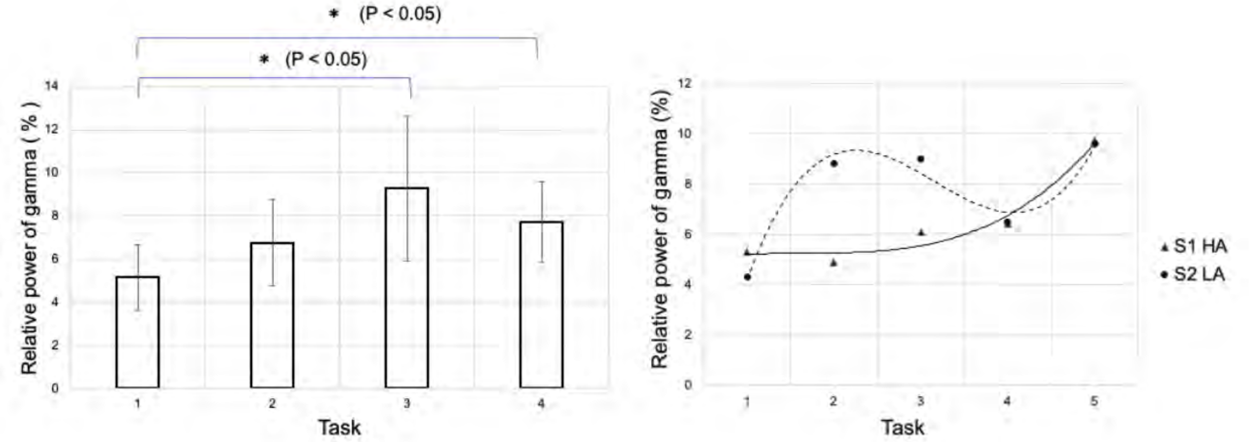
3. Results

3.1. Increase in the Power of Gamma suggests Encoding in Working Memory during Classroom Learning

The power of gamma in the EEG can provide a measure of the ability of the neurons to hold information in working memory via the mechanism of feature binding (Pina et al., 2018). In feature binding, various aspects of the world that we perceive like shapes, color, motion and direction, amongst others, are held in the form of objects in the working memory of the mind. During attention-based learning, information is retained in working memory to support cognitive functions. Hence, monitoring the power of gamma while working on learning tasks can shed light on the changes in working memory (Howard et al., 2003). Since a change in working memory supports cognitive functions like learning, the power of gamma can therefore be used as an indicator of active learning in classrooms. To gain insights into the nature of the cognitive processes operating while students worked on the learning tasks, we monitored the power of gamma (30-65 Hz) in the EEG non-intrusively using an EEG headband.

Analysis of the data collected revealed a gradual increase in the power of gamma as students worked from tasks 1 to 3 (Figure 1A). This result was in line with the increasing complexity of the tasks, demanding more cognitive effort. Since the tasks were linked, the load of the information to be retained in working memory increased, which was indicated by the increase in the power of gamma. These results suggest that the students were actively learning.

Figure 1
Changes in the power of gamma of students working on attention-requiring learning tasks



A. The averages of relative power of gamma observed in the EEG recordings of students working on learning tasks 1 - 4 are shown in the bar graph. Error bars represent standard deviation (n = 6). Statistical significance was calculated using the t-test ($p < 0.05$, n=6).

B. The relative power of gamma of student S1HA and S2LA as they worked on tasks 1 - 5 is shown in the line graph.

For task 4, we noted that although the power of gamma did not change significantly when compared to that for task 3, it was significantly higher than that of task 1 (Figure 1A). Perhaps, the difficulty in responding to task 4 failed to add any further load to items to be retained in the working memory, resulting in no further increase in the power of gamma after task 3.

All students scored full marks for task 1 (Table 2). For task 2, the scores fell between 80 - 100 % of the marks allotted for the task. In contrast, for task 3, the range of scores varied from 66 - 100 %. Lastly, the highest score for task 4 was 50 % of the marks allotted for the task with four out of six students scoring zero marks. The marks scored by the students probably reflect the increasing difficulty of tasks.

A high-achiever, Student S1HA and a low-achiever Student S2LA were given an additional task. The task required solving a word puzzle (Table 1). Although the power of gamma increased for Student S1HA while working on task 5, it did not increase much above those of tasks 3 and 4 for Student S2LA (Figure 1B). This result indicates individual differences in cognitive processing by the two students. Intriguingly, both students elicited almost similar power of gamma while working on task 5, which was highest when compared to any other task (Figure 1B), suggesting that the students may have reached the upper limit of the capacity of working memory.

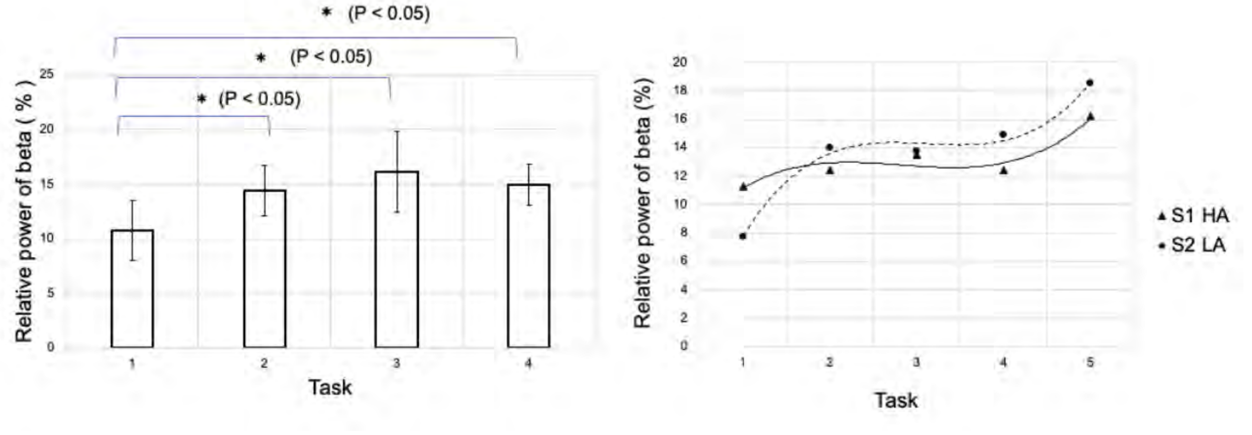
3.2. Linked Tasks in Classroom Learning Require Readout and Clearance of Information Stored in Working Memory

Attention-based cognitive tasks require the storage of information in working memory and its retrieval for various cognitive purposes. While gamma power in the EEG indicates retention of items in working memory, recent studies have correlated the power of beta to reading out information stored in working memory, putting it to use and clearing out information that is no longer required (Lundqvist et al., 2018; Schmidt et al., 2019). We examined the EEG data to find out if the students were using the information assimilated in the working memory for responding to the learning tasks.

We observed a gradual increase in the power of beta (13-30 Hz) as the students worked from tasks 1 to 3 (Figure 2A). This suggests that they were probably actively processing information in the working memory, searching for and retrieving items from the working memory for the purpose of applying it; in this case, for formulating responses to the task. As the complexity of the tasks increased, more items are likely to be retrieved from the working memory as indicated by a progressive increase in the power of beta. Items that are no longer required were probably erased.

Figure 2

Changes in the power of beta of students working on attention-requiring learning tasks



A. The averages of relative power of beta observed in the EEG recordings of students working on learning tasks 1 - 4 are shown in the bar graph. Error bars represent standard deviation (n = 6). Statistical significance was calculated using the t-test ($p < 0.05$, n=6).

B. The relative power of beta of student S1HA and S2LA as they worked on tasks 1 - 5 is shown in the line graph.

There was no further increase in the power of beta after task 3. However, it stayed significantly higher than that of task 1 (Figure 2A). These results seem to suggest that there was probably either no further need for additional information from working memory for responding to task 4 or there was no additional information available over what had already been retrieved from the working memory that could have aided in responding to task 4. Moreover, there were probably no additional objects that needed to be cleared.

We noticed that the trends for the power of gamma and beta in the EEG were almost similar. Both increased gradually for tasks 1 to 3 and then there was no further increase for task 4 (Figures 1A and 2A). Tasks 1 to 3 were linked. Therefore, it seems like students were retaining items from the previous tasks in the working memory and adding new items to them as indicated by an increase in the power of gamma. They also seem to be searching, retrieving and discarding items from the working memory while responding to the next task as suggested by an increase in the power of beta. Thus, the tasks were conceptually as well as cognitively linked. As noted earlier, students found task 4 difficult (Table 2). Although task 4 was conceptually linked to the other three tasks, it seems almost as if the items required for specifically responding to task 4 were insufficient or missing in the working memory. This could be the likely reason for no further increase in the power of beta for task 4.

Taken together, the results show that conceptually and cognitively linked attention-based tasks probably require some information to be retained in the working memory and retrieved later for use in responding to tasks. Because of the linked nature of tasks, items may not be erased completely from working memory.

We observed individual differences in the elicitation of the power of beta for Student S1HA and Student S2LA (Figure 2B). In particular, the power of beta correlating search and retrieval of information stored from task 1 in the working memory for retention or disposal was relatively higher for Student S2LA when compared to Student S1HA. After task 2, the trend for the power of beta was steady and comparable for both the students. Task 5 evoked the largest power of beta for both students (Figure 2B). This was concomitant with an increase in the power of gamma, indicating a renewed addition of items in the working memory, retrieval and disposal of items deemed unnecessary. Thus, task 5 induced a robust stimulation of cognitive processing requiring reading out information from working memory for problem solving.

3.3. Reduction in the power of alpha attenuates the inhibition of cognitively useful distracting images

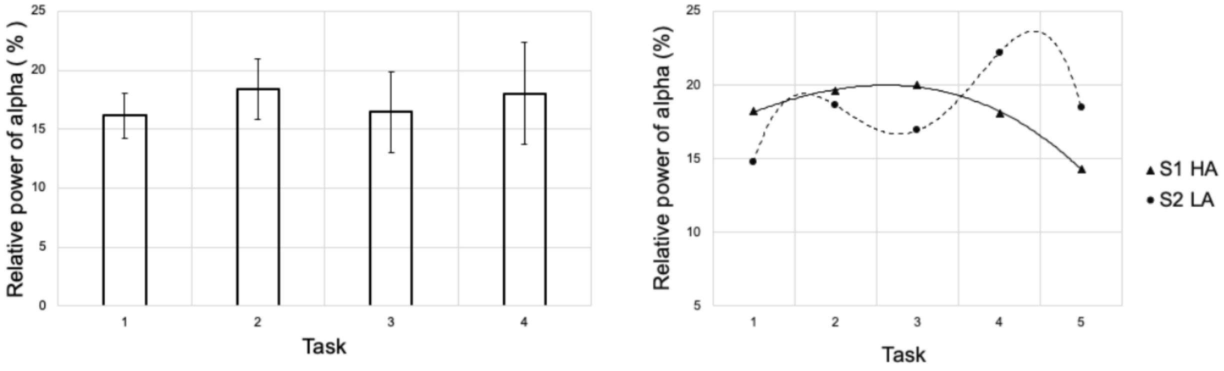
Recent studies have extended the role of alpha power to attention-based tasks involving changes in working memory. In particular, the power of alpha waves has been positively correlated with 1) active suppression of distracting stimuli or irrelevant information (Foxe & Snyder, 2011) and 2) feature binding involving a much broader region of the brain (Johnson et al., 2011; Zhang et al., 2019). Both these features related to alpha power were likely to have been evoked during cognitive processing of attention-based classroom learning tasks.

Monitoring of the brain waves while working on the learning tasks revealed that the power of alpha (8 – 13 Hz) of the group did not change significantly as students worked from task 1 through 4 (Figure 3A). This could be probably due to the nature of the tasks, which probably did not require any further changes in the level of endogenous inhibition of distracting stimuli or perhaps the localized feature binding function of the gamma power was sufficient for completing the tasks. But, we did notice individual differences in the elicitation of the power of alpha by the students. These were more pronounced when task 5 was taken into account because it involved construction of a vivid and strong mental imagery to solve the word puzzle.

Analysis of the power of alpha in the EEG recordings of student S1HA and S2LA revealed that while the power remained fairly stable throughout tasks 1 to 4 for S1HA, it fluctuated for S2LA. Specifically, we noticed that the power of alpha in the EEG of S2LA increased for tasks 2 and task 4 (Figure 3B). Intriguingly, both students showed a drop in the power of alpha for task 5. The results seem to suggest that the students were probably modulating the inhibition of distracting information; increasing the inhibition or reducing it, depending on the nature of the task for supporting the changing cognitive demand.

Figure 3

Changes in the power of alpha of students working on attention-requiring learning tasks



A. The averages of relative power of alpha observed in the EEG recordings of students working on learning tasks 1 - 4 are shown in the bar graph. Error bars represent standard deviation (n = 6). Statistical significance was calculated using the t-test ($p < 0.05$, n=6).

B. The relative power of alpha of student S1HA and S2LA as they worked on tasks 1 - 5 is shown in the line graph.

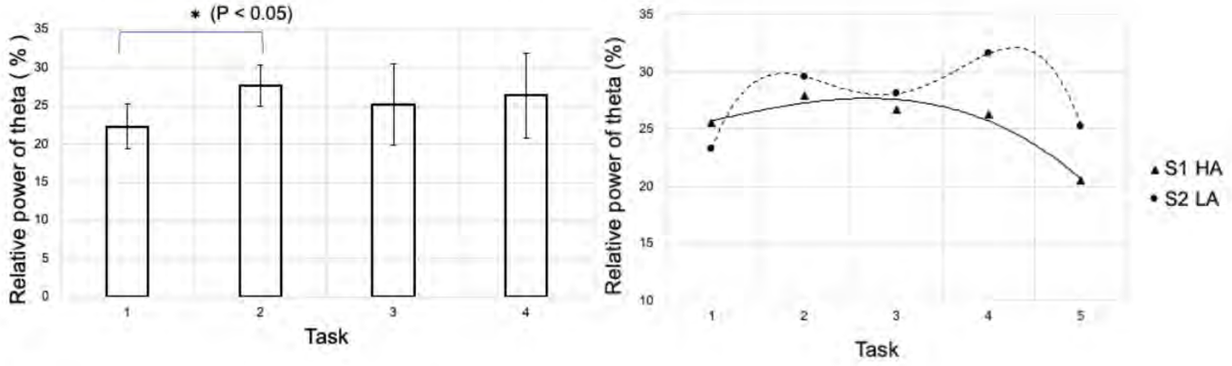
3.4. Encoding, Altering and Retrieving Items from Memory Increases Load in Working Memory

While the power of theta has been in general associated with cognitive load and control (Brzezicka et al., 2019), it has also been shown to be specifically related to neuronal signalling pathways involved in the processing of memory (Colgin, 2013). For instance, encoding of episodic memory and retrieval of memory have been tied to the modulation of the power of theta. In one study, the power of theta was shown to increase when the memorized word was successfully recognized later in a different task (Klimesch, 1997). In order to gain an understanding of the role of the power of theta in the cognitive processes of students working on a series of attention-based learning tasks, we analysed the power of theta (3 – 7 Hz) in the EEG recordings while the students worked on these tasks. The results of the analysis revealed that after an increase in the power for task 2 when compared to task 1, the power of theta did not change any further for the group for tasks 3 and 4 (Figure 4A). It seems that the cognitive load was perhaps similar for the group of students for tasks 2, 3 and 4.

The power of theta varied in the EEG recording of student S1HA and S2LA. In case of student S2LA, it rose for task 2 and then stayed steady at the same level for tasks 3 and 4, before dropping down for task 5 (Figure 4B). In contrast, the power of theta did not change much for student S1HA while working on tasks 1 to 4. But, similar to student S2LA, it dropped down for task 5. Solving the word puzzle in task 5 probably required the students to fall back on memory to retrieve 5-letter words and try them out. The reduction in the power of theta probably suggests that many attempts were made at quickly accessing memory and successfully retrieving numerous 5-letter words; one of which subsequently resulted in the correct answer. Such a process is likely to have increased the load in working memory, resulting in the lowering of the power of theta.

Figure 4

Changes in the power of theta of students working on attention-requiring learning tasks



A. The averages of relative power of theta observed in the EEG recordings of students working on learning tasks 1 - 4 are shown in the bar graph. Error bars represent standard deviation (n = 6). Statistical significance was calculated using the t-test ($p < 0.05$, n=6).

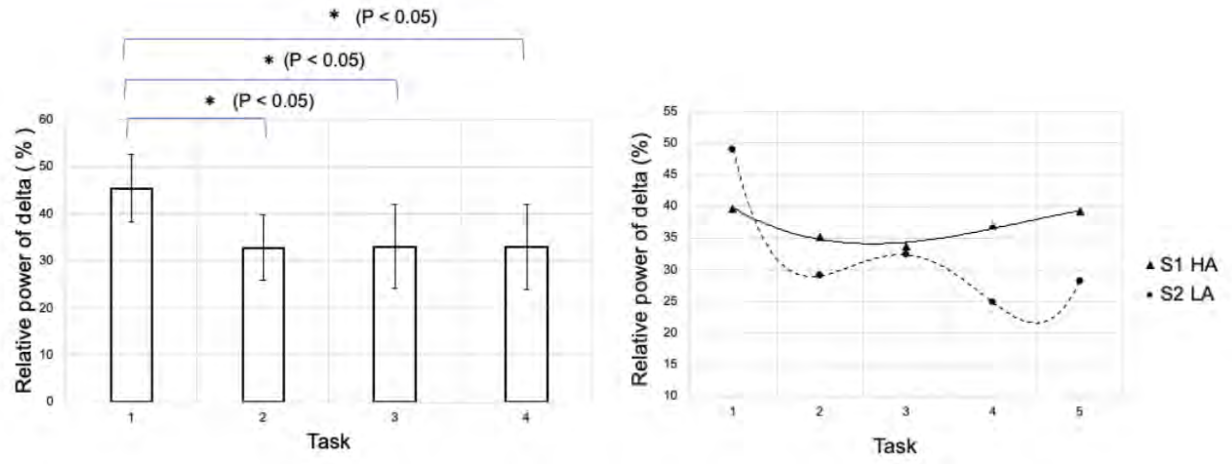
B. The relative power of theta of student S1HA and S2LA as they worked on tasks 1 - 5 is shown in the line graph.

3.5. A Change in the Power of Delta Activity Suggests Wakeful and Alert State while Working on Tasks

Delta activity has been largely studied for its role in deep sleep, meditation and mindfulness (Jaiswal et al., 2019). Few studies have investigated the role for delta activity in wakeful mental tasks. These studies seem to imply a role for delta activity in the inhibition of interfering items and increasing alert attentiveness (Constantinople et al., 2011; Harmony, 2013; Steriade et al., 1993). We investigated the role of delta activity in attention-based classroom learning tasks by monitoring the activity of delta (1 – 3 Hz) in EEG recordings made while students worked on tasks. The results revealed that the activity of delta for the whole group dropped significantly after task 1 (Figure 5A). It stayed steady with no significant changes in the delta power for tasks 2 to 4.

Figure 5

Changes in the power of delta of students working on attention-requiring learning tasks



A. The averages of relative power of delta observed in the EEG recordings of students working on learning tasks 1 - 4 are shown in the bar graph. Error bars represent standard deviation (n = 6). Statistical significance was calculated using the t-test ($p < 0.05$, n=6).

B. The relative power of delta of student S1HA and S2LA as they worked on tasks 1 - 5 is shown in the line graph.

We noticed individual differences in delta activity for students S1HA and S2LA while working on the tasks (Figure 5B). While the activity stayed mostly steady for the students S1HA, it dropped for tasks 2 and 4 for the student S2LA, suggesting that the later student probably deployed additional resources for staying alert and attentive while working on these tasks. Taken together, these results suggest that the group of six students exhibited a wakeful and alert state while working on tasks which was probably accomplished by lowering the delta activity.

4. Discussion and Conclusion

The power of gamma in the EEG has been shown to increase in attention-based cognitive processing, where information needs to be retained and modulated in working memory while working on related or linked tasks (Hashimoto et al., 2017; Pina et al., 2018). Also, there is evidence for a role for the gamma power in feature binding that allows the assimilation of different items in working memory into bound objects for supporting cognition (Singer, 1993). In agreement with these correlates, we observed a task based increment in the power of gamma. Each task was linked to the previous task, requiring the retention of information from the previous task in the working memory as the students moved from one task to the next. When compared to task 1, the power of gamma increased gradually for the subsequent tasks 2 and 3, suggesting that the students were actively processing information and constructing new knowledge anchored to the previous knowledge. Thus, classroom learning tasks should be preferably linked to previously known knowledge.

There was no significant increase in the power of gamma for task 4 when compared to that of task 3. But, nevertheless it stayed above that of task 1. Task 4 required the application of the knowledge to solve a problem in an unfamiliar situation. Specifically, students had to apply the knowledge of the enzyme lipases 'ability to degrade oil in clearing the oil spill (Supplementary files 1 and 2). There was some difficulty in responding to this task. Two students scored half the marks allotted for this task, while the remaining four scored zero marks. It seems that the nature of the task did not require any further loading of items to those to be retained in the working memory. Therefore, the power of gamma did not probably increase any further.

The power of gamma evoked by task 5 for Student S2LA was only slightly more than those observed for tasks 3 and 4. Notably, the high-achiever Student S1HA and average achiever Student S2LA seems to have evoked similar power of gamma while working on task 5, suggesting that they may have reached the upper limit of working memory. The capacity of working memory has been studied previously (Baddeley, 2003; Cowan, 2011; Luck & Vogel, 1997; Todd & Marois, 2004; Vogel et al., 2001). In our study, the load in working memory could be monitored in real-time under authentic classroom learning conditions non-intrusively. Such information could be probably used to adjust the learning experiences to ensure everybody is learning. Furthermore, while designing learning tasks, it is important to keep in mind that working memory has a limited capacity. Although this would limit the number of conceptually linked tasks that students could work on efficiently, the optimal number of tasks for each student is likely to vary.

The pattern of the power of beta in the EEG was similar to that of gamma. As the students worked on attention-requiring tasks with increasing complexity, the power of beta increased until task 3 and then there was no further increase for task 4. The students seem to be retaining information from previous tasks in working memory and retrieving it for use in the next task or clearing it out as indicated by a gradual increase in the power of beta (Schmidt et al., 2019). However, there may have not been any relevant information in working memory for use for task 4 and therefore the beta power did not increase any further for task 4. The low marks scored for task 4 by the students seem to partly support this observation. It is quite likely that there are other unknown factors that may have affected the cognitive processing for task 4.

While tasks 1 to 4 were linked and related to the concept of enzymes, task 5 required students S1HA and S2LA to solve a word puzzle. This task was not related to the concept of enzymes. In spite of this, the power of beta evoked by task 5 was the highest for both students. A similar trend was observed for the power of gamma. It can be argued that since there was no time interval between the tasks and that the students started work on task 5 immediately after finishing the task 4, they did not get a chance to clear items from the working memory. Also, they were probably not aware that they would not be needing information retained from the previous tasks for working on task 5. Therefore, it is likely that they renewed loading and retrieving information from working memory while working on task 5, causing an increase in the power of gamma and beta, which was greater than any of the previous tasks. Another explanation for this could be that the nature of task 5 required a more frequent loading of new items and disposal of unwanted items from the working memory, causing the power of gamma and beta to increase. It has been shown that the stimulation of neural activity during cognition is energy intensive and prolonged periods of intense activation of neurons, as indicated by the power of gamma and beta, can cause brain damage (Palacios-García et al., 2021). Periodic clearing of unwanted items held in working memory can lower the burden of the cognitive machinery. In context with this, introducing kinesthetic brain-breaks while working on attention-based learning tasks can help, amongst several other things, release items held in working memory that are no longer needed and thereby make space available for holding new information in working memory for new tasks, enhancing and making cognition more efficient.

Many learning tasks require the building of vivid mental imagery. In this study, task 5 required the use of cues like color, type and position of letters, elimination of letters and sifting through 5-letter words for solving the puzzle. Such a task would benefit from generating images of many words that could serve as a pool of resource for picking and choosing features or letters while comparing and contrasting them with the mental model of the word being constructed for solving the puzzle. In line with this, the students seemed to have attenuated the inhibition of supposedly distracting alternative images of words to be able to make a range of images of words available for use in solving the puzzle. The task required rationalizing the inclusion or rejection, including change in position of letters while constructing the model of the correct word for which an attenuation of endogenous tunnel-vision like attention as indicated by the lowering of the power of alpha was essential. In contrast to task 5, for tasks 1 to 4, it seems like the students did not feel the need to suppress or rather there was no distracting information from the previous tasks and therefore the power of alpha did not change significantly for the whole group. In addition, the localized feature binding function of the power of gamma may have been sufficient for these tasks, without the need for a more complex broader feature binding brought about by the power of alpha. Lastly, there was probably very limited opportunity for constructing mental imagery due to the nature of tasks and therefore there was no significant impact on the power of alpha as a group for the tasks 1 to 4. The results of our study clearly show that the design of classroom learning tasks plays an important role in evoking specific cognitive functions.

Students come across lots of words during their academic endeavors. Many of these words are encoded in memory and this memory can be retrieved during the process of recognition of the words when they are encountered later. While working on task 5, the students were probably attempting to retrieve all possible 5-letter words from memory and match them with the template of the puzzle to arrive at the correct solution.

In a previously published study, Brzezcka et al. (2019) had noted a reduction in the power of theta in the prefrontal cortex with an increase in the load in working memory. Results of our studies on attention-based learning tasks seem to be in line with this observation. Both the students S1HA and S2LA were successful in solving the puzzle. But, before arriving at the correct word, there were probably numerous attempts that were made initially in their minds where they may have retrieved memory of words that were likely to be best fits. These words could have been tweaked further by changing letters. Such a mode of cognitive processing would have probably increased the load in working memory, leading to a decrease in the power of theta. These results coupled with the changes in the power of gamma, beta, and alpha noted in the EEG recording of students seem to suggest that a complex set of higher order cognitive functions were elicited by task 5.

Delta power has been mostly studied in context with deep sleep. Few studies have investigated the role of the power of delta in attentive mental tasks. Amongst these, some have noted an increase in the power of delta for inhibition of distracting information while working on difficult tasks (Harmony, 2013). In contrast, others have noted a decline in the power of delta for the purpose of increasing attention (Constantinople et al., 2011; Steriade et al., 1993). It seems like the power of delta and thereby its interpretation varies with the nature of the task and its intended goal. We observed a reduction in the power of delta, indicating that the students were trying to increase their attention and stay alert while working on the learning tasks.

The EEG headband used in the study reads data from three dry electrodes placed on the forehead near the prefrontal cortex region (Huang et al., 2020; Minteer et al., 2019). It is known that the cognitive functions involved in learning are processed in this region. Especially, processes pertaining to executive functions relying on working memory that are relevant to the attention-based classroom learning tasks used in the study, are carried out in the prefrontal cortex. Decisions related to retention of images, reading information from stored images and using it to solve problems are some of the cognitive processes relevant to the tasks of the current study that are performed in working memory. Interestingly, a recent study has shown that Homo sapiens may have out competed Neanderthals by way of intellect since their version of the TKTL1 gene produced a significantly larger number of neurons in the frontal lobe region, conferring better cognition, further supporting the importance of reading brain waves emanating from the frontal cortex region (Pinson et al., 2022). Lastly, the students worked on a series of tasks one after another without a break. The total time estimated for completing tasks 1 to 4 was 26 minutes. An additional time of about 15 minutes was estimated for the completion of task 5. The brain wave patterns were recorded for the full duration of each task. Thus, the patterns are likely to represent the actual workings of the brain in authentic conditions and not a snapshot of a discrete event. Hence, the data collected and the inferences drawn may be probably representative of the cognitive functions operating during the performance of the classroom tasks.

Most of the neural pathways are connected with changes in the power of one wave impacting another. In addition, the waves probably function in a concerted manner to accomplish cognitive functions, much of which is poorly understand. Our study provides information on the changes in the relative power of these waves as a function of cognition. Importantly, it takes into account changes in the power of all the waves and not just snapshots of specific frequencies. These results therefore enhance our understanding of the nature of cognitive processes operating during authentic attention-based classroom learning tasks to a great extent. Such information can be invaluable for designing learning strategies for improving learning outcomes.

Supplementary Materials:

Figure S1: This file contains the details of attention-requiring learning tasks 1 - 5 and responses of student S1HA to each of these tasks. The responses have been graded based on task-specific rubric or marking scheme;

Figure S2: This file contains the details of attention-requiring learning tasks 1 - 5 and responses of student S2LA to each of these tasks. The responses have been graded based on task-specific rubric or marking scheme.

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