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Research Article

HOW DO WE LEARN?

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Abstract

As virtual assistants driven by artificial intelligence get integrated and deeply entrenched in our daily lives, humans with exceptional higher order thinking skills will be needed to combat the complex challenges of the 21st century. However, the molecular and cellular basis of cognitive functions like learning, memory and problem solving are not clearly understood. Here, we have used electroencephalography (EEG) to monitor the electrogram of the brain of students in real time as they worked on attention based tasks to find out how they construct knowledge and use it to solve problems. We observed an increase in the power of gamma as the students added items in the working memory, retained them, modulated them and assimilated them into mental models. Remarkably, the power of delta went down as the students built mental models, suggesting a conscious wakeful effort on the tasks. Our results show that a ratio of the power of delta to the power of gamma is indicative of 'active cognition'. For linked tasks in learning, the ratio decreases gradually as students construct knowledge and use it for solving problems. Success in learning outcomes and cognition can be predicted by monitoring this ratio.

Keywords: Cognition, Brain oscillations, Mental model, Contingent instructions, Power of gamma.

INTRODUCTION

Words, numbers, equations, diagrams, flow-charts, mind maps, shapes, colors, sound, equipment and chemical reactions perceived by students while working on tasks in the classroom are processed in the working memory for the purpose of constructing knowledge [1, 2]. Information perceived is sorted, grouped, organized and imprinted as a framework for building mental models [3]. When new information that is related to the framework is presented to the students, it is assimilated quickly. However, slightly different but linked information is internalized only after accommodation [4, 5]. Although this simplistic explanation of how information is processed and stored in the working memory is generally accepted, the molecular details underpinning the processes are just beginning to be unravelled. The cells of the prefrontal cortex (PFC) region of the brain play a pivotal role in adding, retaining, refining and organizing knowledge for performing executive functions and sending it out for long term storage [6]. Construction of knowledge begins with perception of cues during learning and relay of this information along the neurons in the form of nerve impulses, leading to the activation and synchronization of the activity of neuronal networks [7]. Storage of information is an emergent property arising out of physical and chemical changes occurring in these neural networks. In a resting neuron, the ATP-dependent Na-K pumps create an electrical potential difference between outer and inner membranes of the axon [8]. A stimulus sets off an action potential characterized by depolarization followed by a quick re-polarization. In practice, depolarization occur at nodes of Ranvier because the voltage gated ion pumps involved in moving ions for setting up electrical potentials are accessible at these nodes. Depolarization at one node of Ranvier in turn triggers depolarization at an adjacent node of Ranvier, causing the action potential to travel down the axon [10]. Thus, the action potential jumps from one node of Ranvier to another until it reaches the end of the axon. In order for the signal to be passed to another neuron, it must transverse the gap, called the synaptic cleft, present between the axons of two neurons. Here, the action potential is converted into a chemical signal with the help of neurotransmitters that relay the signal from the pre-synaptic neuron to the post-synaptic neuron. The signal is converted back into an electric impulse and transmitted down the axon of the next neuron in the form of action potentials [11]. In this manner, a number of neuron are activated forming a large ensemble of activated neurons. The synchronized rhythmic fluctuation in electrical potential during the transmission of nerve impulses and the synaptic activity for relaying the impulse to the next neuron within an ensemble of neurons gives rise to neuronal oscillations or brain waves that can be recorded using an electroencephalographic (EEG) monitoring device [12]. An analysis of these neuronal oscillations seems to suggest that the resonance emanating from neuronal ensembles can be grouped into gamma (> 30 Hz), beta (12 - 29 Hz), alpha (8 - 11 Hz), theta (4 - 10 Hz) and delta (< 4 Hz) oscillations [13]. Importantly, each of these oscillations is associated with specific brain function and therefore can be used as a biomarker to study cognition [14]. Learning in classrooms is accomplished by working on attention-based tasks requiring problem-solving. The initial steps involve adding objects in working memory, manipulating them and using them to perform executive functions; a task that is primarily carried out in the PFC [15]. In a recent study, the gamma oscillations emanating from the PFC region were shown to play an essential role in cognition. Mice deficient in gamma oscillations were unable to learn a set of rules and perform executive functions effectively [16]. Upon restoring the gamma oscillations, the mice regained their cognitive abilities. Similarly, several other studies have attributed specific roles to beta, alpha, theta and delta waves in learning, problem solving and memory. Thus, by monitoring brain oscillations produced by the PFC region, during attention-based tasks, one can find out if learning is being accomplished.

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In this study, we have used an EEG head band to monitor the brain oscillations of the PFC region of a group of high school students while they worked on a series of attention based tasks. Analysis of the EEG patterns reveals that for a series of linked tasks, the ratio of the power of delta to the power of gamma is indicative of active cognition; in particular, learning and problem solving.

MATERIALS AND METHODS

Design of the study

Five high school students, comprising of 3 girls and 2 boys, were enrolled for the study. Amongst these one student was a high achiever. All the procedures related to ethics, including obtaining informed written consent were followed. All the students worked on grade-level appropriate tasks. There were a total of 5 tasks given to the students. The first three tasks were designed to help students to learn to transcribe, translate and align very short protein sequences to identify point mutations. At the end of task 3, students were expected to have learned the steps involved in working out a point mutation when DNA sequences of the wild type (normal) and mutant proteins were provided. The learning was accomplished using contingent instructions with the tasks becoming progressively difficult and the responsibility of problem solving being transferred to students gradually such that after task 3, students could solve mutations from DNA sequences independently [17]. Tasks 4 and 5 required students to use the learning about mutations to analyze the effect of point mutation in the hemoglobin gene on the shape of red blood cells and consequently the physiological implications for the change in structure-function of red blood cells as a result of the mutation.

Table 1. Design of the study

	Task	Expected time (min)	Marks
Task 1	Translating mRNA sequence	5	4
Task 2	Transcription and translation of DNA sequence	5	5
Task 3	Working out and identifying point mutation from DNA sequences	5	10
Task 4	Analysis of effect of point mutation on structure-function of red blood cells	10	8
Task 5	Analysis of physiological effect of mutation	5	3

Although there was no time limit imposed for the completion of the tasks, the students were asked to work on the tasks in the order 1, 2, 3, 4 and 5; starting from task 1 and finishing with task 5. In addition, they had to finish the tasks in one seating without any break between the tasks. The total time estimated for completing all the tasks was less than 30 minutes. The marks assigned to each task are shown in Table 1. Detailed instructions of the task, marks or rubrics for grading and questions with space for writing the responses were printed on paper and handed to students. The students worked on the tasks individually with complete focus (Supplemental files S1 and S2). An EEG headband was used to collect data on brain waves as the students worked on the tasks.

Ethics

Students were provided details of the study orally and in written. In addition, they were informed about the type of data that would be collected, how it would be used, and stored. Privacy policy pertaining to personal information of the students being kept confidential and the anonymization of names were discussed prior to recruitment. Participation was voluntary and there was no monetary benefit for participants. Project details, data collection, storage and privacy policy were printed and handed to the students along with a consent form. Students were asked to discuss the details of the study with their parents. If they agreed on their participation in the study, then the parents had to indicate that in the consent form by putting their signature in the space provided on the form.

Monitoring of EEG data in real time

BrainLink^{TM} (Macrotellect, USA) headband was used to record electrogram of brains of students working on tasks. The headband can connect to a device like iPad or phone via Bluetooth^{TM}. An Apk called Basic Detection^{TM} (Macrotellect, USA) was used as an interface to collect data on five brain oscillations, gamma, beta, alpha, theta and delta, in real time as students worked on the tasks. The headband contains three dry electrodes that rest on the temple and collect data on brain oscillations emanating from the prefrontal cortex region [18].

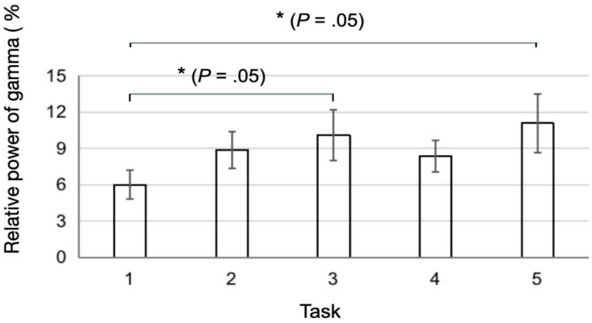
Data processing

Data collected by the Apk was collated and analyzed in excel. Standard deviations were calculated and averages of the data of oscillations with their standard deviations were plotted as bar graphs. The student's t-test was applied for finding statistically significant differences between pairs of data at the $P = .05$ level.

RESULTS

A gradual decrease in the ratio of power of delta to the power of gamma observed while working on a series of linked tasks is indicative of active cognition

While working on tasks in the classroom, a subset of the neurons of the PFC of all the five students produced gamma oscillations indicating addition of objects in the working memory, retention, manipulation and temporary storage of the items (Figure 1) [19]. Such internalization of information requires attention and conscious perception. A lowering of the power of delta oscillations produced by the neurons suggested that a wakeful and purposeful effort was being put into internalizing information (Figure 2) [20]. Thus, the power of gamma and delta oscillations can provide useful glimpses into engagement of students with the task and whether this engagement would result in a successful learning outcome. Tasks 1-3 involved learning of a method for working out a mutation (Table 1, Supplemental files S1 and S2). In task 4, the students had to use the learning to analyze a real-life problem, sickle cell anemia, caused by a mutation in the hemoglobin gene. Lastly, in task 5, the students had to dissect the implications for the mutation. We observed a gradual increase in the power of gamma of the group as students worked on tasks 1-3 (Figure 1). These tasks were related and therefore students seem to be retaining items from previous tasks in the working memory so that they could be used in the next task. Interestingly, one student out of the five, had a reduction in the power of gamma for task 2. However, the power of gamma rose back again for task 3. Perhaps, the student found task 2 difficult and so it was hard for the student to accommodate information in the mental model being constructed in the brain. The difficulty seemed to be resolved subsequently as suggested by an increase in the power of gamma for task 3. This task signaled the culmination of learning for working out mutations from DNA sequences and after this task the students were expected to be able to solve for mutations independently.



Bars represent an average (n=5) of the relative power of gamma calculated from the EEG recording of students working on tasks. Error bars represent standard deviation (n=5). Statistical significance was calculated using the t-test (P = .05, n=5).

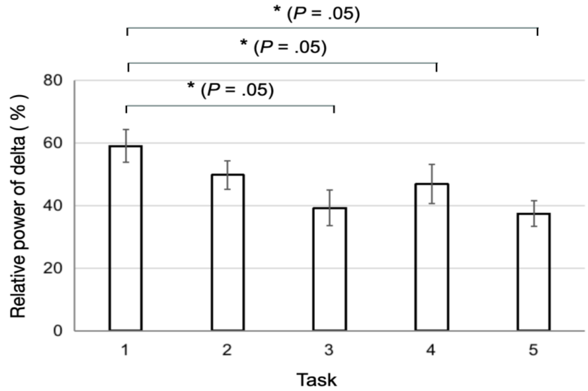
Figure 1. Changes in the relative power of gamma as students worked through the tasks

The power of gamma went down for all the students except one while working on task 4. The student happened to be a high achiever and seemed to continue adding items to the working memory. The student seemed to have found a way to integrate and link the items from tasks 1-3 with task 4 and use the information to answer the questions. Students had to answer two questions in task 4 (Supplemental file S1). The first question required working out the mutation, a task that they learned while working through the previous tasks 1-3. All students could do this successfully (Table 2). The second question for task 4 required students to relate the mutation causing the change in shape of the red blood cell from bi-concave to sickle-shape to its function. Only the high achieving student could answer this question correctly (Table 2). Since the problem could be solved successfully by the student, the power of gamma increased for this student. In contrast, the other four students could not solve this question and this may have caused the power of gamma to go down (Figure 1, Table 2). Task 5 required students to interpret experimental data related to sickle cell anemia shown in a graph and find out how it would affect the physiology of a person. All the students could perform this task satisfactorily using the knowledge constructed from previous tasks and therefore the power of gamma seems to have gone up when compared to that observed for task 4.

Table 2. Marks scored by students

Student	Task 1	Task 2	Task 3	Task 4	Task 5	Total marks
S1	4/4	5/5	10/10	8/8	3/3	30/30
S2	4/4	4/5	10/10	5/8	2/3	25/30
S3	4/4	4/5	10/10	6/8	3/3	27/30
S4	4/4	5/5	10/10	5/8	2/3	26/30
S5	4/4	5/5	10/10	4/8	2/3	25/30

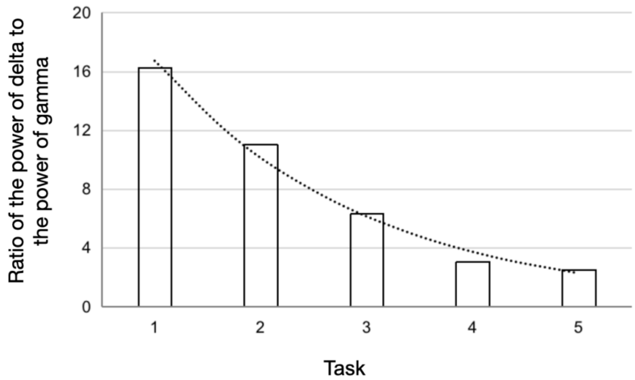
Working on the tasks required wakeful attention and effort [15]. Consequently, a drop in the power of delta was observed as the students worked through tasks 1-3, suggesting a wakeful and attentive processing of information as required by the nature of the tasks (Figure 2). For task 4, except for the high achieving student, all students showed an increase in the power of delta. This task seemed challenging as revealed by the low marks scored by the students and the reduction in power of gamma. Since the students could not answer the question; in particular question 2 of task 4, they seem to have reduced wakeful attention while working on the task. The power of delta however decreased again for the subsequent task 5, suggesting that the students were able to focus by increasing wakeful attention (Figure 2).



Bars represent an average (n=5) of the relative power of delta calculated from the EEG recording of students working on tasks. Error bars represent standard deviation (n=5). Statistical significance was calculated using the t-test (P = .05, n=5)

Figure 2. Changes in the relative power of delta as students worked through tasks 1-5

The above results seem to suggest that while working on a series of linked tasks in classroom, students increase the power of gamma and reduce the power of delta for learning. However, when any of the tasks within the series of linked tasks is very difficult or confusing, the reverse may be observed. Therefore, a ratio of the power of delta (wakeful attention) to the power of gamma (construction of knowledge via building mental models) could be used to gauge 'active cognition'; in particular, whether the students are learning actively and solving problems. For a series of related tasks, the ratio of the power of delta to the power of gamma is likely to decrease gradually as the learning progresses and translates into successful problem solving. Consistent with this line of reasoning, we observed a reduction in the ratio for the high achieving student who was successful in solving all the mutations and answering all the questions correctly (Figure 3).

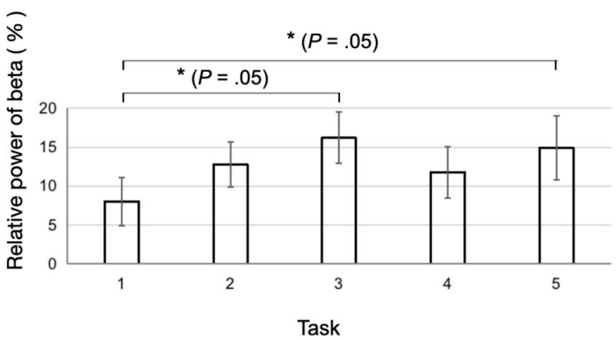


The ratio of the power of delta to the power of gamma calculated for each task for a high achieving student is shown as a bar. The ratio reduces gradually, indicating 'active cognition'.

Figure 3. Ratio of the power of delta to the power of gamma is indicative of active cognition

The power of beta in active cognition

A number roles have been ascribed to the PFC power of beta while working on attention based tasks. An over-arching role proposed for beta is closely tied to working memory, where it provides regulatory control over processing of information [21]. In particular, it has been shown to aid in deciding whether an item needs to be retained or erased from working memory. This is important because there is an upper limit to the capacity of working memory and therefore items that are no longer needed must be cleared periodically [22]. In addition, beta waves have been implicated in regulatory control of actions subsequent to the decision making in working memory. We observed that, as a group, students steadily increased the power of beta while working on tasks 1-3 (Figure 4). Task 3 concluded the learning of working out mutations from DNA sequences (Supplemental files S1 and S2). A number of items deemed unnecessary were probably cleared out from the working memory at the end of this task, resulting in the highest power of beta observed across all tasks. Information required for the learning seemed to have been condensed and optimized. The power of beta returned back to the levels observed for task 2 when the students worked on task 4 before it increased again for task 5 (Figure 4). Except for the high achieving student, all other students had difficulty in working on task 4. Although all the students could work out the mutation, they could not explain the effect of the mutation on the structure-function of red blood cells. The regulation of information in working memory seemed to have dropped probably because very little decision making was made on retaining or deleting items from working memory during this task. However, task 5 involved interpretation of graphical data in context with the learning from tasks 1-4 (Supplemental file S1). Items from the graphical data were probably matched with the mental models created in previous tasks for constructing logical reasons to explain the physiological effects of the mutation. This probably involved regulation of information in working memory; in particular, deciding whether an item must be retained or deleted. Therefore, the power of beta seemed to have increased for task 5 when compared to task 4 (Figure 4).

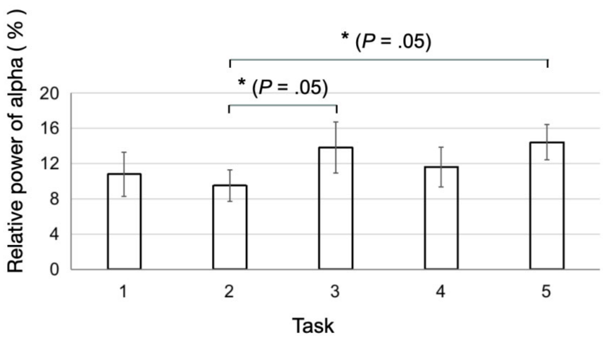


Bars represent an average (n=5) of the relative power of beta calculated from the EEG recording of students working on tasks. Error bars represent standard deviation (n=5). Statistical significance was calculated using the t-test (P = .05, n=5)

Figure 4. The relative power of beta of students as they worked on tasks

The power of alpha in suppressing distracting information and adding items from visual imagery in working memory

The human brain has an uncanny ability to enhance attention on relevant cues, while ignoring or suppressing distracting information [23]. The power of alpha emanating from the PFC has been implicated in conscious suppression of distractors while working on attention based tasks [24]. In addition, it has been shown to participate in the internalization of visual imagery in working memory and recall of memory in order to compare and contrast it with the imagery. However, this function involves a concerted effort between the PFC and the visual cortex. Analysis of the EEG of students working on tasks 1-5 revealed that the power of alpha of the group went down marginally for tasks 2 and 4, while it increased for tasks 3 and task 5 (Figure 5). Task 2 contained large amounts of contingent instructions when compared to tasks 1 and 3 (Supplementary file S1). It seems like the students were trying to suppresses distractive sources of information while working on the tasks and focus on the most relevant information. But, they were not as successful in doing this for task 2 when compared to tasks 3 and 5. Therefore, the power of alpha of the group for task 2 was lower when compared to those observed for tasks 3 and 5. Task 4 contained images of normal red blood cells and sickle shaped red blood cells. For this task, the students were probably releasing the inhibition imposed on distracting visuals of red blood cells obtained from recalled memory so that these images were available for comparison with the images perceived in task 4. Therefore, the power of alpha of the group seems to have reduced while working on task 4 (Figure 5).

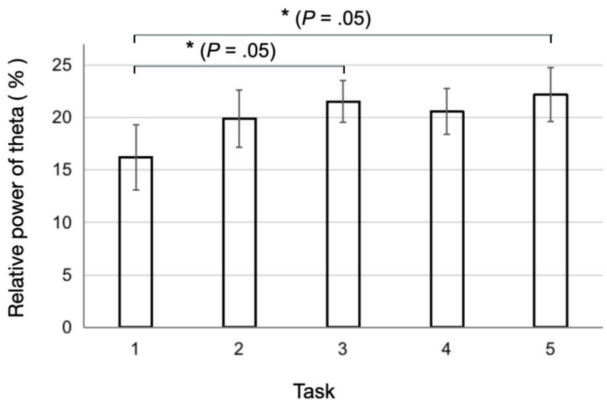


Bars represent an average (n=5) of the relative power of alpha calculated from the EEG recording of students working on tasks. Error bars represent standard deviation (n=5). Statistical significance was calculated using the t-test (P = .05, n=5)

Figure 5. Changes in the relative power of alpha as students worked on tasks

Cognitive effort during learning can be gauged by the power of theta oscillation

Theta oscillations have been studied extensively in context with episodic memories stored in hippocampus and accessing the subconscious state of the brain through meditation. Interestingly, the PFC has been shown to produce theta oscillations during attention based tasks [25]. Here, theta oscillations have been shown to play important roles in allocation of resources for cognition. The working memory has a limited capacity. Therefore, prioritization of items to be incorporated and retained in working memory from visual imagery, a task associated with theta oscillations, is important to avoid memory overload [26]. Thus, theta oscillations are indicators of cognitive effort during attention based tasks. Analysis of the EEG of students working on tasks 1-5 revealed an increase in the power of theta for all the tasks, except for task 4 (Figure 6). All the students, except for the high achieving student, had found the task difficult. The cognitive processing of information had probably stalled for this task and the effort seems to have reduced as indicated by a small reduction in the power of theta. In addition, there was probably a slight reduction in memory load since none of the items from task 4 could be added to the mental models being constructed and some items may have gotten offloaded or dislodged while performing this operation in the working memory.



Bars represent an average (n=5) of the relative power of theta calculated from the EEG recording of students working on tasks. Error bars represent standard deviation (n=5). Statistical significance was calculated using the t-test (P = .05, n=5)

Figure 6. Changes in the relative power of theta as students worked on tasks

DISCUSSION

The frontal lobe region of *Homo sapiens* has a dense network of neurons that act as a gateway for perception based learning and memory [27]. In particular, the PFC region organizes information for temporary use in working memory as well as for sending it off for long term storage. A correlate for such activity is the gamma oscillations resulting from the resonance of a subset of activated neurons from the PFC, which aids in attention, addition of objects to working memory, retaining them, modulating them and storing the mental models constructed for use in decision making or problem solving [28]. In the current study, an EEG headband that places three dry sensors on the temple for measuring oscillations from the PFC region was used to monitor cognitive functions like learning, decision making, problem solving and memory of a group of high school students in real time as they worked on five attention-based linked tasks. A consistent trend observed for all the students as they worked on the series of tasks was a drop in the power of delta and an increase in the power of gamma (Figures 1 and 2). Although the power of delta has been studied mostly in context with deep sleep; while awake and working on tasks requiring conscious attention, the power of delta goes down [15]. This opens up the possibility of using the power of delta as an indicator of attention and cognition when interpreted in tandem with the power of gamma. Previously, a number of studies have indicated a role for the power of gamma in internalizing perceived information and integrating it in mental models that can be used for decision making or problem solving [29, 30]. Hence, a ratio of the power of delta to the power of gamma can be possibly used to gauge whether or not students are actively constructing knowledge. In a broader context, it can indicate 'active cognition'. In the present study, the ratio of delta to gamma went down progressively as the students worked through the task of learning to work out mutations and applying the knowledge constructed to dissect a real-life problem, sickle cell anemia, caused by mutations (Figure 3 and Supplemental file S1). A reduction in the ratio exemplified features of cognition like internalization of information, construction of mental models, learning, analysis, decision making, problem solving and memory [30]. Instances of difficulty in performing the task or solving the problem, either because the intermittent step is hard or confusing, are highlighted by a perturbation in the ratio. Under such circumstances, the ratio is likely to increase, suggesting a need for additional support. Thus, the ratio of the power of delta to gamma can be used to monitor the extent of 'active cognition' and indicate whether the learning objectives are likely to be accomplished.

High school students have to demonstrate an ability to transcribe and translate DNA sequences. This skill is useful in comparing DNA sequences for identifying mutations and finding out how the mutations are likely to impact the protein and thereby its function. As part of this learning, students worked on 5 linked tasks consecutively without any breaks, simulating authentic classroom learning environment. They were expected to finish the tasks in less than 30 minutes (Table 1). The first three tasks involved learning to transcribe a given DNA sequence into mRNA, translate it into protein, compare two DNA sequences for mutations, transcribe as well as translate wild type (normal) and mutant DNA sequences, align them and identify the point mutation in the protein (Supplemental file S1). After learning the steps and solving DNA sequences for the mutation, students were expected to apply the learning to analyze the cause of sickle cell anemia and the implications for this causative factor in the function of red blood cells. Contingent instructions were used during the learning of working out mutations [31]. The difficulty of the steps involved in the learning was increased gradually as the responsibility of working out the steps shifted gradually to the students until at the end of task 3 students were able to work out the mutation independently. Since the tasks 1-3 were linked, students retained the items from the previous task in the working memory for use in the next task. This was indicated by an increase in the power of gamma (Figure 1). Students were actively constructing knowledge by adding items to the mental models as they worked through the tasks and learned the rules to solve for mutations based on DNA sequences. The power of theta can indicate the load in working memory; information that is important for resource allocation and prioritization of items to be added in working memory [32]. Except for task 4, the power of theta increased steadily for the group of students (Figure 6). The students had found this task difficult since no more items could be accommodated in the existing mental models. Students seemed to have reduced the power of alpha to make distracting information in the form of images of red blood cells stored in memory being made available for comparison with the mental model of mutations constructed in tasks 1-3 (Figure 5). However, there seemed to be difficulty in linking them together to come up with a logical answer. These results highlight the importance of monitoring all the oscillations of the brain to get an overview of the cognitive processes operating during learning and creation of memory. Working memory has a limited capacity [33]. But, the upper limit for the capacity is likely to differ amongst individuals [15]. Epistemic motivation, intrinsic as well as extrinsic, is likely to push through the barriers imposed by working memory capacity [34]. Certain students are intrinsically motivated for learning, while some others can be motivated extrinsically by offering rewards. In both these motivations, hormones or neurotransmitters are released by the body. Recent studies have suggested an important role for neurotransmitters like dopamine and serotonin in creating memory [35]. When released during learning, these neurotransmitters translocate to the nucleus of the cell body, where they trigger the unwinding of specific regions of DNA via chromatin re-modeling; a process induced by the modification of histone proteins covering these sites. Non-coding RNA is transcribed from these regions. The RNA migrates to the synaptic clefts and coordinates events in the synapses like forging connections with other cells of the network for encoding memory [36]. Thus, rewards are useful tools for engagement and enhancing memory.

Conclusion

Several useful insights emerge from the current study that could be used to enhance learning and memory in students. The ratio of the power of delta to the power of gamma reduces progressively for linked tasks. This can be used as a measure of attention based construction of knowledge or active cognition. An increase in the ratio for linked tasks could suggest reduced attention and difficulty in accommodating information in the mental model constructed. In such situations, interventions are required to put the student back on track for learning. The working memory has a limited capacity and therefore it is important to limit the learning of a method or skill to a few steps. Although the optimal number of steps is likely to vary between individuals, they can be stretched by introducing rewards. Rewards increase the efficiency of encoding of memory. Since the working memory has a limited capacity, an opportunity must be created to clear items from working memory to make space for the addition of new items and their assimilation or accommodation in the mental models. This can be done by changing the nature of task or introducing brain-breaks. Kinaesthetic tasks are known to help in this regard. As we face an increasing threat of encroachment of human cognition by a more efficient AI-dominated cognitive space in future [37], it is essential to gain an understanding of how the brain makes cognition possible. Once we know how the brain dissects problems and creates solutions to solve problems, key elements of cognition like authentic creative and critical thinking that are currently beyond the realms of AI, can be enhanced in humans. The results of this study open up new possibilities for accomplishing this purpose and for instilling enhanced cognitive capacity in students to tackle more complex problems of the 21st century.

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Competing interests: The author has declared that no competing interests exist.

Author's contributions: NS designed the study, collected data, processed data and drafted the manuscript.

Consent: The study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the participants to publish this paper.

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APPENDIX

Supplemental file S1: This file contains the details of the five tasks that students worked on. The file was printed on paper and handed to students.

Supplemental file S2: This file contains an example of responses to questions by one of the five students recruited for the study.

Abbreviations

EEG - electroencephalography
PFC - Pre-frontal Cortex
Hz - Hertz

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