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Original Research

RECSAE: An interactive model of relevance cognitive load, spatial memory, ADHD and EEG for special educators and mental health professionals

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Abstract: The cognitive load (CL) increases as the brain is confronted with high-volume audiovisual and other multimodal information from the external environment. Spatial memory is a broad term for recording and recovery of this information. It has three dimensions, such as sensory memory, which is responsible for information capture and preprocessing, working memory, which is responsible for information processing and output generation, and long-term memory, which is responsible for registration/encoding and retrieval/decoding of what has been learned after the information processing. Cognitive training for long-term memory formation is a complex task that is conducted by analysing the "relevance" of the information. Relevance refers to the degree of meaningfulness of the input information based on logic, beliefs and perceptions. A high degree of relevance promotes the firing of the reentrant circuit for capturing similar information to create memory in the brain. An electroencephalogram (EEG) measures brain activities by using electrodes to deliver waveform signals through the scalp at a particular duration. This article proposes an interactive RECSAE model for the formation of relevant long-term memory through CL training and attempts to corroborate it with the EEG signals. The model is finally explained and correlated with Attention Deficit Hyperactive Disorder (ADHD) as a real-world use case. The proposed model is generic and would help psychologists, neurophysiologists, EEG researchers and special educators to evaluate CL training and memory dysfunctions by using EEG waves.

Keywords: RECSAE model, Cognitive load, Cognitive overload, Relevance, EEG, Memory, ADHD, Special educator, Psychology, Psychobiology

The brain and EEG

The brain is a non-stationary sensorimotor organ. It consists of three main parts – the cerebrum, the cerebellum and the brain stem. The cerebrum is the largest part and is divided into left and right hemispheres. It performs higher functions such as interpreting touch, vision, hearing, language, emotions, reasoning, learning, fine movements, etc. The cerebellum is the smaller part located under the cerebrum and controls muscle movements and maintains posture and balance. The brain stem connects the cerebrum and cerebellum to the spinal cord. It controls vital functions such as breathing, circulation, temperature, sleep-wake cycle, digestion, sneezing, coughing, vomiting, swallowing, etc. The electroencephalogram (EEG) is a non-invasive method of capturing various brain signals (waves) through the scalp by placing electrodes (a set of small metal discs with thin wires stuck to the scalp) on several cortical regions. The electrodes detect tiny electrical charges and their potential difference as the consequence of the neural firing. The waves are interpreted as maximum

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voltage as amplitude (y-axis) by the time (x-axis) plot. The voltage difference between any two scalp electrodes is amplified and then a line plot can be jotted on paper with the drawing pen or it can be displayed completely digitally. The frequency of each EEG wave is inversely proportional to its amplitude, which means as the frequency decreases, the corresponding amplitude increases under normal conditions. Table 1 shows seven types of EEG waves, their frequencies, amplitudes and active brain regions under normal conditions [1]. The EEG waves are extensively studied to understand neurodevelopmental processes [2], neurological disorders [3], addictions [4], neuropsychiatry [5] and so on. The key utility of EEG is to map the dynamic cerebral functions.

Relevance and cognitive load

Cognition is a complex process of thought. It is initiated relentlessly with or without any stimulus. Metacognition is the thoughtlets within the thought. Cognitive ability refers to the analytical ability (reasoning with speed) while performing a task consciously or subconsciously. Cognitive load refers to the amount of information that the working memory can hold at a particular time. When the amount of information exceeds the limit, which is defined as the working memory space, cognitive overload (COL) happens, and, as a result, the learning-memory circuit becomes vulnerable. Learning takes place when the task is initiated until it is completed. If the input and the processing task are relevant, the learning also becomes relevant, and it is then encoded in the brain as a "meaningful" memory for reuse, or the thought processes are redefined to give relevance to the task, otherwise it will be forgotten.

CL varies from individual to individual and also depending on the phase and time of their lives. Figure 1 shows the CL circuit, postulated by the author.

Table 1. The EEG waves

Wave type	Frequency (Hz)	Amplitude	Usual conditions	Brain/Cortical region
Delta	<4	High	Adult sleep stage, children as an arousal sequence.	Adult: frontal; Child: posterior
Theta	4-7	Moderate	These are strong in adultsduring deep thinking and relate to the subconscious mind during internal focus. In young children, on the other hand, it is a normal occurrence up to the age of 13.	Hippocampus (posterior)
Mu	7- 11	Moderate to- high	Sensorimotor activity; attenuated with contralateral motor actions as the load is distributed on the other side.	Precentral areas
Alpha	8- 12	Higher amplitude on the dominant side	Relaxed state with eyes closed; weakened with attention	Bilateral parietal and occipital
Beta	12-30	Low	Alert state	Bilateral parietal and frontal
Lambda	>50 [6]	Single sharp triangular shaped	Ocular movement/eye gazing	Occipital
Gamma	34- 100	Low	Metacognition (deep thinking/problem solving) and fine motor functions	Antero-posterior area across the cortex

The next section discusses the cognitive load (CL) and the importance of relevance in reducing it.

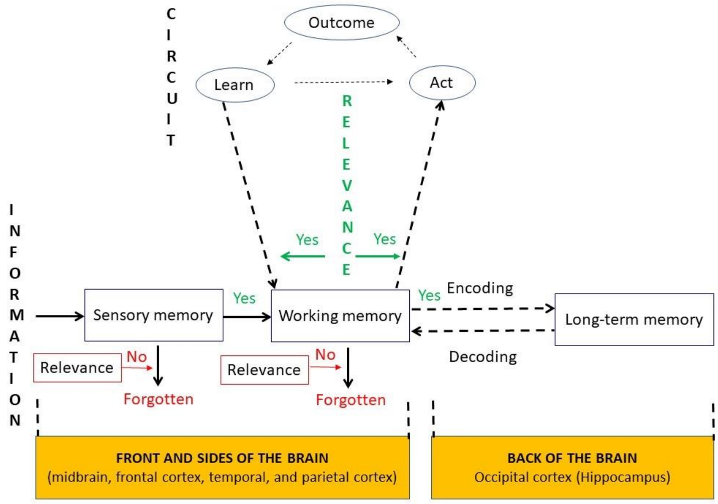

Figure 1. The proposed Relevance-CL-Learning memory circuit

Figure 1 shows a comprehensive Relevance-CL-Learning memory circuit in a 2D format. It is originally multidimensional and much more complex than what has been comprehended so far. It was conceived from the original work of Atkinson and Shiffrin (1968) [7] and then modified by introducing the concept of "relevance" in this paper. According to the Figure 1, information from the environment is first perceived by the human sensory systems, such as the visual, auditory, tactile, gustatory, olfactory, thermal and proprioceptive senses (the sense of movement, location, position, etc.). Relevance is assessed by the logical unit of the brain located at the prefrontal and frontal cortex before responding to any of these stimuli. If the information is relevant or logical, it is taken up by the sensory memory for further processing, otherwise it will be forgotten. If it is relevant, the information is taken up by the working memory (the next-level of memory) to complete the task and finally stored in the brain. If there any relevance presents in the input received, the learning cycle begins through actions (e.g., initiation, pursuit, and completion of a task), and the outcome measurement continues for specific iterations as the brain continues to learn. On many occasions, thoughts are redefined to find the relevance of the given task. The sides (temporoparietal cortex) and the front (frontal and prefrontal cortex) of the brain are responsible for receiving and preprocessing the sensory inputs. It is also worth noting that the thalamocortical pathways [8] and the olfactory bulbs [9] also perform similar tasks. Once the task is completed, the "learning" that takes place throughout the process is then encoded in the hippocampus (memory region) at the back of the brain [10]. Encoding is a specialized process for creating short and long-term memories through the visual, auditory, tactile, elaborative, organizational, and semantic information processing [11]. The high relevance and rigorous use of neurofeedback leads to the creation of a long-term memory (encoding) in the brain, provided that the CL does not supersede the predefined memory space at any given time. In the case of similar events/information, the long-term memory is decoded and retrieved for a meaningful use, which is desired [12]. Therefore, the chance of cognitive overload COL is unusual. Hence, alongside the nature and weightage of information, relevance also plays a crucial role in CL and COL. Feeding a large amount of irrelevant concurrent information or a delay in the learning process or problems with encoding and retrieval result in COL, as the author hypothesizes in this article. The brain tries its best to accommodate it in its normal state, when it fails to do so, COL occurs. Concerning the retention of episodic short-term memory, a study has shown that it is dopamine-mediated and that the main brain areas are locus coeruleus, ventral tegmental area, and hippocampus, contributing to such memory formation by setting the reentrant circuits [13]. Visual plasticity is another important concept for attention-based learning that has a diffuse neuromodulatory basis [11]. To further understand the relevance, in a recent study, researchers have reported that the level of neuromodulation may change the cluster of synapses minutes or hours after the learning process to retain certain types of information in the form of a recurrent neural network [14] after deep learning. Therefore, effective construction and reconstruction of the schema that is a cognitive framework or a concept for helping to organize and interpret any information [15], and to reduce the working memory load are two important factors to encourage learners' activities towards optimizing intellectual performances and positive learning outcomes [16].

In the following section, the information gathered in section 2 is explained by the knowledge from section 1.

The CL and expected EEG signal

The author extends the postulated Relevance-CL-Learning memory training circuitry model, which is available in Figure 1 by adding EEG signals (refer to Figure 2).

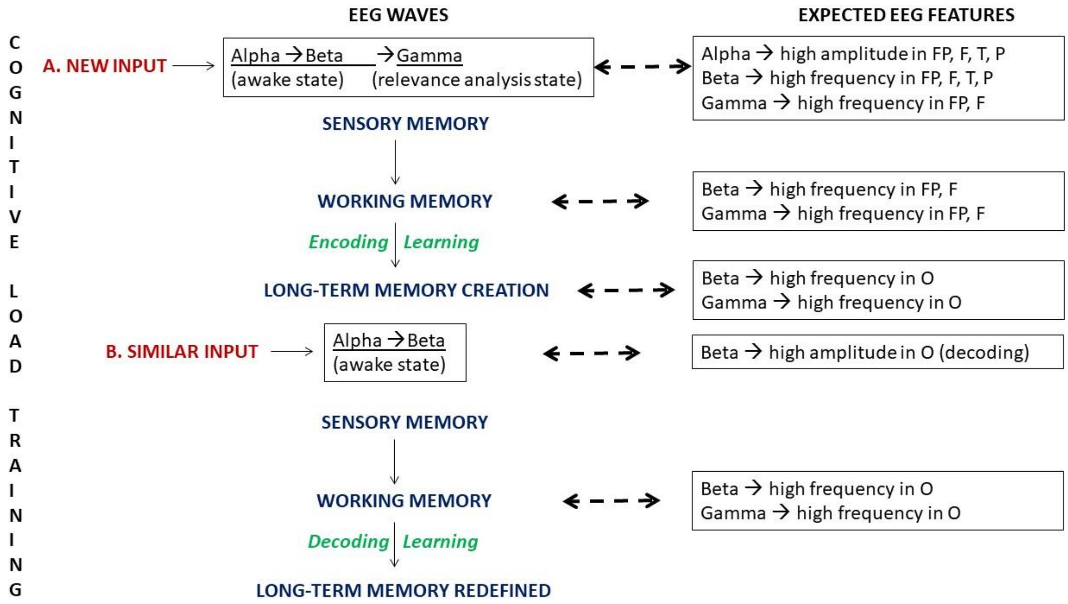

Figure 2. Postulated EEG mapping of CL training via relevance
(FP: Prefrontal cortex; F: Frontal cortex; T: Temporal cortex; P: Parietal cortex; O: Occipital cortex.)

Figure 2 shows the postulated EEG-Relevance-CL-Learning memory mapping model. It is assumed that CL is high when a new input is fed into the sensory memory of the brain. As shown in Table 1, beta and gamma waves predominate in the FP, F, T and P areas of the brain during normal brain functions. Relevance analysis (as per the model shown in Figure 1) is a complex task involving fast and deep thinking (metacognitive activities) and can be represented by gamma waves in the FP and F areas. Once training is completed and learning happens, the information is encoded in working memory, which can be represented by high-frequency beta and gamma waves in the O region of the brain, where the hippocampal memory center is located. If a similar input is then fed in as repetition, what has been learned is decoded in the memory center, which is represented by comparatively lower frequency beta and gamma waves. The CL is also expected to be reduced as compared to the previous state when it was new to the brain. Therefore, repeated similar tasks over time would help to redefine long-term memory until it is stored as an input-output rule in the brain. This could also help to generate neuroplasticity, as the author hypothesizes. In the case of COL, therefore, attenuated alpha-beta-gamma and accentuated theta-delta could be the key features of EEG.

The following section helps us to better understand CL based on several proposed theories before proceeding to section 5, which explains the model under the light of ADHD as a real-life use case.

The PASS theory of human cognition

Human cognition is a much more complex phenomenon than what we usually perceive. Intelligence is a finer form of cognition. The theory of planning, attention, simultaneity, and succession (PASS) was coined by Nagleri & Das (1977) [17] and was originally adapted from the work of A. R. Luria (1966) [18], which speaks of the three highly coupled functional units of the brain, such as (i) brainstem (responsible for arousal and attention), (ii) occipital, parietal and temporal cortex (processes successive and simultaneous conceptual, perceptual and memory encoding and decoding), and (iii) frontal cortex (responsible for analysis and planning). It is important to note that all three functional units work together during the "awake" state. The relevance of the sensory unit must comply with these processes in a coordinated manner. In case the relevance is low or nil, the first unit remains inactive, i.e. attention and arousal would not take place and all simultaneous and sequential processes such as planning and memory formation would not take place in the brain. Repeated similar sensory stimuli then may reduce COL or, if the relevance is too low, they are simply forgotten.

Relevance, pass theory and EEG in the light of ADHD as a use case

To understand the PASS theory and how the hypothesized "Relevance-CL circuit" of the RECSAE model works and its relevant EEG mapping, attention deficit hyperactivity disorder (ADHD) was explained as a use case, as studies have confirmed a very high COL in patients with ADHD [19]. Normally, the human brain can buffer overstimulation with sensory inputs. It quickly switches among multiple processes, according to the principle of "do it now" and "do not do it now", in a heuristic manner that corresponds to the relevance in the respective phase and at respective time. The sensory crowding in an ADHD brain hinders this "switching". As a result, the focus on a particular environmental input is lost. It is important to note that autistic spectrum disorder, traumatic brain injury, dyslexia, mental retardation, including Down's syndrome, etc., where similar types of COL occur.

ADHD and brain

ADHD is a cognitive disorder characterized by persistent inattention, hyperactivity, and random impulsivity in the behavior over 6 months (DSM-V) in more than two settings, such as school, home, or any other places, and academic and social decline in adolescents and poor occupational performance in those over 17 years of age [20]. The prevalence rate in young adults is 4.4% worldwide, with males more commonly affected (5.4%) than females (3.2%) [21]. It is diagnosed mainly by self-reporting and observing behavioral patterns. However, it has limitations due to the high subjectivity within the process of diagnosis. In ADHD [22], the frontal lobe (center for high-level reasoning and analysis), the basal ganglia (help with motor learning, processes executive behavior and related functions, and maintain the affect), the cingulate gyrus (an important part of the limbic system that regulates emotions and pain), temporal lobe (perceives visual sensory inputs, language as auditory inputs, and emotions/affects), parietal lobe (processes touch, pain, temperature and their optimal integration that are known as somatosensory perceptions) and the reticular activating system (the inward and outward relay systems of the brain that are responsible for attentiveness and coherence in behavior) are mainly involved. Dopamine and norepinephrine are the two major neurotransmitters that are deficient in ADHD [23]. These two neurotransmitters are responsible for maintaining attention and concentration to pursue and accomplish a task in daily life. They also regulate the associated emotions to achieve rewards and make the whole process feel pleasurable. Studies have also found that gamma-aminobutyric acid (GABA) in the motor cortex is reduced in ADHD, which causes inattention and hyperactivity [24], while high glutamate levels may lead to high impulsivity and aggression [25]. Therefore, a high glutamate-GABA ratio can also be found in ADHD. Another important neurotransmitter called serotonin is also reduced in ADHD. It regulates the affect and related behavioral processes [26].

Summary of ADHD and EEG [27]

According to recent studies, the most important findings of EEG in both children and adults are based on the ADHD subtypes (inattentive: ADHD-I, hyperactive: ADHD-H and combined: ADHD- C) [28]. The EEG signals are analyzed using task and event-related potentials (ERP) and spectral power (SP). The summarized results of the signals are as follows [27]:

Increased:

• Slow-wave (theta and/or delta) activity in all subtypes
• Theta power in the right hemisphere (visual queuing center)
• Beta-band along the midline posterior zone (the posterior parietal area responsible for planning motor activities and integrating visual information by reaching and grasping an object)
• Relative theta in the left hemisphere (responsible for reading, writing and calculation)

Reduced:

• Gamma band in the medial centroparietal area (through the efferent from the medial septal nucleus, it contributes the formation of the hippocampus, which is responsible for the encoding and decoding/retrieval of long-term memory) and the right hemisphere
• Right hemisphere relative delta
• Left hemisphere relative alpha
• Midline posterior relative alpha
• Theta/beta ratio in the left hemisphere, and the central part of the brain
(midbrain, where arousal and attention are processed) relative beta activity.

It should be remembered that EEG findings in ADHD are gender-specific, because the neurophysiology of males and females is different in many aspects. Females are found to be more inattentive, while males are more hyperactive and impulsive, although they respond equally to the treatment [29].

Poor sleep quality in ADHD is reflected by higher theta oscillations, which affect cognition and thus memory formation [30].

Corroborating relevance with COL and EEG in ADHD

The increased slow waves such as theta and delta are related to impulsivity and the alpha and beta waves are diminished due to hyperactivity. It is worth noting that hyperactivity decreases with age, while impulsivity is maintained in ADHD patients [31]. Therefore, the theta-delta and alpha-beta combinations could be the corroborative sign of COL in ADHD patients, which cause impulsivity and attention deficits, as many processes are simultaneously and successively running in the brain. It can be related to the triangular functionalities (arousal and attention, analysis and planning, and memory formation including the encoding/registration and decoding/retrieval) of the aforementioned PASS theory. A diminished resting gamma-band indicates a lack of deep thinking and memory formation [32]. It persists throughout their lifetime. Such an electrical phenomenon may be negatively correlated with relevance analysis when the brain receives a visual or auditory cue. A non-suppressed rather increased alpha wave in the occipital zone following an instructional/cued task can be noted in ADHD-I and confirms the short-lasting or lack of relevance of that cue for the formation of a long-term memory. Rather, it cannot be handled by the working memory due to the relevance issue. Reduced norepinephrine and dopamine in the brain of an ADHD patient could play an important role in the difficulty in relevance analysis and COL due to the dysregulation of the neural circuits. In EEG, the theta, beta and gamma bands must to be carefully monitored to recognize the training mode of the brain, which varies from time to time for the same task, but the general pattern might be the same. This is especially true for special educators. Elevated gamma bands indicate the ability of deep thinking. Relevance analysis requires deep thinking. Therefore, when the EEG wave patterns show alpha-beta-gamma-mu dominance instead of theta-delta dominance, it may be ascertained that the brain is responding well to the training/therapy/education.

EEG and COL

There is a consensus that prominent theta waves in the mid-frontal region and alpha waves in the parietal areas indicate cognitive processing in the brain [33-35]. Alpha and theta waves reflect the difficulty of processing a task by the brain. Progressively suppressed alpha waves are found with high CL and COL. It is also worth noting that theta activity is increased in magnitude with more difficult tasks. Therefore, the difficult task carried out by spatial working memory can be reflected through alpha attenuation (desynchronization) and theta enhancement (synchronization) in EEG signal analysis in a normal brain [34]. Memory formation is one of the essential tasks during cognition. The functional magnetic resonance imaging study that examined the brain areas for memory decoding and retrieval (an essential function of cognition) shows that the parahippocampus, cerebellum, superior lateral occipital cortex, the fusiform and lingual gyri, the precuneus and the posterior cingulate gyrus are responsible, while a reduced activation could be noticed in the anterior cingulate, the insula, the supramarginal and the postcentral gyri [36].

Conclusions

EEG provides the clue to the CL of the brain in a temporal and spatial domain while various tasks are performed simultaneously and successively. Therefore, it can be used as a non-invasive and economical model of CL assessment tool. The multiplicity of alpha, theta, delta, beta, and gamma waves gives several tangible clues to various brain functions involving the working memory that has a limited space.

The instructional sensory-motor training, whether performed actively or passively, helps efficient learning, provided it is relevant to the brain and fulfills the functional principles of the PASS theory. It helps create a long-term memory by reducing COL through high-volume, repetitive (both simultaneous and sequential) tasks for a given period. It can enhance neuroplasticity if the sensory-motor input is made "relevant" to the brain and the brain can process the inputs according to their natures (assigning weightage as per the importance) by constantly changing the processing circuits. It also helps to create cognitive balance. Repetitive neuromuscular training is thus proposed for almost all brain disorders [37]. The frontal lobe (reasoning center), which is intertwined with the posterior parietal lobe, the occipital lobe and the temporal lobe with the midbrain, plays a significant role in the pursuit and accomplishment of this task. The interaction of neurotransmitters, especially norepinephrine and dopamine, is pivotal in circuit formation.

Three important applications of this hypothetical model are cognitive training for special children, airplane pilots, astronauts, emergency surgeons, and many other related professions that have a high demand for situational, complex problem solving and as a result, suffer from COL at a higher rate. On many occasions, they present themselves as ADHD cases under demanding situations. Bringing the relevance to them in a sequential logical way could reduce the extent of COL.

Takeaway message:

• The "relevance" of sensory inputs helps to lower down the CL.
• CL and overload can be measured by EEG signals.
• Prominent theta-delta and attenuated alpha-beta-gamma waves indicate COL.
• COL is high in ADHD and other similar types of neuropsychiatric disorders.

Key definitions

Relevance

Relevance is a term that denotes the meaningfulness of information in a spatio-temporal domain of thought. It enhances the logical connection between the information and memory formation and stimulates the reentrant process of information encoding in the brain.

Cognition

It is all conscious and unconscious processes in which knowledge is acquired.

Cognitive load

The amount of information that the working memory can hold at a particular time.

Cognitive overload

It occurs when the amount of information exceeds the limit of the defined space of working memory, either due to the sudden high-volume information that the brain is exposed to and requires processing or the limitations of working memory space that cause cognitive overloading.

Sensory memory

It is the perception of the brain to capture and process the environmental information by senses, such as touch, smell, optesthesia, auditory sense, gustation, heat sensation, and so on.

Spatial memory

It is a cognitive process that enables a person to remember different locations as well as spatial relations between objects.

Working memory

It is a short-term memory to perform a particular cognitive task.

ADHD

A disorder that hinders the development and functionalities of any individual due to impulsivity, inattentiveness, or hyperactivity at the pathological level.

EEG

A method to record the electrical activities of the brain.

Special educator

A person trained to address the abilities and needs of a child in terms of communication, behavioral issues, physical disabilities, developmental issues, and learning.

Learning disabilities

The disorders affecting the ability to understand or to use spoken or written language, to calculate mathematically, and to coordinate in movement.

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Conflict of interest

The author declares no conflict of interest.

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