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Use of EEG Technique in a Cognitive Process Study- A Review

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Abstract: Cognitive processes have been widely studied using non-invasive electrical recording from the scalp called electroencephalograms (EEGs). However, a review that summarizes the EEG study in overall is lacking. The purpose of the review is to help the reader understand the brain functions based on the EEG technique. This paper attempts to review cognitive process studies using EEG techniques according to the Layered Reference Model of the Brain (LRMB). Based on the LRMB, there are six layers of cognitive processes: Layer 1 (Sensation), Layer 2 (Memory), Layer 3 (Perception), Layer 4 (Action), Layer 5 (Meta cognitive function), and Layer 6 (Higher cognitive function). Each layer of cognitive processes will be presented with a few example research studies. Valuable information from research studies, such as the electrode of interest, task assessment used and EEG analysis applied, will be indicated and discussed to help the reader understand and select the appropriate task assessment and EEG analysis. All extracted EEG information can be extended for use in machine learning.

Keywords: Cognitive process; electroencephalogram (EEG); event-related potential (ERP); event-related desynchronization (ERD); event-related synchronization (ERS)

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1. INTRODUCTION

The brain is a vital organ that controls all bodily functions, interprets information from its surroundings, and creates creativity and emotion. There are three main parts in the brain: the cerebrum, cerebellum, and brainstem. The cerebrum is the largest portion of the brain that performs higher executive functions, such as problem solving, concentrating, hearing, speech, memory, attention and vision. There are four lobes contained in the cerebrum area: frontal lobe, parietal lobe, temporal lobe and occipital lobe. Each lobe is associated with different functions, as shown in Figure 1.

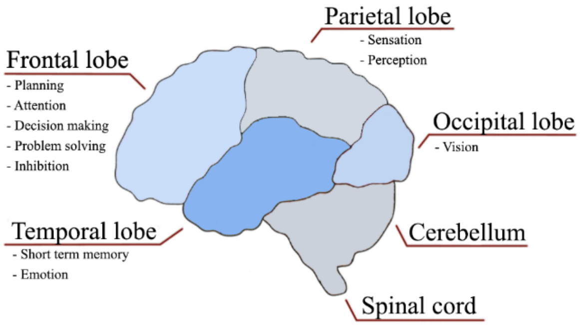

Figure 1: Brain region and function segregated by lobe

Many researchers have studied and demonstrated each part of the lobe functions. Most of them claimed that the frontal lobe functions in planning [1] [2], attention [3], decision making [4], problem solving [1], and inhibition of behaviour [5]. Sensation and perception are being processed in the parietal lobe area. Part of the parietal lobe also functions to integrate sensory and motor signals [6]. The occipital lobe is mainly used for vision, as in [7]. The temporal lobe is responsible for hearing [8], working memory, long-term memory [9] and language [10].

According to [11], the Layered Reference Model of the Brain (LRMB) was developed to explain the cognitive function of natural intelligence. The model contains six function layers: layers of sensation, memory, perception, action, metacognitive functions and higher cognitive functions. The LRMB is described in Figure 2.

In Layer 1 (sensation layer), all input senses, such as vision, audition, smell, tactility and taste, are included. Layer 2 is for the memory layer. The perception layer of LRMB is at Layer 3, and this is a vital part of subconscious mental functions. At this layer, cognitive processes such as self-consciousness, motivation, willingness, goal setting and emotions are developed. Layer 4 is the action layer, which is output oriented and produces a sequence of movements or prepared verbal sentences. Looking, reading and writing are examples of executive function under the action layer of the LRMB.

In conscious life, function encompasses Layer 5 (Meta cognitive functions) and Layer 6 (Higher cognitive functions). At the metacognitive function level, basic cognitive processes such as attention, categorization, concept establishment, and memorization are taking place. To reach the higher cognitive function layer, support from the meta cognitive process layer is compulsory. Recognition, imagery, learning, reasoning, decision-making, problem solving and synthesis are all examples of higher cognitive processes. The researchers in [12] claimed that, at a higher layer cognitive function, a cognitive process interacts with many other cognitive processes. Thus, they developed a set of formal and rigorous cognitive, mathematical and process models of a cognitive process.

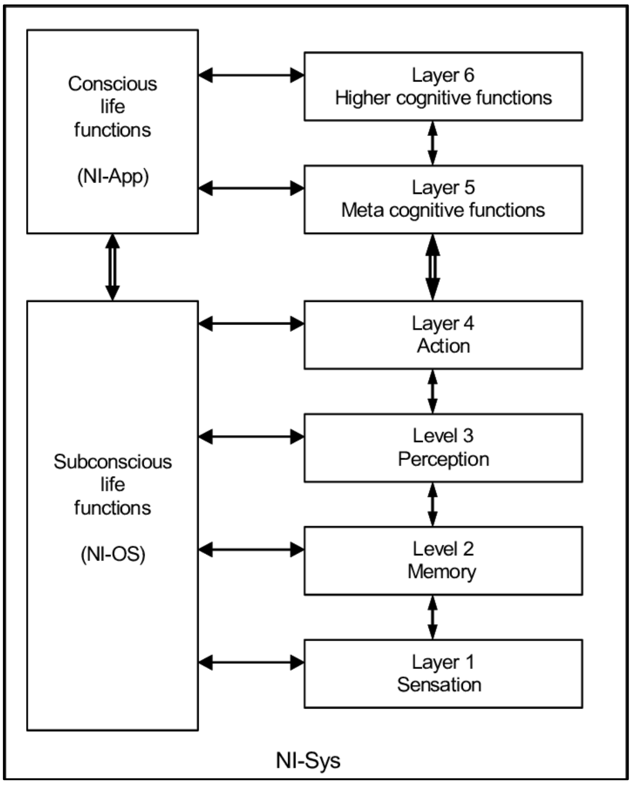

Figure 2: Layered reference model of the brain (LRMB) adapted and proposed by [11]

Brain dysfunction can interrupt an individual's cognitive function and lead to mental disorders such as attention deficit hyperactivity disorder (ADHD) [13], obsessive compulsive disorder (OCD) [14] and schizophrenia [15]. Thus, researchers have performed their research to confirm the affected brain area according to the impairment of cognitive function. In cognitive psychology and neuroscience research areas, various research methodologies have been offered to study the changes in human brain behaviour and the cortical network of the brain. Functional Magnetic Resonance Imaging (fMRI) [16] and functional Near-Infrared Spectroscopy (fNIRS) [17] are examples of advances in neuroimaging technologies that have contributed much to cognitive psychology and neuroscience. However, the electroencephalographic (EEG) technique has the advantage of directly measuring brain activity. EEG is portable equipment and not bulky in size, making it easier to manage. Due to its excellent temporal resolution, researchers are able to study cortical networks between brain regions during cognitive tasks. Even EEG has a low spatial resolution, and with advance EEG signal processing techniques, the result is comparable with others [18].

Thus, this paper gives a brief review of the use of EEG in the research study of cognitive functions. In Section 2, we discuss the fundamentals of EEG measurement. In Section 3, the use of EEG in studying cognitive processes in every layer of the LRMB is discussed in detail.

2. FUNDAMENTALS OF EEG MEASUREMENT

EEG is a method used to capture neuronal brain activity by placing metal electrodes and conductive media on the scalp surface. Before entering into the EEG recording technique, brain wave classification is explained in Section 2.1. Then, the EEG recording technique is explained in Section 2.2.

2.1 Brain Waves Classification

Brain waves are sinusoidal electrical voltage produced from the electrical activity of a brain. There are five bands of brain wave frequencies of human EEG: gamma (>30 Hz), beta (12-30 Hz), alpha (8-12 Hz), theta (4-8 Hz), and delta (0.5-4 Hz).

According to [2], generally, problem-solving activity and concentration brain waves fall under the gamma spectrum. During active mind and busy conditions, the brain produces a beta wave. During rest, drowsiness and sleep, the brain waves are under the alpha spectrum, theta spectrum and delta spectrum, respectively. Figure 3 shows a summary of the brain wave spectrum.

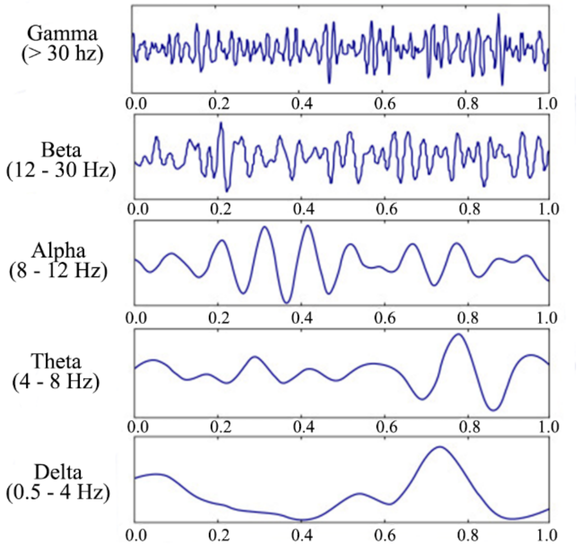

Figure 3: Brain wave spectra from delta, theta, alpha, beta and gamma [2].

2.2 EEG Recording Technique

In this section, the basic EEG recording technique used commonly in the study of cognitive psychology and neuroscience is explained.

In the process of recording EEG measurements, the recording system was comprised of electrodes with conductive media, amplifiers with filters, an analogue-to-digital (A/D) converter and a recording device.

To capture brain signals during task assessment, 10 to 20 electrodes need to be placed on a subject's scalp. Commonly, this procedure needs to follow the standard placement recommended by the American EEG Society, which is called the International 10–20 System, as shown in Figure 4.

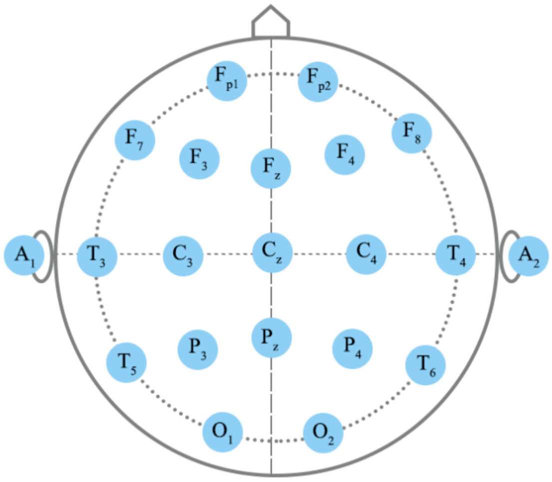

Figure 4: International 10-20 System of electrode placement on scalp

3. STUDY CASES OF COGNITIVE PROCESSES USING EEG TECHNIQUE

In this section, several research studies are reviewed. Data collected were categorized into brain activity according to the LRMB layer, task assessment used in studies, electrode of interest used for analysis and EEG analysis technique used. A summary for each case study is shown in Table 1.

3.1 Case Study of Subconscious Life Functions

The first case study section discusses a cognitive process relying on the subconscious layer of the brain. This layer consists of Layer 1 (Sensation), Layer 2 (Memory), Layer 3 (Perception) and Layer 4 (Action). However, case studies were chosen according to each layer of LRMB based on their task assessments. Assessments done in each case study were related to study specific brain function.

Layer 1 of the LRMB is associated with sensory processing function. Children with sensory processing disorder (SPD) may overreact or underreact to sensory input such as smell, taste, audition, vision and tactility. According to [19], sensory integration as a therapeutic approach was used to enhance the brain's ability to establish sensory input for use in functional behaviour. However, there is no empirical evidence for sensory integration to support the diagnostic category of SPD. A study by Davies [20] demonstrated the assumptions of sensory integration theory by using the EEG technique. Children aged 5-12 years participated in the study. Twenty-eight children had SPD, and 25 children with no behavioural disorder were included as the control group. EEG recording were collected using 32-channel BioSemi ActiveTwo EEG/ERP Acquisition System. The task assessments applied in this study are the sensory gating paradigm and sensory registration paradigm. Then, C_Z electrode data from the sensory gating paradigm were analysed using an event-related potential (ERP) waveform. Two characteristics can be measured from the ERP waveform: amplitude and latency. Amplitude is measured in microvolts (μV), while latency is measured using milliseconds (ms). ERP components are defined as rebound signals from baseline. Positive rebound occurring at 50 ms after the stimulus present is labelled P50. During the sensory gating paradigm, the P50 component and T/C ratio were calculated. In the sensory registration paradigm, the N100 and P200 components were used as the measures. Figure 5 shows the location of the P50 and N100 components on the ERP waveform during the presence of stimulus in study [20].

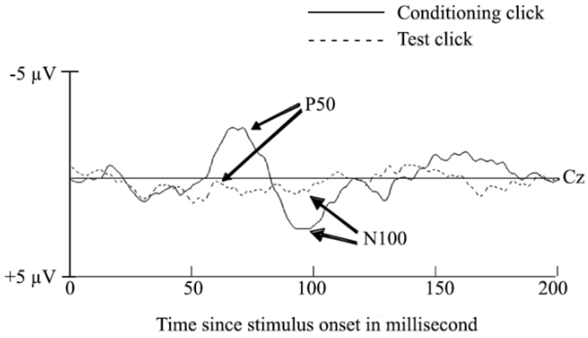

Figure 5: Example of the ERP waveform in a child with SPD from [20]

[21] also used the ERP component method for EEG analysis to study the cross-sensory interactions of non-social stimuli and the integrity of connections between brain areas involved in cross-sensory processing in individuals with autism spectrum disorder (ASD) and schizophrenia. Individuals with pervasive developmental disorder (PDD) [22] and schizophrenia [23] are an example of disorders due to abnormal brain connectivity; specifically, impaired higher-order audio-visual integration. The study subjects involved for the study are 13 adults with schizophrenia, 13 adults with ASD, and 16 healthy adults. For the EEG activity recording, the researcher chose to use 10–20 international systems of electrode placement. In the study, low-level cross-sensory interaction was measured by a cross-sensory P50 suppression paradigm. The EEG technique was applied during the task, and only the C_Z electrode measurement was used in the calculation of the P50, N1 and P2 T/C ratios as to differentiate the response between subjects.

In Layer 2 of the LRMB, case studies are related to memory. According to Moretti [24], the theta to gamma ratio of relative power at peak frequency is connected with memory impairment. This technique can be used to detect individuals who are at risk for dementias or mild cognitive impairment (MCI). 49 subjects with MCI were recruited for the study of the theta to gamma ratio method. The EEG activity was recorded continuously using Electro-Cap International, Inc. and the electrode was placed according to 10–20 international systems. Jiang conducted a study to investigate the differences in EEG power and coherence for MCI patients and healthy individuals [25]. The researcher recruited 35 patients with MCI and 34 healthy subjects for the study, and the EEG signal was recorded at 16 electrode sites according to the 10–20 international system of electrode placement. In the study, three levels of working memory tasks according to recitation of three-digit numbers and mental calculation were executed. Based on the correlation analysis performed in the study, it was found that the EEG coherence was significantly higher for the MCI patients than for the control group. Other than comparing EEG coherence and power analysis, Pijnenburg applied the synchronization likelihood analysis method to study a loss of functional connectivity in Alzheimer's patients and MCI patients [26]. For the study, 11 patients with MCI and 14 subjects with subjective memory complaints were recruited. Then, twenty-one channel EEGs were recorded and placed according to the 10-20 international system standard The synchronization likelihood was higher in the low alpha band (8-10 Hz) for MCI patients than for the control group during the working memory task. Another finding was, decreased beta band synchronization in mild Alzheimer's disease patients at rest and during working memory tasks.

After sensation and memory, perception is the layer where sensory information is organized, interpreted and psychological processes occur. For the selection of case studies under the perception layer (Layer 3), we chose to discuss the sense of motion. However, not all sensations result in perception. Sensory adaptation is the reduced response or stimuli when someone is exposed to a repetitive stimulation or distraction. In a study by Claudio [27], the hypothesis that alpha event-related desynchronization (ERD) before expected painful stimuli is reduced when there is distraction was tested. Three conditions in the task assessment to prove the hypothesis: 1) Pain (control) condition, 2) Pain + Movement condition, 3) Pain + Cognition condition were set. Data acquisition was performed using the EEG technique. Ten healthy subjects participated in the study and EEG recordings were taken from 30 EEG electrodes placed according to the 10-20 international system. Then, event-related desynchronization (ERD) analysis was used to quantify the changes in EEG power. By using this high-resolution EEG study, it was demonstrated that the hypothesis was true. Another research study on the perception of sense of motion is found in [28]. 18 healthy subjects were recruited and a 32-channel electrode was used for EEG recording. Here, the researcher used innocuous stimulation and noxious stimulation to induce pain experience and found a significant alpha-1 power value at T_7 and T_8. For the EEG analysis, power spectral densities were computed for the EEG analysis. Then they calculated the general power of each sub-alpha band using the individual alpha frequency measurement method. These two studies on perception are examples of perception (sense of motion), which is a layer that generates an internal sense of perception on motion and detects and interprets in real time.

The mirror neuron system (MNS) participates in perception and motor actions. This system plays a critical role in social cognition, such as imitation, simulating observed action, process language and empathy [29]. MNSs in humans can be studied using the EEG technique by analysing mu frequency band oscillations. A study on primary motor cortex activation during action observation was performed by Muthukumaraswamy [30]. This case study was selected under Layer 4 (the action layer of LRMB). Eight healthy subjects participated in the study, and the EEG signal was recorded using 128-channel electrode nets. In this study, the spectral response of the EEG was analysed using wavelet-based analysis (family of Morlet wavelets). There were five experimental conditions set in the study: 1) Baseline condition, 2) Move condition, 3) Thumb condition, 4) Object condition and 5) Brush condition. EEG data from channel C_3 were chosen for analysis. The mean beta frequency and mu beta frequency were set at 15-22.5 Hz and 10-12 Hz, respectively. At the end of the study, it was found that execution movement, observation of object-directed movement and observation of somatosensory stimulation caused a decline rebound of beta rhythm. In another study by Gourab [31], movement-related beta-band signals of the brain between people with chronic spinal cord injury (SCI) and healthy volunteers were accessed using auditory-cued toe plantar flexion movement. Eight chronic subjects with SCI and eight healthy volunteer subjects were recruited for the study. A 64-channel EEG system was used during the EEG recording. Changes in beta frequency (13-35 Hz) during event-related desynchronization (ERD) and synchronization (ERS) were analysed. ERD and ERS amplitudes at the C_z electrode was analysed using a t-test to determine the difference between the two groups of SCI and healthy volunteers. ERS was found to be significantly lower in the SCI group than in the healthy group, but there was no significant difference in ERD.

3.2 Case Study of Conscious Life Functions

The second case study section discussed a cognitive process relying on the conscious layer of the brain. This layer consists of Layer 5 (Meta cognitive function) and Layer 6 (Higher cognitive function).

The metacognitive process layer of the LRMB involves attention, categorization, memorization, and knowledge presentation. This part of life function can be controlled by a conscious mind. In psychophysiology cognitive research, attention has been related to the alpha and beta bands. Suseng studied a shift of visual spatial attention associated with the alpha band in EEG [32]. In the study, 29 healthy participants participated, and they performed a cued visual spatial attention task. The EEG signal was recorded from 30 electrodes placed according to the extended 10-20 system. Then, EEG data were analysed using P1 and N1 event-related potentials (ERPs). The results showed that alpha activity is controlled by the prefrontal region. Beta activity was not shown in this study due to the level of difficulty of the task assessment used. In [33], a Stroop task assessment was used to study attention in the human brain. They found that the discrimination between congruent and incongruent task conditions is sensitive at the beta band of 13–20 Hz based on coherence analysis. Higher coherence was observed within the left frontal and parietal areas. Ten healthy subjects participated in the study, and the EEG recording was done using 19 electrodes. In this study, [34], Harmony performed two experiments: 1) a complex arithmetic task and 2) the Stenberg paradigm to study attention to internal processing. The researcher has recruited 10 subjects for the study. The EEG signal was recorded using 20 electrodes according to the 10-20 system. Then, the narrow band analysis and Fast Fourier Transform were also performed in the study. The results showed an increase in the delta band during the performance of the mental task and a higher delta frequency during difficult task performance.

Executive function (EF) is the high level of cognitive process that enables an individual to manage and complete a daily routine. Under higher cognitive function (Layer 6 of LRMB), there are cognitive processes such as recognition, imagery, learning, reasoning, problem solving and decision-making. These cognitive processes can be divided into three control types: 1) updating control, 2) shifting control and 3) inhibition control [35]. Updating control occurs in evaluating incoming information and revising the existing content of working memory. Shifting control engages in an individual's ability to shift attention between different subtasks. Inhibition control is the process by which an individual needs to prepotent mental representation. There are several task assessments in studying EF (updating, shifting, and inhibition), such as the Stroop task (inhibition control) [36] Trail Making Test (TMT) (updating and shifting task) [36], go/no-go task (inhibition control) [37] and stop task (inhibition control) [37]

In [36], studies on functional connectivity and power spectra during TMT and Stroop tasks were examined using (PDC) method. The researchers found that the frontal, temporal and occipital areas generate information and are sent to various scalp locations. In addition, the results showed that theta frequency significantly increased in the frontal area. Gamma and high gamma frequencies were found to be significantly increased in the central-parietal-occipital-temporal regions. In the study, 20 healthy participants were recruited, and the EEG recording was used with 19-channels of electrode cap and placed according to the 10-20 international system. Other studies on the inhibition process were used go/no-go task [38] to identify EEG characteristics of common and specific processes. The same finding was found in [38], who found increased power in the gamma band in the frontal and occipital regions in the Go condition. An increase in the theta band between the fronto-parietal regions was found during the no-go condition. These results support the agreement of an increase in the theta band between frontal, central and parietal regions related to motor inhibition processes.

3.3 Summary of The Case Studies

In this section, a synopsis of the case studies reviewed is tabulated in Table 1. Based on the review, it can be concluded that each brain activity is associated with certain brain waves and brain regions.

As tabulated in Table 1, the cortex around the C_z, C_3 and C_4 locations are clearly associated with sensory and motor function. Sensory and action are closely related, and it has been shown in [39] and [40] that observation can improve motor performance and motor skill learning. Perception is also connected to sensory and action. Different cortical and subcortical interactions participate in human perception. Thus, it gives a sporadic electrode of interest, as seen in Table 1.

In the introduction, it was mentioned that the temporal brain region holds the function of memory. However, in the two papers reviewed here, [25] and [26] did not show any significant results in the temporal brain region. These studies compared MCI patients and healthy subjects. Thus, we recommend referring to research that used healthy subjects to prove the function of memory in the temporal cortex.

As we can see on higher cognitive processes, many electrodes of interest, including frontal, parietal, central and occipital regions, participated in the process. During the process of inhibition control, shifting control and updating control, they interact with many other metacognitive functions, such as attention, memorization, analysis and synthesis. Thus, to complete this executive function, one needs to be able to use all layers, as mentioned in LRMB, and this function uses the entire region of our brain.

3.4 EEG Analysis Summary

The EEG technique has been successfully applied to many cognitive process studies. Various EEG analysis methods were used to analyse specific brain states, such as time domain analysis, frequency domain analysis (power spectral density) and time-frequency domain analysis (wavelet). EEG power analysed using Fourier Transform is clearly useful across many applications because specific EEG frequency bands at a cortical area are associated with a specific brain state during task performance [41]. EEG coherence is the method used to analyse the frequency dependent cross-correlation of electrical signals between two scalp electrodes sites [42]. Another EEG analysis commonly used in neural activity studies is ERP. ERP is derived from ongoing EEG activity and obtained by averaging several temporal trials of interest time segments. Positive and negative deflections in ERP are called ERP components. Recently, N1 (first negative deflection) and P2 (second positive deflection) have been preferred for use compared to classical ERP components such as P300 (positive deflection at 300 ms after stimulus). This is because the specific timing of a component can vary broadly, depending on the task context [43]. Figure 6 shows an example of ERP components of an electrode after averaging across trials.

ERD and ERS analysis are commonly used to study sensory stimuli or motor responses. ERD and ERS are non-phase locked responses. This response can be calculated by bandpass filtering the raw EEG signals. Then, all samples are squared and averaged over all *N* trials. Typically, absolute band power is converted to relative power changes with respect to a reference time epoch and expressed as a percentage. ERD refers to the decrease in power in the alpha and beta bands [44]. ERS is commonly related to reflected deactivation and an increase in power[45].

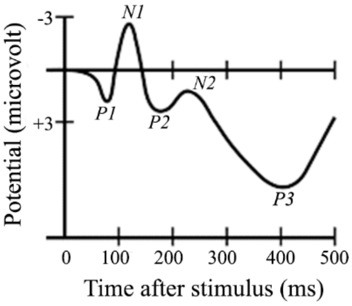

Figure 6: Example of ERP components that show the position of P1, N1, P2, N2 and P3 (adapted from [46])

4. CONCLUSION

EEG is widely used in cognitive psychology and neuroscience research areas. Different EEG analyses were used according to the researcher objective study. There are a few critical points that need to be considered before starting the EEG analysis in this research area. First, task assessment needs to be chosen wisely, as it will affect EEG data recording. Task assessment with much movement will give noisy EEG data. Raw EEG signals need to pass through noise filtering to remove artefacts. The second is the electrode of interest. Different studies may have different locations of electrodes of interest. Last, suitable EEG analysis needs to be identified, either to use time domain analysis, frequency domain analysis, time-frequency domain analysis, ERP or ERD and ERS analysis. Quantification from the EEG analysis will define the hypothesis of a study later.

In addition, the analysis of visual EEG interpretation can be extended to assist and enhance our understanding of EEG and brain function. Thus, this can lead to the development of machine learning and Brain Computer Interface (BCI) application. The machine learning technique is the way to extract information from EEG recordings. Then, the information can be used for EEG - based research and BCI applications, such as mobile robots, robotic arms and robotic wheelchairs. There is an increasing trend in using machine learning in clinical applications. Even though there has been impressive progress in machine learning, improvements such as accuracy, interpretability, and usability can be further explored.

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Table 1: Summary of case studies according to the LRMB

Study	Brain Activity	Electrode of Interest	Task Assessment	EEG Analysis Technique
[20]	Layer 1- Sensory	C_z	1) Sensory gating paradigm 2) Sensory registration paradigm	1) ERP- P50 component, T/C ratio 2) ERP- N100 and P200 components
[21]	Layer 1- Sensory	C_z	Cross-sensory P50 suppression paradigm	N1, P2, P50 components, T/C ratio
[25]	Layer2 - Memory	Parietal area (P_3, P_4) Temporal area (T_5, T_6)	Working memory task	EEG Coherence analysis
[26]	Layer 2 - Memory	F_8, F_7, F_4, F_3, F8, T_4, T_3, C_4, C_3, T_6, T_5, P_3, P_4, O_1, O_2, F_z, C_z, P_z	Working memory task	Synchronization likelihood analysis
[27]	Layer 3 - Perception	Fz, **Cz**, Pz, C3, C4	Pain, pain + movement, pain + cognition (arithmetical mental task)	ERD, ERS amplitudes
[28]	Layer 3- Perception	T_7,T_8	1) Innocuous stimulation 2) Noxious stimulation	Power spectrum
[30]	Layer 4 - Action	C_3	Median nerve simulation	Morlet wavelet analysis Beta and mu rebound rhythms
[31]	Layer 4 – Action	C_z	Brisk toe plantar flexion	ERD, ERS amplitudes
[32]	Layer 5 - Meta cognitive function (Attention)	Posterior parietal region (P_3, P_{01}, P_{03}, P_4, P_{02}, P_{04})	Cued visual spatial attention task	P1, N1 of ERP components
[33]	Layer 5 - Meta cognitive function (Attention)	Posterior parietal region (P_3, P_z) T_5, O_1	Stroop task	ERP analysis, EEG coherence analysis
[34]	Layer 5 - Meta cognitive function (Attention)	P_4, T_6, O_1,C_4	1) Complex arithmetic task 2) Stenberg paradigm	Narrow band analysis, Power spectrum
[36]	Layer 6 - Higher cognitive processes (Inhibition, shifting control)	Frontal area (F_{p1}, F_{p2}, F_3, F_4, F_7, F_z) Temporal area (T_6, T_4) Central area (C_4, C_z)	1) TMT 2) Stroop task	Power spectrum and PDC
[38]	Higher cognitive processes- (Inhibition control)	Frontal area (F_{p1}, F_{p2}, F_3, F_4, F_7, F_8) Central area (C_3, C_4) Parietal area (P_3, P_4) Occipital area (O_1, O_2)	Go/No-Go task	Power spectrum

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