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NON-INVASIVE EEG EXAMINATION ACROSS A SPECTRUM OF ASSESSMENT METHODS AND ITS APPLICATION IN VETERINARY MEDICINE: A REVIEW

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ABSTRACT

The study of the brain electrical activity is used in various fields of medicine, veterinary medicine and neuroscience. With a focus of veterinary medicine, the electroencephalography (EEG) method is widely used to examine cognitive abilities of pets, their behavior and human-pet relationships, as well as to diagnose neuropathologies in adult animals, mainly dogs and cats. Evaluation of EEG data involves performing visual analysis when working with a small amount of information. In recent years, however, more and more attention has been paid to automated software processing of EEG recordings (the so-called quantitative EEG (qEEG) analysis), due to its precision, specificity and ability to valuate a large amount of information. Various monitoring systems have also been developed to calculate indices of consciousness used in anesthesiology to monitor the depth of anesthesia. EEG has yet to establish its importance and place. The number of scientific publications devoted to EEG is growing, but more research is needed to reach a consensus on individual methods for evaluation and processing EEG data. The present review aims to summarize what is known to date, describing the methods for analysis and interpretation of EEGs and its application in veterinary medicine.

Key words: veterinary electroencephalography, brain waves, brain electrical activity, EEG assessment methods.

Introduction

Electroencephalography (EEG) is currently the only non-invasive method for recording dynamic changes in brain activity in humans and animals, with millisecond accuracy (d'Ingeo, S., 2019). It can also be recorded by monitoring changes in cerebrovascular activity, neuronal glucose metabolism or determining oxygen consumption in certain areas of the brain that are of interest. Imaging methods such as MRI, fMRI, CT, PET, SPECT are based on this. The widespread application of this type of research, however, is severely limited due to the high cost of diagnostic equipment and the need for specialized personnel to work with it. The main advantages of the EEG method are that it is much more economical, both in terms of equipment and maintenance and consumables. In addition, EEG can be performed in the natural environment of animals, without disturbing their welfare, using affordable portable EEG devices. This further expands the possible applications of EEG, as a method in human and veterinary practice, neuroanatomy and electrophysiology.

Interest in EEG has been increasing in recent years, as evidenced by the fact that the global EEG device market revenue in 2022 was about $1.4 billion, and is expected to grow by up to 7.1% and reach about $2.96 billion be the end of 2033, according to a 2023 report by Persistence Market Research. The market for veterinary EEG equipment is also growing – the estimate in 2024 reaches

$10 million, with a projected annual growth rate of 7.3% through 2030, according to a study by Grand View Research. Key factors driving the market growth include the increasing prevalence of neurological diseases, and with it the need for increasingly in-depth understanding of their mechanisms of occurrence. The so-called "Intersectoral Global Action Plan on Epilepsy and Other Neurological Disorders 2022-2031" was adopted by the UN Member States at the World Health Assembly in May 2022. The goals include promoting mental health and improving the quality of life of people with neurological disorders through sound management and politics of this issue, effective and rapid diagnosis, treatment and prevention, stimulation scientific research, innovation and information systems. This global initiative highlights the critical need to improve diagnostic and research tools on this topic.

Many of the neurodegenerative diseases in humans have analogous morphology and clinical manifestations in domestic animals (Mishra and Upadhyay 2025, Story at al. 2020, Sisó et al. 2006), for this reason, researches in animals are valuable for human medicine as well. Many EEG studies in animals have an experimental purpose. For example, studying the influence of various drugs on the symptoms of a degenerative disease, investigating mechanisms by which neuropathologies develop (Bassett et al., 2014). EEG is useful to elucidate the complex interneuron connections involved in the processing of sensory information (Kujala et al., 2020; Sandhaeger et al., 2019), cognitive functions and sleep (Ko et al., 2024; Bálint et al. 2024), but also with a purely practical focus (Kulgod et al., 2025; Kumar et al., 2022). Lyon et al. (2024) use video-EEG as a first-line diagnostic procedure in neurological examination in wake dogs and cats (Delsart et al. 2024). Everest et al. (2025, 2024) point the need of knowledge improvement about EEG examination in dogs reviewing the electrode arrays used in dogs. A study with continuous EEG examination in behaving dogs was conducted by Löscher and Worrell (2022) for the aids of epilepsy detection and treatment optimization. Wrzosek et al. (2024) work towards standardization of veterinary EEG recording protocols for dogs. Ko et al. (2024) observed clear changes in EEG in dogs during deep and light stage of isoflurane anesthesia. These varied from mainly isoelectric pattern with occasional burst during deep to predominantly alpha and beta waves with rare burst suppression as the consciousness increased upon electrical stimulation. The same study also revealed strong correlation between EEG and ECG patterns compared with changes in mean arterial blood pressure. Harris et al. (2020) demonstrate that EEG can measure pain in sheep under general anesthesia during routine castration. Kells et al. (2023) examine the EEG responsiveness of post-natal pigs under light anesthesia upon tail-docking. The nociceptive response was characterized with increased F50 and F95, and decreased total power. F95 was significantly changed only in older groups (>7 days of age) which suggests an increase in neuronal sensitivity to pain with age. Kis et al. (2017) show that command learning in dogs have an impact on sleep (both REM and non-REM) expressed by increased beta during REM and increased delta rhythm during non-REM sleep. Through qEEG, Mondino et al. (2023) analyzed the age and cognitive related differences in dogs' performance associated with sleep-wake rhythmicity. A clinical case report of Ștefănescu et al. (2024) describe specific EEG pattern of bilateral triphasic waves of non-convulsive epilepsy in dog with hepatic encephalopathy due to portosystemic shunt which is helpful for treatment optimization. Recording of the brain electrical activity is used in neurological examination to prove epilepsy, Alzheimer's and Parkinson's disease, intracranial inflammatory processes, cerebrovascular diseases, sleep apnea or brain neoplasia (Wijnberg et al., 2013; Aleman et al., 2006; Brigo, 2011; Wagley et al., 2020). Epilepsy in one of the most common neurological conditions observed in dogs, with a prevalence estimated at between 0.6% and 0.7% (Lyon et al., 2024). The integration of quantitative EEG (qEEG) measurements, which analyze EEG data using mathematical and statistical methods, further improves accuracy of brain function assessment (Fletcher et al., 2004). Video-EEG is useful for more complete monitoring of the disease in time (Bongers et al., 2022). EEG, which allows continuous track of brain activity in the patient's natural environment provides valuable information about the frequency and characteristics of seizures (Folkard et al., 2024). Such long-term EEG monitoring in both dogs and humans can improve clinical diagnosis and treatment strategies (Löscher and Worrell, 2022).

Monitoring of the brain's electrical activity can be a reliable indicator and is used in medical practice to determine the depth of anesthesia (DoA) during surgical intervention. This is also the second most common application of EEG testing, after the diagnosis of neurodegenerative diseases. By monitoring brain activation in real time while the patient is in the operating room, the risk of anesthetic overdose is reduced, but also the danger of preserving consciousness and sensation during surgery, from the application of too low doses. This brings advantages both from a physiological point of view – a faster and easier post-anesthesia period, and from a financial aspect – for the accurate titration of. Studies showed that nociceptive-induced EEG changes were associated with specific neurophysiological biomarkers – an increase in delta and beta and decrease in alpha rhythm hypnotics (García et al., 2021; Purdon et al., 2013). The increase in beta rhythm is associated with an increase in motor activity when using low doses of anesthetics. During general anesthesia with a combination of analgesic and anesthetic, increased delta waves and disruption of the alpha rhythm are more characteristic. A study in cats under anesthesia with medetomedine (Wrzosek et al., 2009) showed an increase in delta and theta wave activity, at the expense of alpha and beta rhythms. The change in brain electrical activity associated with sevoflurane-induced anesthesia has been studied using EEG in dogs (Marchant et al., 2014). EEG recordings showed statistically significant differences between the awake state, light anesthesia, and deep anesthesia. Lichtner G. et al. (2024) report that propofol anesthesia attenuates but not completely abolish nociceptive signal processing in the spinal cord. Another study of the same authors (2024) demonstates that robust nociceptive activation persists in both spinal and supspinal region during deep general anesthesia, which indicates that patients during unconsciousness can still exhibit neural responses to noxious stimuli despite they cannot express it behaviorally. Taylor and Vierck (2003) show that despite EEG suppression, certain nociceptive reflex and autonomic responses persist which indicates incomplete sensory blockade. Further studies on EEG analysis during total intravenous anesthesia are needed to reveal its clinical effectiveness (Murrell et al., 2009). The use of EEG offers reliable approach to measure the responses of the central nervous system to various stimuli, including irritant stimuli and the administration of agonist-antagonist medications in anesthetized dogs (Greene et al., 1991). Also EEG markers may contribute to a deeper understanding on individual resilience against stressors (Gupta and Reddy, 2025).

The use of EEG is reliable for studying individual behavior (Toffoli et al., 2024), for revealing the reciprocal or co-activation of individual neural circuits, the participation of the limbic system and the subcortex in motivational and emotional impulses in humans and animals (Bridwell et al. 2018; Harmony, 2013; Jensen et al. 2007). It has been found that emotion and behavior are expressed differently in the two hemispheres in terms of wave activity. Positive emotions predominantly activate the left hemisphere, while at the same time a decrease in alpha waves is observed.

Negative situations and stimuli lead to activation primarily of the right hemisphere and to an increase in beta and gamma rhythms. An inverse correlation has been established between the alpha rhythm and the activation of the hemisphere – a decrease in the former is usually associated with increased brain activation (d'Ingeo, 2019). The appropriate connectivity between pair of regions in the telencephalon ensure the ability to express normal behavior and interactions towards other individuals. It was found that functional connectivity disruption between hemispheres can lead to development of certain neurological conditions such as difficulties in person identification (Epihova et al., 2024, 2023).

A direct relationship between brain wave activity and changes in heart rate has been revealed. A 2003 study of Jurysta et al. demonstrated that during slow-wave nonREM sleep, RR intervals increase, while during REM sleep they shorten, similar to wakefulness. This indicates that heart rate decreases during slow-wave sleep and increases again during paradoxical sleep. In terms of frequencies, the normalized values of low frequencies (LFnu=LF/(LF+HF)) decrease upon entering non-REM and increase upon entering REM. The trend is exactly the opposite for high frequencies (HFnu). In other words, the sympathovagal balance in the heart decreases during non-REM and increases during REM. The main frequency range associated with cardiac activity is the delta rhythm mentioned by the same authors, since the parasympathetic effect on the heart precedes the changes in delta waves.

It has been found that the spectral characteristics of the EEG are also sensitive to metabolic changes (An, 2015). After food consumption, a decrease in delta and an increase in theta and alpha waves are observed, mentioned by the same authors. Prolonged period of fasting, accompanied by a decrease in blood sugar levels, are associated with an increase in theta and a decrease in alpha rhythm in the EEG.

Interpretation of EEG recordings should be proceeded with caution, taking into account the clinical history, age, and species-specific characteristics of the patient (Luca et al., 2023). EEG signals can be affected by fatigue, panic, increased alertness, and even behavioral intentions (Gao et al., 2019). Artifact recognition and management are critical for EEG processing, because various sources of noise can contaminate recordings and overlap brain activity waves. Based on all that has been presented so far, the need to optimize and improve the methods for evaluating EEG studies is essential. This review aims to provide an in-depth overview of current methods for EEG interpretation, highlighting both their strengths and limitations, in order to identify areas for future development and improvement.

Brain waves

In the interpretation of EEG, waves in the range between 0 and 30 Hz are most often taken into account. These, in turn, are divided into delta (0-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz) and gamma (>30 Hz) waves. The alpha rhythm is characteristic of the brain in waking state, when the individual is relaxed or when drowsiness occurs and the eyes are closed (Teplan, 2002). The transition from alpha to beta rhythms upon opening the eyes involves multiple cortical and subcortical areas, reflecting changes in attention and arousal. At the moment of opening the eyes or the occurrence of brain activity, such as calculation or active thinking, for a fraction of a second the alpha waves are replaced by the beta rhythm. Delta and theta rhythms are typical during sleep, during non-REM and REM, respectively, when low-amplitude high-frequency waves are replaced by low-frequency and high-voltage waves. Delta activity has been found in the processes of integration of short-term and long-term memory during sleep (Tononi and Cirelli, 2012), as well as in the processes of neuronal plasticity caused by changes in the synaptic transmission of impulses between neurons (Assenza and Di Lazzaro, 2015). In particular, the N3 phase of slow-wave sleep (characterized by high-amplitude delta waves >75 μV) is strongly implicated in memory consolidation. The N2 phase, characterized by theta waves, sleep spindles (12-15 Hz) and K-complexes (delta bursts), supports memory consolidation, especially declarative memory (Patel et al. 2024; Hristova and Georgiev, 2024; Georgiev, 2020). Slow-wave sleep, stage N3, promotes hippocampal-neocortical connections for the utilization of memories. The appearance of a certain wave rhythm is not registered with equal strength, simultaneously, throughout the brain, but has topographic specificity (Kumar and Bhuvaneswari, 2012). Further research is needed to fully understand the complex interaction between different brain wave frequencies and their function associated with cognition and behavior. Table 1 shows the main types of wave activity in the brain, their physiological significance and anatomical localization.

Table 2: Brain wave characteristics

Wave	Frequency	Meaning	Location
Delta	0-4 Hz	Deep sleep, memory integration, brain plasticity	Frontal lobe in adults, posterior lobe in young
Theta	4-8 Hz	Relaxation	Parietal and temporal lobes
Alpha	8-12 Hz	Calm state	Posterior and occipital part
Beta	12-30 Hz	Focus, Concentration, Alertness	Frontal and parietal (central) part
Gamma	>30 Hz	Emotions, intense thinking, decision making	Somatosensory cortex

Using electrodes (surface or subcutaneous) attached to the scalp, amplifiers and a recording device, the electrical activity of the brain is recorded in real time or on tape, in the form of waves with a certain amplitude, frequency and phase. The EEG mainly reflects the postsynaptic electrical potentials of the pyramidal cells of the cerebral cortex (Silva and Antunes, 2012). Under the influence of various sensory stimuli, these electropotentials change their size and speed. Neural trajectories also change in relation to the topographic organization of the brain (Land et al. 2022), depending on the nature of the stimulus (light, sound and somatosensory). Any deviation and disturbance in a specific area of the brain will also affect the spontaneous neuronal activity and the EEG recording. The accuracy and reliability of EEG interpretation comes from the selection of appropriate combinations of channels which graphical characteristics need to be analyzed. Dubost et al. (2019) found that the best channels for reporting the depth of anesthesia in humans are the frontal 7th and temporal 8th channels. They are located diagonally on the scull, on the left frontal lobe and the right temporal lobe of the skull, respectively. Lewis et al. (2011) performed an analysis of EEGs in cats using data from C3 (central) and Cz (central, midline) channels. The C3 channel is located 2-3 cm to the left of Cz, which is in the center of the skull. Data from these channels were statistically analyzed, comparing them with a reference electrode located on the nasal bone (Lewis et al., 2011). Up to date there aren't any standardized protocols for electrode arrays in animals, as it is in humans. A distinction should be made between reference montage, bipolar montage and averaged potential between two adjacent electrodes. Reference montages compare the electrical activity of each electrode with a common reference electrode, while averaged reference montages use the average value of all electrodes as a reference point. The bipolar montage compares the voltages of two electrodes.

The ratio between the individual frequency ranges should be calculated using bandpass filtering (BPF). Bandpass filtering is an approach that determines the dominant wave activity (Makeig et al., 1996). The method is based on the possibility of selecting some frequency ranges and attenuating others. In this way, only the waves that are of interest at a given moment are visualized on the EEG recording. For example, a 4Hz HFF (high-pass filter) reduces frequencies above 4 Hz and enhances the so-called delta waves, which are in the range from 0.5 to 4 Hz. A 4 Hz LFF (low-pass filter) and an 8 Hz HFF preserve the theta waves in the recording. 8 Hz LFF and 12Hz HFF visualize alpha waves, while 12 Hz LFF and 30 Hz HFF record only beta waves. The results are calculated using different indices reflecting the percentage ratio between the different waves. This determines the dominant and general distribution of waves in the individual brain lobes (frontal, parietal, occipital, temporal). Normal findings in the frontal and occipital regions are high-frequency alpha waves. In the parietal region, beta and gamma waves are clearly expected with open eyes and activity (Chaddad et al., 2023). The temporal region registers sharp waves, which are normal during sleep or hyperventilation, but can be indicative of epilepsy (Chaddad et al., 2023).

EEG evaluation methods

EEG assessment methods can be divided into three groups: 1. Visual assessment; 2. Quantitative EEG analysis (qEEG); 3. Monitoring systems for determining the level of anesthesia.

Visual assessment

Regarding the visual observation of EEG recordings, attention should be paid to several characteristics: electrical sequence and interruptions, lateral synchronization and desynchronization, the appearance of transient activity. Electrical sequence consists in maintaining a frequency rhythm with the same amplitude. When there is sudden activity with high-voltage oscillations or attenuation of the amplitude, we are talking about electrical interruptions. The latter are characteristic specifically of a state of deep sleep or narcosis (anesthesia). This method was applied by Clancy et al. (2003) as a way to visually assess the level of consciousness and the depth of sleep. Lateral synchronization and desynchronization (Lewis et al., 2011) serves to identify heterology in the activity of the two hemispheres of the telencephalon. Asynchrony is spoken of when there are interruptions in the rhythm of morphologically similar complexes with high amplitude, which differ by >1.5 s from their appearance in the left and right hemispheres. The appearance of transient activity is detected when so-called paroxysmal phenomena are present (Lewis et al., 2011). These include sleep spindles (multiple high-voltage, spindle-shaped oscillations that characterize the second stage of non-REM sleep or general anesthesia), vertex waves (biphasic, broad waves), K-complexes (biphasic, high-voltage, broad oscillations), spikes (biphasic, narrow, sharp waves), sharp waves (positive, broad, medium amplitude), and burst suppression (periods of quiet wave activity, close to the isoelectric line, of varying duration and frequency). The meaning on these phenomena should be interpreted with caution, so as they can be completely normal, abnormal, but also non-epileptic or epileptiform.

Quantitative EEG analysis

This approach uses computer algorithms to evaluate various aspects of the EEG recording, such as amplitude, frequency, and sequence. Some of the most commonly used specialized software for analyzing EEG recordings are Chronux, FieldTrip, EEGLAB, ERPLAB. These are tools for the MathLab computing and programming platform developed by MathWorks Corporation. This software offer a set of advanced analytical tools that allow extraction of detailed information from EEG data. The full capabilities of this software include a whole range of functions, but the most commonly used in EEG studies are: Power Spectral Density (PSD), Density Spectral Array (DSA), Permutation Conditional Mutual Information (PCMI), Burst Suppression Ratio (BSR).

PSD shows the distribution of amplitude versus frequency (Freeman et al., 2003). Several variables can be derived from the analysis of the spectral density of the EEG signal. These include absolute power (AP) and relative power (RP), median edge frequency (MEF50), and spectral edge frequency (SEF90). AP is the maximum activity (intensity) in a given frequency range. RP is the AP divided by the total power (TP) of all frequency bands. MEF50 is the midpoint of the spectral density distribution of the signal. SEF90 is the frequency at which 90% of the spectral density of the signal is located and reflects the change from a high-frequency rhythm to a low-frequency one, as observed during premedication.

DSA presents the relationship between frequencies and amplitudes over time as a color graph (Kim et al. 1999). The abscissa is time, the ordinate is frequency, and the amplitude is represented in black and white or color. The advantage of this method is that it detects even subtle changes in brain activity and therefore in the depth of anesthesia.

PCMI is used to assess synchronization between the two hemispheres (Li and Ouyang, 2010). It is a mathematical algorithm that calculates dynamic changes in the direction of electrical activity in the brain, in each hemisphere, with respect to time. The results are presented as indices, which are then used in statistical analysis to establish a relationship that is interpreted as synchrony in the activity of neural circuits on both sides of the telencephalon.

The burst suppression ratio (BSR) is characteristic of deep anesthesia and unconsciousness. This type of EEG pattern is observed in states of insufficient brain oxygenation, such as hypoxia and ischemia in trauma or coma, as well as in hypothermia, which is indicative of neuronal activity in the lower brain structures, in the absence of the same in the cortex (Lobo et al., 2021). BSR shows the ratio between long (over 0.5 s) periods of low (under 5 μV) amplitude, interrupted by high-voltage pulses reaching over 50 μV. There is an inverse relationship between BSR and the level of metabolic activity in the brain, which means that an increase in BSR is associated with a decrease in metabolic processes in the brain. (Chemali et al., 2013). BSR varies in the range between 0 and 1, with 0 indicating increased occurrence of pulses, and 1 – longer periods of suppression.

Monitoring systems for determining the level of consciousness

Brain electrical potential monitoring of depth of anesthesia has been used as a non-invasive method since the 1990s (Fahy and Chau, 2018). Over the past 20 years, the number of devices used for this purpose has increased (they number over 10 as of 2018), as mentioned by the same authors. This specialized monitoring systems report different indices calculated based on certain EEG parameters. These include bispectral index (BIS), brain status index (CSI), patient status index (PSI), and consciousness level index (IoS). The aim of these indices is to summarize EEG information in an easy-to-read form, based on different mathematical algorithms.

The most popular method for determining the depth of anesthesia is the mathematical bispectral index (BIS), both in human and veterinary practice, although there is still no consensus on its reliability, as it has not been statistically proven to reduce the number of cases of preserved consciousness during surgery when relying solely on this indicator. The level of consciousness according to the BIS is reported on a scale from 0 (coma) to 100 (fully conscious, alert). BIS values between 40-60 are considered to be the achieved during general anesthesia, and 15 minutes before the end of the operation these values should vary within 55-70 (Punjasawadwong et al., 2014). However, in a study with cats, values between 5-32 were reported for anesthesia with isoflurane, indicating interspecies differences (Lamont et al., 2004). Greene et al (2002) reveal that canine BIS values correlate predictably with end-tidal isoflurane and sevoflurane concentrations in dogs and could be used as assessing index of CNS depression. March and William (2003) examine BIS index to measure early arousal from anesthesia in cats after noxious stimulation. Ubiali et al (2022) inspect BIS index change during propofol anesthetic protocol in dogs. An alternative indicator is the Cerebral Status Index (CSI), which is calculated based on the frequency of sudden rapid periods of low voltage (Burst Suppression Ratio) and the quantitative relationship between alpha and beta waves, in contrast to the BIS, which uses only the beta rhythm (Cho et al., 2018). Its values vary in the same range as the BIS. In addition to these two indicators, the Patient Status Index (PSI), which is calculated based on the amplitude, frequency and phase of the waves, is also used in practice (Drover et al., 2002). The values of this index in general anesthesia should vary between 25-50 (Kim et al., 2021) but it is recommended not to use it alone in the assessment of DoA (Sakai et al. 2023). The IoS index should vary between 40-60, similar to the BIS and CSI. In isoflurane anesthesia, the IoC index has shown good results in reporting the depth of anesthesia in rats and rabbits (Silva et al., 2010, 2011). The disadvantage of these systems is that they only report the level of consciousness, analyzing the ratio between low-voltage fast waves, characteristic of wakefulness, with high-amplitude slow rhythm during anesthesia or sleep. From the perspective of sensory sensitivity perception, by detecting specific and occasional features in individual frequency lines, these monitoring systems are not enough informative. In developing such a technique, the goal is to be increasingly sensitive and be able to report electrical activity even in the deeper, subcortical layers of the brain, reported by surface electrodes. This seems possible and there are successful studies in this area (Krishnaswamy el al. 2017).

Conclusion

Electroencephalography (EEG) stands as a non-invasive method for recording brain activity in humans and animals. It offers both practical and economic advantages compared to diagnostic imaging methods. EEG equipment allows its use in a natural environment, which is of great importance for veterinary medicine. The growth of the EEG market emphasizes the importance of EEG as a research and clinical technique. Practical applications of EEG include examination of behavioral traits, neurological diagnosis, monitoring the depth of anesthesia during surgical interventions, providing real-time information about the patient’s level of consciousness. EEG reveals the complex neural dynamics associated with emotions, behavioral responses and the interaction between the cerebral hemispheres in the processes of cognition and brain activity. Future improvements in EEG assessment methods, including visual analysis and specialized software, would strengthen the accuracy of interpretation of recordings. This would contribute to a better understanding of neurological conditions and the overall brain function. Further research should focus on developing techniques for registering subcortical activity and providing more comprehensive information about the functional neural connectivity of different brain regions. Despite its advantages, EEG method also has some disadvantages. Additional research is needed to address the artifacts removal and develop more accurate methods for interpreting EEG results.

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