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Low Resolution Electromagnetic Tomography strenghts, limitatioms and feature trends

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ABSTRACT
Attention-Deficit/Hyperactivity Disorder (ADHD) Attention Deficit Hyperactivity Disorder (ADHD) is a socially significant diagnosis that has a substantial impact on the social adequacy of individuals both in childhood and adulthood. In children, ADHD manifests through specific difficulties in learning, behavioural deviations from age norms, increased and often nonspecific motor activity, as well as other symptoms. Some of these manifestations overlap with other developmental disorders in early childhood, highlighting the need for the most precise early diagnosis possible. Timely and accurate diagnosis is crucial for early intervention and the implementation of an individualized approach, which enables the application of appropriate pedagogical methods aimed at optimizing the intellectual potential and social adaptation of children with ADHD.
In adults, an accurate diagnosis is equally important for successful social integration and professional realization in environments that recognize and utilize their specific cognitive and behavioural characteristics.

1. Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is the most commonly diagnosed childhood psychiatric disorder, affecting up to 10% of children, with symptoms often persisting into adulthood. The core behavioural manifestations of ADHD are associated with altered neurochemistry in the anterior cingulate cortex (ACC) and the right caudate nucleus, both of which play a key role in the attention's regulation and executive functions [1-9].

Numerous EEG studies have shown that children with ADHD exhibit reduced regional cerebral blood flow (rCBF) in the striatum during tasks requiring semantic processing and executive attention [2, 10, 18, 19, 28]. Bush et al. [2], using functional magnetic resonance imaging (fMRI) and a response interference task, found reduced activation in the cognitive division of the ACC in adults with ADHD. Additionally, structural MRI studies have revealed cortical thinning in the right hemisphere of the brain in regions associated with attention and executive functions, including the ACC, dorsolateral prefrontal cortex, and inferior parietal lobule [3].

In the context of working memory, particularly spatial working memory, studies in children with ADHD have identified significant electrophysiological deviations [1, 10, 18, 19, 26]. In a detailed study (Figure 1), a marked reduction in alpha wave desynchronization was observed, along with increased power in alpha and mid-frontal theta waves during working memory tasks. The authors concluded that difficulties with attention and encoding compromise the effective maintenance of information in working memory in children with ADHD [4, 16, 17, 18, 21, 26, 27, 28].

Figure 1Experimental studies of schoolkids with ADHD

Neurophysiological Aspects of Working Memory in Adults with ADHD

Adults with Attention Deficit Hyperactivity Disorder (ADHD) often exhibit significant difficulties with working memory [3, 5, 11, 15, 19, 20, 23]. These difficulties are associated with an inability to properly interpret incoming information or to organize actions based on it [5, 20, 23]. Working memory is essential for executive functions and everyday cognitive performance, and its impairment can have a substantial impact on the quality of life of affected individuals.

Electroencephalographic (EEG) studies in healthy individuals have shown that successful retrieval of information from memory is associated with increased activity in the theta range (4–7 Hz) and more pronounced desynchronization in the upper alpha range (10–12 Hz) [6, 14]. These frequency characteristics are considered neurophysiological markers of effective cognitive processing.

Additionally, intracranial EEG recordings covering both cortical and subcortical structures have demonstrated that the retrieval of memorized information is preceded by increased activity in the theta frequency range in the right temporal and frontal cortex [6, 7, 14]. This supports the role of theta oscillations in memory and attention processes.

During verbal working memory tasks, an increase in theta wave amplitude is observed, which gradually decreases toward the end of the task. This pattern of activity supports the hypothesis that theta frequency oscillations are closely linked to the maintenance and manipulation of information in working memory [1, 2, 3, 7, 8, 22].

The best methods for diagnosing ADHD are presented in Table 1 with their strengths and limitations:

Table 1 Best methods for diagnosing ADHD

Method	Strengths	Limitations	Use in ADHD Diagnosis
Standard EEG [4, 6, 14]	Non-invasive, widely available	Low specificity, subjective interpretation	Identifies gross abnormalities
Quantitative EEG (qEEG) [31, 32]	Objective, quantifiable data	Requires expertise, controversial biomarkers	Theta/beta ratio, subtype differentiation
Event-Related Potentials (ERPs) [36]	Insights into cognitive processes	Time-consuming, requires controlled conditions	Assesses attention, inhibition, error monitoring
Functional Connectivity[2, 35]	Network-level insights	Complex analysis, not yet standardized	Altered connectivity in attention networks
Machine Learning[33, 34]	High diagnostic accuracy, handles complex data	Requires large datasets, limited interpretability	Integrates multiple EEG features
Neurofeedback [11, 12, 13]	Non-invasive, therapeutic potential	Time-consuming, efficacy under investigation	Normalizes abnormal EEG patterns

2. Methodology Overview

The primary goal of the present study is to provide a concise yet in-depth review of all significant methods used for diagnosing ADHD and to identify a method that is more easily applicable in practice and more accessible for professionals involved in speech therapy, psychology, and other related fields connected to child development.

In order to evaluate and highlight the most effective methods, it is essential to examine the key characteristics of ADHD within the diagnostic process, as well as to assess the advantages and disadvantages of the most commonly used diagnostic approaches.

To achieve this, a large number of scientific publications (36) were analysed, with over 95% of them published in the last 2–3 years. The selection of publications was based on keyword searches in scientific databases. The reviewed literature sources contain numerous findings and examples related to the diagnosis and monitoring of ADHD, as well as the application of various assessment methods and analyses of the resulting data.

Based on these studies, the advantages, disadvantages, and application potential of the main methods have been systematized. The aim of the article is to provide a comprehensive summary of the results for as many diagnostic methods as possible and to offer a starting point for accurate diagnosis of patients across different age groups, taking into account their specific characteristics. Additionally, the study aims to identify a method that is more easily applicable and economically efficient for widespread use in the diagnosis and monitoring of ADHD following treatment.

LORETA (Low Resolution Brain Electromagnetic Tomography) is one of the leading diagnostic methods. It estimates the three-dimensional distribution of electrical activity in the brain using scalp-recorded EEG signals. The method provides functional imaging with high temporal resolution, making it suitable for studying dynamic brain processes related to attention and executive functions.

3. Most Reliable of Methods for EEG Diagnosis of ADHD

A useful tool for diagnosing ADHD is (EEG), providing information about the brain's electrical activity. The most reliable methods for EEG diagnosis of ADHD are presented in Table 2:

Table 2 Most reliable methods for EEG diagnosis of ADHD

Standard EEG [4, 6, 14]	Traditional EEG records brain activity through electrodes placed on the scalp. It can detect abnormalities in brain waves associated with ADHD
Quantitative EEG (qEEG) [31, 32]	This method analyses brain waves and compares them with baseline data from healthy individuals. qEEG can identify specific patterns characteristic of ADHD.
Functional MRI (fMRI) Combined with EEG [2]	Combining fMRI with EEG provides detailed information about brain activity and structure, which can help with more accurate diagnosis.

3.1. Advantages and Disadvantages for most reliable methods

Some of the advantages and disadvantages over traditional EEG of those methods are presented in Table 3. These advantages and disadvantages should be considered when choosing a method for diagnosing ADHD.

Table 3 Advantages and disadvantages over traditional EEG methods

Method	**Advantages**	**Disadvantages**
Quantitative EEG (qEEG) [31, 32]	**Detailed Analysis**: qEEG uses mathematical and statistical methods to analyse brain activity, providing a more detailed and objective assessment	**High Cost**: Conducting qEEG studies can be expensive and requires specialized equipment and expertise.
	Topographic Mapping: qEEG creates colour maps of brain activity, making it easier to identify abnormalities and specific patterns	**Artifacts and Noise**: qEEG data can be affected by artifacts and noise, which can complicate interpretation.
	Comparison and Monitoring: Allows easy comparison of brain activity between different individuals and tracking changes over time.	**Limited Accessibility**: Not all medical centres have the necessary equipment and resources to conduct qEEG studies.
	Clinical Applications: qEEG is useful for diagnosing and treating various neurological and psychiatric conditions, including ADHD, depression, and anxiety.	
	Neurofeedback: qEEG is a critical tool in neurofeedback therapy, where it is used to monitor and regulate brain activity in real-time.	
Combining fMRI and EEG [2,35]	**High Spatial and Temporal Resolution**: fMRI provides excellent spatial resolution, allowing detailed images of brain structures, while EEG offers high temporal resolution, capturing rapid changes in brain activity. Combining these technologies provides a comprehensive view of brain function	**High Cost and Complexity**: Conducting combined fMRI and EEG studies is expensive and requires specialized equipment and expertise, making it less accessible.
	Identification of Anomalies: The combination can better identify anomalies in brain activity that are characteristic of ADHD, improving diagnostic accuracy.	**Artifacts and Noise:** Combining the two technologies can introduce artifacts and noise into the data, complicating interpretation.
	Complex Analysis: Synchronizing fMRI and EEG data offers a fuller picture of brain function, helping to identify specific neural networks associated with ADHD.	**Artifacts and Noise:** Combining the two technologies can introduce artifacts and noise into the data, complicating interpretation.
	Identification of Anomalies: The combination can better identify anomalies in brain activity that are characteristic of ADHD, improving diagnostic accuracy.	**Artifacts and Noise**: Combining the two technologies can introduce artifacts and noise into the data, complicating interpretation.
		Limited Accessibility: Not all medical centres have the necessary equipment and resources to conduct such combined studies.

EEG research using Low Resolution Electromagnetic Tomography (LORETA) represents an advanced and innovative EEG analysis technique [9, 12, 13, 14] that enables three-dimensional localization of brain activity (Figure 2). This technique allows for the analysis of brain activity not only on the surface but also in deeper brain structures. LORETA estimates the distribution of electrical activity in these deeper brain regions, providing more precise spatial resolution [9, 14]. The method is particularly useful for tracking fluctuations in brain activity in both scientific research and clinical practice, including studies related to ADHD.

The method is non-invasive and painless, but it requires specialized equipment and expertise. Additionally, LORETA is a cost-effective method, making it suitable for routine diagnostic use.

Figure 2 Three-dimensional localization of brain activity

3.2. How LORETA Works [9, 13, 14, 24, 30]

EEG Data Acquisition:

- Standard EEG recordings are taken using electrodes placed on the scalp.
- The electrical activity is measured over time, capturing brain waves in different frequency bands (e.g., delta, theta, alpha, beta, gamma).

Inverse Problem Solution:

- The "inverse problem" in EEG refers to the challenge of determining the sources of electrical activity inside the brain based on measurements taken at the scalp.
- LORETA solves this problem by assuming that the smoothest distribution of electrical activity is the most plausible. It uses mathematical algorithms to estimate the current density at each voxel (3D pixel) in the brain.

Spatial Localization:

- LORETA divides the brain into thousands of voxels and calculates the electrical activity in each voxel.
- The result is a 3D map of brain activity, which can be overlaid on a structural MRI image for anatomical reference.

Frequency Band Analysis:

- LORETA can analyse activity in specific frequency bands, which is particularly relevant for ADHD, as the disorder is often associated with abnormal theta and beta activity.

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3.3. Use of LORETA in ADHD Diagnosis and Research [9, 13, 14, 24, 25, 29, 30]

Identifying Abnormal Brain Activity: LORETA can localize regions of the brain that show abnormal activity in individuals with ADHD. For example:

- Increased theta activity in the frontal and midline regions.
- Decreased beta activity in the prefrontal cortex.
- These patterns are thought to reflect deficits in attention and executive functioning.

Subtype Differentiation: LORETA can help differentiate between ADHD subtypes (e.g., inattentive vs. hyperactive-impulsive) by identifying distinct patterns of brain activity in different regions.

Functional Connectivity: LORETA can assess connectivity between brain regions, which is often disrupted in ADHD. For example:

- Reduced connectivity in the default mode network (DMN), which is associated with inattention.
- Altered connectivity in the frontal-parietal network, which is involved in executive control.

Treatment Monitoring: LORETA can be used to monitor changes in brain activity following interventions, such as:

- Medication (e.g., stimulants like methylphenidate).
- Neurofeedback training.
- Behavioural therapies.

Table 4 Strengths and Limitations of LORETA

Strengths of LORETA [13,14]	**Limitations of LORETA** [13,14]
High Spatial Resolution: Unlike traditional EEG, LORETA provides a 3D map of brain activity, allowing for more precise localization of abnormalities.	**Low Temporal Resolution**: While LORETA improves spatial resolution, it does not enhance the temporal resolution of EEG. It is less effective for studying rapid changes in brain activity.
Non-Invasive: LORETA uses standard EEG data, making it a safe and non-invasive method.	**Mathematical Assumptions**: LORETA relies on assumptions about the smoothness of electrical activity, which may not always hold true.
Objective and Quantifiable: LORETA provides quantitative data that can be statistically analysed, reducing subjectivity in diagnosis.	**Dependence on EEG Quality**: The accuracy of LORETA depends on the quality of the EEG data. Artifacts (e.g., from muscle movement or eye blinks) can affect results.

Research Utility: LORETA is widely used in neuroscience research to study brain networks and their dysfunction in ADHD and other disorders.	**Complexity:** LORETA requires specialized software and expertise to perform and interpret the analysis, limiting its use in routine clinical practice.

3.4. LORETA Findings in ADHD [9, 13, 14]

Increased Theta Activity: Studies using LORETA have found increased theta activity in the anterior cingulate cortex (ACC) and medial prefrontal cortex (mPFC) in individuals with ADHD, which may reflect difficulties with attention and impulse control.

Decreased Beta Activity: Reduced beta activity in the prefrontal cortex has been associated with ADHD, particularly in the inattentive subtype.

Altered Connectivity: LORETA has revealed disrupted connectivity in the default mode network (DMN) and frontal-parietal networks, which are critical for attention and executive functioning.

Treatment Effects: LORETA has been used to show normalization of brain activity following stimulant medication or neurofeedback training, providing insights into the mechanisms of these treatments.

Table 5 Comparison between LORETA and Other EEG Methods

Feature	LORETA	Standard EEG	qEEG	ERPs
Spatial Resolution	High (3D localization)	Low (scalp-level only)	Moderate (scalp-level)	Low (scalp-level)
Temporal Resolution	Low	High	High	High
Use in ADHD	Localizes abnormal activity	Identifies gross patterns	Quantifies frequency bands	Assesses cognitive processes
Clinical Utility	Research-focused	Routine clinical use	Emerging clinical use	Research and clinical use

3.5. Emerging Trends and Applications [10, 12, 13, 19, 25, 30]

- Integration with high-density EEG: Improves spatial resolution and source localization.

- Multimodal imaging: Combining LORETA with fMRI or MEG for comprehensive brain mapping.

- Pharmacological monitoring: Used to assess the effects of treatments like KB220z on brain function in adults with ADHD 2.

- Machine learning: Leveraging LORETA-derived features to develop diagnostic algorithms.

- Developmental and gender-specific studies: Exploring how ADHD manifests differently across age and sex groups.

4. Conclusion

LORETA is a powerful tool for studying ADHD, offering insights into the spatial distribution of abnormal brain activity and connectivity. While it is primarily used in research settings, its ability to localize brain activity with high precision makes it a valuable method for understanding the neural underpinnings of ADHD and monitoring treatment effects. However, its complexity and reliance on high-quality EEG data limit its use in routine clinical practice. As technology advances, LORETA may become more accessible and integrated into diagnostic and therapeutic protocols for ADHD.

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