

Methodological and Application Progress of EEG for Early Screening and Digital Intervention in Alzheimer's Disease

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Abstract. Alzheimer's disease (AD), which has a slow, insidious onset and minimal success in treatment, stresses the significance of early screening and intervention. The paper discusses the latest developments on how electroencephalography (EEG) can be used at an early stage to screen AD and digital intervention solutions. It provides an overview of some fundamental approaches like spectral analysis, functional connectivity analysis, and topographical analysis of a network of the brain. Moreover, it analyses the translational uses created by the application of those approaches in combination with multimodal features and machine learning, especially in the categorisation of risks and digital therapeutics. To summarise, EEG has many benefits, including being non-invasive, cheap, and capable of repeated measurements. Its general acceptance will, however, depend upon creating standard methods, validating using big samples, and integrating multimodal methods, including integrating EEG data with other imaging modalities and clinical evaluations to improve the accuracy of diagnosis. In the future, given that digital health care and intelligent analytics technology are still developing, it is expected that EEG will also be playing a more crucial part in the initial screening, intervention and long-term care of AD.

Keywords: Alzheimer's disease, electroencephalography, brain-computer interface, early screening.

1. Introduction

It should be noted that Alzheimer's disease aetiology (AD) is a neurodegenerative disorder primarily associated with gradual cognitive impairment over time. Since it has an intricate aetiology, a gradual development and gradual onset, Alzheimer's has turned into one of the pressing issues of public health in ageing populations. It has been shown that in the case of AD, the pathological processes could start ten to twenty years prior to the appearance of obvious clinical symptoms [1].

The contemporary clinical approach to diagnosing AD involves medical history, clinical signs/symptoms, cognitive assessment, and structural neuroimaging [2]. As a result, numerous patients are found out after manifesting considerable deficits of memory or behaviour and thus missing the opportunity to receive timely intervention at such a stage.

Although current asymptomatic drug therapies may provide some symptom reduction or delay progression, they are still incapable of curing the disease process [3], which highlights the necessity of developing better approaches to therapy that can target the causative factors of Alzheimer's. Hence, there is a priority given to developing affordable, repeatable, and sustainable means of early detection and longitudinal tracking when it comes to preventing and managing AD.

Electroencephalography (EEG) is a non-invasive, inexpensive neuroelectro physiological method that has a high speed in time and adequate repeatability. EEG can directly and easily represent brain function activity, allowing it to be especially appropriate to use in the dynamic assessment of patients with AD and MCI.

The MCI (mild cognitive impairment) has been generally defined as a critical prodromal phase of AD [3].

There are frequent variations in resting-state EEG in those with AD or MCI, including slowing of the rhythm among other changes in the functional connection and decreased overall system complexity. This process has been integrated by means of machine learning algorithms and it will soon become a platform of quantifiable neurobiological markers. It offers a neurophysiological foundation to be used in early screening as well as in digital intervention applications.

In the context that is being presented here, this paper will be concerned with recent developments in using brain-computer interfaces (BCIs), the use of EEG technology, and how they are used in early screenings as well as digital interventions related to Alzheimer's disease (AD). The goal of this study is to give a guideline of AD risk classification, personalised cognitive training, and remote home monitoring and at the same time offer fresh views about translating BCI applications into neurodegenerative diseases.

2. Methodological Progress of EEG for Early Screening and Digital Intervention in AD

2.1. Spectral Feature Analysis

The use of spectral analysis is among the basic and popular ways to assess AD at an early stage based on EEG data. Numerous pieces of evidence derived from resting-state EEG research show that there is deceleration of characteristic neural rhythms in AD patients, which can be seen as the simultaneous increase of δ/θ band and decrease of α band activity. Similar trends have been reported in MCI populations [4]. These changes indicate a shift of brain function from a more efficient and integrated state into inefficiency. Accordingly, it may be suggested that these are significant markers of electrophysiology indicating early-stage cerebral impairment in AD.

The methodological aspects of fast Fourier transform (FFT) and power spectral density (PSD) analysis include the use of these methods in order to obtain measures like the total or relative power at a given frequency band, as well as maximum frequency. The spectral analysis can be performed simply compared to more complicated models and is simpler to comprehend. Furthermore, the non-invasive, affordable and repetitive nature of the EEG allows its use in longitudinal monitoring. However, clinical translation of the EEG can still be affected due to the inconsistencies in data acquisition and processing [4, 5].

2.2. Functional Connectivity Analysis

The change in the power in one brain region alone or even within one frequency band is not enough to explain the nature of brain dysfunction associated with AD. Therefore, scientific attention has gradually moved towards examining how different brain centres interact with each other. The main Purpose of a functional connectivity analysis is evaluating the level of synchronisation between neuronal activity in various areas of the brain, which provides a model of network disconnection in relation to AD-related cognitive deterioration.

Traditional measures such as coherence are simple to implement, but they may generate spurious connections because of common-source effects such as volume conduction [6].

Hence, in order to reduce the likelihood of spurious connectivity bias, more recent studies have focused on applying phase-based synchronisation measures, including phase-locking value (PLV), phase lag index (PLI), and weighted phase lag index (wPLI). Data currently available indicates a generalised reduction in inter-regional coherence/synchrony in the α -frequency range, which is accompanied by increased synchrony in the δ and θ frequency bands [4, 7].

2.3. Graph-Theoretical Brain Network Analysis

The graph-theoretic approaches are used to expand the connectivity analysis through the representation of the human brain as an intricate system of interrelated nodes and edges. This model involves using measures like the clustering coefficient, average path length, global efficiency and small-worldness in characterising the complete brain topology [8]. Research indicates that brain networks associated with AD tend to move away towards a less efficient and more chaotic topology than the efficient small-world organisation. Similar but milder changes have also been reported in MCI, suggesting that network-topology alterations may already emerge before the onset of clinical dementia [9]. The graph-theoretical analysis is more concerned with the overall properties of AD as

a brain network disease based on spectral indices alone, making it possible to discuss the disease's development at a systems level.

2.4. Trend Toward Method Integration

From a methodological perspective, EEG applications in AD research have evolved from early single-feature spectral analysis to functional connectivity analysis and brain network topology analysis and are now moving toward multi-feature integration.

Table 1 summarizes principal EEG-based methods for early AD assessment. To summarize, EEG-based AD research is bifurcating into two key thrusts: (i) refining metric robustness (stability, reproducibility, bio-validity) and (ii) fusing multimodal features to enrich clinical inputs. In this context, EEG is evolving from a single detection tool into a comprehensive assessment platform, laying the methodological foundation for early screening and individualized intervention.

Table 1. Overview of major EEG-based methods for early AD assessment and their application characteristics

Method Category	Representative Metrics/ Techniques	Main Findings	Strengths	Limitations	Main Application Scenarios
Spectral feature analysis	PSD, relative power, peak frequency	AD/MCI often shows reduced α activity and increased θ/δ activity, indicating slowing of EEG rhythms	Mature methodology; simple computation; good interpretability	Limited ability to capture network-level abnormalities; insufficient specificity	Early screening, baseline assessment, longitudinal follow-up
Traditional functional connectivity analysis	Coherence, Pearson correlation, cross-correlation	Reflects changes in interregional synchronization and suggests impaired long-range information transfer in AD	Convenient for quantifying interregional coordination	Sensitive to volume conduction and may overestimate spurious connectivity	Initial assessment of brain functional connectivity
Phase synchronization analysis	PLI, wPLI, PLV	More sensitive to AD-related abnormalities in phase coupling; PLI/wPLI is relatively more stable	PLI/wPLI is more sensitive to non-zero phase lag and yields more reliable results	Affected by metric selection and parameter settings	Refined connectivity analysis, feature extraction
Brain network topology analysis	Clustering coefficient, characteristic path length, global efficiency, small-worldness	AD brain networks shift from efficient organization toward less efficient and more random topology, indicating impaired global integration	Characterizes network reorganization at the systems level	Model construction is relatively complex and requires high-quality data	Mechanistic studies, disease-stage assessment
Multi-feature fusion analysis	Spectrum + connectivity + graph theory + machine learning	Combining multidimensional features can improve classification and prediction performance	Strong integration capability; high translational potential	Depends on standardized pipelines and validation in large cohorts	Risk stratification, aided diagnosis, individualized intervention

3. Clinical Application of EEG for Early Screening and Digital Intervention in AD

The EEG rhythmic changes, inter-regional synchronization abnormalities, and network efficiency declines, extracted through the above methods, are now being further applied for risk identification, disease course assessment, and feedback-driven digital intervention. Consequently, EEG is progressively evolving from a "mechanistic research tool" into a "clinical application platform," marking a significant transformation in its use.

Figure 1 illustrates the closed-loop relationship between EEG early assessment and risk stratification (above lane) and digital intervention and feedback (below lane). Arrows indicate workflow direction, and the feedback loop denotes adaptive updates to training difficulty/parameters based on EEG outcome measures.

3.1. EEG-Based Early Screening and Risk Stratification for AD

The developments in machine learning combined with neural signal processing encourage the introduction of multiple modalities into classification systems. Such models are often built through support vector machines (SVM), random forests or deep learning architectures like convolutional neural networks (CNN) and long short-term memory (LSTM) networks, which significantly improve skill at distinguishing normal ageing versus MCI and AD.

The EEG model developed using multi-feature combination and artificial intelligence has been proven to be very accurate in helping the detection of the AD spectrum. The current trend indicates that some models, using EEG connectivity characteristics, multimodalities and machine learning, may reach an accuracy level of roughly 90% or even more with the task of MCI/AD recognition. Particularly, one work utilised resting-state EEG time-varying functional connectivity as a basis in creating a classifier, which had a value of 91.97% and 91.17% at cross-validation [10]. Separately, wearable EEG research for MCI screening demonstrated classification accuracy up to 95% [5]. Such results imply that it holds promise as a low-cost, reproducible, tool that may serve as a dynamic follow-up in early screening.

3.2. EEG-Driven Neurofeedback and Cognitive Training

The use of EEG in a digital intervention is expanding its purpose beyond just evaluation to real-time feedback and thus has developed as an example of monitoring, feedback, and adjustment closed-loop training process. The method comprises measuring online the level of attentional or working memory load or target frequency band activity and then changing the level of task difficulty or feedback strategy in response to achieve individualized dosing and the ability to adapt based on plasticity.

Representative studies have provided support for this concept. In a randomized double-blind-controlled trial, it was shown how neurofeedback using EEG improved the memory function of people who were suffering from MCI and results last up to one month [11]. Another review based on a meta-analysis of 21 EEG neurofeedback training studies, showed a slight yet statistically significant improvement of episodic memory performance. It indicates that EEG neurofeedback can be considered as a beneficial cognitive intervention [12].

The latest applications integrate EEG with VR in order to train skills like focus, executive control, and spatial orientation within settings more comparable to real-life experiences; they also track neurophysiological alterations. Thapa et al. demonstrated in a randomized clinical trial that the implementation of VR-based cognitive training three times weekly can enhance executive function and raise resting-state alpha power [13]. The finding is indicative of a measurable neurophysiological change. Other studies show that there are beneficial impacts of using VR interventions on chosen cognitive and functional outcomes with memory enhancement of a moderate effect size $d=0.48$ and a compliance rate of around 89 percent [14]. Despite an existence of considerable heterogeneity

regarding type of device, course length, and measure of results, this trend is nevertheless hopeful concerning clinical possibilities of EEG-virtual reality therapies.

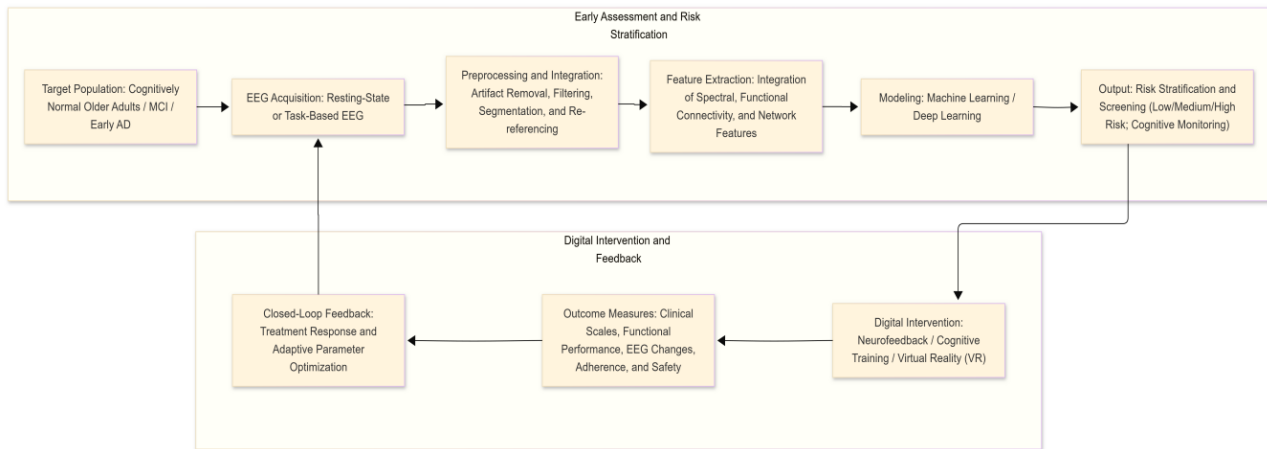


Fig. 1 Closed-loop framework for EEG-based early screening, risk stratification, and digital intervention in AD/MCI (conceptual diagram).

4. Limitations and Future Perspectives

While there is much excitement in the potential of using EEG to screen AD at an early stage and provide a digital intervention, it is difficult to implement practically. Main bottlenecks are focused on three main sectors.

There is not yet any standardisation on methodology. Acquisition conditions can vary with respect to different factors (open/closed eyes or task paradigm), electrode type, artefact removal, bandwidth, and connectivity measures, all leading to a marked influence on feature stability and cross-study consistency.

The second issue is the presence of restrictions in the nature of design and sample size. Small samples, single-centre setups, and population bias (age, education, and comorbidities) make it harder to generalise. Since AD develops slowly, its lack of longitudinal designs and external validation also limits the claims that can be made about risk prediction and treatment control.

Finally, there is a deficiency in moving between correlational results and mechanistic and causal ones. Volume conduction, common-source artefacts, and non-stationarity have been shown to affect network and connectivity measurements such as those used in Alzheimer's disease studies. More reliable connectivity measures, source-based analysis, and multimodal biomarker comparison should be considered to enhance biological understanding.

Further research ought to consider more attention on methodological standardisation, validation in large groups, and multimodality implementation. In parallel, it would be advisable to continue developing wearable EEG and adaptive BCI algorithms so that they could be used at home and allow the EEG to become a reliable indicator with high interpretability and clinical applicability. In general, there will only be real-world application of the EEG when scientific effectiveness equals practicality in everyday practice.

5. Conclusions

AD is characterized by an insidious beginning, gradual advancement, and challenges in early detection. Consequently, developing sensitive, convenient, reproducible ways to evaluate and intervene at an early stage will be highly valuable. The current paper has reviewed the methodological and clinical advances in the application of EEG in the early detection and digital intervention in AD. Existing studies suggest that spectral analysis, functional connectivity analysis, and brain network topology analysis can reveal AD-related brain dysfunction from various perspectives. Building upon

this, the combination of EEG and multi-feature fusion, machine learning, neurofeedback and VR-based digital solutions can further expand its role in mechanistic understanding into clinical practice.

On the whole, the EEG has a great possibility to play a role in early prevention and management of AD. The future work should focus on improving standardisation, carrying out comprehensive validation studies and developing research in multimodal integration.

Also important to mention are wearable EEG devices and adaptive BCI algorithms which have a great impact on improving clinical reliability and scalability. As the digital health system advances, it will be able to take a greater part in the screening, treatment, and long-term management of AD.

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