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PHASE SPACE RECONSTRUCTION FOR BRAIN STATE CLASSIFICATION BY EEG SIGNALS

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Abstract. *This thesis explores the classification of brain states based on EEG data, focusing on the distinction between relaxation and concentration. A classification approach using recurrence plot analysis, a method from chaos theory, is compared with traditional spectral analysis. The optimal phase space reconstruction parameters were determined: a delay equal 25 ms and an dimension of embedding space equal 4. These values align with spectral characteristics of the EEG signal, confirming their physiological relevance. The study suggests that these parameters can be used to develop differential equations describing chaotic brain activity. The findings are relevant for EEG analysis in portable devices, brain-computer interfaces, and cognitive training applications.*

Keywords. *EEG, phase space reconstruction, recurrence analysis, chaotic dynamics, brain state classification.*

Introduction. The development of portable electroencephalography (EEG) devices has increased interest in efficient brain state classification methods that can operate with limited computational resources. EEG-based classification is crucial for various applications, including brain-computer interfaces, cognitive training, and self-monitoring of mental states. This study focuses on distinguishing between two fundamental states—relaxation and concentration—by analyzing EEG signals. Additionally, the classification of open and closed eyes is considered, as eye closure is commonly associated with increased relaxation.

Traditional EEG analysis relies on spectral methods, which examine frequency components of brain activity. However, recent advances in nonlinear dynamics and chaos theory provide alternative approaches, such as recurrence plot analysis. Recurrence plots allow for the extraction of features that capture the complex temporal structure of EEG signals, potentially improving classification accuracy. This study compares recurrence-based classification with conventional spectral analysis to assess its effectiveness.

Methods and Data Processing. The study utilizes the *EEG Motor Movement/Imagery Dataset* [2] , which contains over 1,500 EEG recordings from 109 participants. Each recording lasts between one and two minutes, capturing brain activity during various motor and imagery tasks. The data was collected using a 64-channel EEG system at a sampling rate of 160 Hz. For analysis, recordings corresponding to the open- and closed-eye conditions were selected, as they provide a clear contrast between relaxation and concentration states.

To improve signal quality, preprocessing was performed to remove noise. Low-frequency components below 2 Hz, which may reflect head movements and blinking, were eliminated. Additionally, 50/60 Hz powerline interference and high-frequency muscle artifacts above 50 Hz were filtered out. A Short-Time Fourier Transform (STFT) with a Hann window of 1-second segments was used for noise suppression. The signals were then normalized using Z-score normalization with 1-second overlapping windows to ensure stability and comparability across recordings.

Phase Space Reconstruction and Recurrence Analysis. Phase space reconstruction is a key method in nonlinear time series analysis, allowing the extraction of hidden dynamic structures from EEG signals. It requires two parameters: the time delay τ and the dimension of the embedding space m . The time delay was determined using the average mutual information (AMI) method, which identifies an optimal delay that preserves signal dependencies while reducing redundancy [3]. The dimension of the embedding space was estimated using the false nearest neighbors (FNN) algorithm, which ensures that the reconstructed phase space maintains the original system's geometry without artificial distortions.

Experimental results revealed that the optimal parameters for EEG signals in the closed-eye state were $tau = \mathbf{4}$ samples, corresponding to 25 ms (4 / 160 Hz = 0.025 s), and $m = \mathbf{4}$. Figure 1 shows the computed values of τ and m for all recordings. These values were consistent across different participants and aligned with the spectral characteristics of EEG signals, where a dominant frequency of 10 Hz was observed. Since 10 Hz corresponds to a 100 ms period, the selected delay represents one-quarter of a full oscillatory cycle, ensuring an optimal reconstruction of the system's dynamics.

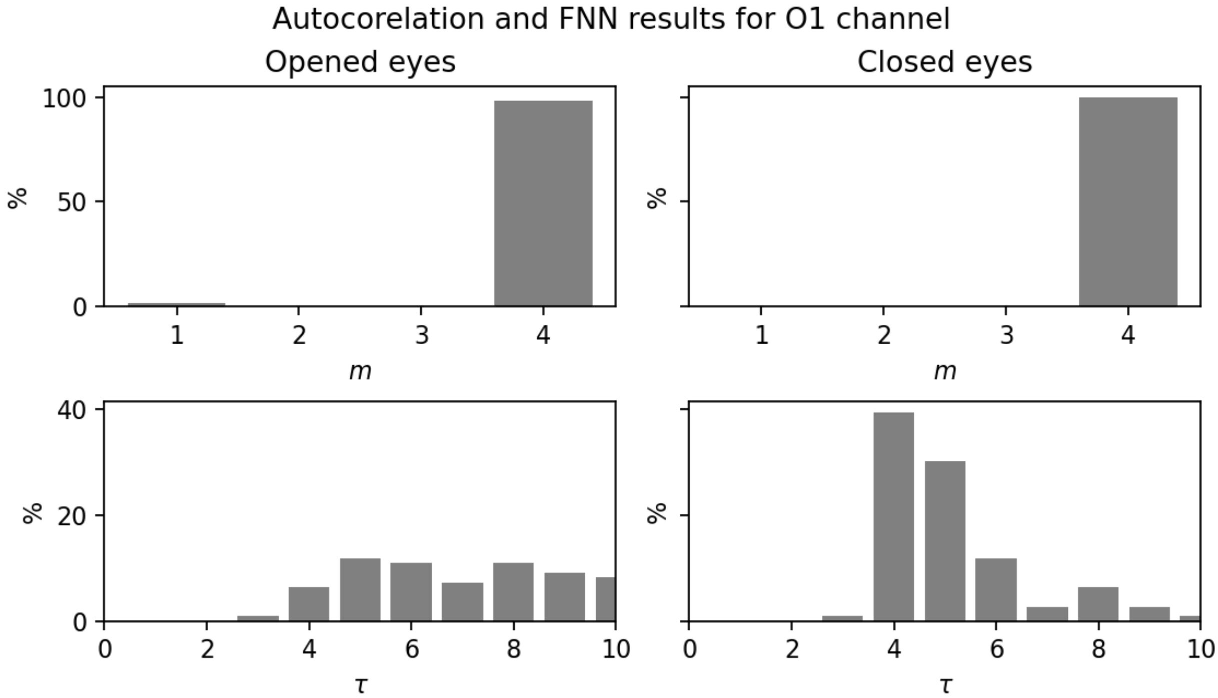

Figure 1 - Calculated τ and m for dataset recording

Conclusion. The findings confirm that EEG signals exhibit low-dimensional chaotic behavior, which can be effectively analyzed using phase space reconstruction and recurrence plots. The determined parameters ($\tau = 25$ ms, $m = 4$) align with the physiological characteristics of EEG rhythms, reinforcing their validity. These parameters provide a foundation for constructing mathematical models of brain activity based on differential equations.

Future work will focus on formulating a system of differential equations that describes the chaotic dynamics of EEG signals. Studying the attractors of such a system using the methods proposed in [1] may provide additional insights into brain states associated with relaxation and concentration. The results of this study contribute to the development of more accurate and computationally efficient EEG analysis methods for portable brain-computer interface applications.

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ВІДНОВЛЕННЯ ФАЗОВОГО ПРОСТОРУ ДЛЯ КЛАСИФІКАЦІЇ СТАНІВ МОЗКУ ЗА СИГНАЛАМИ ЕЕГ

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Анотація. *Ця робота досліджує класифікацію станів мозку на основі даних ЕЕГ, зосереджуючись на розмежуванні станів розслаблення та концентрації. Метод класифікації, заснований на аналізі рекурентних діаграм, що є підходом теорії хаосу, порівнюється з традиційним спектральним аналізом. Визначені оптимальні параметри відновлення фазового простору: затримка 25 мс і розмірність простору вкладення 4. Ці значення узгоджуються зі спектральними характеристиками сигналу ЕЕГ, що підтверджує їхню фізіологічну обґрунтованість. Дослідження показує, що ці параметри можуть бути використані для розробки диференціальних рівнянь, які описують хаотичну активність мозку. Отримані результати є актуальними для аналізу ЕЕГ у портативних пристроях, розробки інтерфейсів "мозок-комп'ютер" та когнітивного тренування.*

Ключові слова: *ЕЕГ, відновлення фазового простору, рекурентний аналіз, хаотична динаміка, класифікація станів мозку.*