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SUPERIOR CLASSIFICATION OF EEG STATES USING RECURRENCE QUANTIFICATION ANALYSIS

Panasenko Y. S [1]., Belozyorov V.[2]

[1] *PhD student, Department of Computer Technologies*

[2] *Doctor of Physical and Mathematical Sciences,* [2] *Professor*

[1,2] *Oles Honchar Dnipro National University, Ukraine*

Abstract. *This study investigates the classification of brain states using electroencephalography (EEG) data, comparing recurrence quantification analysis (RQA) with traditional spectral analysis. The goal is to distinguish between eyes-open and eyes-closed states using EEG data. Experimental results demonstrate that RQA provides superior classification accuracy, particularly at the O1 electrode, where accuracy improved from 86% to 95%. The study also identifies optimal phase space reconstruction parameters and the most informative recurrence features for classification. RQA captures nonlinear dynamics of brain activity more effectively than frequency-based spectral methods. The findings support the use of RQA for improving classification in portable EEG systems. This enables more accurate analysis in real-time applications such as cognitive training and brain-computer interfaces.*

Keywords: *EEG classification, recurrence quantification analysis, spectral analysis, brain states, phase space reconstruction.*

Introduction. The increasing use of portable EEG devices necessitates efficient algorithms for brain activity analysis with limited technical resources. This study investigates the classification of brain states based on EEG data, focusing on distinguishing between relaxation and concentration through the classification of open and closed eyes. The research applies recurrence quantification analysis (RQA) [1], a method derived from chaos theory, and compares its performance to spectral analysis. Experimental results indicate that RQA provides superior classification accuracy, particularly at the O1 electrode, where classification accuracy improved from 86% to 95%. Additionally, key parameters influencing classification were identified, optimizing phase space reconstruction and enhancing classification reliability.

Problem Statement. Classifying brain states using EEG data is crucial for applications in self-monitoring, cognitive training, and brain-computer interfaces. The ability to determine whether eyes are open or closed provides insight into relaxation mechanisms and cognitive processes. The growing market of low-cost portable EEG devices has created demand for effective algorithms that function with limited electrodes and lower-quality signals. Traditional spectral analysis methods rely on detecting characteristic brain rhythms, but alternative approaches like RQA may provide higher accuracy by capturing nonlinear dynamical properties of the brain's activity.

Research Methods. The study used the EEG Motor Movement/Imagery Dataset [2], which includes over 1,500 EEG recordings from 109 participants. EEG signals were recorded using a 64-channel system while subjects performed various motor and imagery tasks. The preprocessing stage involved filtering low-frequency noise (<2 Hz) related to movements and blinking, eliminating 50/60 Hz interference, and removing high-frequency noise (>50 Hz) from muscle activity. Z-score normalization was applied with 1-second segments, ensuring signal continuity through Hann window merging.

Recurrence plots were generated using the PyRQA module [3], leveraging OpenCL technology to accelerate calculations through GPU parallelization. RQA parameters were extracted to quantify the recurrence structure of EEG signals, enabling classification of brain states. Spectral analysis was used as a baseline, focusing on traditional power spectral density estimation of EEG rhythms.

Experimental Results. Analysis of recurrence plots revealed distinct patterns between eyes-open and eyes-closed states. The eyes-open state exhibited chaotic and dispersed recurrence structures, whereas the eyes-closed state showed long diagonal lines, indicating periodicity (fig. 1). Spectral analysis confirmed a dominant frequency of 10 Hz in the eyes-closed state, consistent with the well-known alpha rhythm.

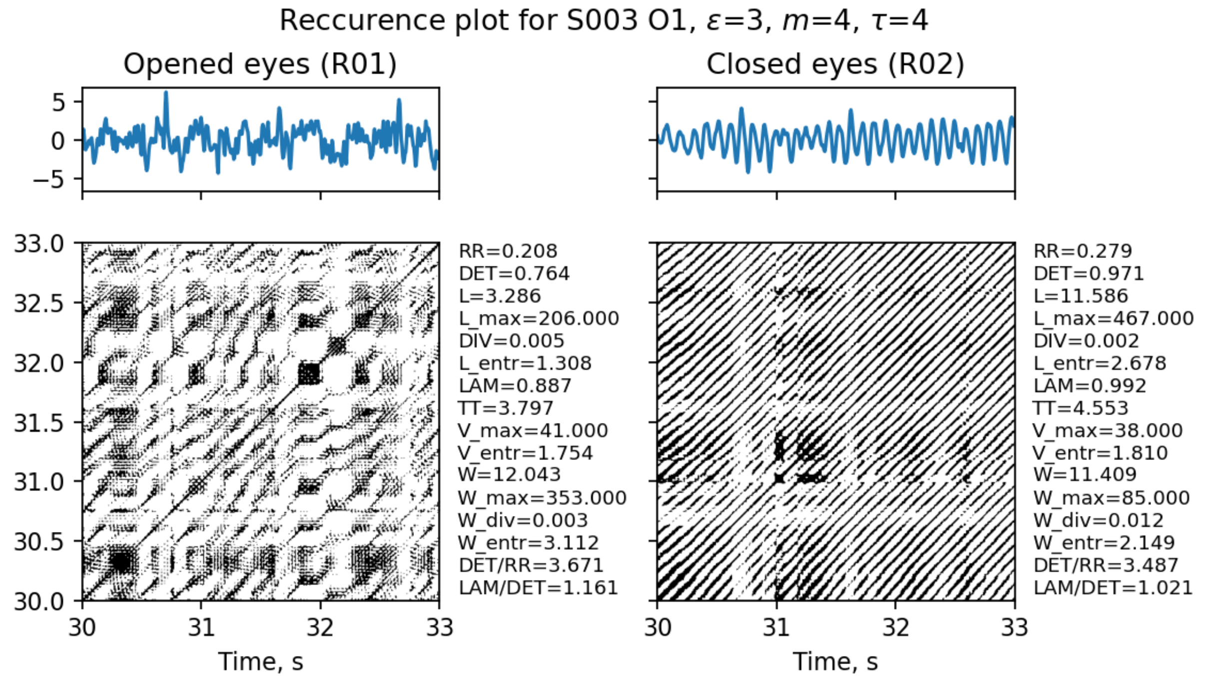

Figure 1 - Recurrence plot

Simple classification using single RQA parameters identified determinism (DET), entropy of vertical lines (V_entr), the average length of white vertical lines (W), and longest white vertical line divergence (W_div) as the most informative features for distinguishing eye states. Further feature importance analysis using the SHAP module for SVM classification demonstrated that the inverse of the longest white vertical line (W_div), entropy of white vertical lines (W_entr), average diagonal line length (L), longest white vertical line (W_max), longest vertical line in the plot (V_max), and laminarity (LAM) were the most significant parameters.

Comparison with Spectral Analysis. RQA-based classification consistently outperformed spectral analysis, particularly at the O1 electrode. The accuracy of spectral analysis in classifying eye states reached 86%, while RQA-based classification improved accuracy to 95%. This demonstrates the advantage of chaos theory-based methods in capturing the complexity of quasi-periodic brain signals. The improved accuracy is attributed to RQA's ability to quantify recurrence patterns that reflect the underlying dynamical structure of EEG signals, whereas spectral analysis is limited to frequency-based representations.

Optimal Parameters for Phase Space Reconstruction. Determining optimal parameters for phase space reconstruction is crucial for accurate classification. The study identified a delay of 25 ms and an embedding space dimension of 4 as the most effective settings. These values align with the spectral characteristics of the EEG signal, ensuring that the recurrence plot captures meaningful temporal dynamics.

Key Features for Classification. Two approaches were used to identify the most significant RQA features for classification. In a simple classifier using optimal threshold search, determinism (DET), entropy of vertical lines (V_entr), average length of white vertical lines (W), and longest white vertical line divergence (W_div) were found to be the most influential. Feature importance analysis using SVM classification further confirmed that the inverse of the longest white vertical line (W_div), entropy of white vertical lines (W_entr), average diagonal line length (L), longest white vertical line (W_max), longest vertical line in the plot (V_max), and laminarity (LAM) were crucial for accurate classification. These parameters highlight the importance of structural patterns in recurrence plots for differentiating between brain states.

Conclusion. The study demonstrates that RQA provides superior classification accuracy compared to spectral analysis in distinguishing eye states based on EEG data. The classification accuracy for the O1 electrode improved from 86% with spectral analysis to 95% with RQA. This confirms that recurrence-based methods offer a more effective approach for analyzing quasi-periodic brain signals. Additionally, the study identified key RQA parameters that significantly influence classification, optimizing phase space reconstruction for improved accuracy. These findings contribute to the development of efficient EEG analysis algorithms for portable devices, enhancing applications in cognitive training and brain-computer interfaces.

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ПОКРАЩЕНА КЛАСИФІКАЦІЯ СТАНІВ ЕЕГ ЗА ДОПОМОГОЮ РЕКУРРЕНТНОГО КІЛЬКІСНОГО АНАЛІЗУ

Панасенко Єгор, Білозьоров Василь

Анотація. *У цьому дослідженні розглядається класифікація станів мозку за даними електроенцефалографії (ЕЕГ) шляхом порівняння кількісного аналізу рекурентних діаграм (RQA) із традиційним спектральним аналізом. Метою є розпізнавання станів із відкритими та закритими очима за допомогою ЕЕГ-даних. Експериментальні результати показують, що метод RQA забезпечує вищу точність класифікації, зокрема для електрода O1, де точність зросла з 86% до 95%. У дослідженні також визначені оптимальні параметри реконструкції фазового простору та найбільш інформативні рекурентні характеристики для класифікації. RQA ефективніше захоплює нелінійну динаміку мозкової активності порівняно зі спектральними методами, що базуються на частотному аналізі. Отримані результати підтверджують доцільність використання RQA для підвищення точності класифікації в портативних ЕЕГ-системах. Це дозволяє проводити більш точний аналіз у реальному часі для застосувань у когнітивному тренуванні та інтерфейсах «мозок-комп'ютер».*

Ключові слова: *класифікація ЕЕГ, кількісний аналіз рекурентних діаграм, спектральний аналіз, стани мозку, реконструкція фазового простору.*