Nonlinear Neural Dynamics of Language Processing: A Recurrence Quantification Analysis of EEG in Dyslexia

Ignacio Rodríguez-Rodríguez[1⋆] **J. Ignacio Mateo-Trujillo**[1]
Marco A. Formoso[1] **Nicolás J. Gallego-Molina**[1] **Andrés Ortiz**[1]
Juan Luis Luque[2]

[1] Communications Engineering Department,
University of Málaga 29004 Málaga, Spain
[2] Department of Developmental and Educational Psychology,
University of Málaga 29004 Málaga, Spain

[1⋆]`ignacio.rodriguez@ic.uma.es`

Abstract: This study investigates the application of chaos theory and Recurrence Quantification Analysis (RQA) to EEG signals in skilled and dyslexic readers. By quantifying the nonlinear dynamics of brain activity, we aim to identify differences in the complexity and predictability of neural oscillations associated with language processing. Our results demonstrate that the recurrence plot of individuals with dyslexia exhibits higher recurrence rate, determinism, and entropy compared to control subjects. These findings suggest that brain activity around T7 (AUC 0.726), crucial for phonological processing in the dorsal route of language processing, is more repetitive, predictable, and less flexible in dyslexia. The observed patterns align with the Hickok and Poeppel's dual-route model of language processing and support the hypothesis that dyslexia involves disruptions in the neural mechanisms underlying phonological processing and auditory-motor integration.

keywords: Dyslexia; Machine Learning; Recurrence Quantification Analysis; Chaos Theory.

1 Introduction

Chaos theory has emerged as a powerful framework for understanding complex systems, including the intricate processes of the human brain. By applying the principles of nonlinear dynamics to electroencephalography (EEG) signals, researchers have gained valuable insights into the underlying neural processes that govern cognitive functions [1]. In the realm of language processing and reading disorders, chaos theory has proven particularly useful in unraveling the complexities of dyslexia, a neurodevelopmental disorder characterized by difficulties in accurate and fluent word recognition, poor spelling, and decoding abilities. By utilizing Recurrence Quantification Analysis (RQA) to quantify the nonlinear dynamics of brain activity, researchers have identified key differences in the complexity and predictability of neural oscillations between skilled and dyslexic readers. This approach aligns with findings by Giraud, Poeppel and Goswami, who identified synchronization deficits between sensory inputs and primary auditory areas, suggesting a broader impact on network connectivity and dynamics crucial for language processing. These insights, underscore the potential of RQA not only to detect these deficits but also to deepen our understanding of their implications for the neural mechanisms underlying dyslexia, thus highlighting the interplay between micro-level neuronal behavior and macro-level cognitive functions in reading impairments.

2 Results and discussion

2.1 Data acquisition and preprocessing

The University of Málaga's Leeduca Study Group conducted a study with 97 participants, including 67 skilled readers and 30 dyslexic readers, aged 88-100 months. They were exposed to a 4.8 Hz modulated auditory stimulus for 5 minutes to investigate synchronicity patterns. EEG signals were recorded using a Brainvision actiCHamp Plus with 32 active electrodes at 500 Hz. All participants were right-handed native Spanish speakers without hearing impairment and with normal or corrected-to-normal vision.

EEG signals were preprocessed using ICA and segment elimination to remove artifacts. Channels were referenced to Cz and filtered using a band-pass FIR filter to extract Theta frequency information, avoiding phase distortion. A two-way zero-phase lag band-pass FIR Least-Squares filter was employed, along with low-pass filtering (80 Hz threshold) and a 50 Hz notch filter.

2.2 Phase Space Reconstruction and Recurrence Quantification Analysis (RQA)

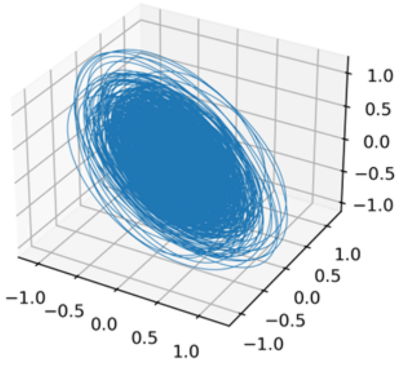

Figure 1: Phase Space reconstruction of EEG signal

The phase states of the different channels will be reconstructed using the Takens' theorem, after preprocessing and filtering the signals to the theta frequency band (4-8 Hz), coherent with the stimulus. Takens' theorem states that it is possible to reconstruct the phase space of a dynamical system from a single time series by creating a set of delayed copies of the original time series, forming a new higher-dimensional space (e.g., Figure 1). This reconstructed phase space preserves the essential dynamics of the original system, allowing for the analysis of its properties [3].

Once the phase space reconstructions have been performed, a Recurrence Quantification Analysis (RQA) will be conducted using Recurrence Plots (RP). RQA is a nonlinear data analysis method that quantifies the recurrence behavior of dynamical systems, providing insights into their complexity and predictability. Recurrence Plots are two-dimensional graphical representations of the recurrence matrix, which captures the times at which the system's trajectory returns to a previous state. From these RPs, several characteristics will be extracted to characterize the system's behavior:

- Recurrence Rate (RR): The percentage of recurrence points in the RP.
- Determinism (DET): The percentage of recurrence points forming diagonal lines.
- Divergence (DIV): The system's divergence or chaoticity.
- Laminarity (LAM): The percentage of recurrence points forming vertical lines, indicating the presence of laminar states or intermittency.
- Trapping Time (TT): The average time the system remains in a laminar state.
- Average Diagonal Line Length (L), Longest Diagonal Line (Lmax), Longest Vertical Line (Vmax), Longest White Vertical Line (WVLmax) and Average White Vertical Line Length (WVLM): The lengths of the lines in the RP, represent the time the system stays in a laminar / non-laminar state.

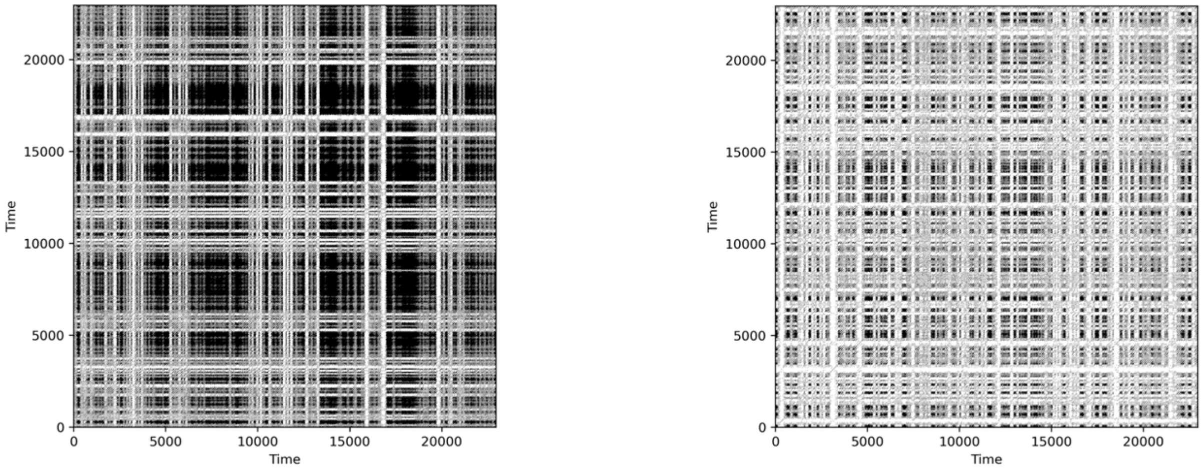

Figure 2: Recurrence Plot T7 electrode. Left, patient with dyslexia. Right, control group

- Entropy of Diagonal Lines (ENTR), Entropy of Vertical Lines (VENTR) and Entropy of White Vertical Lines (WVENTR): The entropy of the lines length distribution, representing the average time the system remains in a non-laminar state.

These RQA measures will provide a characterization of the system's dynamics, enabling the identification of differences between skilled and dyslexic readers in their EEG signal complexity and predictability. In the context of RQA applied to EEG from the T7 electrode (Figure 2), it is coherent that the recurrence plot (RP) of an individual with dyslexia shows a higher recurrence rate (RR), determinism (DET), entropy of diagonal lines (ENT), entropy of vertical lines (ENTR_vert), and entropy of white lines (ENTR_white) compared to a control subject. These results suggest that brain activity in the area around T7, relevant for language processing, is more repetitive, predictable, and less flexible in dyslexia, but at the same time presents greater variability in the duration of recurrent states, laminar states, and in the transition times between states. This combination of increased recurrence and variability could reflect a less efficient, stable, and adaptable brain dynamics for language processing in dyslexia. Visually, these patterns would manifest in the RP of an individual with dyslexia as a generally darker tone, with more ”squares” or recurrence blocks of variable sizes, and greater variability in the space between these blocks, compared to the RP of a control subject.

2.3 Machine Learning classification

The feature selection method employed in this study is the MRMR (Minimum Redundancy Maximum Relevance) algorithm, which combines the SULOV (Searching for Uncorrelated List of Variables) method and Recursive XGBoost. This approach ensures low redundancy and high relevance in the selected features. The results from the Gradient Boosting classifier indicate a maximum performance at electrode T7 with an AUC of 0.726 (Figure 4), alongside commendable performances above 0.7 at electrodes C3 and CP1 (Figure 3). Interpreting these findings within the framework of Hickok and Poeppel's dual-route model of language processing [2], particularly the dorsal route, offers insightful implications. The electrode T7, positioned over the superior temporal area of the left hemisphere, is integral to phonological processing and speech production, (dorsal route), and our result aligns with the hypothesis that dyslexia involves disruptions in the neural mechanisms underlying phonological processing and the integration of sensory speech inputs with motor outputs. Furthermore, the noteworthy performances at C3 and CP1, which are associated with motor functions and somatosensory feedback in the left hemisphere,