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Task-Based Functional Network and Topological Data Analysis of Event Related Potentials in Chronic Tinnitus

Jihoo Kim[1*], Seunghu Kim[2*], June Choi [3†], Sungkean Kim [1,2,4†]

[1]*Department of Interdisciplinary Robot Engineering Systems, Hanyang University, Ansan, Republic of Korea;*
[2]*Department of Applied Artificial Intelligence, Hanyang University, Ansan, Republic of Korea;*
[3]*Department of Otorhinolaryngology-Head & Neck Surgery, Ansan Hospital, Korea University College of Medicine, Republic of Korea;* [4]*Department of Human-Computer Interaction, Hanyang University, Ansan, Republic of Korea*

*P.O. Box 15588, Ansan, Gyeonggi-do, Korea. E-mail: kimsk@hanyang.ac.kr

Introduction: Brain network analysis, powered by advancements in network science and graph theory, provides crucial insights into the neural mechanisms underlying mental disorders and brain pathophysiology. In tinnitus, characterized by the perception of sound without an external source, investigating altered brain networks is essential to understanding its pathophysiology. Graph-theory-based functional networks enable comparisons of the small-world organization characteristic of healthy brain networks with the disrupted architecture observed in tinnitus patients. However, constructing brain networks is often hindered by the lack of standardized criteria for threshold selection, which impacts network topology and interpretation. Persistent homology, a topological data analysis (TDA) method, addresses this challenge by quantifying topological features across multiple scales without relying on arbitrary thresholds.

Material, Methods and Results: Seventy participants, including 38 tinnitus patients and 32 healthy controls (HCs), underwent audiological evaluations and EEG recordings during a cognitive auditory oddball task. P3 components were extracted from midline electrodes (Fz, Cz, and Pz). Neural sources were reconstructed using a minimum-norm imaging technique, and current source density was estimated within predefined functional brain regions. Functional connectivity was computed using wPLI to construct adjacency matrices. Persistent homology was derived from the adjacency matrices to compute Rips complexes, quantifying topological features such as connected components (β0) and higher-order loops (β1). Subsequently, persistent topological features are visualized using persistence diagrams. Persistent entropy, derived from these diagrams, quantifies the complexity of topological features by measuring the distribution of interval lengths. Higher entropy values indicate greater diversity and uniformity in the persistence of features, while lower values reflect dominance by a few significant features, suggesting simpler underlying structures. Bottleneck and Wasserstein distances are used to assess the stability and similarity of topological features, with Bottleneck capturing localized differences and Wasserstein reflecting global variations [1]. Using the random forest algorithm, we employed a filter-based feature selection method utilizing the Fisher score combined with leave-one-out cross-validation. With functional network features from each frequency band, the model achieved a maximum accuracy of 67.14% using 13 selected features. In contrast, incorporating non-linear topological features from each frequency band improved the model's performance to 77.14% with only 5 selected features, highlighting the efficiency and discriminative power of topological features in the classification task.

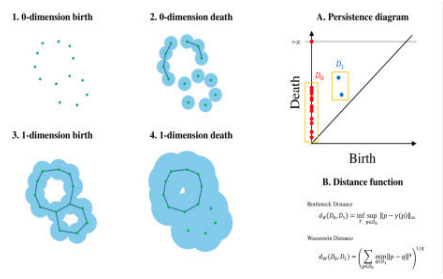

Figure 1: Comprehensive representation of a persistence homology, with A. persistence diagrams and B. the mathematical formulations for persistence distances.

Conclusion: The experimental results demonstrate that persistent homology effectively captures the non-linear and non-stationary topological features of brain networks, which are inadequately characterized by conventional linear graph-theoretical approaches. This study establishes a comprehensive framework for modeling complex brain dynamics in topological systems, offering deeper insights into their nonlinear behaviors and enabling more robust analyses and predictions. It particularly highlights the utility of identifying higher-order topological structures in nonlinear brain functional networks.

References:

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