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Neurophysiologically-guided optimization of neuronal avalanches for BCI

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Introduction: Despite promising clinical applications, motor imagery-based Brain-Computer Interfaces (BCIs) fail to detect the intent of 15-30% of users. This limitation partly stems from a focus on local oscillatory patterns, neglecting inter-regional interactions and treating aperiodic signals as noise. However, recent evidence demonstrated the coexistence of burst events and sustained oscillations, each providing unique insights. Neuronal avalanches, cascades of activity bursts propagating through neural networks, could address these gaps by elucidating mechanisms underlying BCI performance [1, 2]. Identifying optimal neuronal avalanche parameters is crucial to effectively integrate neuronal avalanches into BCI paradigms [2]. This study examines the correlation between BCI performance and factors such as the occurrence of regions of interest (ROIs), mean avalanche duration, and entropy rate of the brain signature, aiming to guide experimenters in selecting neurophysiologically relevant parameters of neuronal avalanches for BCI applications.

Materials, Methods and Results: We analysed EEG data from twenty healthy subjects who alternatively performed a right-hand motor-imagery (MI) task and remained at rest [3]. Using source-reconstructed signals, we estimated an Avalanche Transition Matrix (ATM), which mapped the probability of avalanche propagation across brain regions. To identify and selected task-related brain regions, we applied the PageRank algorithm to the ATMs (Markov Chains) and conducted t-tests and joint diagonalization between resting and MI states. Then, to identify which brain regions were the most often selected, we computed the associated occurrence. By correlating the mean avalanche duration and the ATM's entropy rate with BCI performance scores, we optimized key parameters. Additionally, by correlating the occurrence of significant ROIs with the BCI score, we validated the possibility of dataset reduction. Spearman's correlation was used to perform both correlations, and their significance was confirmed using a t-test (p-value < 0.05) with FDR correction. Our analysis shows significant positive correlations between ROIs occurrence selection and BCI scores, particularly in the alpha band (8-12 Hz) (Fig. 1). Higher selection rates indicate less variability across parameter conditions. Neurophysiologically relevant regions, such as the left precentral and paracentral areas (linked to the primary motor cortex), emerged as key. In the initial 2 seconds of the trials, before providing the feedback, regions typically involved in task preparation showed stronger significant correlations. In contrast, visual and executive regions dominated during the second phase of the trial when the feedback was provided (last 3 seconds). The positive correlation between mean avalanche duration and BCI score is highlighted during the MI task with more significant values compared to resting state, suggesting that longer avalanches reflect more coordinated and sustained neural activity, which enhances BCI performance. In contrast, during the resting state, while a similar trend is observed, the correlations rarely reach statistical significance, indicating a less robust relationship. Additionally, a negative significant correlation between entropy rate and BCI score was found during the MI task with the longest avalanches, whereas the resting state showed a positive correlation with shorter avalanches. These findings suggest that longer avalanches are linked to sustained neural activity and reduced variability, both of which are linked to an improved BCI performance. Notably, the MI task exhibits less variability compared to the rest.

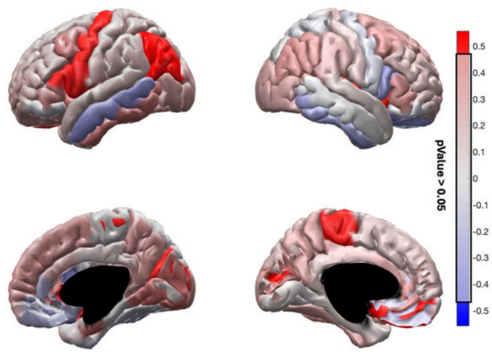

Figure 1: Correlation between ROIs occurrence selection and BCI-scores. During Task+Feedback Interval, Alpha-Band

Conclusion: This study provides a data driven approach to optimize the ATMs characterization and to ensure their neurophysiological relevance. Such a tool could be used during the calibration period to adapt the training program to the subjects' specificities. Taken together, our results offer guidelines to use the neuronal avalanches in the context of BCI experiments.

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