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# Ensemble of Riemannian classifiers for multimodal data: FUCONE approach for M/EEG data

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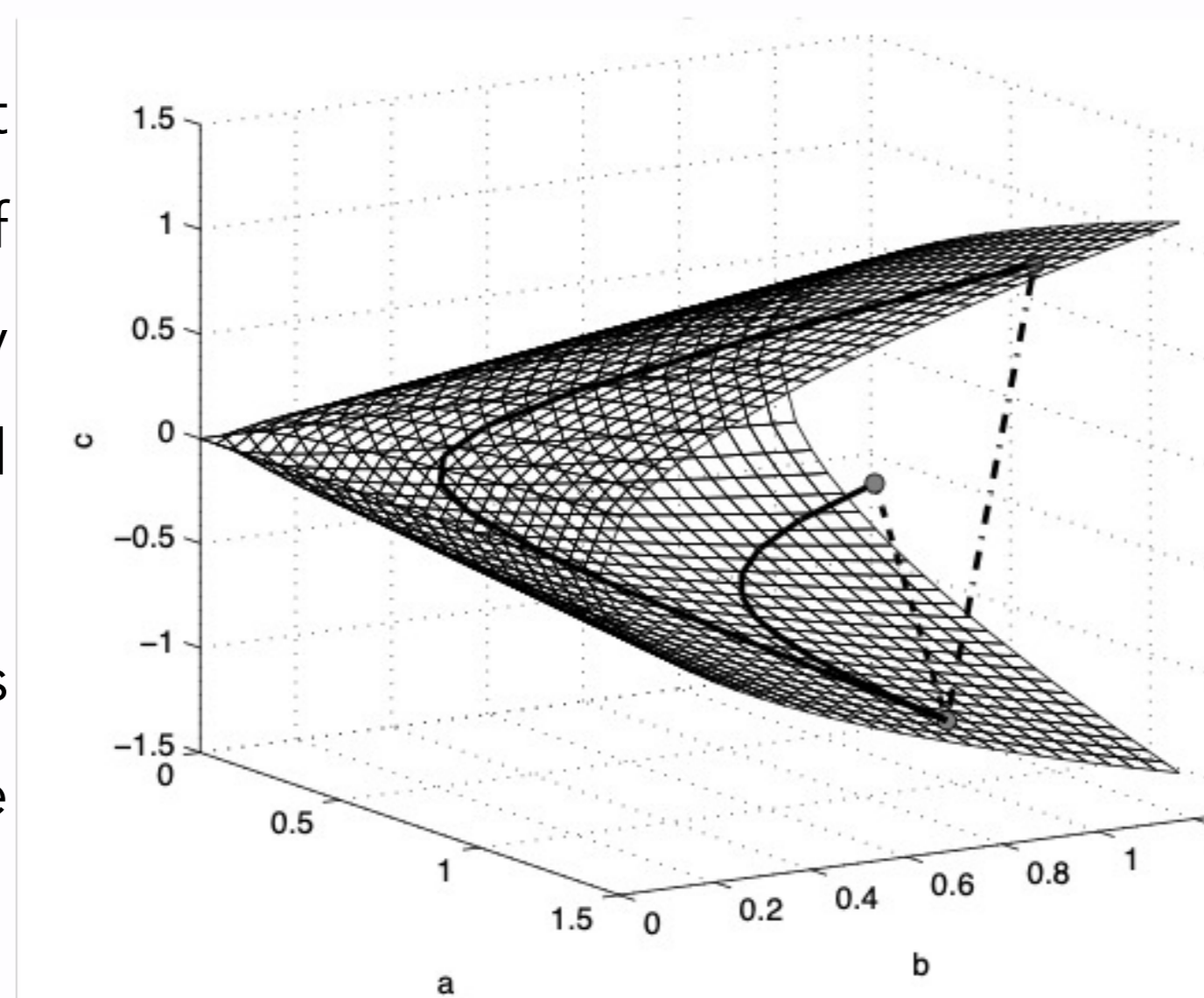
Controlling a brain-computer interface (BCI) requires time to achieve high performance. Despite its clinical applications, one of the main drawbacks is the high inter-subject variability that could be noticed for performance. This is sometimes referred in the literature as the « BCI inefficiency » phenomenon and affects its usability. Among the approaches adopted to tackle these issues are the search for neuromarkers that potentially capture better the neurophysiological mechanisms underlying the BCI performance and the optimization of the classification pipelines, that could be robust enough to be applied to any subject. In this work, we proposed an original approach that combines functional connectivity estimators, Riemannian geometry and ensemble learning to ensure a robust classification.

## Riemannian geometry

The diffusion of Riemannian geometry (RG) for motor imagery BCI has strongly increased in the past decade [3]. This method consists in the estimation of Symmetric Positive Definite (SPD) matrices, usually the covariance matrices among sensors, for each trial and in considering those in their natural space.

Here, to estimate the distance between two matrices A & B, we used the LogEuclidean distance via the Froebenius norm:

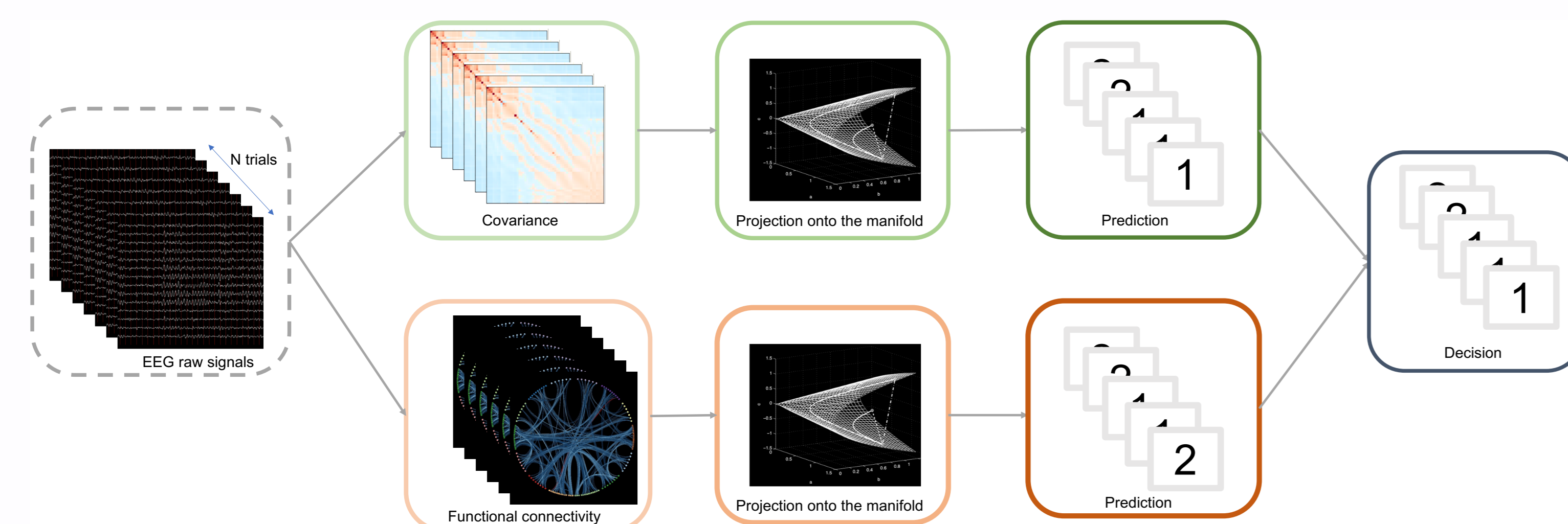
$$\delta_{LE}(A, B) = \|\log(A) - \log(B)\|_F$$



**Problem:** RG approaches in BCI rely only on covariance matrices without considering synchronous interactions between brain areas

**Hypothesis:** Combining functional connectivity estimators and Riemannian geometry will lead to an improvement of classification performance.

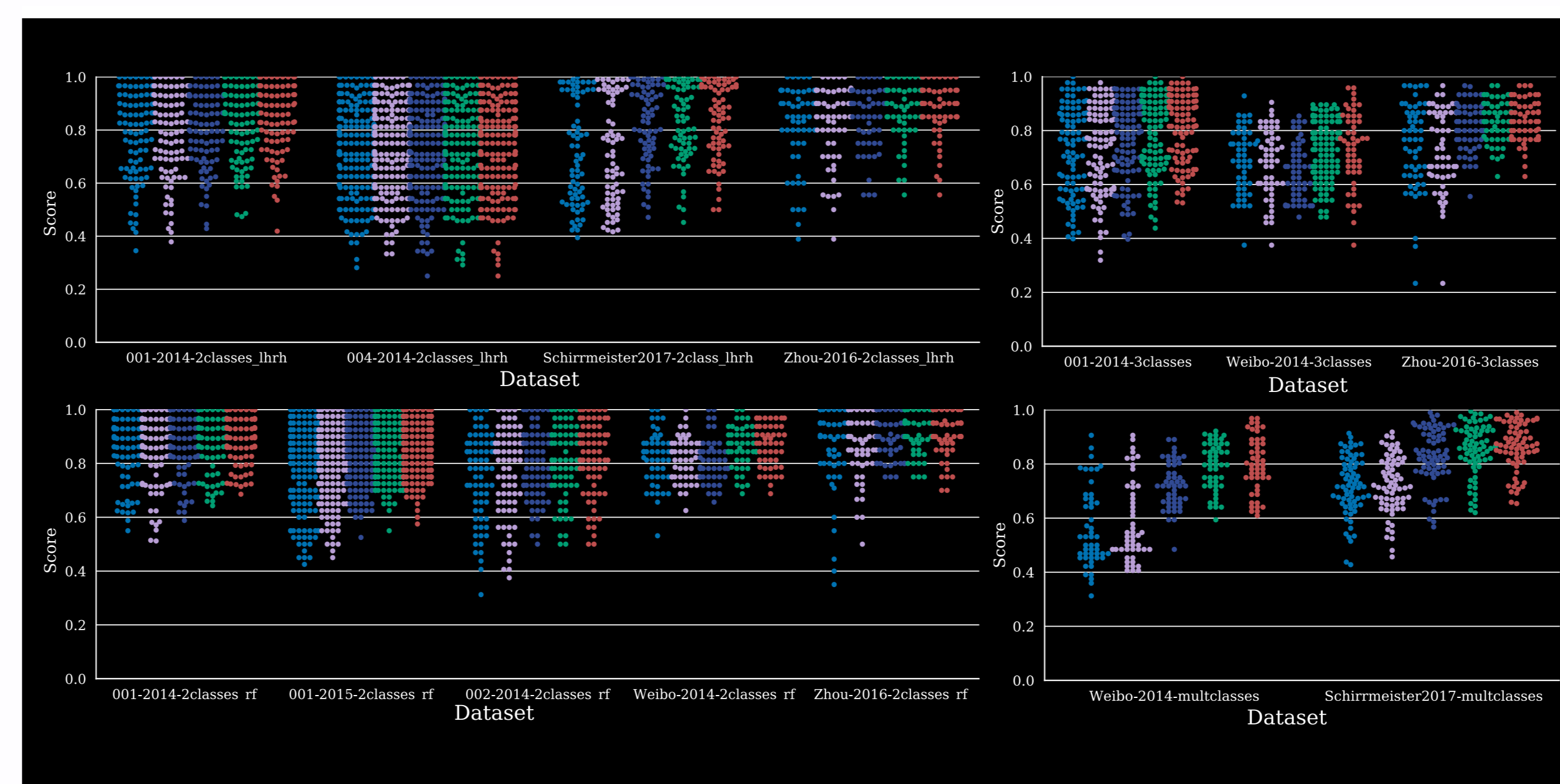
## FUCONE approach



Spatial covariance, instantaneous coherence and imaginary coherence are estimated from magneto/electroencephalographic (M/EEG) signals. A 1<sup>st</sup> level of classification was performed by elasticnet classifiers that yielded output decision probabilities to train a 2<sup>nd</sup> level classifier, an elasticnet classifier, that provided the final decision.

## Proof of concept & replicability analysis

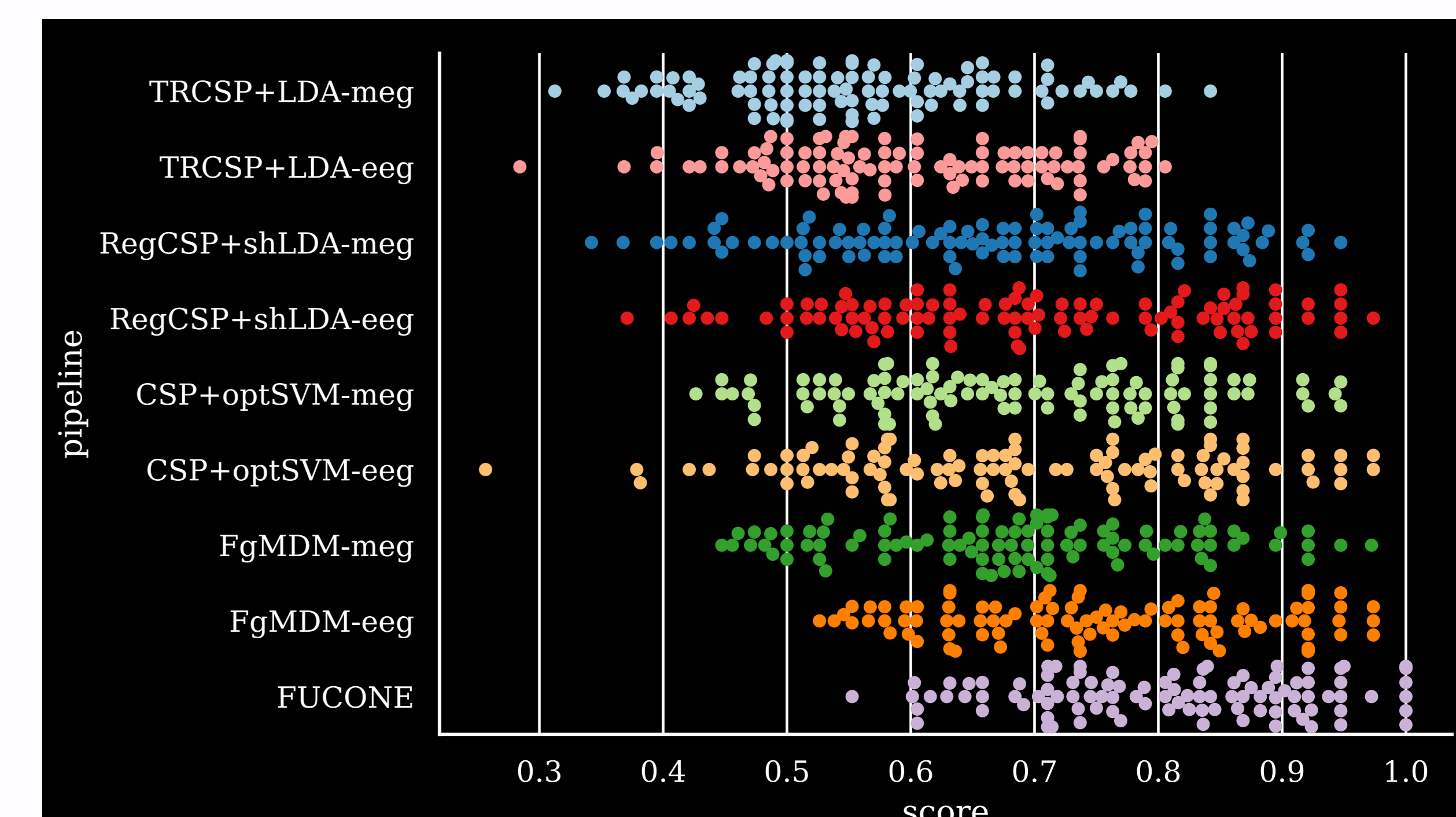
To assess the robustness and the replicability of our approach, we tested it through datasets, and motor imagery tasks. FUCONE performed significantly better than all state-of-the-art methods in a meta-analysis that aggregated results across datasets. In the case of the classification of 2 classes, for four over five datasets, FUCONE showed the best results in terms of average accuracy. The performance gain is mostly imputable to the increased the robustness of the ensemble classifier with respect to the inter- and intrasubject variability.



- Common Spatial Patterns + Shrinkage Linear Discriminant Analysis
- Geodesic filtering + Minimum Distance to Mean classification
- Common Spatial Patterns + Support Vector Machine
- Covariance + Elastic-Net
- FUCONE

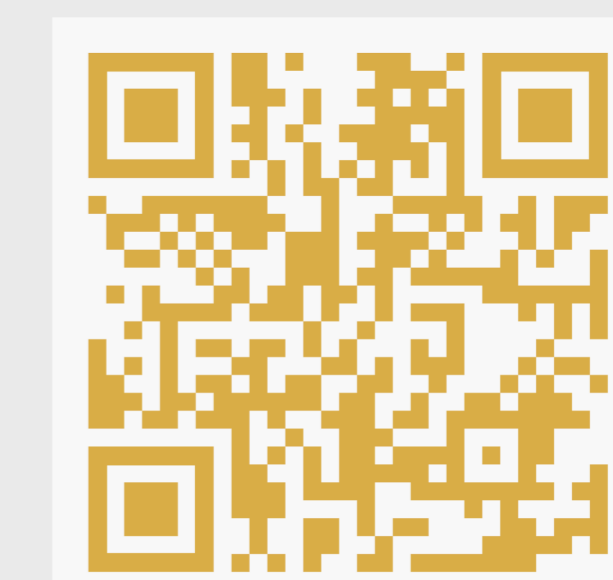
## Extension to multimodal data with M/EEG

We then studied to which extent the FUCONE approach can be relevant for bimodal fusion. To this end, we used a dataset consisting in a motor imagery-based BCI experiment where EEG and MEG data were simultaneously recorded. Data were preprocessed and source reconstructed. Our approach outperforms the state-of-the-art methods applied to each modality taken individually ( $p < 10^{-5}$ , Wilcoxon test)



MEG and EEG data convey complementary information that could be retrieved with the proper machine learning pipelines. This study describes an attempt to gather information from multiple modalities by combining classifiers based on Riemannian geometry. Future works will focus on neurophysiological interpretation of the feature selection.

Interested in this study?  
Scan the QR code to get access to the paper!



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