Multimodal fNIRS-EEG Sensor Fusion: Data-Driven Methods and Perspective for Naturalistic Brain Imaging

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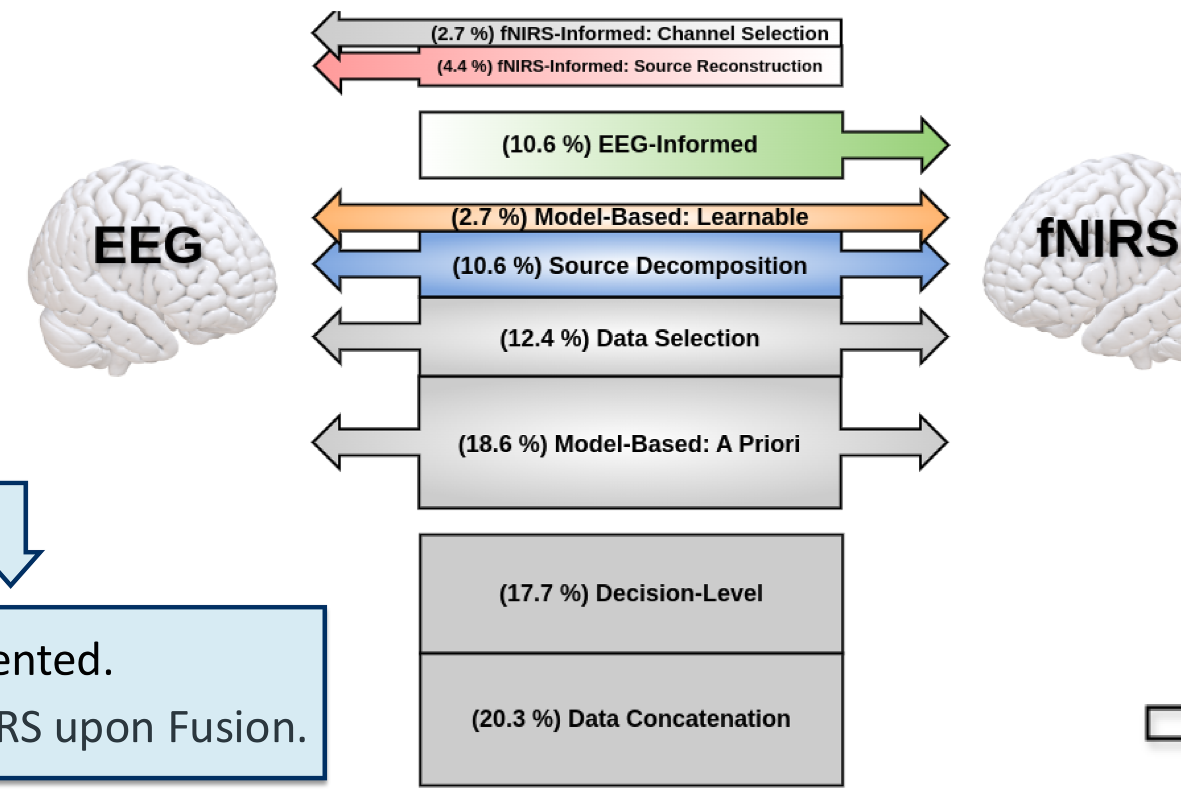
Motivation

Electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS), particularly its high-density variant **Diffuse Optical Tomography (DOT)**, are established, cost-effective, and non-invasive neuroimaging techniques, whose integration represents a promising direction for brain activity decoding in **naturalistic scenarios** with **high spatiotemporal resolution [1]**. However, **robust machine-learning methods for combining these signals remain challenging**.

We focus on **multimodal fusion methods [2]**, emphasizing **data-driven unsupervised symmetric** techniques. We conducted a **survey**, reviewing over 110 articles, identified most **promising methods** and tested them on **synthetic multimodal ground truth**.

- **Source Decomposition Methods:** Best Candidates but Underrepresented.
- In Contrast to EEG: No Proper Physiological Artifact Removal in fNIRS upon Fusion.



Method \ Feature	Symmetric	Data-Driven	Unsupervised	Flexible	Early Fusion
Data Concatenation	Yes	No	Yes	No	No
Model-based: A priori	Yes	No	Yes	No	No/Yes
Decision-Level	Yes	Yes	No	No	No
Data Selection	Yes	No/Yes	No/Yes	No	No/Yes
fNIRS-Informed: Channel Selection	No	Yes	Yes	No	Yes
EEG-Informed	No	No	No	Yes	Yes
fNIRS-Informed: Source Reconstruction	No	No	Yes	Yes	Yes
Model-Based: Learnable	Yes	No	No/Yes	Yes	Yes
Source Decomposition	Yes	Yes	Yes	Yes	Yes

Problem Statement and Methods Overview

PROBLEM: the analysis of multimodal data from continuous brain imaging on naturalistic environments typically suffers from two problems

1. **No Block-Design Paradigms: No precise knowledge about stimuli and timing.**
2. **Unknown physiological relationships and coupling mechanisms between confounders & main modalities.**

Well-established techniques, such as decision-level fusion, data concatenation, or model-based methods like GLM fall short in these regards.

The multimodal challenge requires **flexible early-fusion** methods that leverage **high-dimensional data** to find complex shared latent processes in an **unsupervised** and **symmetric** (bidirectional) fashion.

Source Decomposition

$$S_x(t) = w_x^T \cdot X(t)\,, \quad S_y(t) = w_y^T \cdot Y(t)$$

- **CCA:** Maximizes Corr(Sx, Sy) $\max_{w_x, w_y} w_x^T C_{xy} w_y \quad \text{s.t.} \quad w_x^T C_x w_x = w_y^T C_y w_y = 1$
- **ElasticNetCCA:** CCA + Sparse (L1) + Normalized (L2) Solutions

  $\text{CCA} \quad s.t. \quad \|w_x\|_1 \le c_{x1}\,, \quad \|w_y\|_1 \le c_{y1}\,, \quad \|w_x\|_2^2 \le c_{x2}\,, \quad \|w_y\|_2^2 \le c_{y2}\,.$
- **Structured Sparse CCA:** ElasticNetCCA + Spatial Structure of Data (Lx, Ly)

  $\text{CCA} \quad s.t. \quad \|w_x\|_1 \le c_{x1}\,, \quad \|w_y\|_1 \le c_{y1}\,, \quad w_x^T L_x w_x \le c_{x2}\,, \quad w_y^T L_y w_y \le c_{y2}$
- **tCCA:** CCA + Temporal Embedding $S_x(t) \to [S_x(t), S_x(t-\tau_1), \ldots, S_x(t-\tau_N)]$
- **mSPoC:** tCCA + Bandpower $S_x(t) \to \mathrm{P}[S_x(t)]$

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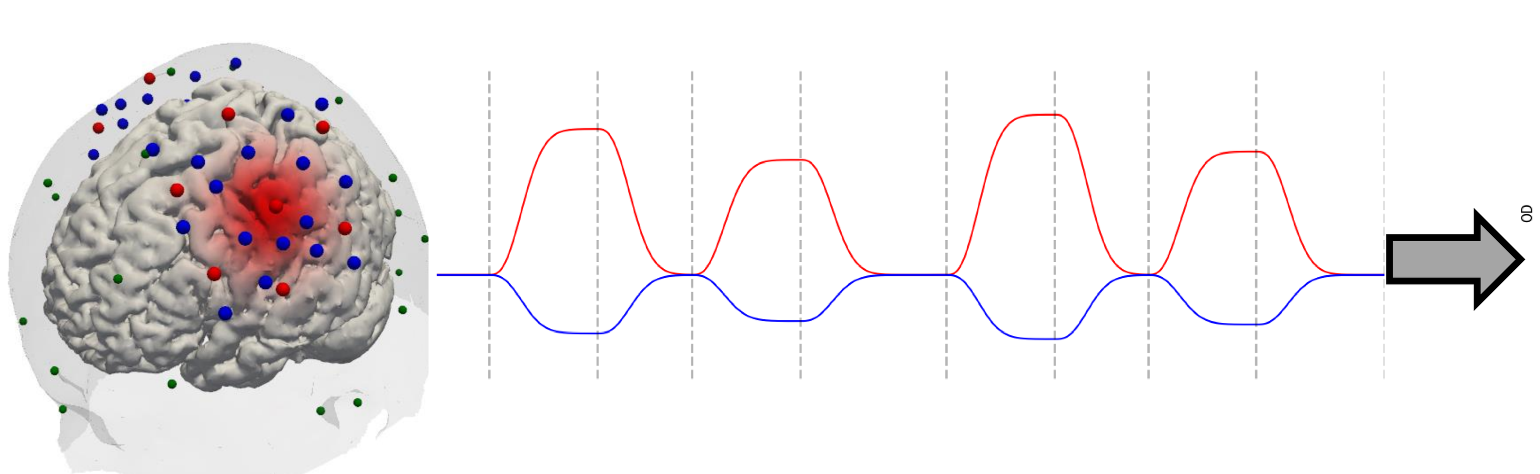
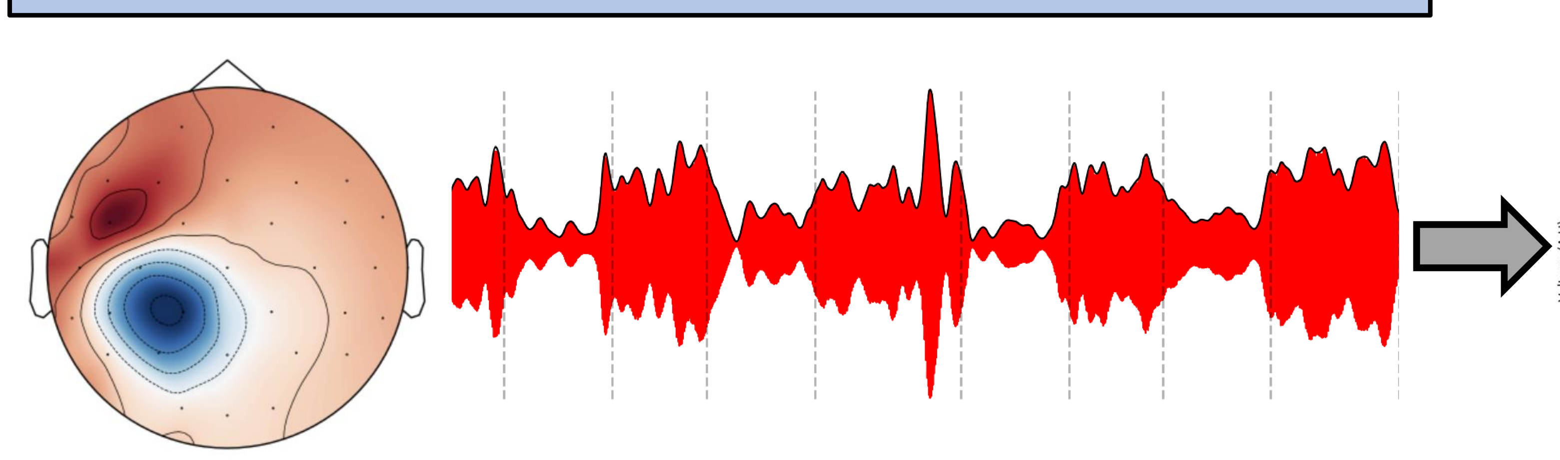
https://github.com/ibs-lab/cedalion

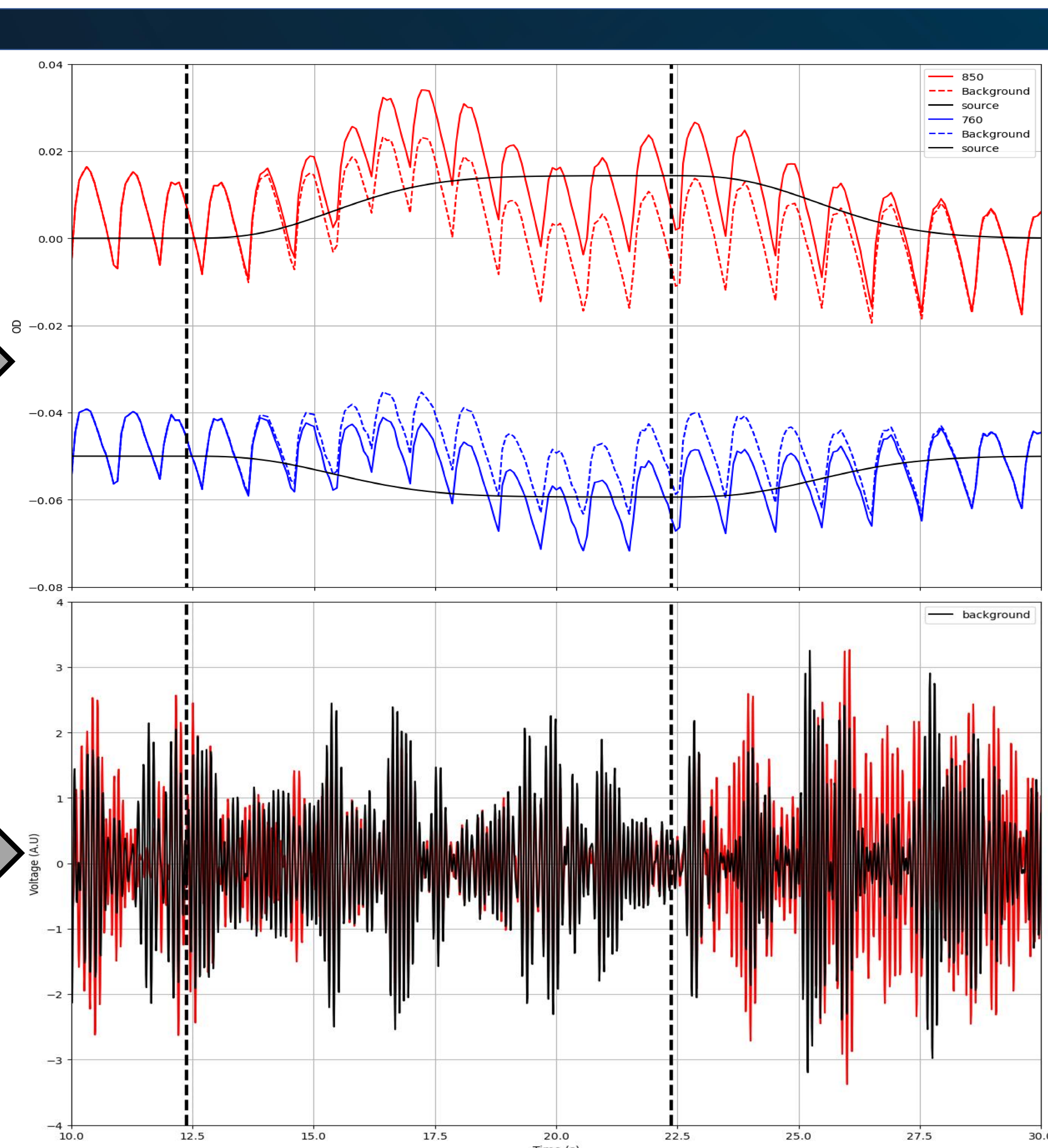
Simulated fNIRS-EEG Data



Synthetic fNIRS with realistic DOT forward model
Canonical HRF + Boxcar at Stimuli



Synthetic EEG with realistic volume conduction forward model
Dipole + Power Decay in Alpha Band at Stimuli

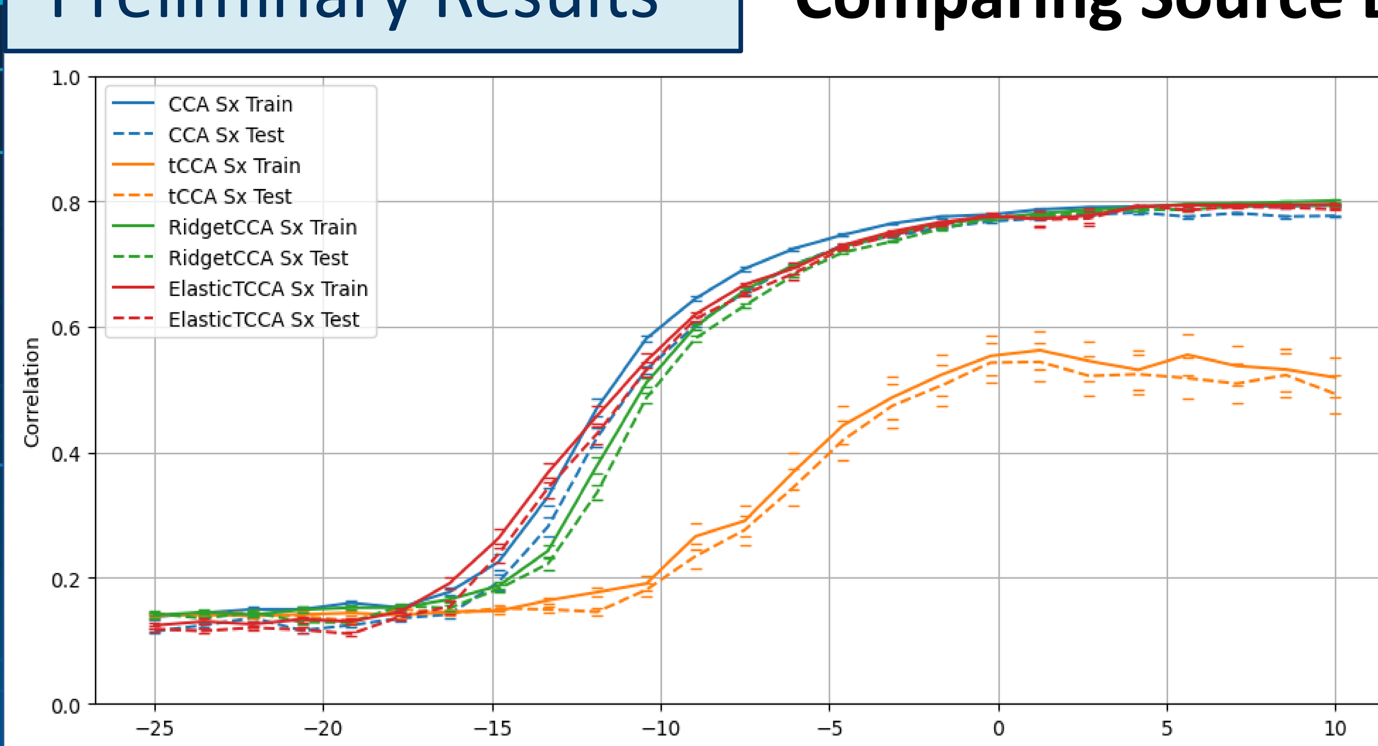


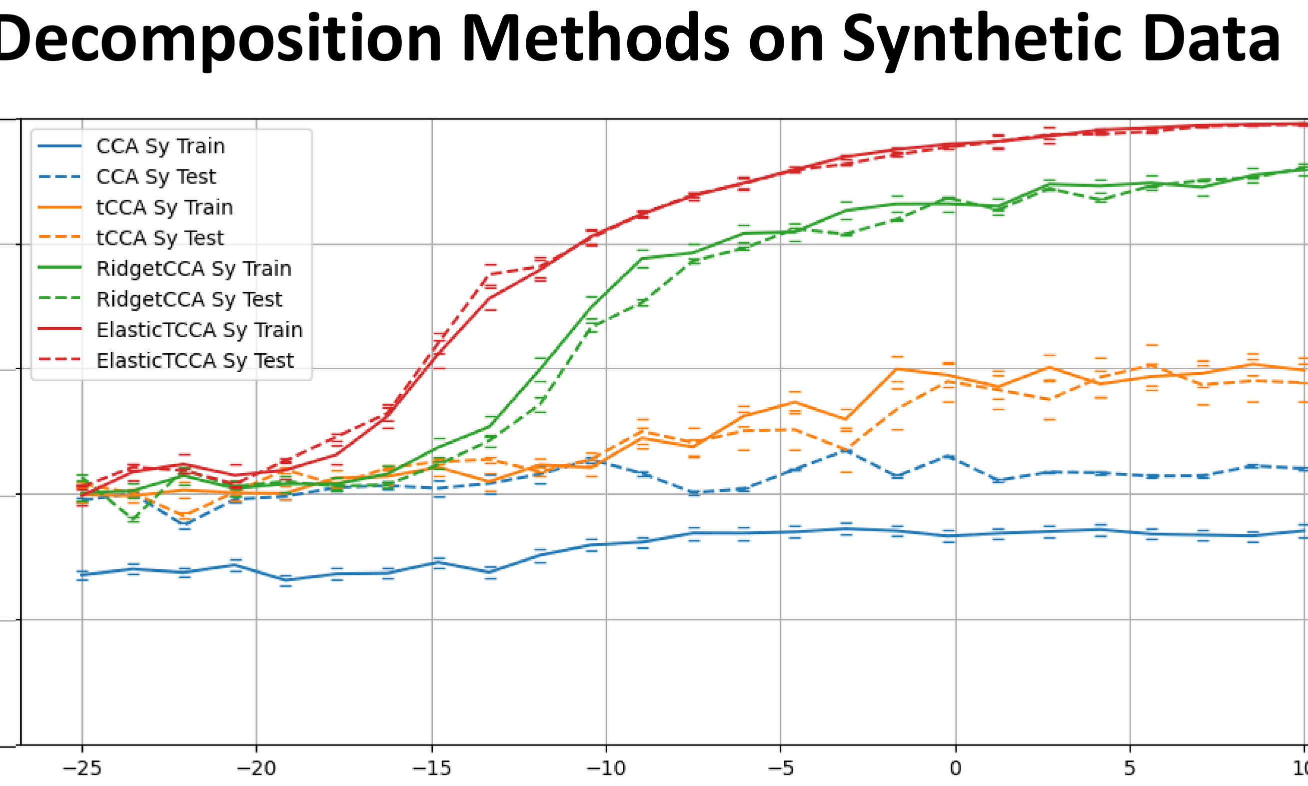
BACKGROUND DATA

Real **concurrent** HD fNIRS-EEG recording with **co-localized** channels

Preliminary Results

Comparing Source Decomposition Methods on Synthetic Data





References

[1] von Lühmann *et al.*, "Toward Neuroscience of the Everyday World (NEW) using functional near-infrared spectroscopy," *Current Opinion in Biomedical Engineering*, vol. 18, p. 100272, Jun. 2021, doi: 10.1016/j.cobme.2021.100272.

[2] Li, R. *et al.*, "Concurrent fNIRS and EEG for Brain Function Investigation: A Systematic, Methodology-Focused Review". Sensors, 22 (15), 5865. https://doi.org/10.3390/s22155865.

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