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Riemannian Tangent Alignment Enhances BCI Decoding Across Subjects, Sessions, and Modalities

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Introduction: Brain–computer interfaces (BCIs) face challenges in generalizability due to variability in neural representations across sessions, modes, and subjects [1]. This study tests the hypothesis that neural activity resides in a latent space [2], comparable across data sources via tangential Riemannian processing, to improve decoding accuracy [3].

Material, Methods and Results: We analyzed data from 16 subjects in the Multimodal Signal Dataset for 11 Intuitive Movement Tasks [4], focusing on motor imagery tasks for cylindrical, spherical, and lumbrical grasping. EEG signals were preprocessed (ICA, 8–40 Hz bandpass, downsampling to 250 Hz), and event-related windows (0.5–4 s post-event) were extracted from central and parietal channels. Covariance matrices were projected into the Riemannian tangent space, aligned via Procrustes Analysis, and reduced using the first three PCA components. The chance level for this dataset is 33%. Cross-session validation showed alignment improved accuracy from 33% to 45% ($p < 0.05$). In cross-mode validation, where models were trained on motor execution and tested on imagery, alignment reduced variability (t = -4.68, $p < 0.001$). Cross-subject validation, aligning one subject as reference and others as targets, yielded significant gains (t = -13.90, $p < 0.001$). To better understand alignment, each subject was used as the reference, aligning the remaining subjects to them. PCA plots showed improved clustering post-alignment, indicating enhanced representation consistency. Models trained on aligned data achieved 51% accuracy on the remaining subjects, compared to 34% without alignment ($p < 0.001$).

Conclusion: This study demonstrates that it is possible to align neural data in a low-dimensional representation, improving BCI decoding across sessions, modes, and subjects. However, the optimal dimensionality for alignment remains untested, and the interpretability of this representation requires further investigation. These findings pave the way for future studies to explore optimal dimensionality and the underlying structure of aligned neural representations.

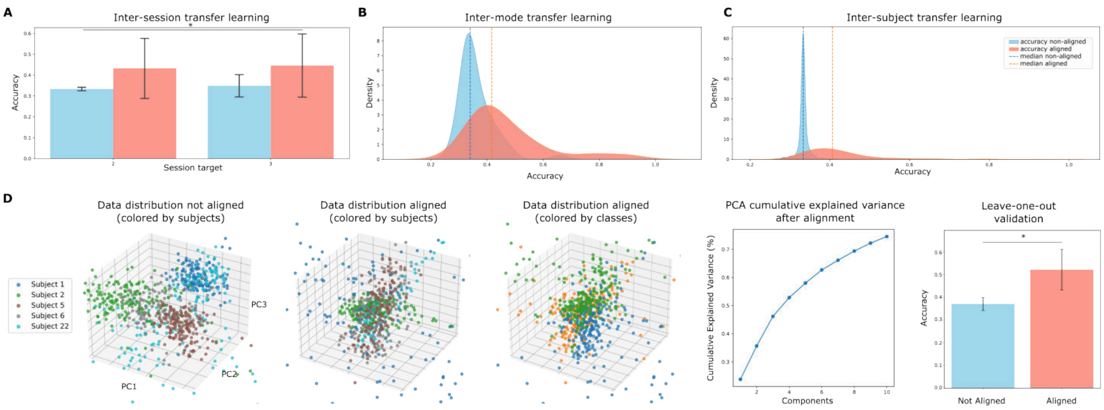

Figure 1: *Visualization of results: (A) Cross-session (B) Cross-mode and (C) Cross-subject alignment. (D) Final validation includes PCA-based visualization of mental class clustering before and after alignment, the cumulative explained variance by PCA components, and leave-one-out accuracy comparison pre- and post-alignment.*

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