# Multimodal EEG–fMRI Contrastive Modeling Proposal

## 1. Why?

• Complementary strengths: EEG captures neural dynamics at millisecond resolution but with poor spatial specificity; fMRI offers millimeter-scale spatial maps of brain activity but at a sluggish temporal pace (seconds per volume). Bridging these modalities can yield a richer picture of brain function.  
• Bridging scales: A joint representation would let us exploit EEG’s fine temporal detail to “fill in” fast-changing patterns across the whole brain, while using fMRI’s spatial precision to localize EEG-derived signals.  
• Clinical promise: In epilepsy or other pathologies, rapid detection of abnormal brain states in both time and space could enable earlier warnings and more precise interventions.

## 2. What?

1. Shared Latent Space  
 - Learn embeddings z\_EEG and z\_fMRI in a common d-dimensional manifold such that simultaneous EEG/fMRI samples map to nearby points.  
  
2. Cross-Modal Prediction  
 - Spatial up-sampling: Given a new EEG segment, retrieve or decode its nearest fMRI embedding to reconstruct a high-resolution volume.  
 - Temporal up-sampling: Given an fMRI volume, predict its corresponding rapid EEG trace to capture transient events.  
  
3. Anomaly Detection  
 - Train only on “normal” EEG–fMRI pairs; flag samples whose embeddings fall far outside the learned manifold as potential pre-ictal or aberrant brain states.

## 3. How?

1. Data & Synchronization  
 - Use simultaneous EEG–fMRI recordings (e.g., resting-state with concurrent scalp EEG, or clinical EEG–fMRI in epilepsy).  
 - Segment both streams into short, aligned windows (e.g., 1–2 s of data maps to one fMRI volume).  
  
2. Encoder Architectures  
 - EEG encoder: 1D-CNN or transformer over multichannel time series → vector of size d.  
 - fMRI encoder: 3D-CNN or lightweight volumetric transformer → vector of size d.  
  
3. Contrastive Training (InfoNCE)  
 - In each mini-batch, pull true EEG–fMRI pairs together and push all other cross-pairs apart, using a cosine-similarity loss with temperature scaling.  
  
4. Decoding & Detection  
 - Nearest-neighbor decoding: Map a new EEG embedding to its closest fMRI embedding, then run the fMRI decoder in reverse.  
 - Anomaly score: Distance from the joint manifold (e.g., Mahalanobis or reconstruction error) flags abnormal events.

## 4. Benefits & Novelty

• High-Resolution Fusion: Harvests millisecond EEG detail to enrich whole-brain fMRI maps and vice versa.  
• Unsupervised Flexibility: Requires no labels beyond temporal alignment, making it scalable to large clinical and research datasets.  
• Real-Time Potential: Once trained, the model can run online—enabling near-instant spatial brain forecasts from EEG or fast temporal reconstructions from fMRI.  
• Clinical Impact: Early detection of epileptic or cognitive state shifts with both spatial and temporal precision, paving the way for advanced neurofeedback or closed-loop stimulation.