Novelty Assessment Report

Paper: Coupled Transformer Autoencoder for Disentangling Multi-Region Neural Latent Dynamics

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Abstract

Simultaneous recordings from thousands of neurons across multiple brain areas reveal rich mixtures of activity that are shared between regions and dynamics that are unique to each region. Existing alignment or multi-view methods neglect temporal structure, whereas dynamical latent-variable models capture temporal dependencies but are usually restricted to a single area, assume linear read-outs, or conflate shared and private signals. We introduce Coupled Transformer Autoencoder (CTAE)—a sequence model that addresses both (i) non-stationary, non-linear dynamics and (ii) separation of shared versus region-specific structure, in a single framework. CTAE employs Transformer encoders and decoders to capture long-range neural dynamics, and explicitly partitions each region's latent space into orthogonal shared and private subspaces. We demonstrate the effectiveness of CTAE on two high-density electrophysiology datasets of simultaneous recordings from multiple regions, one from motor cortical areas and the other from sensory areas. CTAE extracts meaningful representations that better decode behavior variables compared to existing approaches.

Core Task Landscape

This paper addresses: **Disentangling Shared and Private Neural Dynamics Across Multiple Brain Regions**

A total of **50 papers** were analyzed and organized into a taxonomy with **22 categories**.

Taxonomy Overview

The research landscape has been organized into the following main categories:

- **Latent Variable Models for Multi-Region Neural Dynamics**
- **Multi-View and Multi-Modal Integration Methods**
- **Task-Specific Neural Decomposition Approaches**
- **Clinical and Translational Disentanglement Applications**
- **Network Connectivity and Structural Decomposition**
- **Foundation Models and Large-Scale Neural Representations**
- **Specialized Neural Representation Studies**

Complete Taxonomy Tree

- Disentangling Shared and Private Neural Dynamics Across Multiple Brain Regions Survey Taxonomy
- Latent Variable Models for Multi-Region Neural Dynamics
  - Deep Learning Architectures for Shared-Private Factorization ★ (4 papers)
  - [0] Coupled Transformer Autoencoder for Disentangling Multi-Region Neural Latent Dynamics (Anon et al., 2026) View paper
  - [2] Disentangling Shared and Private Neural Dynamics with SPIRE: A Latent Modeling Framework for Deep Brain Stimulation (Rahil Soroushmojdehi, 2025) View paper
  - [21] A Disentangled Low-Rank RNN Framework for Uncovering Neural Connectivity and Dynamics (Chengrui Li, 2025) View paper
  - [37] CREIMBO: Cross-Regional Ensemble Interactions in Multi-view Brain Observations (Mudrik, 2024) View paper
  - Behavior-Aligned Latent Dynamics Modeling (4 papers)
  - [1] Exploring behavior-relevant and disentangled neural dynamics with generative diffusion models (Wang Yule, 2024) View paper
  - [5] Targeted neural dynamical modeling (Hurwitz, 2021) View paper
  - [6] Dynamical modeling of behaviorally relevant spatiotemporal patterns in neural imaging data (Hosseini Mohammad, 2025) View paper
  - [28] Learning in brain-computer interface control evidenced by joint decomposition of brain and behavior (Jennifer Stiso, 2020) View paper
  - Classical Latent Dynamical Models for Multi-Region Data (2 papers)
  - [3] Modeling and dissociation of intrinsic and input-driven neural population dynamics underlying behavior (Parsa Vahidi, 2024) View paper
  - [12] Between-area communication through the lens of within-area neuronal dynamics (Olivia Gozel, 2024) View paper
- Multi-View and Multi-Modal Integration Methods
  - Unsupervised Multi-View Geometry Discovery (2 papers)
  - [27] Demixed shared component analysis of neural population data from multiple brain areas (Takagi, 2022) View paper
  - [30] Unsupervised discovery of the shared and private geometry in multi-view data (Sai Koukuntla, 2024) View paper
  - Multi-Modal Neuroimaging Integration (2 papers)
  - [38] Editor's evaluation: Using multi-modal neuroimaging to characterise social brain specialisation in infants (Jessica Dubois, 2023) View paper
  - [41] Author response: Using multi-modal neuroimaging to characterise social brain specialisation in infants (Maheen Siddiqui, 2023) View paper
  - Dual-Brain and Hyperscanning Paradigms (1 papers)

    - [32] Dual-Brain EEG Decoding for Target Detection via Joint Learning in Shared and Private Spaces (Bingfeng He, 2025) View paper
- Task-Specific Neural Decomposition Approaches
    - Cognitive and Behavioral Task Decomposition (4 papers)
    - [7] Disentangling self-and fairness-related neural mechanisms involved in the ultimatum game: an fMRI study (Corrado Corradiâ Dellâ Acqua, 2013) View paper
    - [9] Neural representation of emotion regulation goals (Carmen Morawetz, 2016) View paper
    - [34] Evidence for independent representational contents in inhibitory control subprocesses associated with frontoparietal cortices. (Negin Gholamipourbarogh, 2023) View paper
    - [45] Distinct but cooperating brain networks supporting semantic cognition (JeYoung Jung, 2022) View paper
    - Sensory and Perceptual Feature Disentanglement (3 papers)
    - [8] Disentangling the independent contributions of visual and conceptual features to the spatiotemporal dynamics of scene categorization (Michelle R. Greene, 2020) View paper
    - [14] Distinct cortical pathways for music and speech revealed by hypothesis-free voxel decomposition (S Norman-Haignere, 2015) View paper
    - [36] Separate neural representations for physical and communicative social interactions along the lateral visual pathway: evidence from data-driven voxel decomposition (Yuanfang Zhao, 2024) View paper
    - Social Interaction Neural Representation (3 papers)
    - [4] The role of motion in the neural representation of social interactions in the posterior temporal cortex (Julia Landsiedel, 2022) View paper
    - [15] Neural dynamics between anterior insular cortex and right supramarginal gyrus dissociate genuine affect sharing from perceptual saliency of pretended pain (Yili Zhao, 2021) View paper
    - [16] Intracranial EEG signals disentangle multi-areal neural dynamics of vicarious pain perception. (Huixin Tan, 2024) View paper
- Clinical and Translational Disentanglement Applications
    - Psychiatric Disorder Phenotype Decomposition (2 papers)
    - [11] Disentangling shared and unique brain functional changes associated with clinical severity and cognitive phenotypes in schizophrenia via deep learning (Jing Xia, 2025) View paper
    - [17] Multi-task deep learning model to disentangle shared and unique brain functional changes associated with illness severity and cognitive functioning in schizophrenia (Jagath Rajapakse, 2025) View paper
    - Neurological Disease and Intervention Models (3 papers)
    - [26] Brain region-specific and systemic transcriptomic alterations in a human alpha-synuclein overexpressing rat model (Vivien Hoof, 2025) View paper
    - [39] Social isolation produces a brain-region specific expansion of microglia structure and reorganization of neural activity (Alex P. Vu, 2022) View paper
    - [49] Region-specific glial homeostatic signature in prion diseases is replaced by a uniform neuroinflammation signature, common for brain regions and prion strains with different cell tropism. (Natallia Makarava, 2021) View paper
- Network Connectivity and Structural Decomposition
    - Functional Connectivity Decomposition (2 papers)
    - [13] Disentangling dynamic networks: Separated and joint expressions of functional connectivity patterns in time (Nora Leonardi, 2014) View paper
    - [35] Joint spectral decomposition for the parcellation of the human cerebral cortex using resting-state fMRI (Salim Arslan, 2015) View paper
    - Structural and Morphological Network Analysis (2 papers)
    - [20] Mapping morphological cortical networks with joint probability distributions from multiple morphological features (Yuqi Wang, 2024) View paper
    - [22] Decomposing cortical activity through neuronal tracing connectome-eigenmodes in marmosets (Jie Xia, 2024) View paper
    - Connectome-Based Neural Activity Decomposition (1 papers)
    - [24] Characterizing and differentiating brain states through a CS-KBRs framework for highlighting the synergy of common and specific brain regions. (Di Zhu, 2025) View paper
- Foundation Models and Large-Scale Neural Representations (3 papers)
    - [19] Time-Evolving Dynamical System for Learning Latent Representations of Mouse Visual Neural Activity (Liwei Huang, 2024) View paper
    - [29] BaRISTA: Brain Scale Informed Spatiotemporal Representation of Human Intracranial Neural Activity (Lucine L. Oganesian, 2025) View paper
    - [33] Towards a "universal translator" for neural dynamics at single-cell, single-spike resolution (Zhang Yizi, 2024) View paper
- Specialized Neural Representation Studies
    - Motor and Sensorimotor Representation (3 papers)
    - [23] Matching patterns of activity in primate prefrontal area 8a and parietal area 7ip neurons during a spatial working memorytask (Matthew V. Chafee, 1998) View paper
    - [25] The neural representation of force across grasp types in motor cortex of humans with tetraplegia (Anisha Rastogi, 2021) View paper
    - [50] Investigating Neural Representation of Finger-Movement Directions Using Electroencephalography Independent Components (Mohamed Mounir Tellache, 2021) View paper
    - Hierarchical and Gradient-Based Cortical Organization (4 papers)
    - [42] Functional hierarchies in brain dynamics characterized by signal reversibility in ferret cortex (SebastiÃ¡n Idesis, 2023) View paper
    - [43] Decision letter: Flexing the principal gradient of the cerebral cortex to suit changing semantic task demands (Xi-Nian Zuo, 2022) View paper
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    - [47] Editor's evaluation: Flexing the principal gradient of the cerebral cortex to suit changing semantic task demands (Muireann Irish, 2022) View paper
    - Language and Bilingual Neural Representation (1 papers)
    - [40] Mapping the neural dynamics of Koreanâ English bilinguals with medium proficiency during auditory word processing (JeYoung Jung, 2018) View paper

- Perception-Imagery Shared Representation (2 papers)
- [10] Neural representation of objects in space: A dual coding account (Glyn W. Humphreys, 2016) View paper
- [31] Shared and Independent Neural Representation Between Visual Perception and Mental Imagery (Yingying Huang, 2021) View paper
- Physiological and Artifact Signatures (1 papers)
- [46] Author response: Physiological and motion signatures in static and time-varying functional connectivity and their subject identifiability (Alba Xifra Porxas, 2021) View paper
- Molecular and Genetic Regional Specificity (1 papers)
- [18] Region-specific RNA m6A methylation represents a new layer of control in the gene regulatory network in the mouse brain (Mengqi Chang, 2017) View paper
- Cannabinoid System and Brain Regions (1 papers)
- [48] Cannabinoids: From the brain to society (Allan H. Young, 2022) View paper

Narrative

Core task: Disentangling shared and private neural dynamics across multiple brain regions. The field has organized itself around several complementary perspectives. Latent Variable Models for Multi-Region Neural Dynamics form a central branch, developing probabilistic and deep learning architectures that explicitly factorize neural activity into components common across regions versus those unique to each area. Multi-View and Multi-Modal Integration Methods address the challenge of combining heterogeneous data sources—such as fMRI, EEG, and behavioral recordings—by learning joint representations that respect both shared structure and modality-specific features. Task-Specific Neural Decomposition Approaches focus on isolating dynamics tied to particular cognitive or motor functions, while Clinical and Translational Disentanglement Applications extend these techniques to disease states and therapeutic contexts. Network Connectivity and Structural Decomposition methods emphasize graph-theoretic and anatomical constraints, Foundation Models and Large-Scale Neural Representations explore scalable architectures for population-level inference, and Specialized Neural Representation Studies examine domain-specific phenomena such as sensory processing or social cognition.

Within the latent variable branch, a particularly active line of work employs deep learning architectures for shared-private factorization. Methods like SPIRE[2] and Disentangled Low-Rank RNN[21] use recurrent or low-rank structures to separate trial-shared dynamics from region-private variability, often emphasizing interpretability and alignment with known neural constraints. The Coupled Transformer Autoencoder[0] sits naturally within this cluster, leveraging transformer-based attention mechanisms to model dependencies across regions while maintaining distinct private subspaces. Compared to SPIRE[2], which relies on explicit probabilistic priors, the transformer approach offers greater flexibility in capturing long-range temporal dependencies. Relative to Intrinsic Input-Driven Dynamics[3], which emphasizes input-driven versus intrinsic components, the coupled autoencoder framework prioritizes the spatial decomposition of multi-region recordings. Open questions remain about how to balance model expressiveness with biological plausibility and how to scale these architectures to whole-brain recordings.

Related Works in Same Category

The following **3 sibling papers** share the same taxonomy leaf node with the original paper:

1. Disentangling Shared and Private Neural Dynamics with SPIRE: A Latent Modeling Framework for Deep Brain Stimulation

Authors: Rahil Soroushmojdehi, Asadi Mehrnaz, Sina Javadzadeh, Sanger, Terence D., et al. (7 authors total) | **Year/Venue**: 2025 | **URL**: View paper

Abstract

Disentangling shared network-level dynamics from region-specific activity is a central challenge in modeling multi-region neural data. We introduce SPIRE (Shared-Private Inter-Regional Encoder), a deep multi-encoder autoencoder that factorizes recordings into shared and private latent subspaces with novel alignment and disentanglement losses. Trained solely on baseline data, SPIRE robustly recovers cross-regional structure and reveals how external perturbations reorganize it. On synthetic benchm...

Relationship Analysis

Both papers belong to the Deep Learning Architectures for Shared-Private Factorization category, employing deep neural networks with explicit architectural mechanisms to separate shared and private latent dynamics across multiple brain regions. They overlap in using autoencoder-based architectures with orthogonality constraints and alignment losses to disentangle cross-regional (shared) from region-specific (private) neural representations. The key differences are: CTAE uses Transformer encoders/decoders with causal self-attention for long-range temporal dependencies and applies fixed weight masks to partition latent dimensions, whereas SPIRE uses GRU-based encoders/decoders with lightweight convolutional temporal alignment modules and is specifically designed for analyzing intracranial LFP recordings under deep brain stimulation perturbations.

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2. A Disentangled Low-Rank RNN Framework for Uncovering Neural Connectivity and Dynamics

Authors: Chengrui Li, Yunmiao Wang, Yule Wang, Weihan Li, Dieter Jaeger, et al. (6 authors total) | **Year/Venue**: 2025 | **URL**: View paper

Abstract

Low-rank recurrent neural networks (lrRNNs) are a class of models that uncover low-dimensional latent dynamics underlying neural population activity. Although their functional connectivity is low-rank, it lacks disentanglement interpretations, making it difficult to assign distinct computational roles to different latent dimensions. To address this, we propose the Disentangled Recurrent Neural Network (DisRNN), a generative lrRNN framework that assumes group-wise independence among latent dynami...

Relationship Analysis

Both papers belong to the Deep Learning Architectures for Shared-Private Factorization category, employing neural network models with explicit mechanisms to separate shared and private latent dynamics across brain regions. Both papers address multi-region neural recordings using autoencoder-based architectures (CTAE uses Transformer autoencoders, DisRNN uses low-rank RNN autoencoders) and enforce orthogonality between shared and private subspaces through architectural constraints and loss functions. The key difference is that CTAE focuses on Transformer-based sequence modeling with fixed weight masks to partition latent spaces and emphasizes temporal dynamics through causal attention, while DisRNN reformulates low-rank RNNs under a VAE framework with partial correlation penalties to achieve group-wise independence and explicitly recovers interpretable sub-circuit connectivity matrices.

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3. CREIMBO: Cross-Regional Ensemble Interactions in Multi-view Brain Observations

Authors: Mudrik, Noga, Noga Mudrik, Ryan Ly, Ruebel, et al. (10 authors total) | **Year/Venue**: 2024 | **URL**: View paper

Abstract

Modern recordings of neural activity provide diverse observations of neurons across brain areas, conditions, and subjects; presenting an exciting opportunity to reveal the fundamentals of brain-wide dynamics. Current analysis methods often fail to harness the richness of such data, as they provide either uninterpretable representations or oversimplify models (e.g., by assuming stationary dynamics). Here, instead of regarding asynchronous neural recordings that lack alignment in neural identity o...

Relationship Analysis

Both papers belong to the Deep Learning Architectures for Shared-Private Factorization category, employing neural network models with explicit mechanisms to separate shared and private latent dynamics across multiple brain regions. Both papers address multi-region neural recordings by learning shared communication subspaces and region-specific private subspaces through autoencoder-based architectures with specialized loss functions. The key differences are that CTAE uses Transformer encoders/decoders with fixed weight masks and explicit orthogonality constraints to partition latent spaces, while CREIMBO employs graph-driven dictionary learning to discover sparse neural ensembles and models dynamics through time-varying decomposition of global sub-circuits, emphasizing cross-session alignment and interpretability through ensemble-based representations.

Contributions Analysis

Overall novelty summary. The paper introduces a Coupled Transformer Autoencoder (CTAE) that combines transformer-based sequence modeling with explicit shared-private latent space partitioning for multi-region neural recordings. It resides in the 'Deep Learning Architectures for Shared-Private Factorization' leaf, which contains four papers total including the original work. This leaf sits within the broader 'Latent Variable Models for Multi-Region Neural Dynamics' branch, indicating a moderately populated research direction focused on deep learning approaches to neural decomposition rather than classical probabilistic methods.

The taxonomy reveals neighboring leaves addressing related but distinct challenges: 'Behavior-Aligned Latent Dynamics Modeling' incorporates behavioral variables explicitly during factorization, while 'Classical Latent Dynamical Models' employ state-space frameworks without deep architectures. The sibling papers in the same leaf (SPIRE, Disentangled Low-Rank RNN, and one other) emphasize recurrent or low-rank structures with probabilistic priors. CTAE diverges by adopting transformer attention mechanisms for long-range dependencies, positioning itself at the intersection of modern sequence modeling and neural decomposition rather than relying on RNN-based or explicitly probabilistic frameworks.

Among eight candidates examined across three contributions, none were flagged as clearly refuting the work. The core CTAE framework examined two candidates with zero refutations, the scalable architecture examined zero candidates, and the behavior-agnostic latent space examined six candidates with zero refutations. This limited search scope—eight papers rather than an exhaustive survey—suggests the analysis captures immediate neighbors but may not reveal all overlapping prior work. The absence of refutations across contributions indicates that within this small sample, no single paper directly anticipates the combination of transformer encoders, orthogonal subspace partitioning, and multi-region electrophysiology applications.

Given the constrained literature search and the moderately populated taxonomy leaf, the work appears to occupy a recognizable niche within deep learning-based neural decomposition. The transformer-based approach differentiates it from recurrent or low-rank methods among its siblings, though the fundamental task of shared-private factorization is well-established in this research area. A broader search beyond the top-eight semantic matches would be necessary to assess whether similar transformer-based multi-region architectures exist in adjacent communities or recent preprints.

This paper presents **3 main contributions**, each analyzed against relevant prior work:

Contribution 1: Coupled Transformer Autoencoder (CTAE) framework

Description: CTAE is a novel sequence modeling framework that uses Transformer encoders and decoders to capture long-range, non-stationary neural dynamics while explicitly partitioning each brain region's latent space into orthogonal shared and private subspaces. This addresses limitations of existing methods that either neglect temporal structure or fail to separate shared and region-specific signals.

This contribution was assessed against **2 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

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1. Aligning Transregional Neural Dynamics with Transformer-based Variational Autoencoders*

URL: View paper

Brief Assessment

Transregional Neural Alignment[52] uses separate Transformer-based VAEs for each region with linear alignment of latent variables, rather than a coupled architecture with explicit orthogonal shared/private subspace partitioning and multi-loss disentanglement as in CTAE.

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2. Disorder-specific neurodynamic features in schizophrenia inferred by neurodynamic embedded contrastive variational autoencoder model

URL: View paper

Brief Assessment

Schizophrenia Neurodynamic Features[51] focuses on psychiatric disorder analysis using contrastive VAE with neurodynamic models for schizophrenia-specific feature extraction, not general neural dynamics modeling across brain regions. The candidate does not address multi-region neural latent dynamics separation or transformer-based sequence modeling for non-stationary dynamics.

Contribution 2: Scalable multi-region architecture with mixing weights

Description: The architecture employs region-specific weight masks and a weighted latent fusion mechanism that enables scalable extension to more than two brain regions without exponential parameter growth, unlike existing multi-region methods that suffer from scalability issues.

This contribution was assessed against **0 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

Contribution 3: Behavior-agnostic latent space for downstream decoding

Description: CTAE produces generic latent representations that can support multiple downstream behavioral decoding tasks such as kinematics, forces, or cognitive variables using simple linear decoders, without requiring retraining of the model for each specific task.

This contribution was assessed against **6 related papers** from the literature. Papers with potential prior art are analyzed in detail with textual evidence; others receive brief assessments.

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1. Multi-robot scene completion: Towards task-agnostic collaborative perception

URL: View paper

Brief Assessment

Multi-robot Scene Completion[54] focuses on task-agnostic collaborative perception for multi-robot systems, not behavior-agnostic neural latent representations for decoding behavioral variables from brain recordings.

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2. Spectroscopy Pre-Trained Transformer (SpecPT): A Universal Spectroscopic Analysis and Redshift Measurement Framework

URL: View paper

Brief Assessment

SpecPT[57] focuses on spectroscopic analysis and redshift measurement in astronomy, not neural decoding or behavioral tasks. The domains are entirely different—spectroscopy versus neuroscience—making comparison of novelty claims impossible.

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3. Behaviorally Irrelevant Feature Matching Increases Neural and Behavioral Working Memory Readout.

URL: View paper

Brief Assessment

Feature Matching Memory[55] focuses on working memory readout and neural feature matching, not on behavior-agnostic latent representations for multiple downstream decoding tasks. No full text context was provided for this candidate paper to assess potential overlap.

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4. Structure Matters: Deciphering Neural Network's Properties from its Structure

URL: View paper

Brief Assessment

Structure Matters Networks[58] focuses on encoding neural network architectures as graphs to predict their task performance, not on creating behavior-agnostic latent representations from neural recordings for downstream behavioral decoding tasks.

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5. Discover-then-name: Task-agnostic concept bottlenecks via automated concept discovery

URL: View paper

Brief Assessment

Discover-then-name Bottlenecks[53] focuses on task-agnostic concept bottlenecks for image classification using sparse autoencoders on CLIP features, not neural population dynamics or behavioral decoding from multi-region brain recordings.

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6. Sample-Efficient Representation and Reinforcement Learning in Robotic Manipulation

URL: View paper

Brief Assessment

Sample-Efficient Robotic Manipulation[56] focuses on robotic manipulation tasks with task-agnostic policies and linear decoders for state-action values, not on multi-region neural recordings with multiple behavioral decoding tasks (kinematics, forces, cognitive variables) as in CTAE.

Appendix: Text Similarity Detection

No high-similarity text segments were detected across any compared papers.

References

- [0] Coupled Transformer Autoencoder for Disentangling Multi-Region Neural Latent Dynamics View paper
- [1] Exploring behavior-relevant and disentangled neural dynamics with generative diffusion models View paper
- [2] Disentangling Shared and Private Neural Dynamics with SPIRE: A Latent Modeling Framework for Deep Brain Stimulation View paper
- [3] Modeling and dissociation of intrinsic and input-driven neural population dynamics underlying behavior View paper
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