Novelty Assessment Report

Paper: Representational Alignment Across Model Layers and Brain Regions with Hierarchical Optimal Transport

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Abstract

Standard representational similarity methods align each layer of a network to its best match in another independently, producing asymmetric results, lacking a global alignment score, and struggling with networks of different depths. These limitations arise from ignoring global activation structure and restricting mappings to rigid one-to-one layer correspondences. We propose Hierarchical Optimal Transport (HOT), a unified framework that jointly infers soft, globally consistent layer-to-layer couplings and neuron-level transport plans. HOT allows source neurons to distribute mass across multiple target layers while minimizing total transport cost under marginal constraints. This yields both a single alignment score for the entire network comparison and a soft transport plan that naturally handles depth mismatches through mass distribution. We evaluate HOT on vision models, large language models, and human visual cortex recordings. Across all domains, HOT matches or surpasses standard pairwise matching in alignment quality. Moreover, it reveals smooth, fine-grained hierarchical correspondences: early layers map to early layers, deeper layers maintain relative positions, and depth mismatches are resolved by distributing representations across multiple layers. These structured patterns emerge naturally from global optimization without being imposed, yet are absent in greedy layer-wise methods. HOT thus enables richer, more interpretable comparisons between representations, particularly when networks differ in architecture or depth. We further extend our method to a three-level HOT framework, providing a proof-of-concept alignment of two networks across their training trajectories and demonstrating that HOT uncovers checkpoint-wise correspondences missed by greedy layer-wise matching.

Core Task Landscape

This paper addresses: **Aligning Neural Representations Across Networks and Brain Regions**

A total of **50 papers** were analyzed and organized into a taxonomy with **27 categories**.

Taxonomy Overview

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

- **Cross-Subject and Cross-Species Neural Alignment**
- **DNN-Brain Correspondence and Alignment**
- **Representation Similarity and Alignment Metrics**
- **Neural Encoding and Decoding Models**
- **Neural Representation Structure and Organization**
- **Spatial and Hierarchical Organization of Representations**
- **Temporal Dynamics and Neural Synchrony**
- **Multisensory Integration and Recalibration**
- **Clinical Brain Network Analysis**
- **Theoretical and Computational Frameworks**

Complete Taxonomy Tree

- Aligning Neural Representations Across Networks and Brain Regions Survey Taxonomy
- Cross-Subject and Cross-Species Neural Alignment
  - Human Cross-Subject Alignment (4 papers)
  - [1] Unsupervised alignment reveals structural commonalities and differences in neural representations of natural scenes across individuals and brain areas (Ken Takeda, 2025) View paper
  - [10] Neural Representational Consistency Emerges from Probabilistic Neural-Behavioral Representation Alignment (Zhu Yu, 2025) View paper
  - [11] Graph alignment exploiting the spatial organization improves the similarity of brain networks (Calissano Anna, 2024) View paper
  - [48] Through their eyes: multi-subject Brain Decoding with simple alignment techniques (Matteo Ferrante, 2024) View paper
  - Cross-Species Alignment (2 papers)
  - [21] Whole brain alignment of spatial transcriptomics between humans and mice with BrainAlign (Biao Zhang, 2024) View paper
  - [35] Establishing neuroanatomical correspondences across mouse and marmoset brain structures (Christopher Mezias, 2024) View paper
  - Graph-Based Structural Network Alignment (1 papers)
  - [24] A novel node-level structure embedding and alignment representation of structural networks for brain disease analysis (Jiashuang Huang, 2020) View paper
- DNN-Brain Correspondence and Alignment
  - Vision Model-Brain Alignment (6 papers)
  - [3] Enhancing neural encoding models for naturalistic perception with a multi-level integration of deep neural networks and cortical networks (Yuanning Li, 2024) View paper
  - [4] Language modulates vision: Evidence from neural networks and human brain-lesion models (Chen, 2025) View paper

- [6] Factorized visual representations in the primate visual system and deep neural networks (Jack W Lindsey, 2024) View paper
- [20] Human Visual Pathways for Action Recognition versus Deep Convolutional Neural Networks: Representation Correspondence in Late but Not Early Layers (Isolina Ballesteros, 2024) View paper
- [22] Multiple visual objects are represented differently in the human brain and convolutional neural networks (Viola Mocz, 2023) View paper
- [45] Deep neural networks rival the representation of primate IT cortex for core visual object recognition (Charles F. Cadieu, 2014) View paper
- Language Model-Brain Alignment (2 papers)
- [8] Convergent representations and spatiotemporal dynamics of speech and language in brain and deep neural networks (Peili Chen, 2024) View paper
- [50] Brain-like Functional Organization within Large Language Models (Sun Haiyang, 2024) View paper
- Auditory Model-Brain Alignment (1 papers)
- [15] Alignment of auditory artificial networks with massive individual fMRI brain data leads to generalisable improvements in brain encoding and downstream tasks (MaÃ«lle Freteault, 2025) View paper
- Hierarchical Network-Brain Correspondence ★ (1 papers)
- [0] Representational Alignment Across Model Layers and Brain Regions with Hierarchical Optimal Transport (Anon et al., 2026) View paper

- Representation Similarity and Alignment Metrics (1 papers)
  - [2] Estimating Neural Representation Alignment from Sparsely Sampled Inputs and Features (Chun, 2025) View paper
- Neural Encoding and Decoding Models
  - Visual Encoding Models (3 papers)
  - [7] Neural encoding with affine feature response transforms (Lynn Le, 2025) View paper
  - [25] A Convolutional Neural Network Interpretable Framework for Human Ventral Visual Pathway Representation (Mufan Xue, 2024) View paper
  - [33] Convolutional neural network-based encoding and decoding of visual object recognition in space and time (K. Seeliger, 2018) View paper
  - Visual Decoding Models (3 papers)
  - [14] Brain2GAN: Feature-disentangled neural encoding and decoding of visual perception in the primate brain (Thirza Dado, 2024) View paper
  - [28] Neural encoding and decoding with deep learning for dynamic natural vision (Haiguang Wen, 2018) View paper
  - [39] Decoding dynamic visual scenes across the brain hierarchy (Ye Chen, 2024) View paper
  - Semantic Decoding Models (2 papers)
  - [38] Predicting neural activity patterns associated with sentences using a neurobiologically motivated model of semantic representation (Andrew James Anderson, 2017) View paper
  - [49] Tracking neural coding of perceptual and semantic features of concrete nouns (G. Sudre, 2012) View paper
  - Multimodal Encoding Models (1 papers)
  - [26] Latent Representation Learning for Multimodal Brain Activity Translation (Arman Afrasiyabi, 2024) View paper
- Neural Representation Structure and Organization
  - Population Coding and Feature Representation (2 papers)
  - [18] Population encoding of stimulus features along the visual hierarchy (Luciano Dyballa, 2024) View paper
  - [47] Parietal and frontal cortex encode stimulus-specific mnemonic representations during visual working memory (Edward F. Ester, 2015) View paper
  - Clustering and Discrete Representations (1 papers)
  - [36] Clustering of neural activity: A design principle for population codes (Michael J. Berry, 2020) View paper
  - Conceptual and Semantic Representation Structure (1 papers)
  - [16] Decoding the information structure underlying the neural representation of concepts (Leonardo Fernandino, 2022) View paper
  - Emotion and Social Representation (3 papers)
  - [12] Commonalities and variations in emotion representation across modalities and brain regions (Hiroaki Kiyokawa, 2024) View paper
  - [23] Distributed and hierarchical neural encoding of multidimensional biological motion attributes in the human brain (Ruidi Wang, 2023) View paper
  - [44] The neural representation of visually evoked emotion is high-dimensional, categorical, and distributed across transmodal brain regions (Tomoyasu Horikawa, 2020) View paper
- Spatial and Hierarchical Organization of Representations
  - Spatial Encoding and Navigation (3 papers)
  - [17] Neuroanatomical correlates of peripersonal space: bridging the gap between perception, action, emotion and social cognition (Gianpaolo Antonio Basile, 2024) View paper
  - [32] Spatial information encoding across multiple neocortical regions depends on an intact hippocampus (Ingrid M. Esteves, 2021) View paper
  - [41] Temporal misalignment in scene perception: Divergent representations of locomotive action affordances in human brain responses and DNNs (Evelyne I. C. Fraats, 2025) View paper
  - Hierarchical Representation Learning (2 papers)
  - [34] Learning reshapes the hippocampal representation hierarchy (Michele Nardin, 2024) View paper
  - [40] The neural representations underlying human episodic memory (Gui Xue, 2018) View paper
  - Developmental Maturation of Functional Networks (1 papers)
  - [13] Developmental maturation of millimeter-scale functional networks across brain areas (Nathaniel J. Powell, 2024) View paper
- Temporal Dynamics and Neural Synchrony
  - Dynamic Network Representations (1 papers)
  - [5] Dynamic representations in networked neural systems (Harang Ju, 2020) View paper
  - Inter-Subject Neural Synchrony (2 papers)
  - [31] How a speaker herds the audience: multibrain neural convergence over time during naturalistic storytelling (Claire H C Chang, 2024) View paper
  - [37] What guides us to neurally and behaviorally align with anyone specific? A neurobiological model based on fNIRS hyperscanning studies (Hila Z. Gvirts, 2020) View paper

- Real-Time Behavioral Decoding (1 papers)
- [9] Spectral-switching analysis reveals real-time neuronal network representations of concurrent spontaneous naturalistic behaviors in human brain (Hongkun Zhu, 2024) View paper

- Multisensory Integration and Recalibration
  - Cross-Modal Recalibration (1 papers)
  - [42] Contrary neuronal recalibration in different multisensory cortical areas (Fu Zeng, 2022) View paper
  - Categorical Encoding in Multisensory Areas (1 papers)
  - [46] Abstract encoding of categorical decisions in medial superior temporal and lateral intraparietal cortices (Yang Zhou, 2022) View paper
- Clinical Brain Network Analysis
  - Disease Classification and Diagnosis (3 papers)
  - [19] Unraveling Brain Synchronisation Dynamics by Explainable Neural Networks using EEG Signals: Application to Dyslexia Diagnosis (Wilson R. LourenÃ§o, 2024) View paper
  - [27] Brainmass: Advancing brain network analysis for diagnosis with large-scale self-supervised learning (Yanwu Yang, 2024) View paper
  - [29] BrainOOD: Out-of-distribution Generalizable Brain Network Analysis (Xu-Jiaxing, 2025) View paper
  - Auditory Pathology Analysis (1 papers)
  - [43] Spike Analysis of the Neural Activities Across the Rats' Auditory Brain Structures. (Alexis Meeker, 2024) View paper
- Theoretical and Computational Frameworks (1 papers)
  - [30] Human Brain Inspired Artificial Intelligence Neural Networks. (Paschalis Theotokis, 2025) View paper

Narrative

Core task: Aligning neural representations across networks and brain regions. This field addresses how to compare and map representational structures between different neural systems—whether across subjects, species, or between artificial deep neural networks (DNNs) and biological brains. The taxonomy reflects a multifaceted landscape: one major branch focuses on cross-subject and cross-species alignment, establishing correspondences despite anatomical and functional variability. Another prominent branch examines DNN-brain correspondence, exploring how hierarchical layers in artificial networks relate to processing stages in sensory cortices, as seen in works like Brain2GAN[14] and BrainAlign[21]. Additional branches address representation similarity metrics, neural encoding and decoding models, and the spatial or temporal organization of neural codes. Complementary directions investigate multisensory integration, clinical network analysis, and theoretical frameworks that unify these diverse alignment challenges.

Within the DNN-brain correspondence branch, a particularly active line of work explores hierarchical network-brain alignment, seeking to match layer-by-layer representations in DNNs with neural activity patterns across cortical hierarchies. Hierarchical Optimal Transport[0] sits squarely in this area, proposing a principled method to align representations at multiple levels of abstraction. This contrasts with approaches like Unsupervised Alignment Commonalities[1], which emphasizes discovering shared structure without explicit supervision, and Multilevel Integration Enhancement[3], which focuses on integrating information across hierarchical stages to improve correspondence. Meanwhile, related efforts such as Language Modulates Vision[4] and Convergent Speech Representations[8] highlight how modality-specific processing influences alignment strategies. The central challenge remains balancing the flexibility to capture diverse representational geometries with the constraint of preserving hierarchical structure, a trade-off that Hierarchical Optimal Transport[0] addresses through its layered transport framework.

Related Works in Same Category

No sibling papers were found in the same taxonomy leaf. A taxonomy-subtopic-level comparison will be produced instead.

Taxonomy-Level Summary

Sibling Subtopics

- **Auditory Model-Brain Alignment** (leaves: 1, papers: 1)
- Scope: Methods aligning auditory artificial neural networks with individual brain activity using large-scale fMRI data.
- Exclude: Excludes language-focused models or vision models; see Language Model-Brain Alignment or Vision Model-Brain Alignment.
- **Language Model-Brain Alignment** (leaves: 1, papers: 2)
- Scope: Alignment of language or speech neural networks with brain regions processing linguistic or auditory information.
- Exclude: Excludes vision models or purely auditory encoding without language; see Vision Model-Brain Alignment or Auditory Encoding Models.
- **Vision Model-Brain Alignment** (leaves: 1, papers: 6)
- Scope: Alignment and comparison of visual deep neural networks with primate or human visual cortex representations.
- Exclude: Excludes language or auditory models, or purely biological vision studies; see Language Model-Brain Alignment or Visual Encoding Models.

Contributions Analysis

Overall novelty summary. The paper proposes Hierarchical Optimal Transport (HOT), a framework for aligning neural representations across networks by jointly inferring soft layer-to-layer couplings and neuron-level transport plans. It resides in the 'Hierarchical Network-Brain Correspondence' leaf of the taxonomy, which currently contains no sibling papers. This leaf sits within the broader 'DNN-Brain Correspondence and Alignment' branch, which includes six papers on vision model-brain alignment, two on language models, and one on auditory models. The sparse population of this specific leaf suggests HOT addresses a relatively underexplored niche within the larger alignment literature.

The taxonomy reveals that most DNN-brain alignment work focuses on single-modality comparisons (vision, language, auditory) rather than hierarchical correspondence methods. Neighboring leaves like 'Vision Model-Brain Alignment' contain six papers examining layer-to-region mappings, while 'Representation Similarity and Alignment Metrics' addresses quantitative comparison methods. The 'Cross-Subject and Cross-Species Neural Alignment' branch (seven papers across three leaves) tackles biological alignment without DNN involvement. HOT's hierarchical transport approach bridges these areas by providing a unified metric applicable to both artificial networks and brain recordings, positioning it at the intersection of representation similarity metrics and hierarchical correspondence.

Among the 14 candidates examined through limited semantic search, none clearly refute any of HOT's three contributions. The core HOT framework examined one candidate with no refutable overlap. The rotation-invariant extension reviewed five candidates, all non-refutable or unclear. The three-level training trajectory alignment examined eight candidates, again with no clear prior work. This suggests that within the examined scope, HOT's specific combination of hierarchical optimal transport with soft layer couplings and global alignment scores represents a novel methodological direction, though the limited search scale (14 papers) means substantial related work may exist beyond this analysis.

Based on the examined literature, HOT appears to introduce a distinctive approach to hierarchical alignment, particularly in its treatment of depth mismatches and global consistency. However, the analysis covers only top-14 semantic matches plus citation expansion, not an exhaustive survey. The sparse population of its taxonomy leaf and absence of refutable candidates within this scope suggest novelty, but a broader search across the 50-paper taxonomy and beyond would be needed to fully assess whether similar transport-based hierarchical methods exist in adjacent research areas.

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

Contribution 1: Hierarchical Optimal Transport (HOT) framework

Description: HOT is a novel framework for representational alignment that simultaneously optimizes neuron-to-neuron couplings within layers and layer-to-layer couplings across network hierarchies. Unlike standard pairwise methods, it allows source neurons to distribute mass across multiple target layers while enforcing global consistency through marginal constraints, producing a single network-level alignment score and naturally handling depth mismatches.

This contribution was assessed against **1 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. FedPFT: Federated Proxy Fine-Tuning of Foundation Models

URL: View paper

Brief Assessment

FedPFT[51] addresses federated learning for foundation model fine-tuning through layer-wise compression and knowledge distillation, not representational alignment across neural networks. The technical focus is entirely different from HOT's joint optimization of neuron-to-neuron and layer-to-layer couplings for comparing representations.

Contribution 2: Rotation-invariant extension of HOT

Description: This extension augments HOT with learned rotation matrices for each layer pair, enabling the framework to recover correspondences even when shared representational features are embedded in rotated subspaces. The method alternates between optimizing transport couplings and orthogonal Procrustes alignment, ensuring geometric equivalences are properly captured.

This contribution was assessed against **5 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. Orthogonal Transforms For Learning Invariant Representations In Equivariant Neural Networks

URL: View paper

Brief Assessment

Orthogonal Transform Learning[53] focuses on embedding rotation-invariant positional encodings using polar harmonic transforms in equivariant CNNs for image classification, not on rotation-invariant optimal transport methods for neural network alignment across layers.

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2. VBA: VECTOR BUNDLE ATTENTION FOR INTRINSI

URL: View paper

Brief Assessment

VBA[56] focuses on vector bundle attention with parallel transport for geometric alignment in transformers, not on optimal transport methods with orthogonal transformations for neural network layer alignment. The technical approaches and problem domains are fundamentally different.

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3. Scale, translation, and rotation invariant orthonormalized optical/optoelectronic neural networks.

URL: View paper

Brief Assessment

Scale Translation Rotation[54] full text is not available (marked as 'n/a'), making it impossible to assess whether it refutes the novelty of the rotation-invariant HOT extension.

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4. A linear optimal transportation framework for quantifying and visualizing variations in sets of images

URL: View paper

Brief Assessment

Linear Optimal Transportation[52] focuses on linearized optimal transport for image analysis with rotation alignment of centers of mass, not hierarchical neural network layer alignment with orthogonal Procrustes optimization.

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5. SEINT: AN EFFICIENT SE (p)-INVARIANT TRANSPORT METRIC DRIVEN BY POLAR TRANSPORT DISCREPANCY-BASED REPRESENTATION

URL: View paper

Brief Assessment

SEINT[55] focuses on SE(p)-invariant optimal transport for comparing probability distributions in Banach spaces, not on hierarchical layer-to-layer alignment in neural networks. The rotation-invariance mechanisms differ fundamentally: SEINT achieves invariance through polar transport discrepancy representations, while the original paper uses orthogonal Procrustes alignment between network layers.

Contribution 3: Three-level HOT for training trajectory alignment

Description: This extension adds a third hierarchical level to HOT that operates over training checkpoints, enabling alignment of entire training trajectories between two models. The method solves an additional optimal transport problem over checkpoint-level costs derived from two-level HOT comparisons at each checkpoint pair.

This contribution was assessed against **8 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. TransMarker: Unveiling dynamic network biomarkers in cancer progression through cross-state graph alignment and optimal transport

URL: View paper

Brief Assessment

TransMarker[59] focuses on cross-state alignment of gene regulatory networks in cancer progression using Gromov-Wasserstein optimal transport, not on aligning neural network training trajectories across checkpoints using hierarchical optimal transport.

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2. Optimal hierarchical modular topologies for producing limited sustained activation of neural networks

URL: View paper

Brief Assessment

Optimal Hierarchical Topologies[64] focuses on hierarchical modular network topologies for sustaining neural activation patterns in brain-inspired networks, not on aligning training trajectories of neural networks using optimal transport methods.

3. Tree Mover's Distance: Bridging Graph Metrics and Stability of Graph Neural Networks

URL: View paper

Brief Assessment

Tree Movers Distance[63] focuses on hierarchical optimal transport between computation trees of graphs for measuring graph distances and GNN stability. It does not address training trajectory alignment across checkpoints, which is the core novelty of the three-level HOT contribution.

4. Adaptive Distribution Calibration for Few-Shot Learning with Hierarchical Optimal Transport

URL: View paper

Brief Assessment

Hierarchical Optimal Transport[57] focuses on few-shot learning with distribution calibration using a two-level hierarchical OT framework (base classes to novel samples, and samples within base classes). It does not address training trajectory alignment across checkpoints.

5. Generalization, Expressivity, and Universality of Graph Neural Networks on Attributed Graphs

URL: View paper

Brief Assessment

Graph Neural Universality[61] focuses on graph neural networks and uses hierarchical optimal transport for comparing graph structures via computation trees, not for aligning training trajectories of neural networks across checkpoints. The domains and applications are fundamentally different.

6. Predefined-time distributed optimization and anti-disturbance control for nonlinear multi-agent system with neural network estimator: A hierarchical framework.

URL: View paper

Brief Assessment

Predefined Time Optimization[60] focuses on distributed optimization and anti-disturbance control for nonlinear multi-agent systems, which is an entirely different domain from neural network training trajectory alignment using hierarchical optimal transport.

7. Deep Shells: Unsupervised Shape Correspondence with Optimal Transport

URL: View paper

Brief Assessment

Deep Shells[58] focuses on unsupervised 3D shape correspondence using optimal transport for spatial matching between geometric surfaces, not on aligning neural network training trajectories across checkpoints.

8. On Online Unsupervised Domain Adaptation

URL: View paper

Brief Assessment

Online Domain Adaptation[62] focuses on incremental domain alignment across time-steps in unsupervised domain adaptation scenarios, not on aligning training trajectories of neural networks across checkpoints using hierarchical optimal transport.

Appendix: Text Similarity Detection

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

References

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