Common representations underlie idiosyncratic neural topographies

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Abstract

Primary sensory brain areas contain innate stereotyped topographies like retinotopy and somatotopy, but association cortex shows more idiosyncratic organization. Using a twin sample from the human connectome project and functional magnetic resonance imaging, we test the hypothesis that idiosyncrasies are the byproduct of convergent learning and subserve common functional representations.

We combined representational similarity analysis, full brain neuromaps and twin heritability models to investigate the spatial profiles and sources of representational and topographic similarity across diverse task conditions and at rest. We found common representational geometry with idiosyncratic topographies in both task evoked responses and resting state network organization. Common representations with idiosyncratic topographies were especially common in transmodal brain areas, late in the cortical hierarchy, but did not show consistent associations with neuromaps of genetic or developmental markers. Additionally, while topography was heritable, response geometry was not, indicating it was learned.

These findings are consistent with experience dependent but convergent circuit organization during development, and echoes learning principles in artificial neural networks where circuit weights are always idiosyncratic but learned representations are nevertheless predictable. This shows how similar principles affect brain organization. Differing topographies in association cortex are at least in part subtle implementation differences that underlie shared representations.

Keywords: interindividual differences; cortical topographies; representational geometry; fMRI; genes; learning

Introduction

Sensory cortices are organized topographically (e.g. retinotopy, tonotopy, somatotopy), but association cortex tends to be more idiosyncratic (Sydnor et al., 2021). Topographic idiosyncracies are assumed to represent functional differences, based largely on findings in sensory cortices. However, an alternative is that seemingly idiosyncratic organization can arise from convergent learning processes that yield common functional representations across individuals but with different spatial implementations. Consistent with this view, artificial neural networks (ANNs) with identical architectures but different random initializations converge on similar representational geometries while differing in internal weight ”topographies” (Kornblith et al., 2019). Unlike computational models, the experiences shaping brain organization are diverse and build on an equally diverse genetic scaffold, so it remains unclear whether adult functional representations are also convergent in association cortex. Here, we test this hypothesis by assessing the relationship between topographic similarity (which function maps where) and representational similarity (what information is encoded).

Methods and Results

First we inspected topography and representational geometry across 23 task evoked responses in 207 independent dyads of unrelated individuals. This included motor, gambling, social, working memory, emotional processing and an abstract shape-matching tasks (Barch et al., 2013). For each dyad we subdivided the brain into 518 regions and computed mean between-participant cosine similarity of evoked responses for each region, a measure of topographic similarity. We then estimated cross-validated Mahalanobis distances between response topographies, capturing how each parcel distinguishes among tasks within an individual. This produced representational dissimilarity matrices (RDMs) which we compared between participants (i.e., whitened unbiased cosine similarity of RDMs, WUC (Diedrichsen et al., 2021)). Topographic similarity and geometric similarity showed differing spatial profiles (**Figure 1**).

Topographies are more idiosyncratic in association cortex than sensory cortex (Sydnor et al., 2021), but the reason why remains unknown and these brain areas differ in many ways. We evaluated the profiles of geometric and topographic similarity with respect to published neuromaps aligned with the sensory-association axis (Markello et al., 2022). These included measures of transcriptomic variation, evolutionary recency, developmental timelines, and computational con-

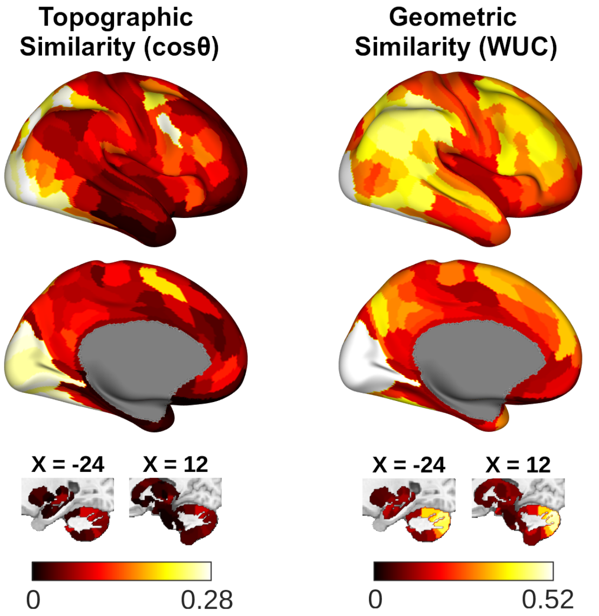

Figure 1: Similar representations are more common than similar topographies.

straints (mylenation, thickness, network hierarchy). In particular, wiring constraints (e.g. myelnation), and network hierarchy determine the extent of idiosyncratic organization or representational convergence (respectively) in computational models (Margalit et al., 2024; Saxe et al., 2019; Kornblith et al., 2019), while cortical thickness may indirectly indicate myelination (Natu et al., 2019), neural density or laminar differentiation and corresponding architectural constraints. We found representations were more similar while topographies were more dissimilar in evolutionarily recent transmodal areas late in the network hierarchy and late to develop (**Figure 2**).

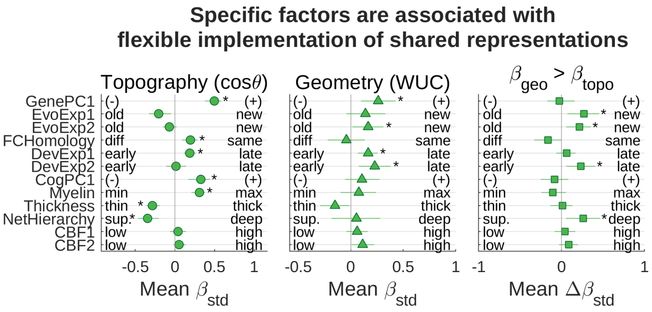

Figure 2: Geometry and topography are associated with and distinguished by distinct neuromaps (spatial regression). *p <0.05, spatial permutation (spin) test, Holm-Sidak corrected.

To test the generality of our findings we repeated this analysis with 1 hour of resting state data per participant. We derived individualized resting state networks for our participants using dual regression and a 25 network template provided by the HCP. We treated networks the same as our evoked response data to compute topographic and geometric similarity (WUC of network RDMs). We once again found regions late in the cortical network hierarchy showed idiosyncratic topographies with similar geometry (Standardized $\beta_{geom} - \beta_{topo}$ = 0.154, p = 0.0004, spatial permutation (spin) test). No other neuromap associations were found.

ANN models suggest representational convergence is a consequence of learning dynamics when architecture, training data and learning rules are similar (Saxe et al., 2019). Topographies are under strong genetic control, but whether geometry is innate or learned remains poorly understood. We tested the heritability of task evoked response geometry and topography using related individuals in the HCP dataset. We found topography was highly heritable (ACE model, h^2=0.04±[0.02, 0.06], $CI_{.95}$, family-wise BCa bootstrap), but geometry was not (h^2=0.01±[-0.02, 0.05], **Figure 3**). Common early life environment played no role. This suggests response geometry is likely learned from generic environmental factors shared among all HCP participants.

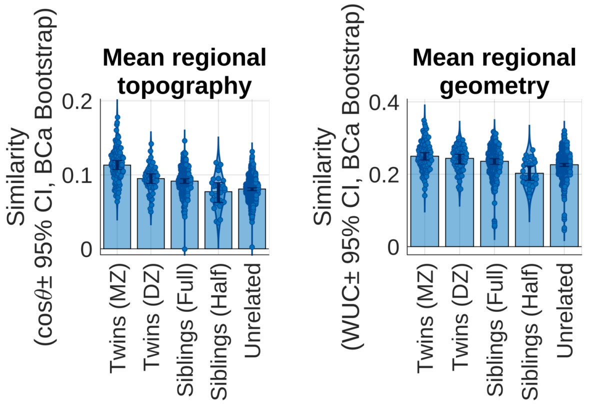

Figure 3: Familial similarities show topography (left), not geometry (right), is heritable. MZ: monozygotic, DZ: dizygotic.

Conclusion

Our results show that association cortex exhibits substantial idiosyncratic topographic organization but nonetheless supports a convergent representational code across individuals. This parallels insights from ANNs, in which distinct weight configurations can yield highly similar functional representations. Additionally, genetic influences significantly constrain cortical topographies yet appear to have less impact on emergent representational geometry, suggesting that higher-level functional organization is more plastic and learned. Together, these findings bridge computational theory and neuroscience by highlighting how similar functional solutions can emerge despite individual differences in spatial organization of the brain.

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