Comparative and reproducible three-dimension functional spaces in primate cortical connectomes

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ABSTRACT

Intrinsic activity or spontaneous oscillations are believed to be essential for the brain to maintain flexible, adaptive, and responsive cognition to both internal and external demands. However, a functional space remains elusive for understanding this inside-outside organization in the primate cortex. Here, we leverage comparative fMRI analysis to identify three conserved and reproducible functional connectivity gradients as three axes of manifold (FMA), which span a low-dimensional organizational space of wakeful primate connectomes. In humans, the primary FMA covers a sensorimotor-to-transmodal gradient that supports signal detection for allostatic anticipation. The second FMA mirrors a representation-to-modulation gradient that integrates attention and performance monitoring to compute prediction errors. The third FMA profiles a self-to-goal gradient that links salience processing and episodic memory to update brain prediction by weighting errors and contextual relevance. Marmosets exhibit a homologous tripartite structure, suggesting evolutionary conservation of predictive coding motifs, albeit with species-specific topological variations. These findings unify predictive coding, allostasis, and intrinsic activity into a signal-error-salience predictive modeling framework, where sensory integration, error computation, and salience modulation interact to optimize adaptive responses. By bridging neurocomputational theory with empirical connectomics, this work establishes a cross-species blueprint of brain organization, offering experimental evidences or insights into conserved mechanisms of free energy principles and dark energy explorations. These FMAs highlight how evolution refines neural architectures while preserving core computational principles, paving the way for mechanistic studies of predictive dysfunction and evolutionary drivers of primate brain complexity.

INTRODUCTION

The organization of brain activity and its relationship to cognition and behavior has increasingly been approached through the lens of manifolds of connectivity or gradients [1,2]. This mathematical framework offers a way to analyze and represent complex neural data in spacetime, providing information on the underlying structures and dynamics of the organization of the primate brain [3]. The concept of cortical gradients refers to continuous spatial variations in connectomic profiles across the cortex. The brain organizes its connectivity along these gradients, with functional regions smoothly transitioning from one state to another [4]. By modeling these gradients as manifolds, researchers are now able to uncover how different brain regions interact and how they change in response to different cognitive states or behaviors, with implications for linking brain structure with function [5].

Previous research highlights how gradients in neuron density, connectivity, and gene expression shape primate cortical organization and suggests that gradients play a crucial role in brain function and offer insight into the evolution and development of brain networks between species [6,7]. The cortical gradients derived using functional magnetic resonance (fMRI) data characterize the main axes of continuous variations in brain connectivity across the cortex, a function manifold reflecting spatially organized patterns, where the cortical regions are hierarchically or topographically organized and related along the gradients. We note that the cortical gradient methods only keep a set of the most strong functional connectivity (e.g., the top 10% connectivity) for consideration [8]. This threshold-based choice has derived consistent gradients of cortical organization between functional connectivity in the human brain and structural connectivity in the monkey brain [4]. Beyond the tenet behind such a threshold choice to approximate the underlying structural connectivity, the wave-like perspective of brain function indicated that all connectivity are meaningful properties of cortical wave propagation [9,10]. Thus, a function manifold from the full fMRI connectivity data is essential to understand the cortical organization of primate brain function but remains elusive.

Comparative and reproducible analysis of the function manifolds has been difficult due to challenges of performing fMRI in wakeful nonhuman primate brains. In this work, we used two large-scale open datasets of resting-state fMRI (rfMRI) measurements from the Human Connectome Project (HCP) and the Chinese HCP (CHCP) to reconstruct the function manifold in the human cortical organization. Meanwhile, the same manifold analysis was also performed for wakeful marmoset brains based on two open rfMRI datasets from the National Institute of Health (NIH) and the Institute of Neuroscience (ION) at the Chinese Academy of Sciences.

RESULTS

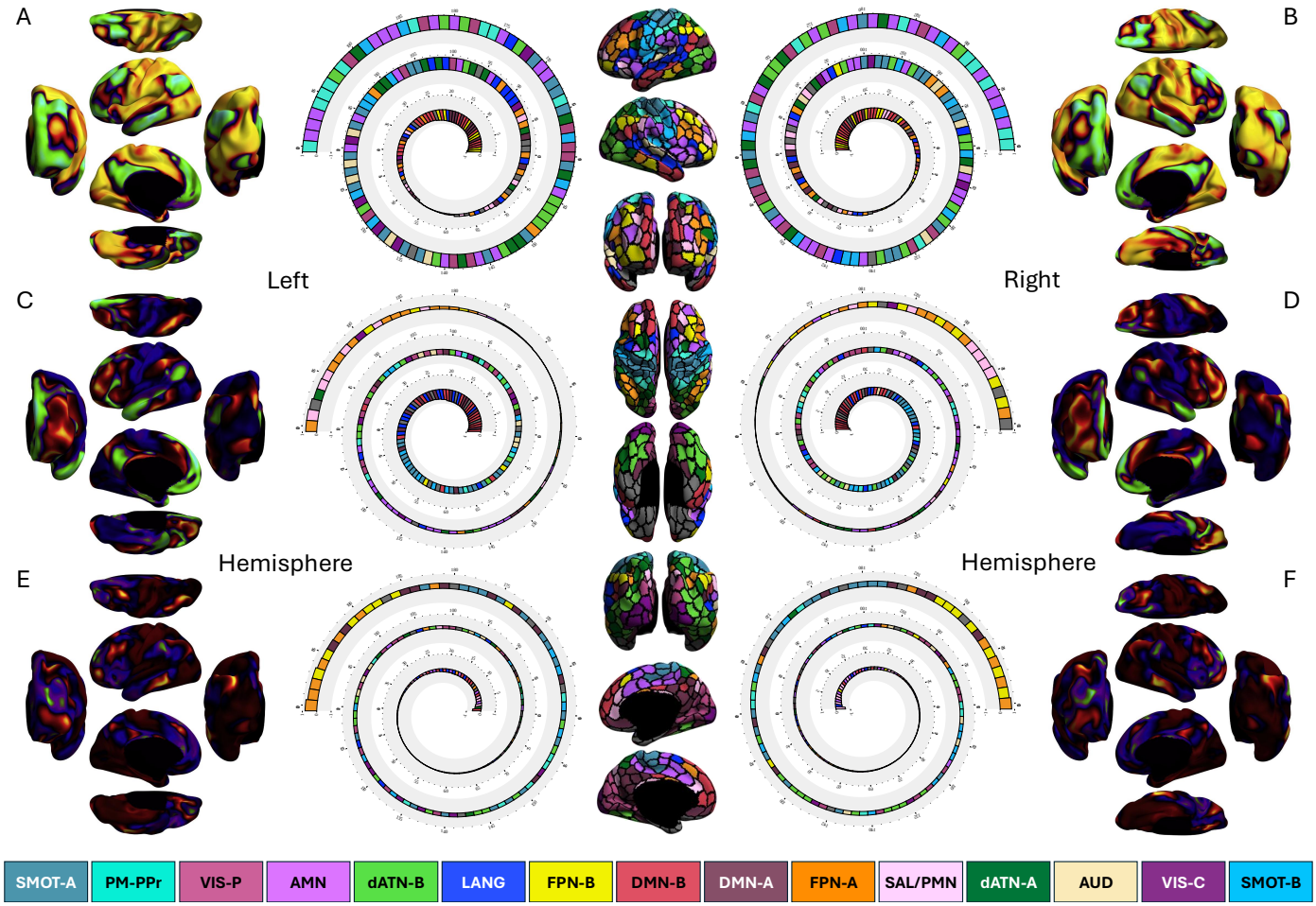

Figure 1: Top three gradient maps derived from the complete HCP connectivity matrix as axes of the functional manifold in the human cortical connectome. The left column (A,C,E) depicts the maps in the left hemisphere, and the right column (B,D,F) depicts the maps in the right hemisphere. The gradient values are averaged and ranked along spiral trajectories from the green-end inside to the yellow-end outside according to 200 parcellating units of each hemisphere [11]. These parcels are colored and rendered onto the human cerebral cortex in terms of the fifteen canonical cortical networks defined in previous studies [12,13]: Somatomotor-A (SMOT-A), Somatomotor-B (SMOT-B), Premotor-Posterior Parietal Rostral (PM-PPr), Action-Mode Network (AMN), Salience/Parietal Memory Network (SAL/PMN), Dorsal Attention-A (dATN-A), Dorsal Attention-B (dATN-B), Frontoparietal Network-A (FPN-A), Frontoparietal Network-B (FPN-B), Default-Mode Network-A (DMN-A), Default-Mode Network-B (DMN-B), Language (LANG), Visual Central (VIS-C), Visual Peripheral (VIS-P), and Auditory (AUD).

The Mega-ICA Group-PCA (MIGP) method [14] is used to construct a group-level connectome matrix from preprocessed rfMRI data, which are described in previous publications [15–17]. It is designed to efficiently reduce the dimensionality of large-scale fMRI datasets while preserving meaningful functional connectivity patterns across individuals. MIGP generates dense connectomes from HCP, CHCP, NIH and ION datasets, respectively. These complete connectivity matrices are analyzed (that is, without the sparsity threshold) using BrainSpace toolbox [8], producing a series of gradients on the organization of the cortical connectivity. Specifically, the top three gradients are reproducible between independent datasets and explain a large portion of the observed variances in complete brain connectivity maps (HCP: 20.6%, 14.0%, 6.0%; CHCP: 20.3%, 12.2%, 6.6%; NIH: 46.8%, 19.2%, 6.5%; ION: 36.6%, 26.5%, 7.2%). We thus take the three gradients as a low-dimensional approximation of the high-dimension cortical connectivity space or its low-dimension geometry. From this perspective, these gradients form a three-dimensional manifold on the cortical connectivity geom-

etry of the human brain function, that is, a function manifold. To visualize the functional manifold, we rescale each gradient to the same range from -1 to 1 and plot each vertex on the cortical surface as a point in the 3D space of the function manifold spanned by the three gradients as axes. The function manifold forms the surface of a regular tetrahedron or a functional representation in the human (HCP/CHCP, Fig. S1A/S2A) but not marmoset (NIH/ION, Fig. S1B/S2B).

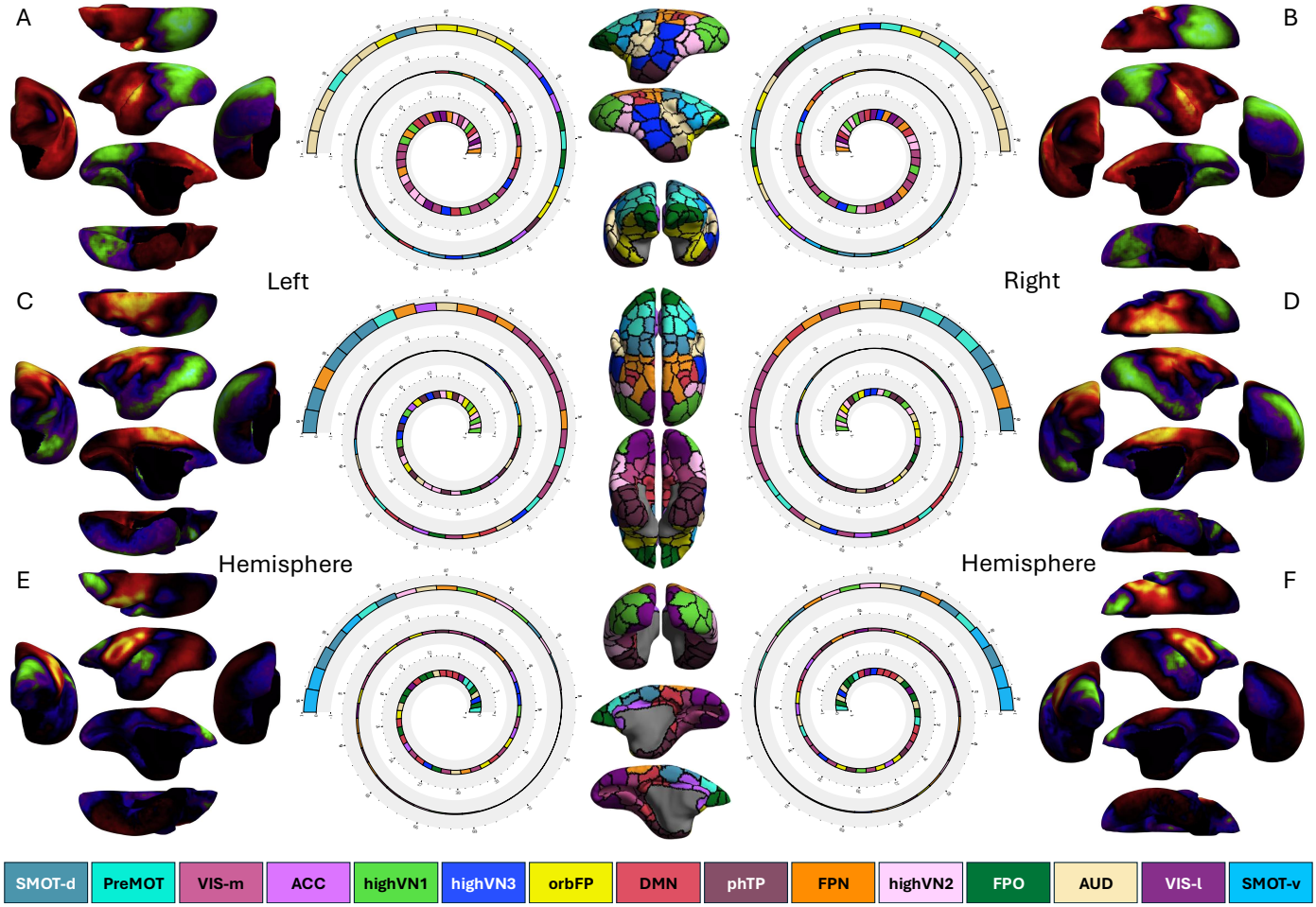

Figure 2: Top three gradient maps derived from the complete NIH connectivity matrix as axes of the functional manifold in the marmoset cortical connectome. The left column (A,C,E) depicts the maps in the left hemisphere, and the right column (B,D,F) depicts the maps in the right hemisphere. The gradient values are averaged and ranked along spiral trajectories from the green-end inside to the yellow-end outside according to 96 parcels in each hemisphere [17]. These parcels are rendered onto the marmoset cerebral cortex in terms of the fifteen canonical cortical networks defined in [17] using the same colorset as in the human cortical network parcellation: dorsal somatomotor (SMOT-d), ventral somatomotor (SMOT-v), premotor (PreMOT), medial primary visual and MT/MST (VIS-l), lateral primary visual and MT/MST (VIS-m), auditory and insular cortex (AUD), anterior cingulate cortex (ACC), frontal pole (FPO), high-level 1 visual-related network (highVN1), high-level 2 visual-related network (highVN2), high-level 3 visual-related network (highVN3), orbital frontal (orbFP), frontoparietal-like network (FPN), default-mode-like network (DMN), the parahippocampus/temporal pole (phTP).

To further delineate anatomy of the function manifold in the human cortex, we extract mean rescaled gradient values of all the vertices within each of the 200 parcellating units [11] assigned to fifteen canonical cortical networks defined in DU15NET [12] for each hemisphere, and plot them along a spiral trajectory in ascending order. As shown in Fig. 1A/1B, the first FMA (FMA-I) starts inside the spiral from the frontoparietal network (FPN-B) and default-mode network (DMN-B and DMN-A), and ends outside the spiral at the premotor-posterior parietal rostral network (PM-PPr), action-mode network (AMN) [13], dorsal attention network (dATN-B), visual network (VIS-P). The second FMA (FMA-II, Fig. 1C/1D) starts inside the spiral from DMN-B and DMN-A, language network (LANG), and ends outside the spiral at FPN-A, salience and parietal memory network (SAL/PMN), dATN-A. The third FMA (FMA-III) starts inside the spiral from SAL/PMN, DMN-B, AMN, dATN-A, and ends outside the spiral at FPN-A and FPN-B, DMN-A (Fig. 1E/1F). All the findings reported here are reproducible between HCP and CHCP (Fig. 1, Fig. S3).

We delineate the anatomy of the function manifold in the marmoset cortex in a similar vein by extracting mean rescaled gradient values of all vertices within each of the 96 parcellating units assigned to fifteen canonical cortical networks defined in [17]. FMA-I (Fig.

2A/2B) starts inside the spiral from the high-level 2 visual-related network (highVN2), frontoparietal-like network (FPN), lateral primary visual and MT/MST visual-related network (VIS-l), default-mode-like network (DMN), and ends outside the spiral at the auditory and insular cortex salience-related network (AUD), premotor network (preMOT). FMA-II (Fig. 2C/2D) starts inside the spiral from the high-level 1 visual-related network (highVN1), highVN2, orbital frontal network (orbFO), and ends outside the spiral at the dorsal somatomotor network (SMOT-d), FPN. FMA-III (Fig. 2E/2F) starts inside the spiral from the frontal pole network (FPO), preMOT, high-level 3 visual-related network (highVN3), AUD, and ends outside the spiral at the dorsal and ventral somatomotor networks (SMOT-d and SMOT-v). All the findings reported here are reproducible between NIH and ION (Fig. 2, Fig. S4).

DISCUSSION

The brain operates as a highly dynamic and self-organizing system governed by the principles of free energy and predictive coding, where it continuously minimizes prediction errors through the constant comparison of sensory input with internal models [18]. This enables the brain to anticipate and optimize responses to the environment, supporting allostasis, the regulation of internal states for adaptive survival [19]. The brain exhibits the feature of the cost of "dark energy" through spontaneous intrinsic neural activity [20] to maintain homeostasis, prepare for future events and facilitate communication between functional networks, and supports efficient cognitive processing [12]. These processes, from inside-outside interactions between the brain and the body to top-down predictions and bottom-up sensory integration, form a unified system that allows the brain to remain flexible, adaptive, and responsive to both internal and external demands. Our findings, for the first time, provide three reproducible dimensions of functional space in such a complex system as a basis to characterize its inside-out coordination observed by using fMRI to primate connectomes.

Although the three axes (that is, gradient maps) of this functional space conceptually represent distinct aspects of characterizing the inside-outside organization in the primate cortex [21], it is quite open and challenging to determine or interpret their exact roles in achieving predictive models of brain function. In human cortex, FMA-I has been documented as the sensorimotor-association, unimodal-transmodal or external-internal gradient for a core feature of the human brain organization to support a domain-general motif [4,22]. We argue that it serves as a signal-detection motif to capture the predictable information flow along the external environment and the internal environment to serve the prediction of allostasis [23]. FMA-II has a similar spatial profile to the multiple demand system or the representation-modulation system [22], forming an error-calculation motif to compute predictive errors by combining attention regulation, goal maintenance, strategy selection, performance monitoring with mental content. FMA-III has rarely been reported by previous gradient studies, although several recent work demonstrated some sparse evidence linking it to the recognition process of goal-directed and self-directed functions related to salience learning and episodic memory [24–26]. We speculate on this axis as a salience-generation motif to support updates of the prediction by providing weights on both prediction signals and errors. In the marmoset cortex, we note that a similar structure of the outside-inside functional space was observed. We argue that the three axes revealed form a signal-error-salience predictive model in marmosets similar to humans but with a different shape as in Figs. S1 and S2. However, understanding their comparative insights raises challenges and opportunities for future studies [27] because fMRI studies in awakened animals are much limited compared to those in humans [28,29].

Our work produces comparative and reproducible low-dimensional representations of primate functional connectomes at the group level. This addresses functional references in the brain connectivity space for individualized FMA mapping methods. The spacetime dual regression [30] on these references will achieve reliable and valid FMA measurements at the individual level.

MATERIALS AND METHODS

The wakeful resting-state fMRI data are from the Human Connectome Project (HCP, N = 1003) [15] and the Chinese HCP (CHCP, N = 217) [16] for healthy human young adults while the NIH (N = 26) and the ION (N = 13) resource from the Marmoset Brain Mapping Project [17]. All our analyses are based on group average preprocessed whole brain dense functional connectome (.dconn) data identifying temporal correlations between all cortical vertices and subcortical voxels. Specifically, each preprocessed individual data set was temporally trimmed and variance normalization applied and submitted to the principal component analysis (PCA) at the group level (MIGP) [14]. The output of the group PCA with the spatial eigenvectors weighted in the upper N (N = 4500 for HCP, 2000 for CHCP, N = 1800 for NIH and ION) is then renormalized, reweighted and correlated to form the average dense connectomes at the

group level ($91,282 \times 91,282$ entries for the HCP/CHCP and $76,457 \times 76,457$ entries for the NIH/ION). Diffusion map embedding is applied to identify a set of low-dimensional manifolds (i.e., gradients) capturing principal dimensions of spatial variation in connectivity. In particular, this algorithm is implemented in BrainSpace toolbox[8] without thresholding functional connectivity to derive the functional affinity or similarity of the functional connectivity matrix. The first three gradients span a 3D functional manifold in the wakeful connectome organization.

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AUTHOR CONTRIBUTIONS

Conception and Design: X-X.X., X-N.Z. Data Analysis: X-N.Z. Initial Drafting of the Manuscript: X-X.X. Critical Review and Editing of the Manuscript: X-X.X., X-N.Z.

AUTHOR COMPETING INTERESTS

Competing interests

The authors declare that they have no competing interests.

DATA AVAILABILITY

MIGP-derived data will be deposited in the Chinese Color Nest Project (CCNP) - Lifespan Brain-Mind Development data Community in the Science Data Bank (https://ccnp.scidb.cn/en).

CODE AVAILABILITY

All the codes will be deposited in the Chinese Color Nest Project (CCNP) - Lifespan Brain-Mind Development data Community in the Science Data Bank (https://ccnp.scidb.cn/en).

SUPPLEMENTARY INFORMATION

Supplementary Figures

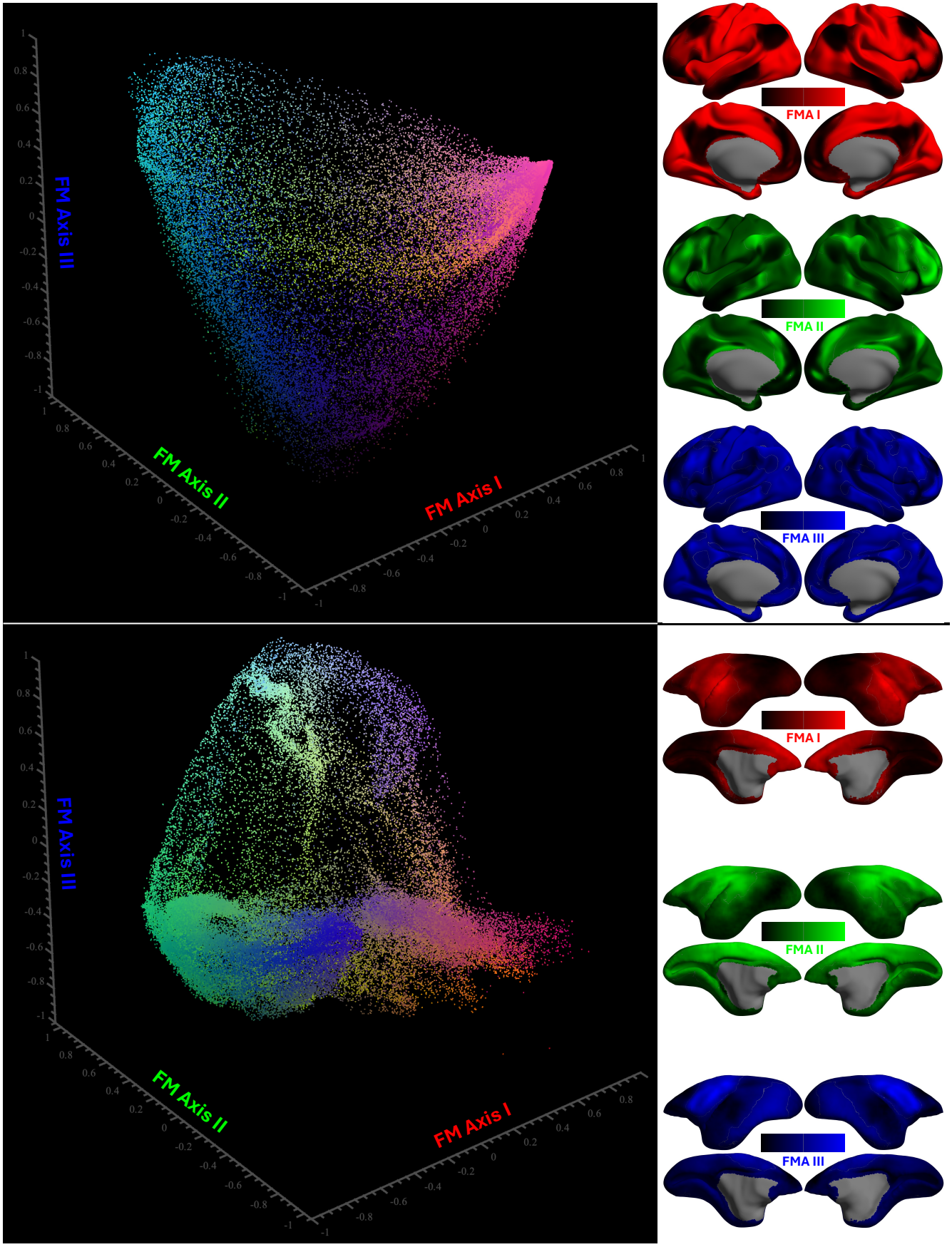

Figure 3: 3D space of the functional manifold in primate cortical connectomes. Three axes are the three gradients of functional connectivity (gradient 1: red, gradient 2: green, gradient 3: blue). Given a vertex on the cortical surface, we plot a point in the 3D space with its coordinates as its three gradient values (Top panel: HCP, Bottom panel: NIH).

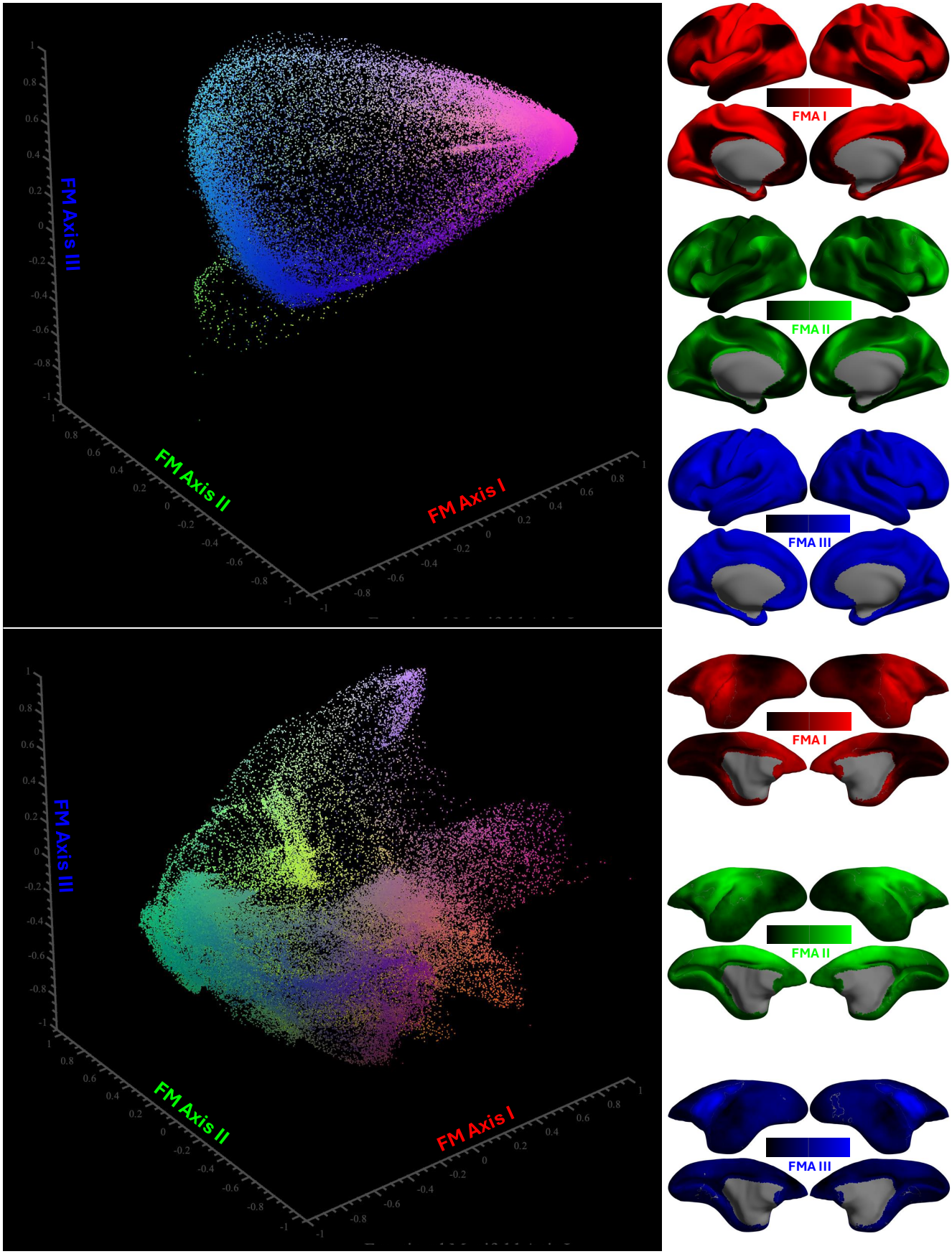

Figure 4: 3D space of the functional manifold in primate cortical connectomes. Three axes are the three gradients of functional connectivity (gradient 1: red, gradient 2: green, gradient 3: blue). Given a vertex on the cortical surface, we plot a point in the 3D space with its coordinates as its three gradient values (Top panel: CHCP, Bottom panel: ION).

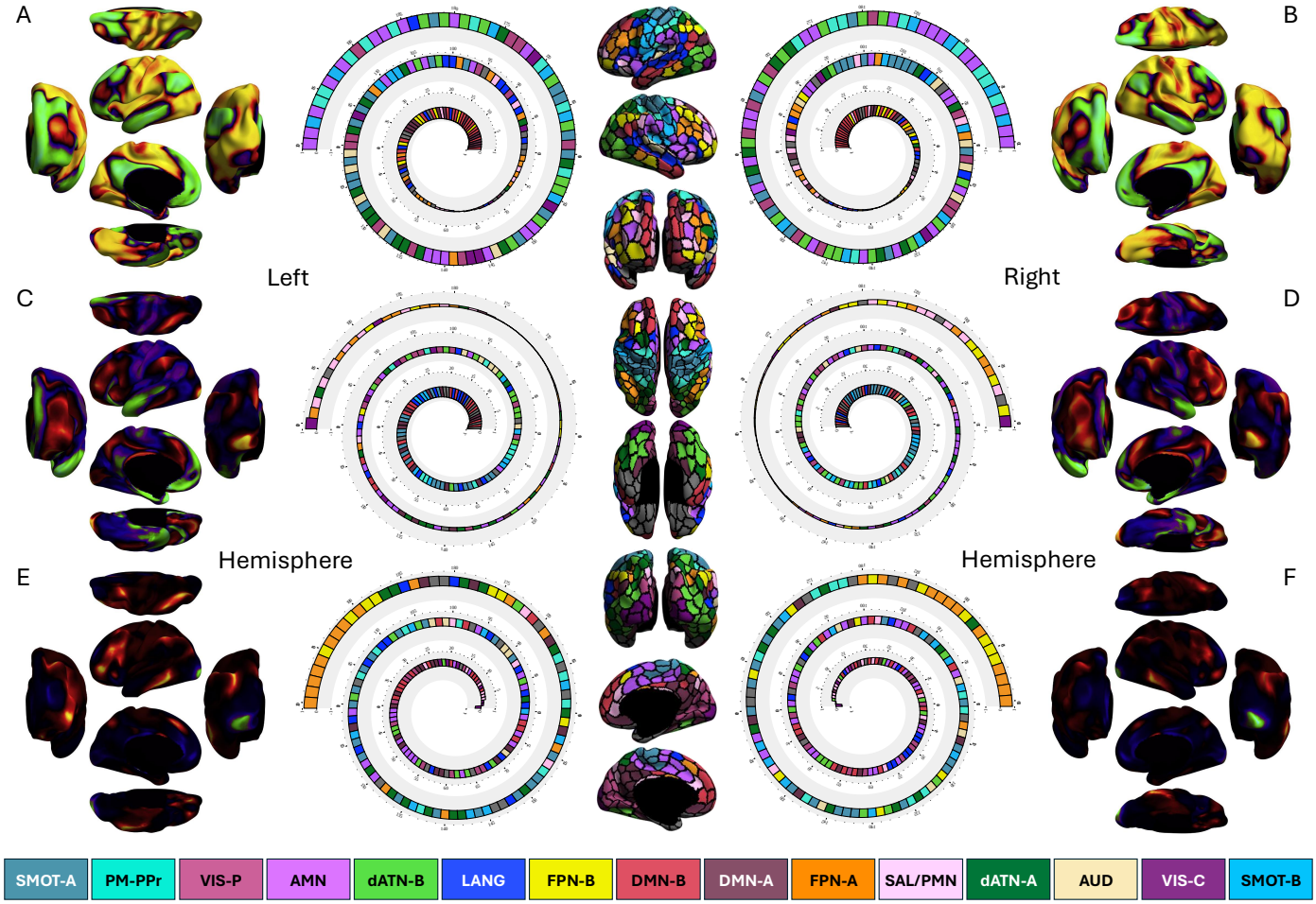

Figure 5: Top three gradient maps derived from the complete CHCP connectivity matrix as axes of the functional manifold in the human cortical connectome. The left column (A,C,E) depicts the maps in the left hemisphere, and the right column (B,D,F) depicts the maps in the right hemisphere. The gradient values are averaged and ranked along spiral trajectories from the green-end inside to the yellow-end outside according to 200 parcellating units of each hemisphere [11]. These parcels are colored and rendered onto the human cerebral cortex in terms of the fifteen canonical cortical networks defined in previous studies [12,13]: Somatomotor-A (SMOT-A), Somatomotor-B (SMOT-B), Premotor-Posterior Parietal Rostral (PM-PPr), Action-Mode Network (AMN), Salience/Parietal Memory Network (SAL/PMN), Dorsal Attention-A (dATN-A), Dorsal Attention-B (dATN-B), Frontoparietal Network-A (FPN-A), Frontoparietal Network-B (FPN-B), Default-Mode Network-A (DMN-A), Default-Mode Network-B (DMN-B), Language (LANG), Visual Central (VIS-C), Visual Peripheral (VIS-P), and Auditory (AUD).

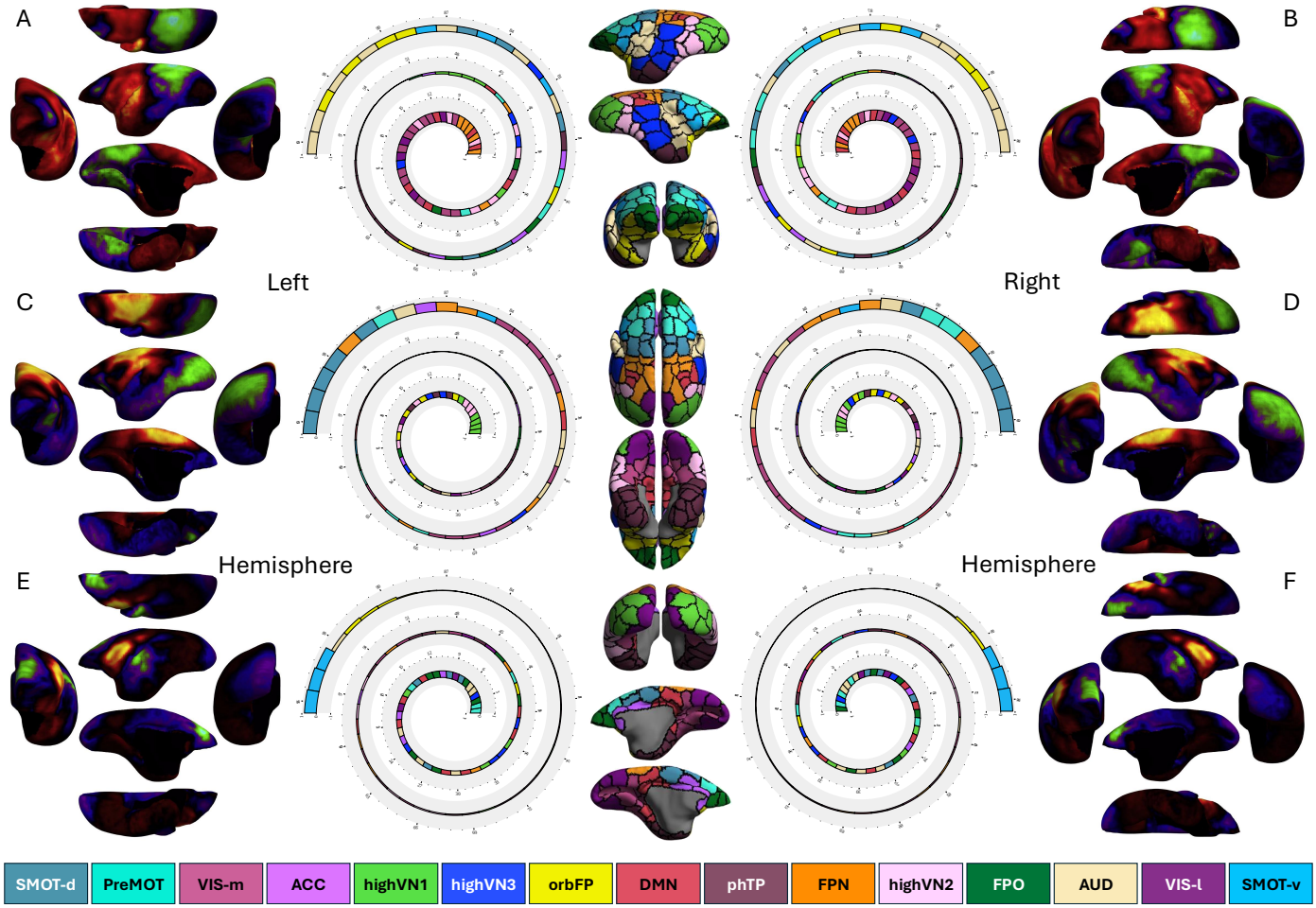

Figure 6: Top three gradient maps derived from the complete ION connectivity matrix as axes of the functional manifold in the marmoset cortical connectome. The left column (A,C,E) depicts the maps in the left hemisphere, and the right column (B,D,F) depicts the maps in the right hemisphere. The gradient values are averaged and ranked along spiral trajectories from the green-end inside to the yellow-end outside according to 96 parcels in each hemisphere [17]. These parcels are rendered onto the marmoset cerebral cortex in terms of the fifteen canonical cortical networks defined in [17] using the same colorset as in the human cortical network parcellation: dorsal somatomotor (SMOT-d), ventral somatomotor (SMOT-v), premotor (PreMOT), medial primary visual and MT/MST (VIS-l), lateral primary visual and MT/MST (VIS-m), auditory and insular cortex (AUD), anterior cingulate cortex (ACC), frontal pole (FPO), high-level 1 visual-related network (highVN1), high-level 2 visual-related network (highVN2), high-level 3 visual-related network (highVN3), orbital frontal (orbFP), frontoparietal-like network (FPN), default-mode-like network (DMN), the parahippocampus/temporal pole (phTP).

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