Fully Hyperbolic Neural Networks:
A novel approach to discover aging trajectories from MEG brain networks

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Characterizing age-related alterations in MEG brain networks holds great promise in understanding aging trajectories and revealing aberrant patterns of neurodegenerative disorders, such as Alzheimer's disease. Recently, graph neural network models have shown great potential in representing complex network (graph) data into embedding spaces where nodes are mapped onto low-dimensional vectors. However, the prevalent approach in graph representation learning involves embedding in the Euclidean space, which has limited representational capacity and high distortion when embedding the scale-free brain networks. In contrast, hyperbolic space, characterized by negative curvature, offers a direct solution to preserving local and global geometric information in scale-free brain graphs. This is because hyperbolic geometry is characterized by an exponential growth of space as we move away from the center, mirroring the exponential growth of brain networks (Figure 1a). Building upon this insight, we designed a novel hyperbolic MEG brain network embedding framework that transforms high-dimensional complex MEG brain networks into lower-dimensional hyperbolic representations. Our approach involved the design and validation of a new hyperbolic model built upon the architecture of the fully hyperbolic neural network (FHNN). Using this model, we computed hyperbolic embeddings of the MEG brain networks of 587 individuals from the Cambridge Centre for Ageing and Neuroscience (Cam-CAN) dataset (Figure 1b). In addition, we included in the model anatomical features of cortical grey matter thickness and myelination (as obtained by magnetization transfer ratio). Notably, we introduced *a unique metric—the radius of the node embeddings—which effectively proxies the hierarchical organization of the brain*. We leveraged this metric to characterize subtle hierarchical organization changes of various brain subnetworks attributed to the aging process. Our findings revealed that a considerable number of subnetworks exhibit a reduction in hierarchy during aging, with some displaying gradual changes and others undergoing abrupt transformations in the elderly (examples in Figure 1cde). Overall, our study presents the first evaluation of hyperbolic embeddings in MEG brain networks, introduces a novel multi-modal measure of brain hierarchy, and uses this measure to highlight aging trajectories in the large cohort of the Cam-CAN dataset.

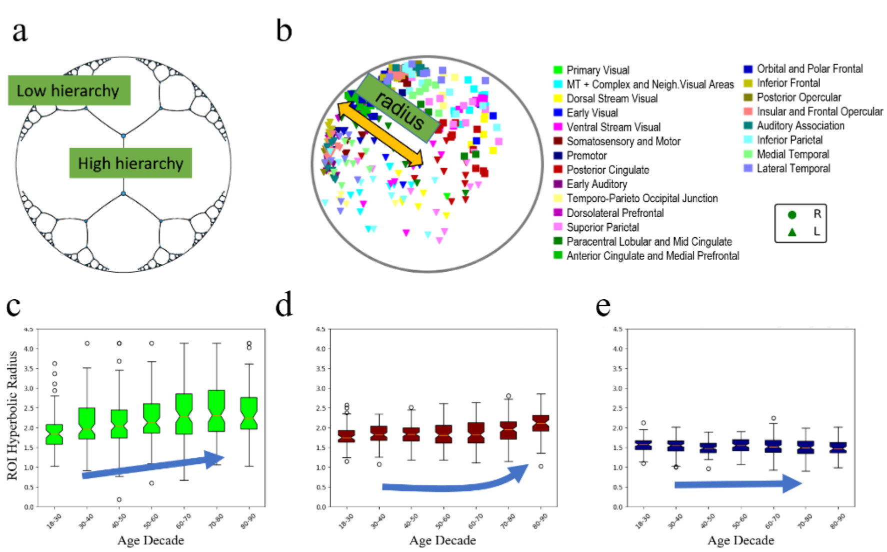

Figure 1: Hyperbolic embeddings of brain networks reveal aging trajectories. *(a) Example hyperbolic embedding of a binary tree. Hyperbolic space expands exponentially from center due to its negative curvature, enabling embeddings with minimal distortion. (b) Example hyperbolic embedding of the MEG network of a Cam-CAN participant. The hyperbolic radius effectively proxies the hierarchical organization of the brain. (c-d-e) Hyperbolic radius of left primary visual cortex, right orbital and polar frontal, and left paracentral lobular and mid cingulate, respectively. Each ROI undergoes a different trajectory over decades.*

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