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Self-Supervised Learning of Nerve Fiber Representations in 3D-PLI Data of the Human Brain

Analyzing the structural organization of the human brain involves the study of nerve fibers that connect neurons and whole brain regions. In addition, a deeper knowledge of the arrangement of these anatomical connections, also known as connectome, contributes to a better understanding of how the brain processes information. 3D Polarized Light Imaging (3D-PLI) exploits the birefringence of the myelin sheath to visualize short- and long-range single nerve fibers and fiber bundles, providing detailed images of fiber organization at the microscopic level. However, analyzing and interpreting the large amounts of complex data is time-consuming and requires expert knowledge. Since the complexity of nerve fiber organization is difficult to capture in a scalable manner using traditional feature extraction methods, we propose a data-driven approach to learn characteristic features of fiber architecture.

We train a deep neural network to map high-resolution image patches extracted from 3D-PLI sections to feature vectors that encode the fiber architectonic properties in the image patch. The model is trained on 500.000 patches (size 2048x2048 px at 2.66 μm/px) from 26 3D-PLI human brain sections using a contrastive learning approach. The method is based on the assumption that spatially close image patches have more structural similarity than more distant pairs. The idea is to train a neural network that pulls feature representations of similar inputs closer together and pushes those of dissimilar inputs apart in feature space. Similarity between two image patches is computed using the Radial Basis Function (RBF) kernel applied to the Euclidean distance between their corresponding 3D brain coordinates.

Our analysis shows that clustering in latent space reveals distinctions between subcortical regions and remaining tissue, and that atlas labeling reveals a grouping of structures that aligns with brain regions and fiber bundles. Evaluating coordinate regression and spatial anchoring tasks demonstrates that the learned features better preserve spatial relationships and achieve lower Mean-Squared-Error (MSE) than classical texture features. These results demonstrate that the learned representations encode nerve fiber properties and structural information, providing an important foundation for developing scalable analysis methods for fiber architecture in the human brain.

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