Diffusion-adapted spatial filtering of fMRI data for improved activation mapping in white matter

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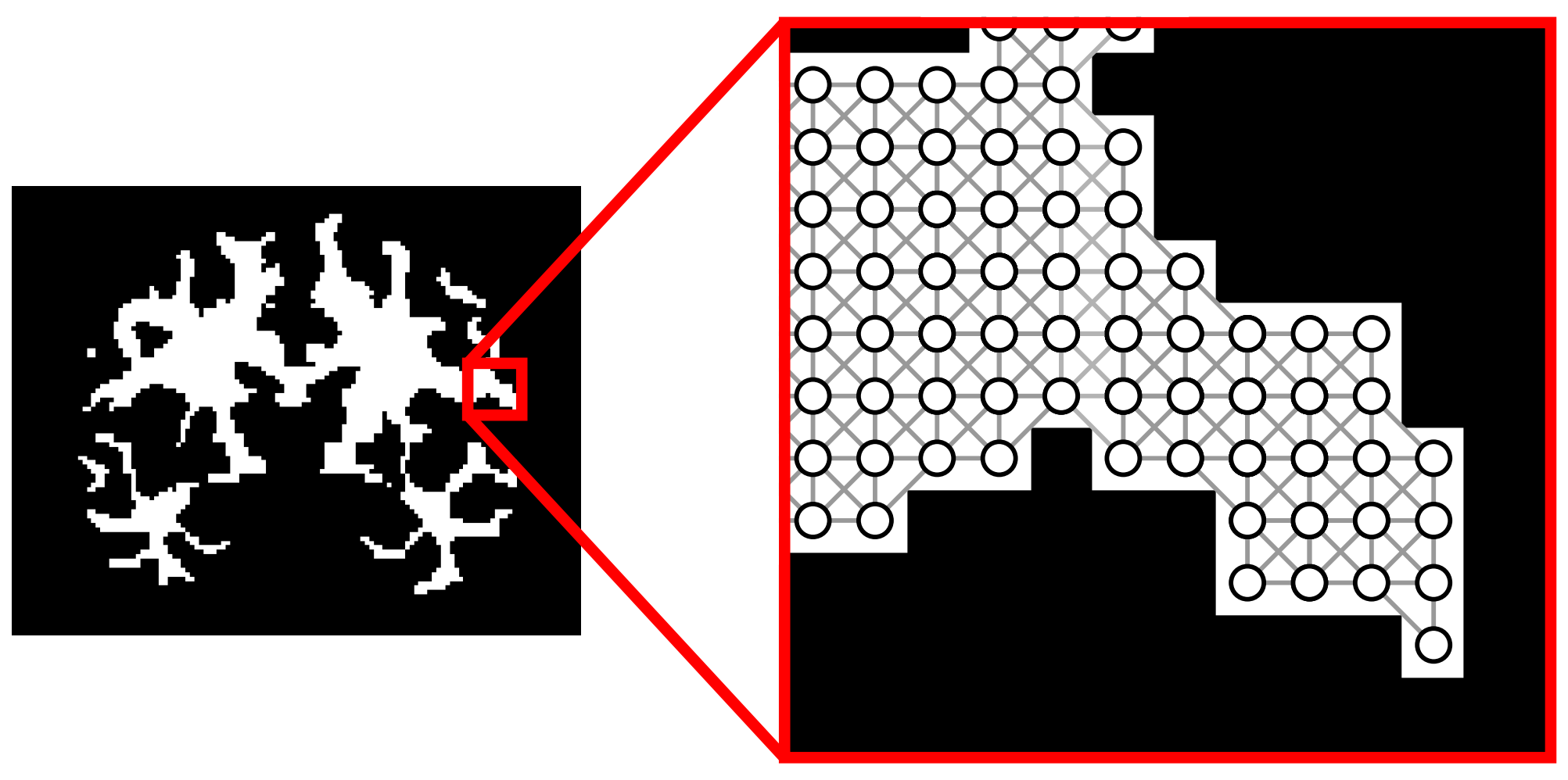
Abstract

Task-related BOLD activations in white matter are a controversial topic. However, the amount of reports of such activations is increasing [1]. We suggest that isotropic Gaussian filtering may be inadequate for finding activations in white matter, and propose instead a graph-based and diffusion-informed filtering approach that adapts to both the topology and microstructure of white matter. White matter differs from gray matter in the directionality of its microstructure. The BOLD signal of white matter voxels shows elevated correlation along structural tracts [2]. Isotropic filtering approaches will potentially mix together signal present in distinct tracts, while a diffusion-informed graph-based representation is capable of accounting for the local microstructure at each point, and thus, prevent the mixing of activations along different tracts. Similar domain-adapted approaches have successfully been implemented for gray matter [3].

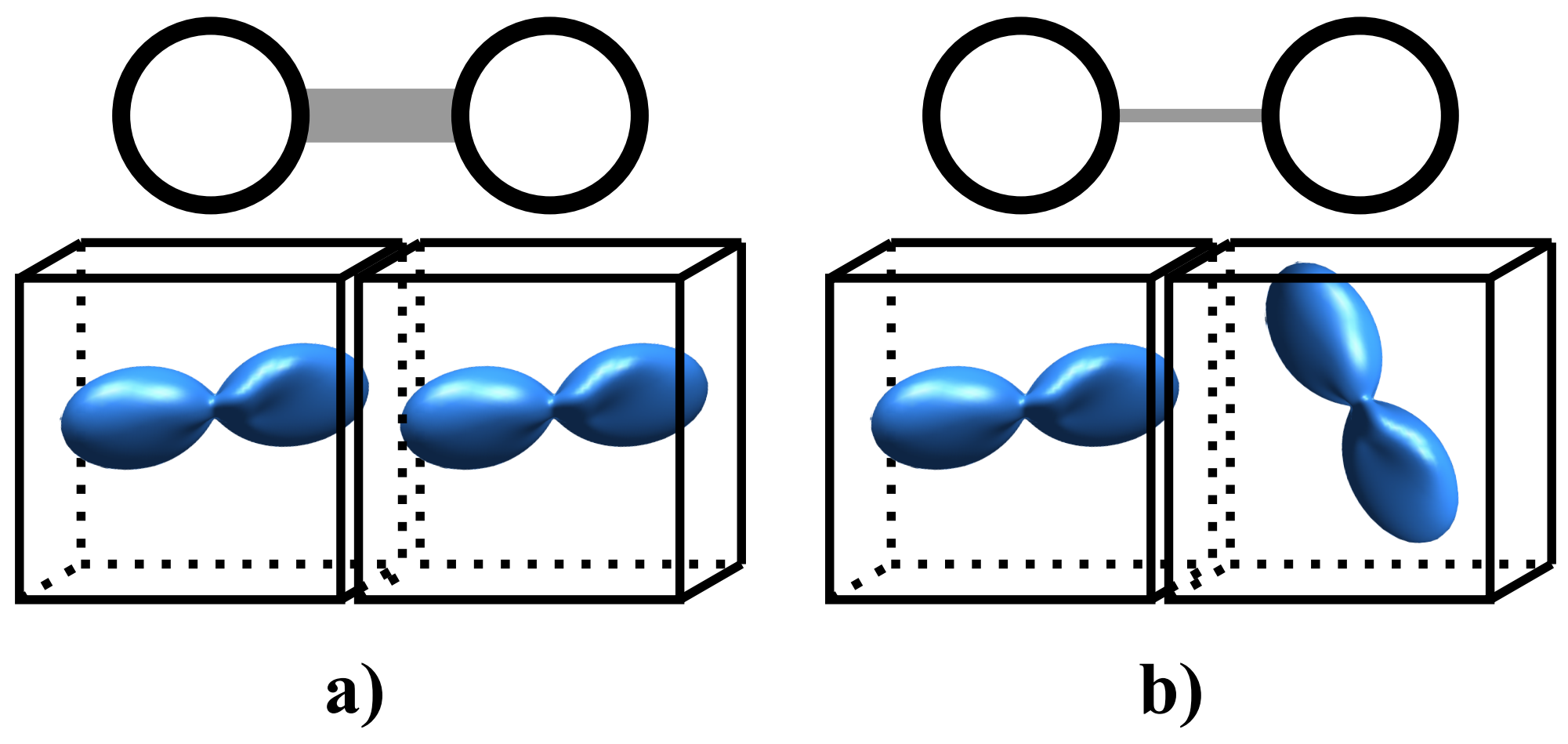
Methods

Diffusion-informed white matter graph

A graph scheme was used to encode the directionality and spatial extent of axonal connections in white matter. White matter voxels constituted the nodes of the graph, and the edges were specified based on the adjacency of voxels within a 5x5x5 neighborhood. A weight, derived from diffusion data, was assigned to each edge to represent the degree of coherence in the directions of the axons passing through the associated voxel pair.



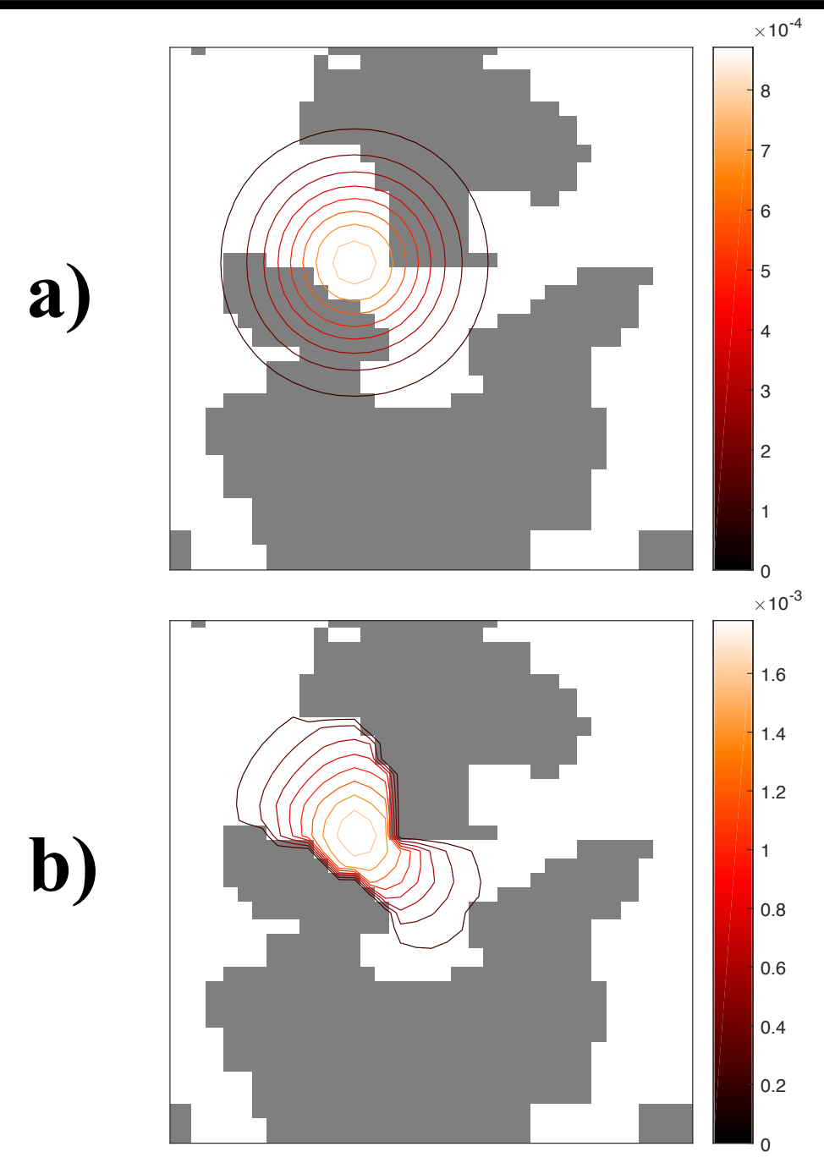
Graph defined on white matter voxels, with 26 connectivity used for illustration.



a) High degrees of diffusion coherence result in large edge weights between voxels and b) vice versa.

Spectral graph filtering of white matter fMRI data

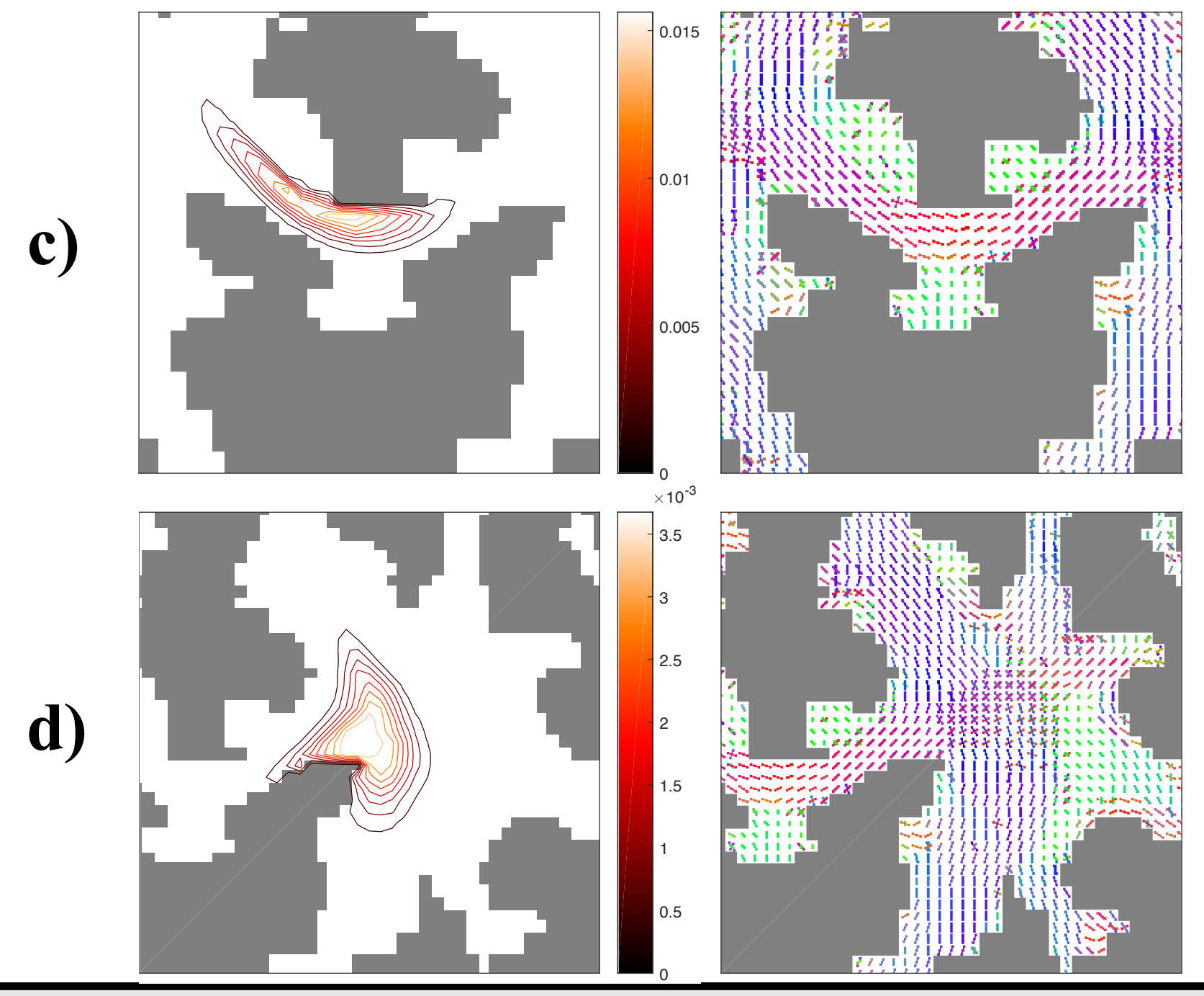
Filters were defined on the spectral domain of the constructed graph. The spatial extent of such filters when localized at any given point is dependent on the graph's edge weights, and thus adapts to the underlying local axonal structure of white matter. Heat kernel filters were used, as they were found to be roughly equivalent to Gaussian filters in the Euclidean domain. The extent of these filters is defined by a single parameter τ.



a) Gaussian isotropic filtering accounts for neither the topology nor the microstructure of white matter.

b) Graph filters constructed using the unweighted white matter graph adapt to the white matter topology, but not the microstructure.

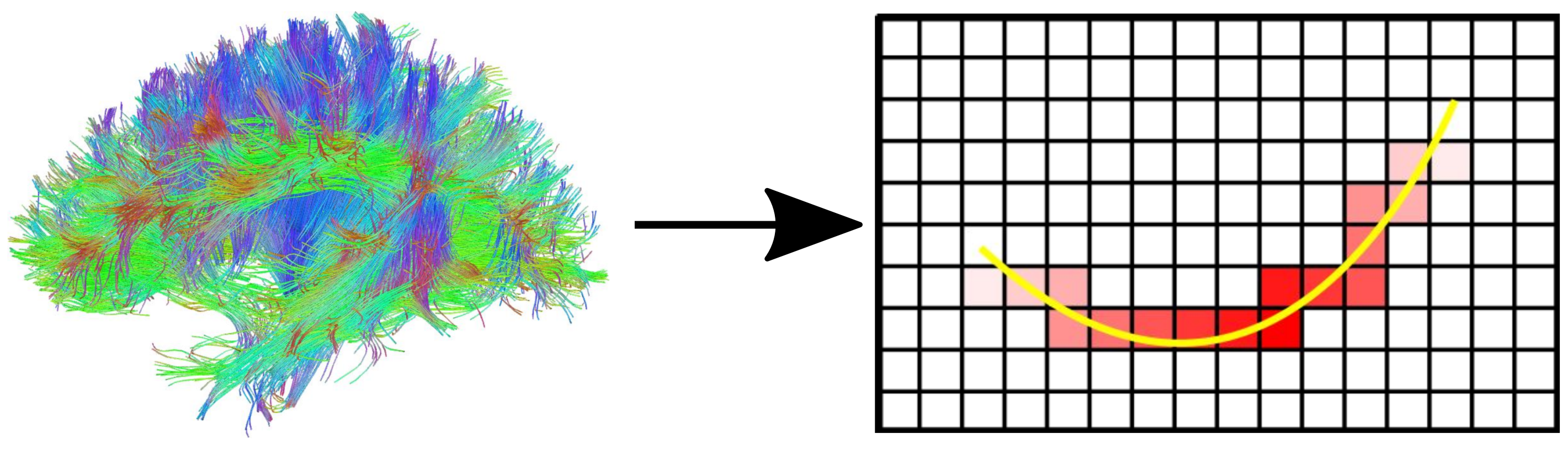
c) - d) Graph filters constructed using the weighted white matter graph adapt to both the topology and microstructure of white matter. The associated white matter diffusion directions are shown to the right.



Results

Datasets

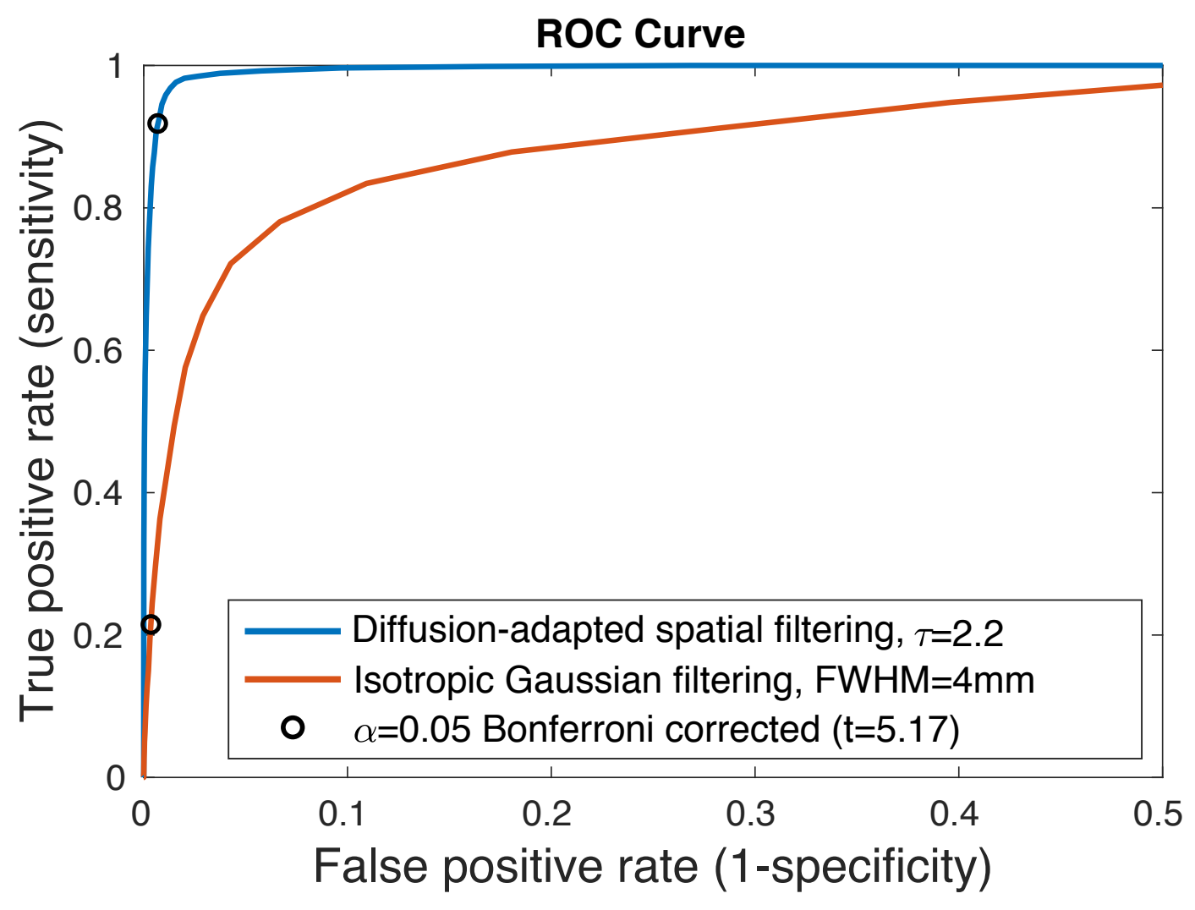
The proposed filtering method was evaluated on a semi-synthetic dataset, as well as on real data from the Human Connectome Project. The semi-synthetic data consisted of synthetic activation patterns produced using streamlines obtained through tractography of a real subject. The activations were then combined with resting state fMRI data as a realistic source of noise. The real data was obtained from subjects undertaking a motor task. Following filtering, a GLM was fitted to the data and statistical inference was performed.



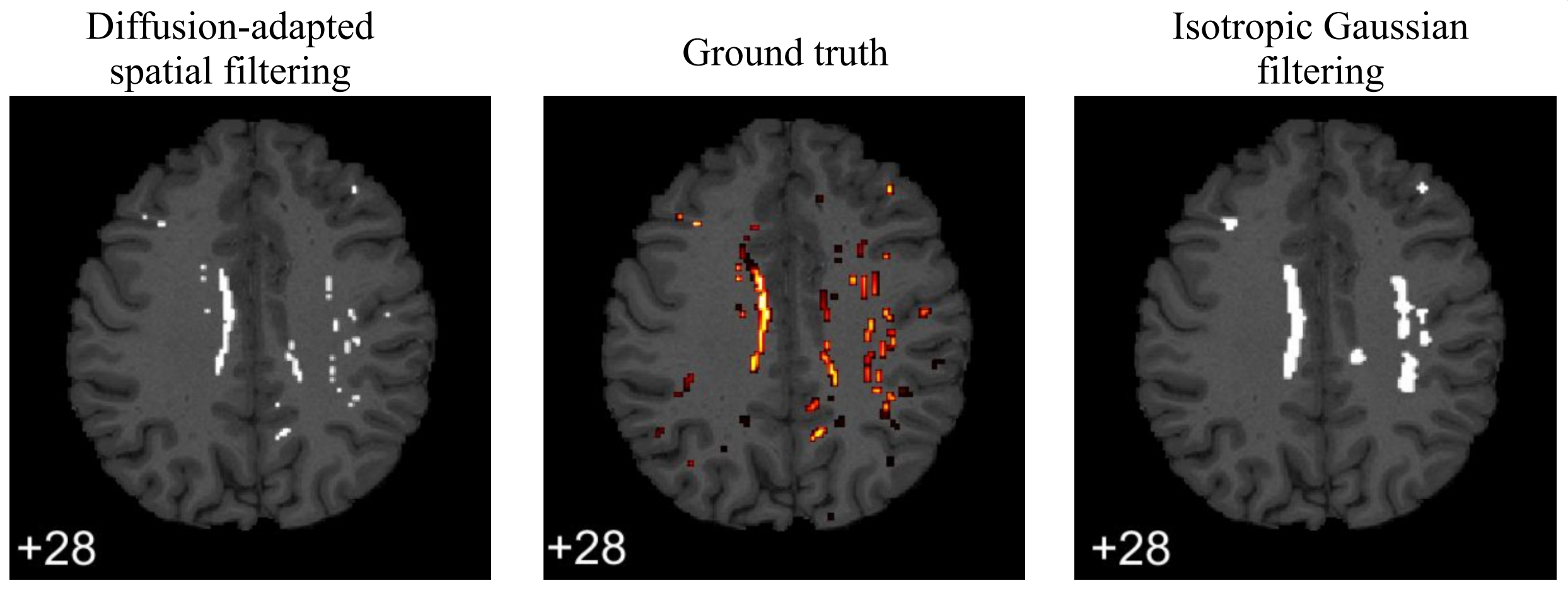
To create streamline-shaped activations random sets of streamlines were extracted from a whole-brain tractography and rasterized. Activations were created starting at a random point, and diffused along the length of the streamline.

Semi-synthetic data

The proposed diffusion-adapted spatial filtering approach shows enhanced sensitivity and specificity compared to isotropic Gaussian filtering across a wide range of filter sizes and thresholding levels. Activations detected using graph filtering conserve the intricate shapes of the original phantom.



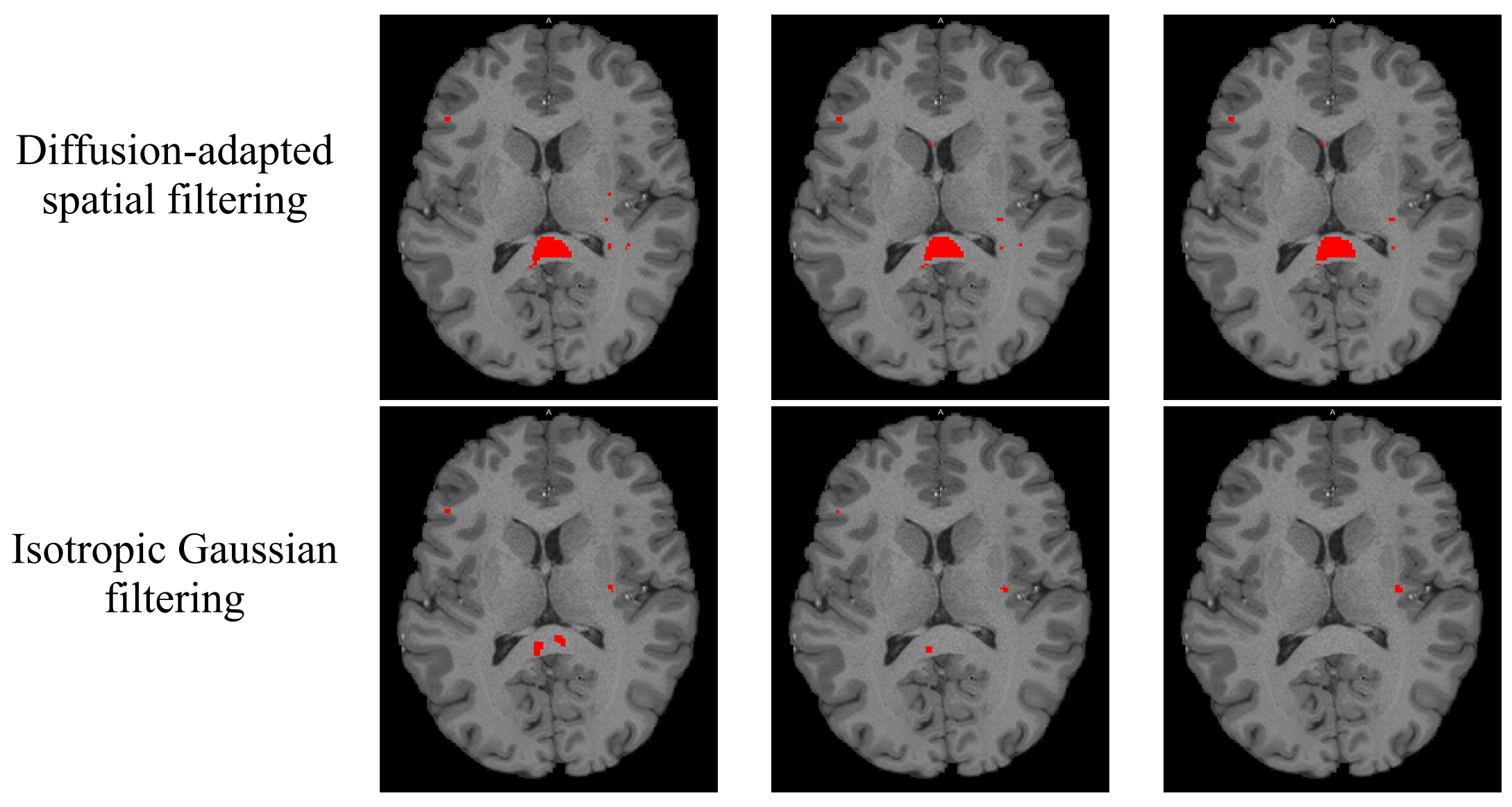
ROC curve comparing both filtering approaches. Diffusion-adapted spatial filtering outperformed isotropic Gaussian filtering at all threshold levels.



Detected activations for 50 streamline phantom, filtered with τ=2.2 and FWHM=4mm, and thresholded at α=0.05, Bonferroni corrected.

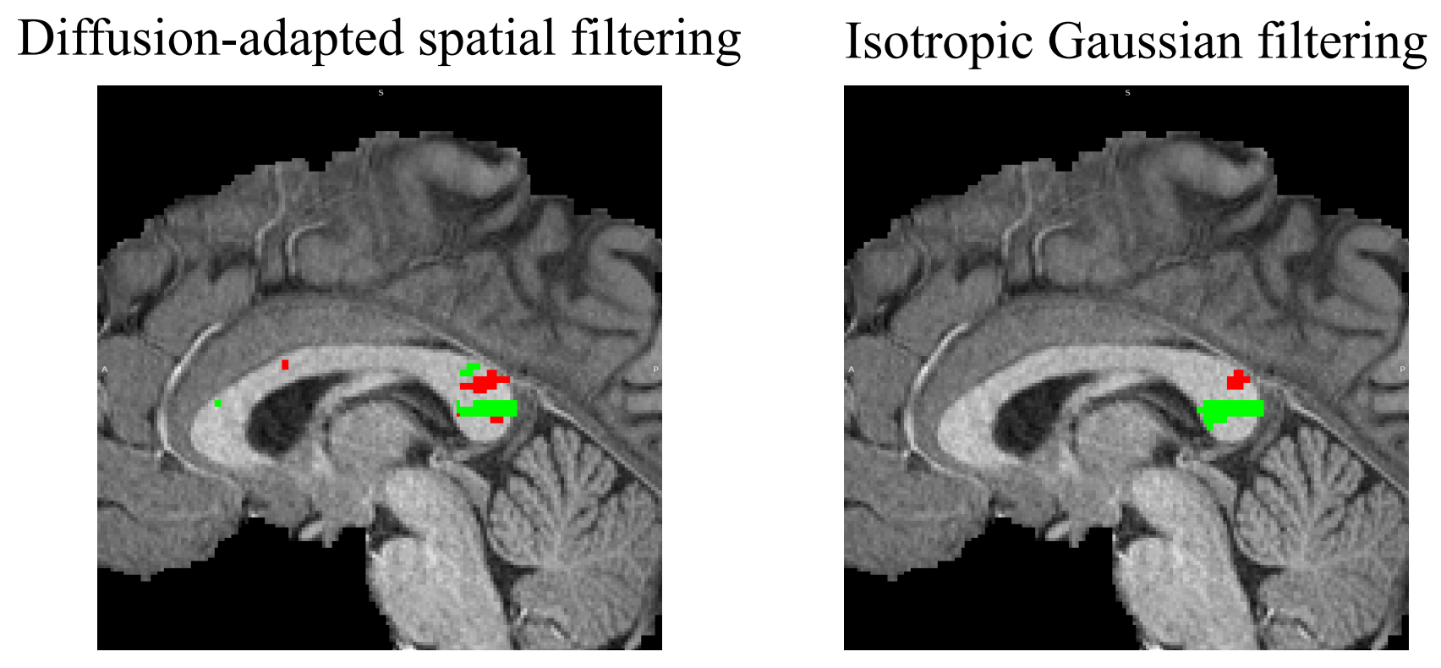
Real data

Diffusion-adapted spatial filtering shows larger activation patterns, suggesting a higher sensitivity. The detected patterns are intricate and highly directional. Moreover, consistent activations are observed across a range of filter sizes.



Results for HCP motor task using various filter sizes for both approaches. Diffusion-adapted spatial filtering finds substantially larger activations on the corpus callosum, accross filter sizes. Isotropic Gaussian filtering mixes large amounts of unrelated signal as the filter size increases, limiting its capacity of finding white matter activations.

Top row: τ=2.2, 2.75, 3.3.
Bottom row: FWHM = 4, 5, 6 mm.
Both corrected at 5% FDR.



Diffusion-adapted spatial filtering can facilitate the creation of a corpus callosum atlas, which illustrates which regions experience activation under different tasks.
Red and green correspond to left and right hand activations respectively.
τ = 3.3, FWHM = 6 mm, both corrected at 5% FDR.

References

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