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Unified analysis of shape and structural connectivity of neural pathways

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Introduction :

An abnormal brain development due to a neuropsychiatric disorder can influence the shape and the anatomical organization of both white and grey matter structures. An example is the syndrome of Gilles de la Tourette (GTS) which is thought to be associated with dysfunctions of the cortico-striato-pallido-thalamic circuits [6]. These anatomical complexes should be studied as a whole, analysing both the shape and the relative position of their structures.

Atlas constructions permit to estimate an average shape complex of a given population, called template, and its deformations towards the shape complexes of each subject. The template represents the morphological invariants of the population whereas the deformations capture its variability.

Previous works defined these deformations as single diffeomorphisms acting on the entire 3D space, so that ending points of fiber bundles could not move independently of grey matter structures [1,2,4,5]. This implicitly assumes that fiber bundles connect the same areas of grey matter structures across subjects. This assumption is not compatible with the aforementioned hypothesis about GTS [6] which relates the syndrome to atypical configurations of neural circuits.

We propose a new atlas construction method which can handle both fibers and surfaces and which is based on a double diffeomorphism. This permits to analyse the morphological variations of each structure and the changes in the relative position between fiber bundles and grey matter structures, namely the variations in structural connectivity.

Methods :

The template is deformed towards each subject using a composition of two diffeomorphisms. The first one deforms only the fiber bundles keeping fixed the grey matter structures (White deformation). It makes the fiber bundles “slide” onto the grey matter structures. Thus, it models the changes in the relative position between white and grey matter structures. The second deformation acts on both grey and white matter objects, putting into correspondence the homologous anatomical structures (All deformation).

Template and deformation parameters are estimated using a Bayesian framework similarly to [2]. This permits to automatically estimate the weight of each component within the cost function. This is crucial in a multi-object analysis.

Fiber bundles are approximated with tubes called weighted prototypes [3]. They are chosen among the fibers and their radius is related to the number of fibers approximated. This new representation is more concise than the original one permitting to reduce the computational cost.

We illustrate the approach on 5 subjects (2 controls and 3 GTS patients) using left cortex, putamen and the fiber bundle connecting them. Cortex and putamen were segmented from T1-weighted MRI using FreeSurfer and FSL respectively. The fiber bundle was obtained using a deterministic tractography from DWI [6].

Results :

A double diffeomorphic matching between two shape complexes is shown in Fig.1.

Fig.2 and 3 show the deformation of the fiber bundle template along the first mode of PCA based on the parameters of the White deformation. They highlight the main changes in structural connectivity. Changes concern mainly the frontal and parietal lobe of the cortex and the dorsal part of the putamen.

Fig.4 shows the deformation of the grey matter templates along the first mode of PCA based on the parameters of the All deformation. It describes the main morphological changes in the grey matter structures. There is mainly a shortening/elongation along the anterior-posterior axis of the cortex and an elongation and rotation of the inferior part of the putamen.

Conclusions :

We proposed an approach to study the variability of structural connectivity and the shape variations of both white and grey matter structures within a population. It is based on a new mathematical concept called double diffeomorphism. It shall provide a useful tool to study atypical configurations of neural pathways associated with brain disorders.

References:

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Double diffeomorphic registration

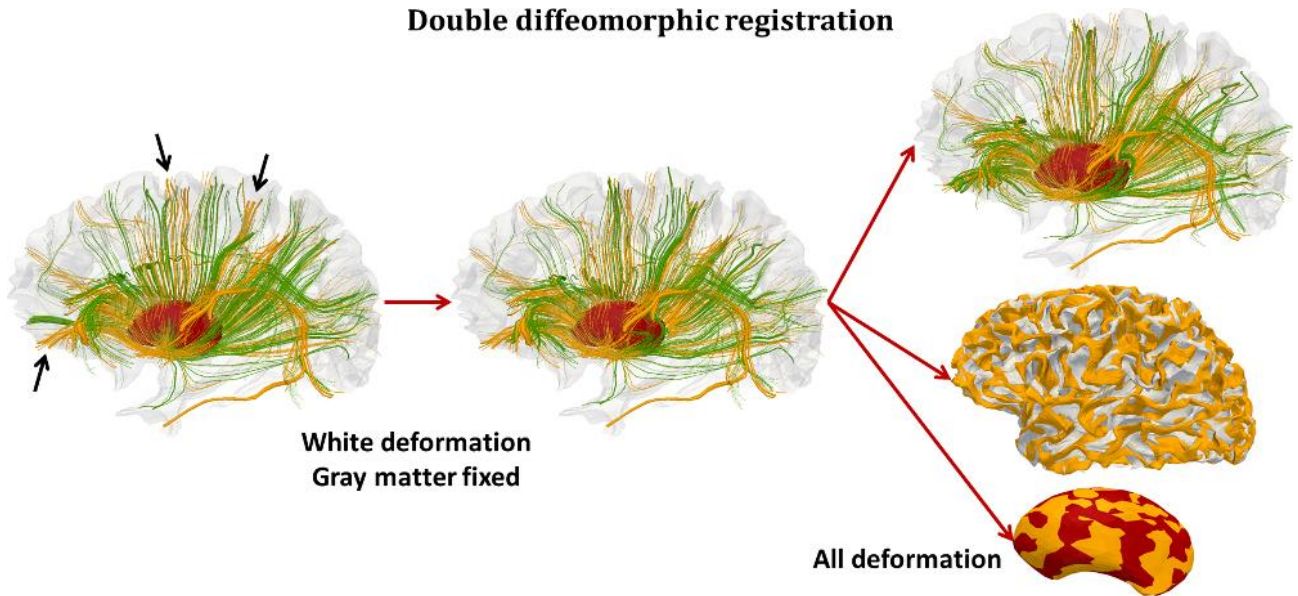


Figure 1 – The complex composed by the red putamen, grey cortex and green fiber bundle is deformed towards the orange complex. The first deformation acts only on the green fiber bundle. Then, all structures are well matched via the second deformation. Arrows indicate the most deformed fascicules of the green fiber bundle.

Main variations in the connected areas due to the White deformation

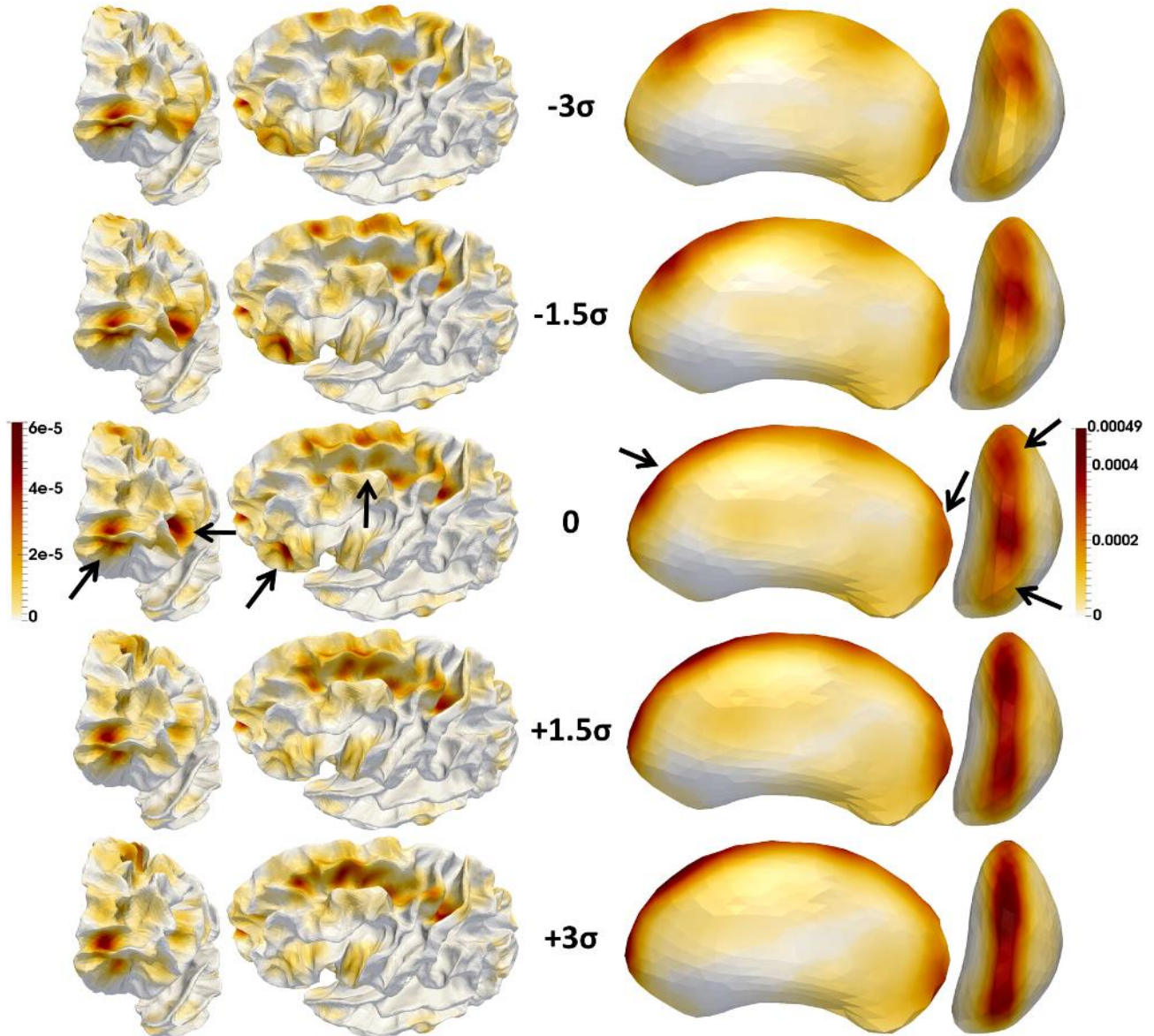


Figure 2 – Deformation of the fiber bundle template along the first mode of PCA based on the parameters of the White deformation. Colors refer to the probability densities of the endpoints of the fibers onto the fixed grey matter templates. Arrows indicate the areas showing the greatest variability.

Main variations in the fibers pathway due to the White deformation

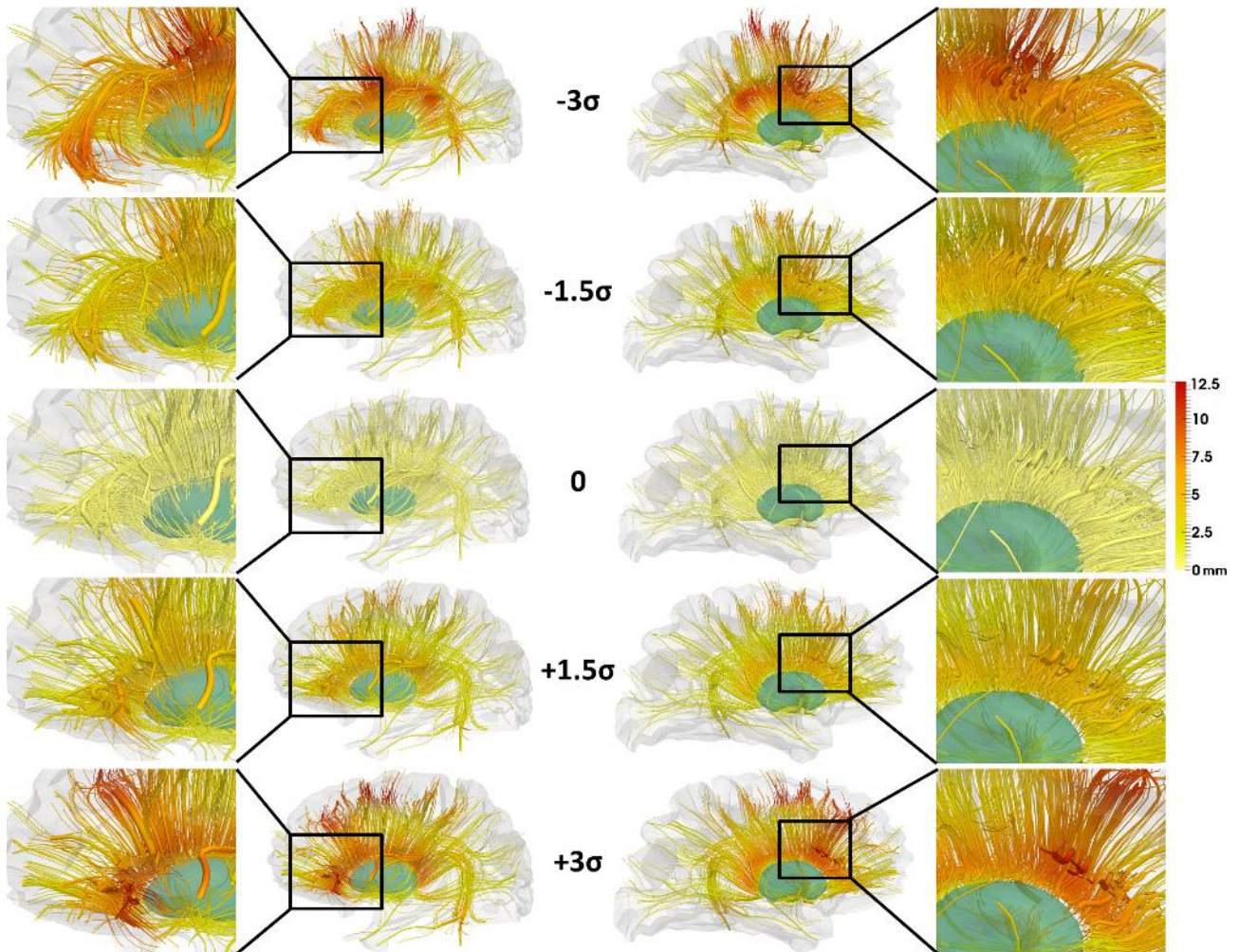


Figure 3 – Deformation of the fiber bundle template along the first mode of PCA based on the parameters of the White deformation. Colors refer to the magnitude of the displacement of the points from the template, shown in the middle row. Grey matter templates are fixed.

Main morphological variations of the grey matter structures

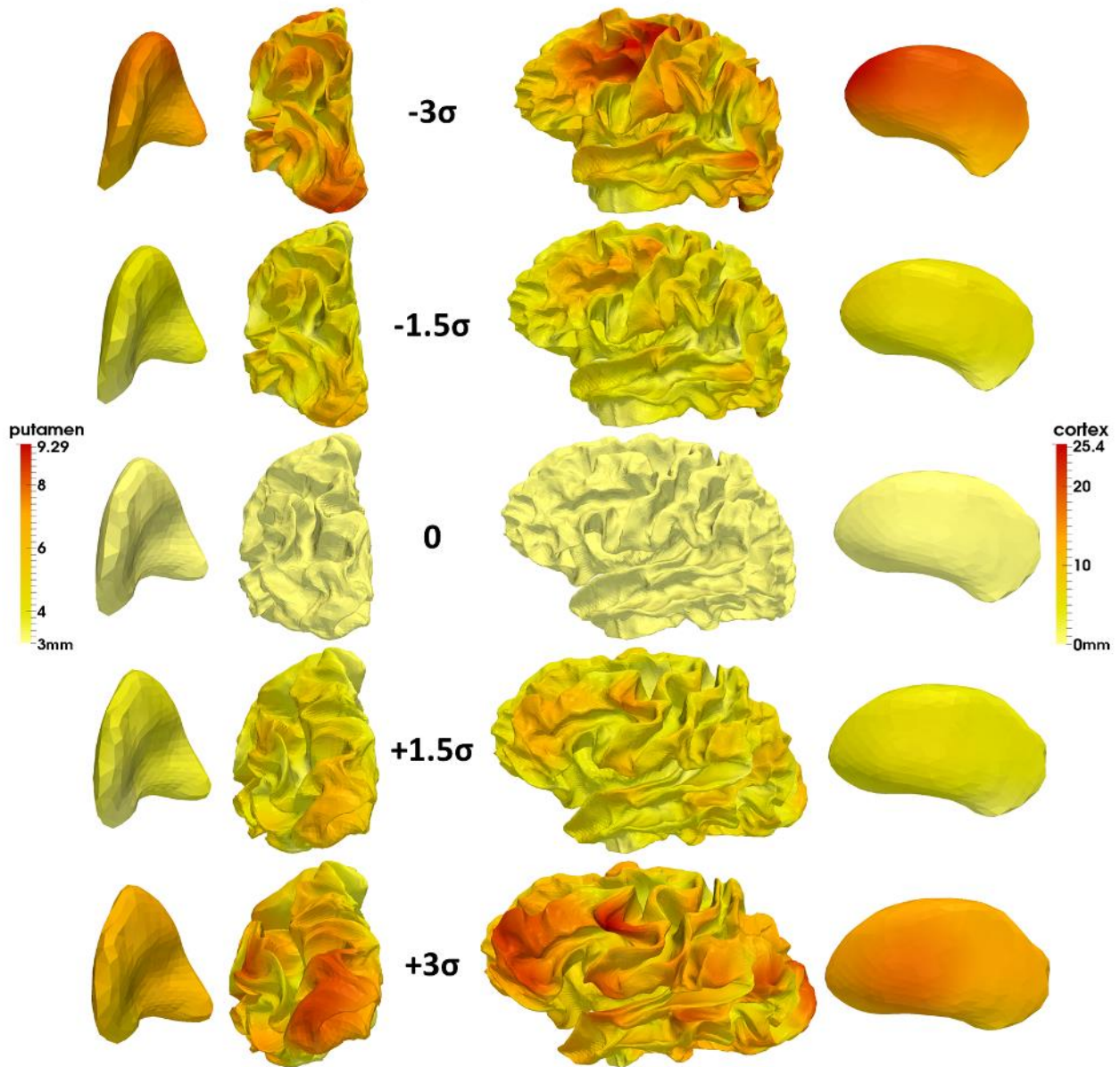


Figure 4 – Deformation of the grey matter templates along the first mode of PCA based on the parameters of the All deformation. Colors refer to the magnitude of the displacement of the points from the template, shown in the middle row.