Exploring the Large-Scale Connectivity of the Human Visual System using Diffusion Tensor Tractography

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Introduction

In order to understand the distributed and interactive functions of the visual system it is essential to unravel its large-scale structure. However, due to the limitations of current techniques, the structural connectivity of the human visual system remains largely unknown. We use Diffusion Tensor Imaging (DTI) to map the connectivity between a large set of areas in the visual system, including subcortical, primary visual and higher visual areas. Results on human hemianoptic or blindsight patients have shown that despite unilateral lesions in early visual areas, activity in the higher visual areas of the damaged hemisphere can still be close to the activity of the normal undamaged hemisphere [1,2]. Recent work by us suggests that direct routes from the subcortical structures to the cortex might explain these results [3]. Therefore, these connections were the main focus of this study.

Functional localization

To study the areas in the visual system, functional Magnetic Resonance Imaging (fMRI) was used to localize the subcortical nuclei Lateral Geniculate Nucleus (LGN), Superior Colliculus (SC) and Pulvinar (PUL) and the cortical areas V1, V2, V3, V3A, VP, V4v, hMT+, FEF, FFA, PPA, LOC, and V4. Localizing subcortical areas with a saccade task proved to be more reliable than using the retinotopic stimuli commonly used. In figure 1 all localized areas are shown in 3D space in individual subjects. Transversal, coronal and sagittal slices of the anatomical volume are added for reference.

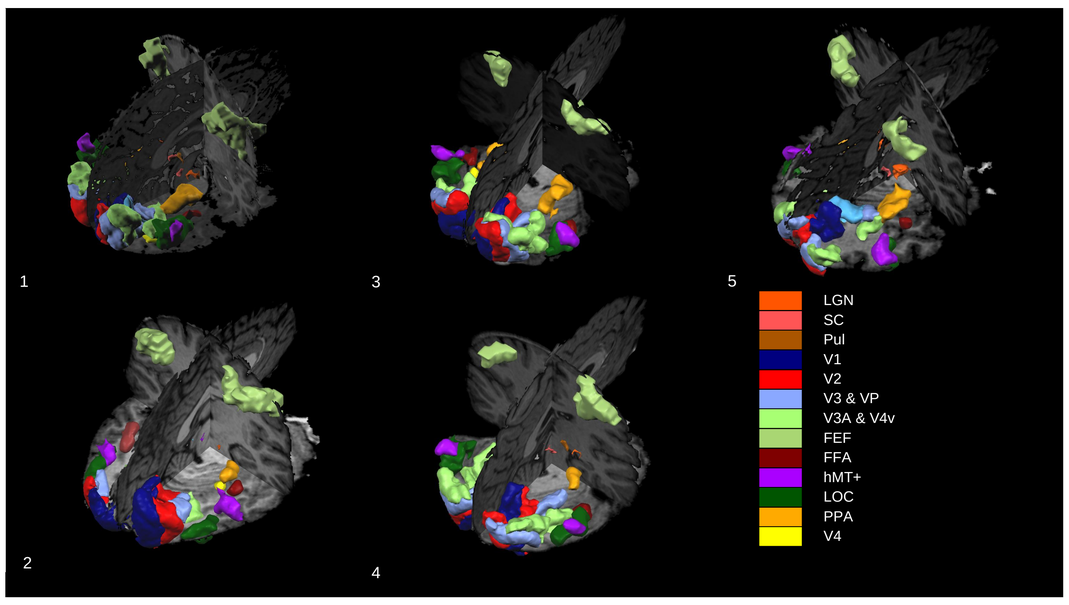

Figure 1

Diffusion Tensor Imaging

The resulting subject-specific regions-of-interest (ROIs) in 'original space' were used as a starting point to ascertain structural connectivity using DTI and deterministic fiber tractography. Figure 2 shows the probabilistic method used to summarize the data over subjects, hemispheres and 'directions' (from A to B and from B to A).

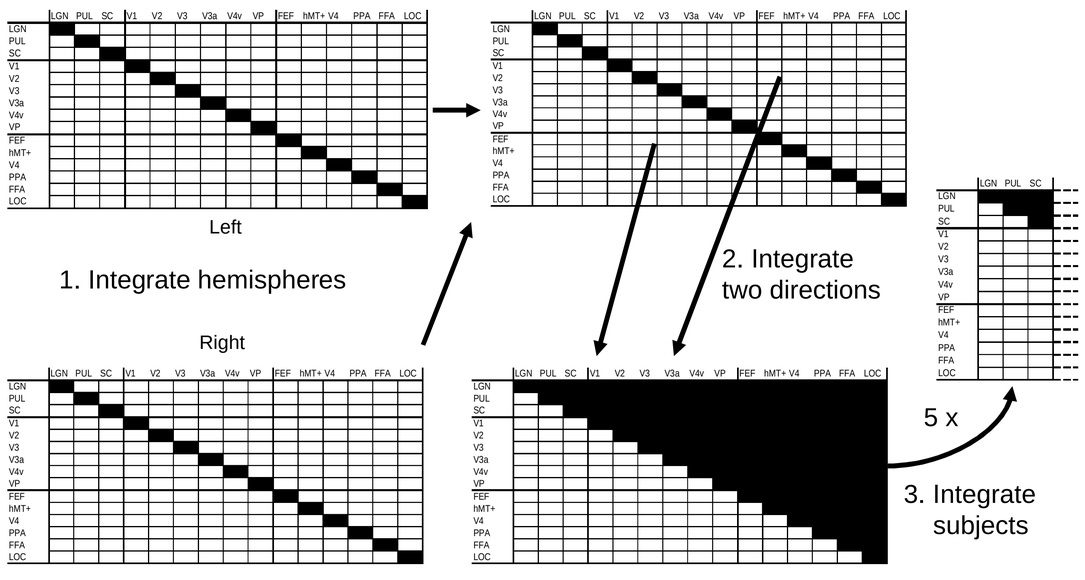

Figure 2

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Some examples of the fibers tracked can be seen below in figure 3 and figure 4. The connections in figure 3 (LGN – V1) serve as a validation of our methods. It is safe to state that these connections exist and their shapes are well established. Indeed the optic radiations with separate Meyers loops can be distinguished.

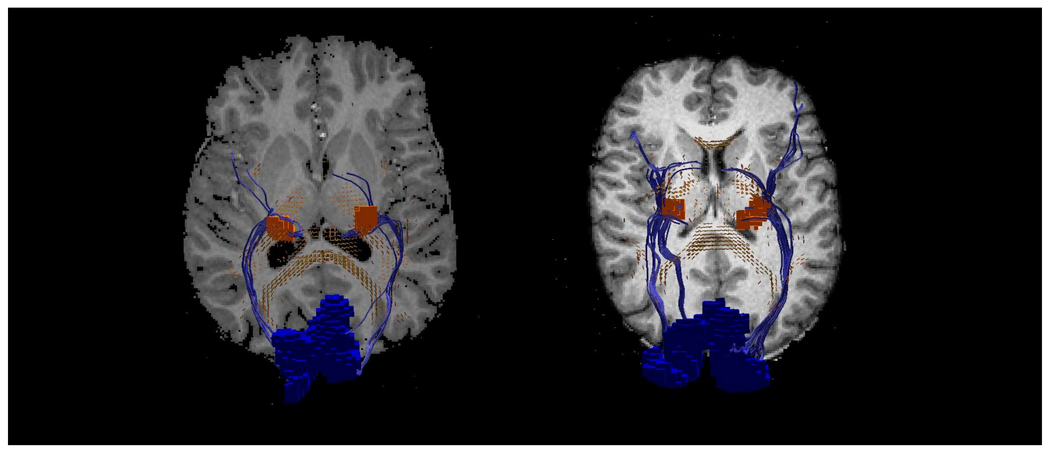

Figure 3: Tracked connections between the LGN and V1 in subjects 1 and two, both 'to-from' and 'from-to'. V1 in blue, LGN in orange.

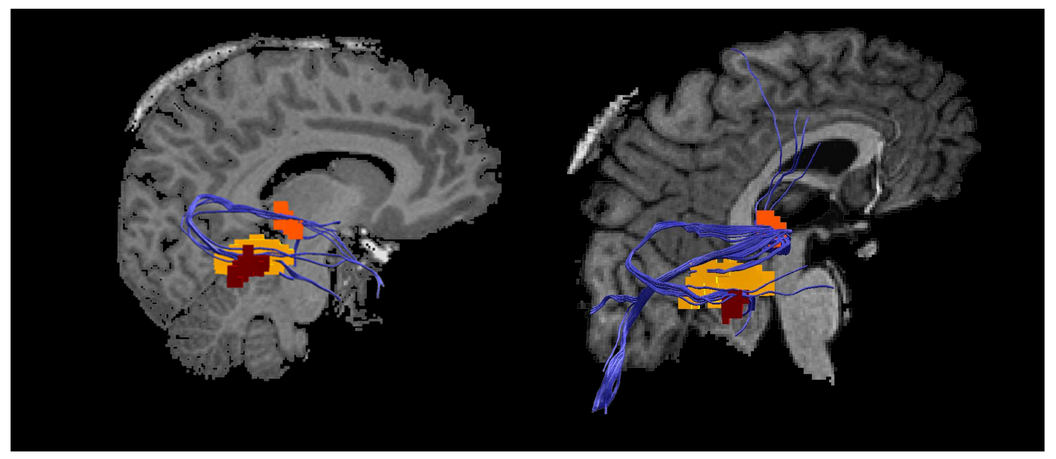

Figure 4: Tracked connections from the LGN to PPA and FFA, in the right hemisphere, in subjects 1 and 5, both 'to-from' and 'from-to'. The LGN is orange, the PPA is yellow, the FFA is red.

The final DTI connection matrix can be seen in the table below. The table integrates all individually tracked connections over all subjects, hemispheres and 'directions'. The cell entries represent the percentage of connections where the tracking led to a connection between the two areas under investigation. Grey connections have been tracked in more then 50 % of the cases. A green number represents that the connection has been found with neuro-anatomical tract tracing methods according to the CoCoMac database [4,5], red numbers indicate such a connections has been researched but not found.

	LGN	PUL	SC	V1	V2	V3	V3a	V4v	VP	FEF	hMT+	V4	PPA	FFA	LOC
LGN															
PUL	100														
SC	75	65													
V1	85	30	0												
V2	80	25	5	100											
V3	80	25	15	95	100										
V3a	100	50	13	94	94	100									
V4v	80	15	0	95	100	95	100								
VP	60	20	0	100	100	70	56	100							
FEF	30	25	15	0	5	0	0	0	5						
hMT+	15	5	0	0	15	20	25	10	0	25					
V4	33	8	0	33	67	42	63	100	83	0	8				
PPA	55	35	5	70	85	45	75	100	95	0	20	67			
FFA	60	20	15	40	40	35	63	80	50	35	70	83	75		
LOC	45	20	5	20	50	90	100	80	40	35	95	67	70	95	

Discussion and Conclusion

Despite the limitations of the technique, a large degree of similarity was found between subjects and between the resulting human connectivity and the known monkey connectivity data, which shows the connections were reliably tracked. Like in the monkey brain, the connectivity between the LGN and the early visual system was high and the connectivity between the subcortical areas was maximal. Tracts between the subcortical areas and PPA and FFA were found remarkably often. These 'long-range' connections [6] might explain some of the recent patient results mentioned earlier.

References:
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2. Schoenfeld et al., 2002, Ann Neurol
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4. Kötter, 2004, Neuroinformatics
5. Stephan et al., 2001, Proceedings of the Royal Society
6. Kaiser & Hilgetag, 2006, PLOS Computational Biology