An investigation of the white matter microstructure in motion detection using diffusion MRI

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Abstract

One of the most widely investigated functions of the brain is vision. Special attention is often paid to motion detection and its modulation by attention, while still little is known about the structural background of this function. Therefore, we examined the white matter microstructural background of coherent motion detection. A random-dot kinematogram paradigm was used to measure individuals' sensitivity to movement coherence. Correlation was calculated between the motion detection threshold and white matter microstructure as measured by high angular resolution diffusion MRI. The Track Based Spatial Statistics method was used to address these correlations and probabilistic tractography to reveal the connection of identified regions. Significant positive correlation was found between the behavioural data and the local FA in the posterior part of the right superior frontal gyrus, right juxta-cortical superior parietal lobule, left parietal white matter, left superior temporal gyrus and the left optic radiation. Probabilistic tractography identified pathways that are highly similar to the segregated attention networks, which have a crucial role in the paradigm. This study calls attention to the structural determinant of a behavioural function.

Introduction

The neural substrate of motion-sensitivity is located in different level of the visual system. Electrophysiological investigations showed that in the retina, ganglion cells react differently to moving lights, one of the subgroups respond with activation while the other one produced a decreased firing in response (Sivyer et al., 2010). Similarly, the lateral geniculate nucleus (LGN) (Stanley et al., 2012), striate cortex (Beckett et al., 2012) and some peri- and parastriate areas (Larsson et al., 2010; Sary et al., 1995) respond to a dot when moving across the neurons' receptive fields. The higher levels of perception, such as global motion recognition seems to be located in the middle temporal area (MT), medial superior temporal cortex (MST), and the fundus of the superior temporal cortex (FST), that are similar in monkeys and humans (Morrone et al., 2000), and was suggested to make up a complex: V5/MT+ (Boussaoud et al., 1990; Morrone et al., 2000). This area has direct input from the primary visual cortex (V1) (Felleman and Van Essen, 1991; Maunsell and van Essen, 1983), LGN (Sincich et al., 2004), and also from extrastriate regions, like V2 (Lewis and Van Essen, 2000). These neurons have broadly binocular representation and a relatively large receptive field (~15-20°, (Angelucci et al., 2002)). The neurons of this region have a principal role in motion and directional sensitivity (Chawla et al., 1998). Extrastriate areas, mainly V5/MT+, have substantial attentional modulation from attention networks (Buchel et al., 1998; Kellermann et al., 2012). Fundamental components of these networks are located in the frontal and parietal lobes. Functional magnetic resonance imaging (fMRI) and neurophysiological studies suggest two separate attention systems (Corbetta and Shulman, 2002): a goal-driven, endogenous and a salience detection, exogenous attention system. These networks were shown to be partially segregated in spatial terms also (Corbetta and Shulman, 2002). Goal directed attention includes parts of the intraparietal cortex and superior frontal cortex, while sailence detection network includes the temporoparietal cortex and inferior frontal cortex and lateraled to the right.

Motion transparency (e.g. two motions superimposed on each other) as applied in the form of random dot kinematogram is frequently used to identify motion sensitive cortical regions in functional imaging (Friston et al., 1997) and electrophysiological experiments (Antal et al., 2005; Braunitzer et al., 2012). It gives the opportunity to analyse the integrated action vision in close to real situations. By modulating the attention to the various components of the task one can also reveal the mechanism by which attentional networks interact with motion detection areas (Buchel et al., 1998; Kellermann et al., 2012).

Although functional imaging experiments offer a unique opportunity to examine functional activation in various behavioural conditions, recently it was proposed that behavioural performance is also strongly influenced by the underlying brain structure. It was shown that correlation between the individual structural variability with behavioural performance can identify the involved neuroanatomical structures (Maguire et al., 2000). Moreover, this approach, if white matter structure related parameters are investigated, gives the unique opportunity to identify white matter tracts that can be associated with the certain functions (Floel et al., 2009). Such parameters can be defined by diffusion tensor imaging that may address the integrity of white matter microstructure. Relating the locally measured diffusion parameters with behavioural data was shown to be capable of revealing the coupling of structure and function (Johansen-Berg, 2010).

Most of our information about the V5/MT+ stems from monkey experiments, human fMRI and PET studies. This kind of knowledge is mostly functional in nature. However, the structural background of motion detection is not sufficiently well known, especially regarding the white matter pathways. In the current study, we aimed to identify the white matter structural background of motion detection. We correlated the intersubject variability for the threshold of detection for coherent motion in a random dot kinematogram paradigm, with white matter diffusion parameters.

Methods

Subjects

Sixteen healthy subjects were included in the study. The average age was 26.5 (range: 21-40 years). None of them suffered from any neurological or psychiatric diseases. All subjects had normal or corrected-to-normal (20/20) visual acuity.

Ethics

All study participants gave written informed consent in accordance with the Declaration of Helsinki; the study was approved by the ethics committee of the University of Szeged (Ref. no.: 87/2009).

Psychophysical test

Motion detection threshold was measured with random dot kinematogram. Stimuli were generated with Psychophysics Toolbox Version 3 (http://psychtoolbox.org/), under MatLab (MathWorks, Inc.) on a PC, and presented on a 24-inch LCD monitor at a resolution of 1920 by 1200 pixels and at a 60 Hz refresh rate. The stimuli were 100 moving black dots in random positions with variable coherence rates. Stimuli were presented on a neutral grey background in a rectangular stimulation field occupying 60% of the whole screen. Subjects were seated at 0.5 m from the screen and the stimulation field subtended an area of 35.74 by 22.34 visual angles. The diameter of each dot was 10 pixels (~ 3 mm). In each trial a given percentage of the dots moved coherently to the right or to the left, while the rest moved in random directions. After each trial, movement-starting points were regenerated. One trial lasted approximately 0.8 s (50 consecutive frames), during which each dot travelled 38.4 mm. The task of the subjects was to indicate whether the coherently moving dots moved to the left or to the right by pressing the appropriate cursor button on the keyboard. The absolute coherence threshold was determined by the QUEST adaptive threshold seeking algorithm (Watson and Pelli, 1983).

Data acquisition:

Neuroimaging data acquisitions were carried out on a 1.5 T GE Signa Excite HDxt MR Scanner (GE Healthcare, Chalfont St. Giles, UK). Three dimensional spoiled gradient echo images (FSPGR: echo time [TE]: 4.1 ms; repetition time [TR]: 10.276 ms; matrix: 256 * 256; field of view [FOV]: 25 cm * 25 cm; flip angel: 15 degree; in-plane resolution: 1 mm * 1 mm; slice thickness: 1 mm) and 60 directions diffusion-weighted images with 6 non-diffusion-weighted reference volume (TE: 93.8 ms; TR: 16.000 ms; matrix: 96 * 96; FOV: 23 cm * 23 cm; flip angle: 90 degree; in-plane resolution: 2.4 mm * 2.4 mm; slice thickness: 2.4 mm; b: 1000 s/mm^2; number of excitations [NEX]: 2; array spatial sensitivity encoding technique [ASSET]) were acquired for all subjects.

Data analysis:

Correlation of diffusion parameters with behavioral measures

Diffusion data were corrected for eddy currents and movements artefacts by twelve degree of freedom affine linear registration to the first non-diffusion-weighted reference image. An algorithm included in FMRIB's Diffusion Toolbox (FDT) of FSL (v.4.0) fit diffusion tensors at each voxel (Smith et al., 2004). Fractional anisotropy (FA) was computed for the whole brain. In order to reduce the possible errors arising from misalignment of the images, we used the Tract Based Spatial Statistics (TBSS) method (Smith et al., 2007). All subjects' FA images were aligned into a common space, using the non-linear registration tool, FNIRT, which use a b-spline representation of the registration warp field. A mean FA image was created and the threshold set at FA=0.2, deriving a mean FA skeleton that represented at the centres of all tracts common to the group. Each subjects' aligned FA data were then projected onto this skeleton and the resulting data fed into voxel-wise cross-subject statistics. Modelling and inference using standard general linear model (GLM) design set-up was accomplished using permutation-based cluster analysis (n=5000) as implemented in FSL software package (Nichols and Holmes, 2002). The design encoded for the motion detection threshold value. Statistical thresholding was carried out with a novel method of Threshold Free Cluster Enhancing (Smith and Nichols, 2009). Since correlation was expected only in well-circumscribed regions of the visual and attention networks, it would be over-conservative to correct for multiple correlations based on the total number of voxels in the skeleton. Hence we used the non-corrected stats thresholded at 1% significance level. Only clusters larger than four voxels were considered for further analysis and discussion.

Structural connectivity

Connectivity of the regions showing significant correlation with motion detection threshold was defined by probabilistic tractography (FDT, part of FSL: www.fmrib.ox.ac.uk/fsl/fdt). A Multifibre diffusion model was fitted that estimates probability distribution on the direction of 1 or more fibre populations at each voxel (Behrens et al., 2007). Probabilistic tractography was then performed from any brain voxel by tracing streamline samples through these probabilistic distributions on fibre direction. For tractography, we generated 5000 streamline samples from each seed voxel to build up a connectivity distribution. The number of these samples passing through each brain voxel is interpreted as proportional to the probability of connection to the seed voxel. By fitting a multifibre model to our diffusion data, we were able to trace pathways through regions of fibre crossing (Behrens et al., 2007). Seed masks were the binary masks of the suprathreshold clusters of the TBSS analysis. The result of the tractography was registered to standard space, binarised and summed over subjects for visualisation.

Results

Motion detection threshold

The mean of motion detection threshold was 18.87 ± 5.79 % coherent motions. Significant positive correlation ($p<0.01$, non-corrected) was found between the motion detection threshold and the local FA in the right frontal cortex in the posterior part of the right superior frontal gyrus, right juxta-cortical superior parietal lobule, left parietal white matter, left superior temporal gyrus and left optic radiation (Table 1, Figure 1).

Connectivity of the white matter region having correlated microstructure

with behavioral data

The right frontal cluster showed strong connections to the identical region in the left hemisphere, to the right cortico-spinal tract and a smaller pathway leading to the right parietal lobe (Figure 1 and Figure 2). The right superior parietal cluster showed the strongest connectivity to the right superior temporal gyrus. The cluster in the left parietal white matter had strong connections to the angular gyrus, frontal white matter (through the putative superior longitudinal fascicle) and to the occipito-temporal junction. The cluster in the superior temporal gyrus had connections to the angular gyrus that further on led to the frontal cortex through the arcuate fascicle and a smaller fibre tract connected the cluster to the parietal white matter under the precuneus (not shown).

Discussion

In this study we showed local correlations between diffusion MRI measured white matter microstructure and coherent motion detection performance. The correlation was found in several regions that can be linked to motion detection and attention function. Our findings showed that there is a substantial correlation between the white matter microstructure and function.

Earlier electrophysiological (Dubner and Zeki, 1971), lesional (Zihl et al., 1983) and imaging studies (Tootell et al., 1995; Zeki et al., 1991) identified motion sensitive visual areas, along the occipital-temporal-parietal axis, which is also known as the dorsal visual stream. Within these, probably the most important is the V5/MT+ complex that was shown to express robust activation in tasks applying moving stimuli. It is important to point out that none of the identified white matter regions in our analysis was along the pathway running from the primary visual areas to

V5/MT+. This might represent a highly tuned visual processing system that can effortlessly process the visual information.

However, there was a strong correlation between motion detection threshold and the microstructure of white matter pathways that are connected to regions, which are seemingly identical to those having attention related activity. Such correlation seems feasible, since the detection of a coherent motion in a random noise is highly attention demanding task, hence better performance can be expected in individuals with stronger attentional modulation.

In their seminal paper Buchel et al using similar random dot kinematogram, identified areas related to attention to visual motion (Buchel et al., 1998). The identified areas in the frontal eye field, premotor cortex and posterior parietal cortex showed high correspondence with the cortical regions, to where the white matter regions projected to in our analysis. Corbetta and Shulman proposed a framework for two segregated attentional systems: the dorsal attention network, responsible for goal-directed (top-down) attentional modulation which includes parts of the dorsal parietal cortex (superior parietal lobule, intraparietal sulcus), superior frontal cortex (near or at the frontal eye field - FEF) and the ventral network driven by salient stimuli (bottom-up modulation), including also the temporo-parietal junction and the inferior frontal cortex (Corbetta and Shulman, 2002). Recent investigation were able to find structural correlates of such a separated attention system (Yin et al., 2012). The bottom-up orienting function was negatively correlated with cortical thickness in the angular gyrus and the superior parietal lobule and mean diffusivity under the inferior parietal lobe. Contrary, the alerting, putatively top-down attention function was correlated with fractional anisotropy in the superior frontal region (the white matter under the frontal-eye field, similar to what our analysis yielded).

Interestingly, in our analysis correlation was found with motion detection threshold in white matter tracts that overlap with both the dorsal and ventral attention systems. This is not surprising, since continuous attention is directed to the moving dot pattern during the experiment and the ventral salience system might also activate when the coherent motion pattern is finally detected. Moreover, recent reports showed that segregated branches of the superior longitudinal fascicle are involved in the two attention networks (Thiebaut de Schotten et al., 2011). The cortical projection of the most dorsal branch overlaps with the dorsal attention network and the projections of the most ventral part overlaps with the ventral attention network. In contrast, the projection of a third branch of the superior longitudinal fascicle overlaps partially with the dorsal as well as with the ventral attention network. This structural link might suggest a communication between the two systems and redirects goal-directed attention mediated by the dorsal network to the events identified as salient by the ventral network (Corbetta and Shulman, 2002; Thiebaut de Schotten et al., 2011). Recent findings (Gruber et al., 2010) and an integrative theory of mind (Abu-Akel and Shamay-Tsoory, 2011) suggest the importance of the interaction in both systems, where the temporo-parietal junction plays an important role of connection and shifting of mental states and orientation. Caclin and co-workers (Caclin et al., 2012) in their recently published paper suggested a hypothesis that V5/MT+ response depends on the dorsal/ventral interactions. Further evidences showed temporo-parietal junction involvement of both attentional networks (Chica et al., 2011).

It was also shown in previous imaging and electrophysiological studies that the activity of V5/MT+ is strongly modulated by attention (Buchel et al., 1998; O'Craven et al., 1997; Treue and Maunsell, 1996). Functional and effective connectivity analyses suggested that the attentional modulation arising from modulation of connectivity strength within a network containing visual, parietal and frontal regions (Buchel and Friston, 1997; Marreiros et al., 2008). Functional connectivity studies debated the possible site of attentional modulation (Buchel and Friston, 1997; Friston et al., 1997; Penny et al., 2004). Recently a two-state dynamic causal modelling analysis suggested that modulation of forward connections from V1 to V5 are crucial in attention to visual motion (Marreiros et al., 2008). Our results seem somewhat contradictory. The performance on the attention demanding motion detection task correlated with the integrity of white matter tracts within the attention networks rather than those paths connecting the attention networks to visual regions or connecting various visual areas. This could suggest that the bottom line of the performance on the motion detection task is the “structural integrity” of the attentional networks.

Functional imaging is the classical approach to identify the structures behind certain brain function. Recently, by refined imaging and analysis methods it becomes possible to correlate brain structural variation with variations in behavioural measures (Johansen-Berg, 2009; Johansen-Berg, 2010). The relevance of white matter diffusion properties in certain behavioural performances are not yet clear, but nerve diameter and myelination that relates to the microstructure measurable with DTI, can relate to conduction velocity and dispersion of the neuronal signal (Hodgkin and Huxley, 1952). Along these lines, it was showed that greater BOLD response in the visual cortex correlated with higher FA in the optic radiations (Toosy et al., 2004). Higher FA detectable in corpus callosum if better the bimanual coordination (Johansen-Berg et al., 2007). Training induced FA increase was detected in the intraparietal sulcus (Scholz et al., 2009).

Our study is certainly not without limitations. The correlation of white matter structural connectivity and functional and effective connectivity needs further investigation. Additionally, modulating the attentional component of the motion detection task may reveal further characteristics of the network. Furthermore, the TBSS approach restricts the analysis to the core of the white matter fibre bundles, in order to eliminate the errors arising from miss-registration, but neglects the periphery of the tracts (Smith et al., 2006).

We hope our results may help to better the understanding of visual perception, the mechanism of motion detection and that this would help to put the pathomechanism of neglect and other attention related disorders into perspective.

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Figure legends

Figure 1. Correlation of white matter microstructure with motion detection threshold and the connectivity of regions.

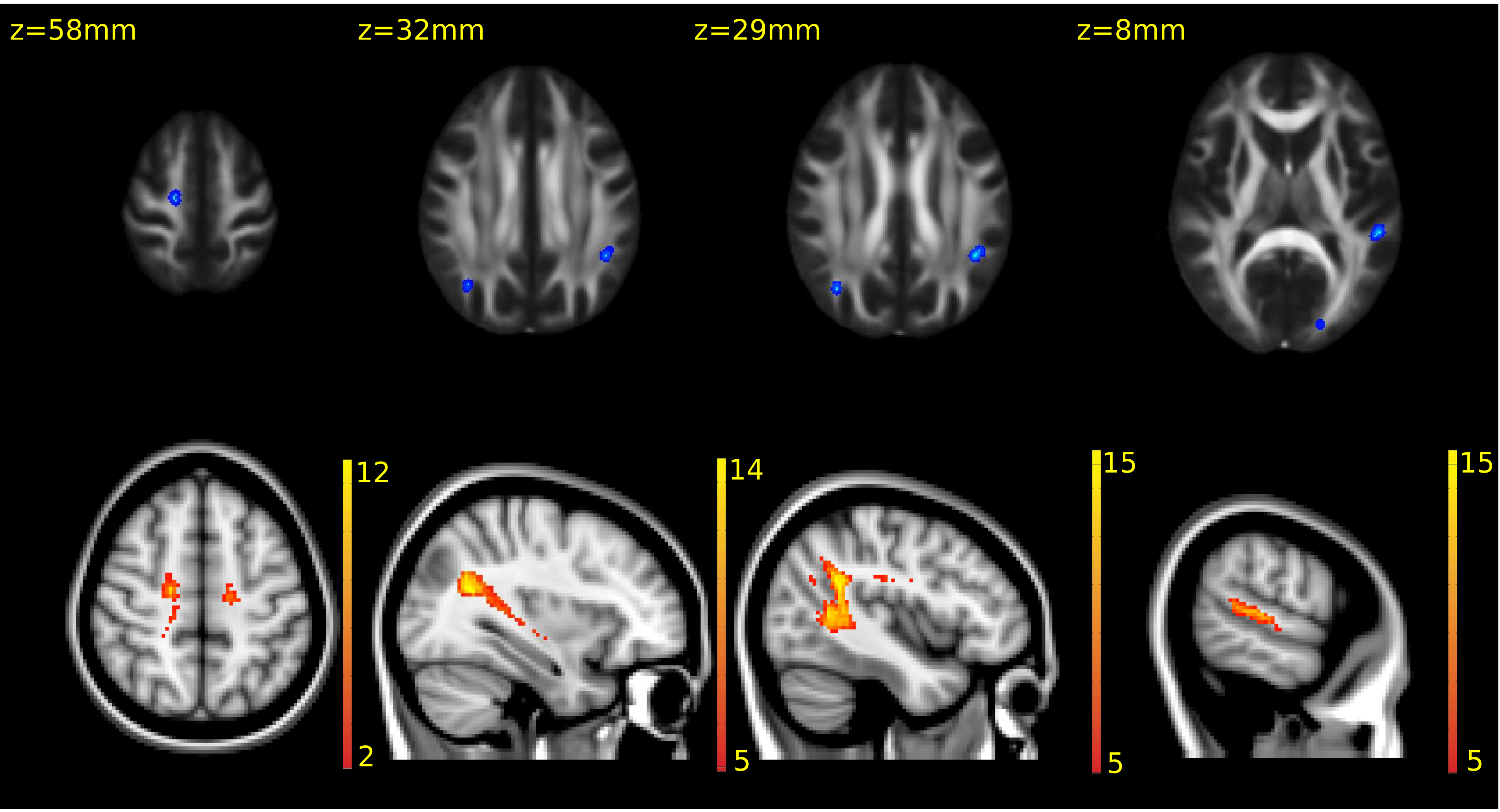
Upper row show regions of significant correlation between voxel-wise fractional anisotropy and motion detection threshold ($p<0.01$, uncorrected, clusters are thickened for better visualisation). Statistical images are overlaid on the FMRIB58 standard brain. Lower row indicate the connectivity of the regions in the upper row. Individual probabilistic tractography is thresholded at 500 particle, binarised and summed across subjects. Various thresholds are chosen for each tractography results for better visualization. See text for the description of the regions and pathways.

Figure 2. Pathways running through the white matter regions showing significant correlation between microstructure and behavioral measures.

Lower image indicate the pathways, the upper two images (right and left view) the cortical projections. The inferior and medial branch of the superior longitudinal fascicle on the left indicated in blue and green. The superior branch of the right superior longitudinal fascicle and part of the cortico-spinal tract originating from the putative frontal-eye-field indicated in red. The connection on the right, between the superior parietal lobule and the superior temporal gyrus is indicated in brown.

Table 1. Regions show correlation with white matter structural integrity.

Location and size of the associated regions and the standard MNI-based coordinates are shown.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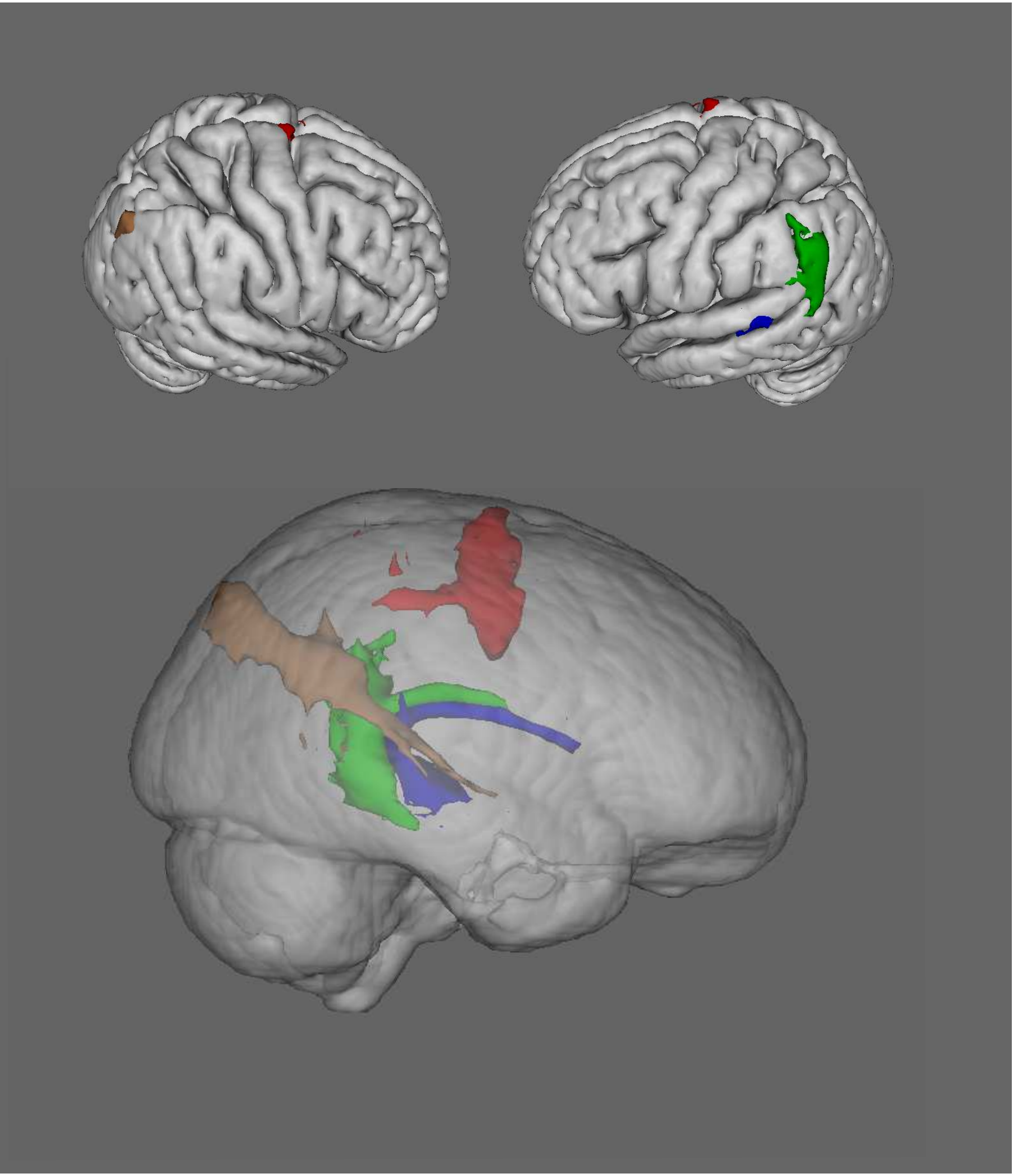

Table

Anatomical structure	Side	Size (voxel)	X (mm)	y (mm)	z (mm)
Deep intraparietal white matter under the parieto-occipito-temporal junction	Left	21	-42	-48	29
Juxtacortical white matter in the superior temporal gyrus	Left	16	-51	-33	8
Juxtacortical superior parietal lobule	Right	6	36	-64	32
Juxtacorical white matter under the posterior part of the right superior frontal gyrus	Right	4	16	-15	58
White matter in the occipital pole	Left	4	-18	-86	12