

Relative contribution of motor and association fibres to the white matter underlying motor cortex in human and macaque.

T. E. Behrens¹, M. W. Woolrich¹, H. Johansen-Berg¹, M. Pinski², W. Richter², M. Richter², C. Gross², S. Kastner², M. D. Robson³, J. K. Rilling⁴

¹Centre for Functional MRI of the Brain, University of Oxford, Oxford, Oxon, United Kingdom, ²Princeton University, Princeton, New Jersey, United States, ³OCMR, University of Oxford, Oxford, Oxon, United Kingdom, ⁴Emory University, Atlanta, Georgia, United States

Introduction

The region of white matter underlying the face area of sensorimotor cortex in primates contains at least two major populations of axons. The arcuate fasciculus (SLFIII) runs in an anterior/posterior orientation connecting lateral parietal and posterior superior temporal regions to ventral lateral regions in prefrontal cortex (e.g. [1]). Two of these regions in humans – Wernicke’s area and Broca’s area – are involved in production and perception of language. The same white matter region contains axons connecting sensorimotor cortex to the cortico-bulbar tract and callosally to contra-lateral sensorimotor cortex. At this level, these axons run in a medial-lateral orientation. These two separate populations have previously been identified in humans using high angular resolution diffusion imaging techniques (e.g. [2]). Here, by modelling the effect of multiple fibre populations on the diffusion-weighted MR signal, we are able to obtain a quantitative measure of the relative contribution of each population. We hypothesise that the evolution of language in the human brain will be reflected in an increase in the proportion of the MR signal accounted for by the human arcuate fascicle - carrying language information - when compared to the macaque brain, where motor pathways are expected to dominate.

Methods

Data Acquisition: We acquired diffusion-weighted images along 60 diffusion-encoding orientations with $b=1000s/mm^2$ from 8 human volunteers and 2 macaque monkeys exactly as in [1]. For example anisotropy maps, see figure 1.

Modelling the diffusion signal: The diffusion-weighted MR signal is taken as a mixture of signal from each fibre population, and a single isotropically-diffusing compartment. This model is exactly as proposed in [3], but here we infer on multiple fibre populations.

$$S_i = S_0 \left[1 - \sum_{k=1}^n f_k \exp(-b_i d) + \sum_{k=1}^n f_k \exp(-b_i d (\mathbf{e}_k \cdot \mathbf{r}_i)^2) \right]$$

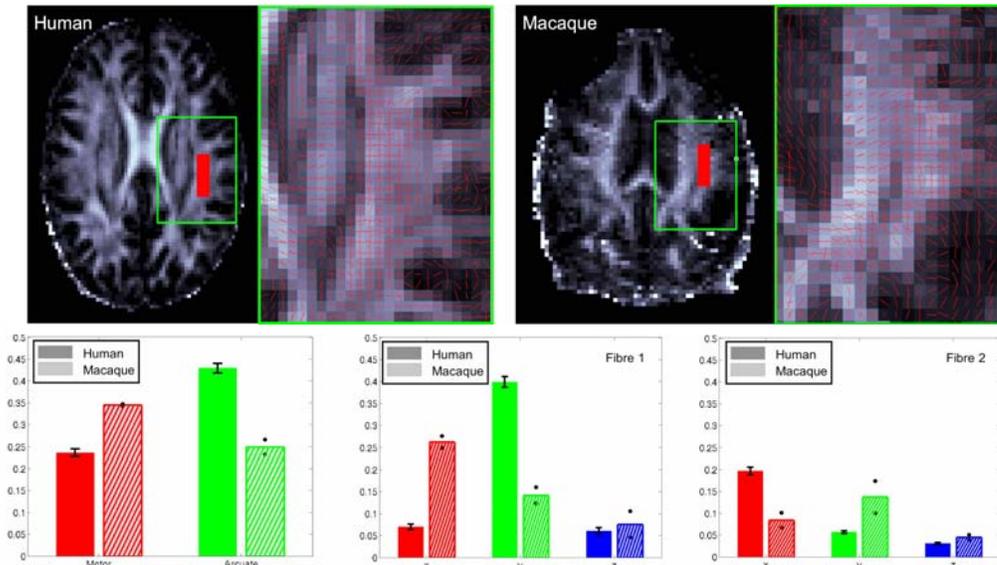
where S_i is the diffusion-weighted signal, S_0 is the signal without diffusion-encoding gradients, b is the i^{th} b-value, \mathbf{r}_i is the i^{th} diffusion-encoding orientation, d is the apparent diffusion coefficient and \mathbf{e}_k is the orientation of the k^{th} fibre population. Crucially, note that f_k is the volume fraction associated with the k^{th} fibre population. By estimating this parameter, we can

quantify the relative contributions of the fibre populations of interest.

Automatic determination of the number of fibre populations: We use *automatic relevance determination (ARD)* ([4]) to determine the model order (number of populations). ARD makes use of Bayesian priors that force to zero with infinite precision any parameters in the model that are not supported by the data. In analytic cases, model selection or averaging by ARD is equivalent to the use of the Bayesian evidence. We use a Dirichlet ARD prior on f_k (for $k > 1$), and a uniform prior on f_1 . Note that we could also apply a model-selection prior to f_1 , but we choose to enforce that at least one fibre population is estimated at each voxel. All other priors are as described in [3].

Model Estimation: Estimation is performed with MCMC as in [3]; here we burn-in for 2000 transitions then jump the chain for 4000, sampling every 20.

Results: Figure 1 shows example anisotropy maps from the white matter where the arcuate fasciculus crosses the motor pathways in example human and macaque brains. Overlaid are the mean orientations of fibre populations inferred in each voxel. The number of orientations shown in a voxel reflects the number of fibre populations supported by the data according to automatic relevance determination. In the region of interest, we are able to find two fibre populations, one in an anterior-posterior orientation, and one in a medial-lateral orientation. Note that with 60 diffusion orientations and $b=1000s/mm^2$, we did not find any voxels in this region in which 3 or more fibre populations were supported.



We performed quantitative analyses of the fibre populations within a region of interest covering 3 axial slices (red region in figure 1 shows central slice). In this region, we split fibre populations into those with an orientation closer to L/R than A/P (motor), and those with an orientation closer to A/P than L/R (arcuate). Fig 2a shows the mean volume fractions for the two fibre populations in both species. In human (filled bars), arcuate fibres dominate over motor fibres ($p < 0.0005$). Conversely in macaque (hatched bars), motor fibres dominate over arcuate fibres ($p < 0.1$). There is a species by fibre tract interaction, ($F(1,8)=61.75$, $p < 0.0005$). Figs 2b and 2c show the average volume fraction multiplied by x,y, and z component of the two fibre orientations estimated from the data. These figures confirm that the arcuate fascicle has been estimated as the principal fibre population in humans, but the subordinate fibre population in macaques.

Refs: [1] Croxson et al J. Neurosci 2005, [2] Tuch et al Neuron 2004, [3] Behrens et al MRM 2003, [4] MacKay et al. 1995