Fibre directionality and information flow through the white matter: Preliminary results on the fusion of diffusion MRI and EEG

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Abstract

Diffusion MRI can recover white matter fibre bundles, but it is blind to their directionality. We propose to identify the directionality of white matter fibre bundles by combining diffusion MRI and EEG data. Based on a realistic model of the brain and simulated EEG data, our preliminary results show that our proposed method is able to differentiate between afferent and efferent white matter connections.

1 Purpose

Diffusion MRI (dMRI) allows the recovery of white matter fibre bundles which connect regions of the brain. However, directionality information cannot be retrieved, i.e. it is impossible to determine if fibres are efferent, afferent, or both (Jbabdi and Johansen-Berg, 2011). We propose a new method to combine electroencephalography (EEG) and dMRI to infer information flow in the white matter of the brain and thus gain insight into the directionality of white matter fibre bundles.

2 Methods

We suppose streamlines identified in dMRI act as wires which allow communication between connected regions of the brain. We further assume that information is transferred along the streamlines and that the delay between emission and reception of signals is proportional to the length of the streamlines. This implies that if two connected regions of the brain are activated with a delay that is consistent with their streamline length, information is likely to have "flowed" through this connection. EEG measurements, which are directly related to cortical activity, can thus be used to infer information flow. We propose a modified version of the maximum entropy on the mean (MEM) approach (Amblard et al., 2004) to detect this information flow. The MEM algorithm is driven by a Bayesian network where the intensity of a cortical source is influenced by the state of the region where it is located. To include the connectivity information provided by dMRI, a second layer was added to the initial network to regulate the state of a cluster based on its connections as illustrated in Figure 1. The output of this method is the probability that a connection is active for every time sample of EEG data. These probabilities can be mapped back to streamlines and animated to observe inferred information flow in the white matter. To test this new methodology, we acquired diffusion images of a healthy subject and used it to simulate EEG signals. These simulated signals, along with streamlines, are used as input to the modified MEM algorithm to estimate cortical source intensities and information flow in the white matter.

Diffusion images were acquired on a Phillips 3T using an EPI sequence with 60 gradient directions and a b-value of 1500 s/mm^2. Fiber orientation distribution functions where computed constrained spherical deconvolution (Tournier et al., 2007) implemented in *dipy* (Garyfallidis et al., 2014). Fiber tracking was performed using particle filter tracking (Girard et al., 2014). An additional T1 weighted image was acquired to segment the surface of the cortex using freesurfer (Dale et al., 1999). This surface was used to compute the EEG leadfield matrix using OpenMEEG (Gramfort et al., 2010) where each vertex of the surface represents a cortical source.

Streamlines were clustered into bundles using Quickbundles (Garyfallidis et al., 2012) with a distance parameter of 10mm. A bundle was then selected and the sources nearest to the ends of each streamline were given an intensity of 1 with a delay Δ. The delay Δ was computed using the average length of the streamlines in the bundle and the conduction velocity of axons estimated at 6 m/sec as in Fukushima et al. (2015). Additional source clusters were randomly selected to simulate cortical activity not related to communication. To generate a second set of data, the same procedure was repeated but cortical sources at the end of the streamlines were activated before those at the start. Given the source intensities, the EEG signals on 64 electrodes were simulated using the forward model with additive noise (SNR 10). This noisy EEG signal and the clustered streamlines are the inputs given to the modified MEM algorithm.

3 Results

The selected fibre bundle is located in the corpus callosum and the streamlines connect sources in the right and left hemisphere. The top row of Figure 2 illustrates the source intensities and information flow computed by the modified MEM algorithm for the first simulation. The algorithm correctly identified the fibre bundle that generated the simulated signal and the direction of the information flow. For the second simulation illustrated in the bottom row of Figure 2 the recovered flow is reversed because the activation first occurs in the left hemisphere and then in the right hemisphere.

4 Discussion and conclusion

Our preliminary results show that the fusion of diffusion MRI and EEG data can recover directionality of information flow in the white matter. More generally, our algorithm provides information flow through the white matter with a time resolution of a few milliseconds. This new methodology offers great potential in understanding the interaction between cortical regions. However, many challenges need to be addressed. For example, the conduction velocity of axons was selected as a parameter of the simulation and was assumed to be a known constant. In practice, many factors, such as axonal diameter and myelination, can affect this value.

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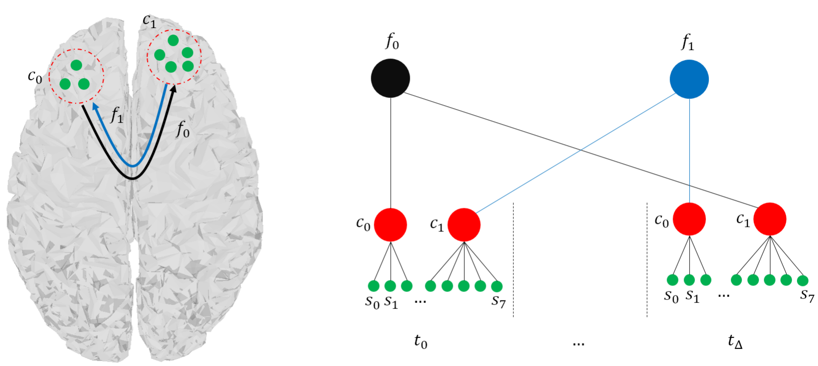

Figure 1: The Bayesian network used to model cortical activity of a simplified brain with 7 sources, 2 source clusters, and 2 connections. The connections f_0 and f_1 are associated with the same white matter fibre bundle, but have a different directionality. The connection f_0 carries information from the sources in c_0 at time t_0 to those in c_1 at time t_Δ The connection f_1 carries information in the opposite direction.

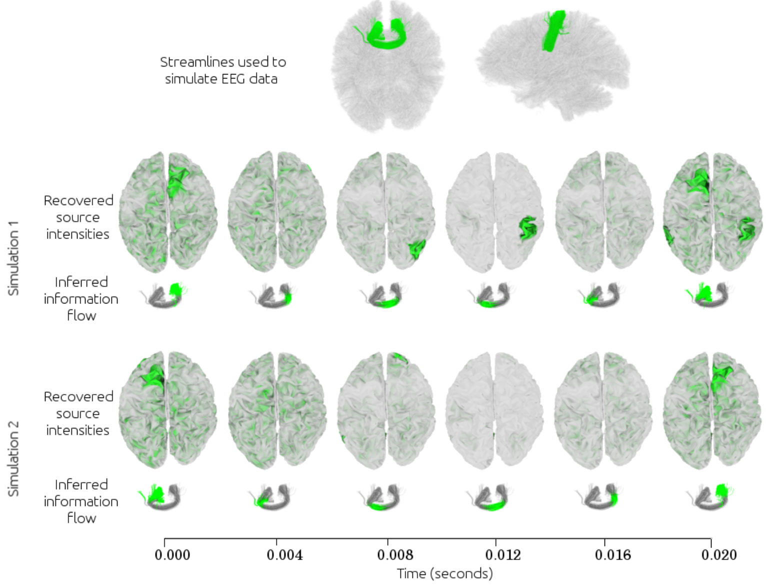

Figure 2: Information flow in the white matter inferred from the streamlines recovered in dMRI and the simulated EEG data. The top row illustrates information flow from the right hemisphere to the left hemisphere. The bottom row shows information flow in the opposite direction for the same white matter bundle. Fibres with with a probability below 0.1 where removed for clarity.