Estimation of Axon Conduction Delay, Conduction Speed, and Diameter from Information Flow using Diffusion MRI and MEG

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1 Introduction

The different lengths and conduction velocities of axons connecting cortical regions of the brain yield information transmission delays which are believed to be fundamental to brain dynamics (Caminiti et al., 2013). While early work on axon conduction velocity was based on ex vivo measurements (Hursh, 1939), more recent work makes use of a combination of diffusion Magnetic Resonance Imaging (MRI) tractography and electroencephalography (EEG) to estimate axon conduction velocity in vivo (Horowitz et al., 2015). An essential intermediary step in this later strategy is to estimate the inter hemispheric transfer time (IHTT) using EEG. The IHTT is estimated by measuring the latency between the peaks or by computing the lag to maximum correlation on contra lateral electrodes (Saron and Davidson, 1989). These approaches do not take the subjects anatomy into account and, due to the limited number of electrodes used, only partially leverage the information provided by EEG.

In previous work (Deslauriers-Gauthier et al., 2017), we proposed a method, named Connectivity Informed Maximum Entropy on the Mean (CIMEM), to estimate information flow in the white matter of the brain. CIMEM is built around a Bayesian network which represents the cortical regions of the brain and their connections, observed using diffusion MRI tractography. This Bayesian network is used to constrain the EEG inverse problem and estimate which white matter connections are used to transfer information between cortical regions. In our previous work, CIMEM was used to infer the information flow in the white matter by assuming a constant conduction velocity for all connections. In this context, the conduction speed, and thus the delays, were inputs used to help constrain the problem. Here, we instead assume that the connection used to transfer information across the hemispheres is known, due the design of the acquisition paradigm, but that its conduction velocity must be estimated.

2 Methods

Our estimation of the axon diameter is based on the relation between axon diameter d and conduction speed v given by $v = 6d$ (Hursh, 1939). Assuming a constant diameter along axons yields a relation between the information conduction delay s and the axon diameter which is $d = \ell/(6s)$ where ℓ is the axon length in meters. Here, we propose to estimate the conduction delay using CIMEM and the axon length using diffusion MRI. Results illustrating the ability of CIMEM to estimated delays on simulated data were previous published. Briefly, CIMEM estimates delays by building a Bayesian network using the structural connectivity estimated using diffusion MRI. For each connection of the model and at every time instant, a variable is added to the model with two possible state: active (0) or inactive (1). MEG signals are then used as evidence into this network to compute the posterior probability of a connection being active at a particular time. Let $Z(C_{i,n} = 1)$ be the posterior probability that the i^{th} connection is active at the n^{th} time point obtained by solving the CIMEM problem described in Deslauriers-Gauthier et al. (2017). We define the connectivity power of the i^{th} connection as $\Gamma_s(C_i = 1) = N^{-1} \sum_{n=0}^{N-1} Z(C_{i,n} = 1)^2$ for a given delay s. The connectivity power is then computed for a series of delays and the estimated delay for a given connection is the one that maximizes $\Gamma_d(C_i)$. The rationale is that the CIMEM model will only be able to use the connection to explain the EEG measurements if the selected delay is correct.

The axon diameter in the splenium of the corpus callosum was estimated for four subjects of the Human Connectome Project. The MEG data was formatted using MNE-HCP[1] processing was performed using MNE-python (Gramfort et al., 2013, 2014). The MEG epochs were created by selecting a -0.1 to 0.250 second window around the apearance of a visual cue in the motor task. They were then averaged to produce a evoked potential, which was lowpass filtered at 50 Hz and resampled at 100 Hz.

Describe diffusion MRI processing.

Our estimate of the axon diameter is given by $d = \ell/(6s)$ where ℓ is the connection length in meters and s is the conduction delay in seconds. In CIMEM, a Bayesian network is built using the structural connectivity estimated using diffusion MRI. For each connection of the model and at every time instant, a variable is added to the model with two possible state: active (0) or inactive (1). MEG signals are then used as evidence into this network to compute the posterior probability of a connection being active at a particular time. Let $Z(C_{i,n} = 1)$ be the posterior probability that the i^{th} connection is active at the n^{th} time point obtained by solving the CIMEM problem described in Deslauriers-Gauthier et al. (2017). We define the connectivity power of the i^{th} connection as $\Gamma_s(C_i = 1) = N^{-1} \sum_{n=0}^{N-1} Z(C_{i,n} = 1)^2$ for a given delay s. The connectivity power is then computed for a series of delays and the estimated delay for a given connection is the one that maximizes $\Gamma_d(C_i)$. The rationale is that the CIMEM model will only be able to use the connection to explain the

[1] https://github.com/mne-tools/mne-hcp

EEG measurements if the selected delay is correct.

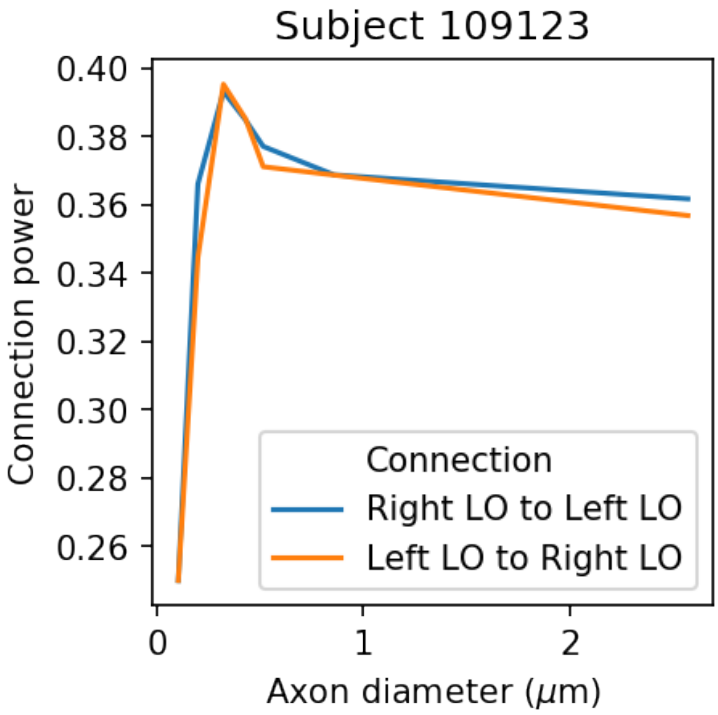


Figure 1: Axon diameter as a function of the internodal distance. Taken from Hursh (1939).

3 Conclusion

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