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Information transfer between rich-club structures in the human brain

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Abstract

The performance of the human brain depends on how effectively its distinct regions communicate, especially the regions which are more strongly connected to each other than to other regions, or so called "rich-clubs". The aim of the current work is to find a connectivity pattern between the three brain rich-club regions without any a priori assumptions on the underlying network architecture. Rich-clubs for the analysis were previously identified with structural MRI. Functional magnetic resonance imaging (fMRI) data from 25 healthy subjects (1000 time points from each one) was acquired and Transfer Entropy (TE) between fMRI time-series from rich-clubs was calculated. The significant results at the group level were obtained by testing against the surrogate data generated on a novel approach. We found stable causal interactions between rostral Anterior Cingulate Cortex L and Dorsal Anterior Cingulate Cortex L, dorsal Anterior Cingulate Cortex L and Paracentral Lobule R but not vice versa. Our work provides an approach to causal analysis of experimental data and demonstrates the applicability to real fMRI study.

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Keywords: effective connectivity; information transfer; rich club; transfer entropy.

1 Introduction

Some studies have shown the existence of highly interconnected regions (hubs), that play a key role in global information integration between different parts of the brain [1]. These regions are of critical importance due to their role as integrator which was demonstrated in studies on patients with

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damaged links between rich-clubs [2]. This study aims at finding a causal pattern between three previously defined (Kartashov et al., in press) rich-clubs based on Transfer Entropy (TE) as well as pro-vides a possible significance test of obtained TE values.

Many researchers explore the connectivity between rich-clubs in terms of statistical dependencies between spontaneous activities in them (i.e. functional connectivity). These dependencies do not show anything about causal effect one neural system exerts over another. To be able to reproduce biological principles of the brain in artificial systems we need to know this functional architecture in terms of effective connectivity. There are two main groups of methods proposed to measure effective connectivity for fMRI study. One group consists of model-based approaches like DCM (Dynamic Causal Modelling) [3]. Previously its application to resting-state fMRI was demonstrated [4–6]. Another group consists of methods with no prior assumptions or hypotheses on the brain structures interaction. One of these methods taken from information theory is called Transfer Entropy (TE). TE was first introduction by Schreiber [7] and has been recognized as a powerful tool to detect the transfer of information between joint processes. The most appealing features of TE are that it has a solid foundation in information theory and it naturally detects directional and dynamical information transfer. TE has been previously applied to assess interactions between brain networks (but not rich-clubs) [8,9]. One of the novelties of the current work is a proposed procedure of generating surrogates and formulating a null hypothesis for significance testing.

2 Materials and Methods

2.1 Transfer Entropy

In 1956 Norbert Wiener proposed the definition of causality: an improvement of the prediction of the future of a time series X by the incorporation of information from the past of a second time series Y is an indication of a causal interaction from Y to X. In 2000 Schreiber proposed [7] a new information theoretic measure – Transfer Entropy (TE), which is a non-parametric statistic measure of the amount of directed (time-asymmetric) information transfer between two or more random processes, for details see [9].

2.2 Subjects

MRI data were obtained from 25 healthy subjects, mean age 24 (range from 20 to 35 years). Consent from each participant was provided. The participants were instructed to close their eyes and lie still and relaxed. Each participant was asked about wakefulness during the study; those who fell asleep in scanner were excluded from the study. Permission to undertake this experiment has been granted by the Ethics Committee of the NRC "Kurchatov Institute". 1000 time points (with a repetition time of 2 s) were acquired resulting in approx. 35 min. of scanning.

2.3 Scanning parameters

MRI data were acquired using a SIEMENS Magnetom Verio 3 Tesla. The T1- weighted sagittal three-dimensional magnetization-prepared rapid gradient echo sequence was acquired with the following imaging parameters: 176 slices, TR = 1900 ms, TE = 2.19 ms, slice thickness = 1 mm, flip angle = 9°, inversion time = 900 ms, and FOV = 250 × 218 mm2. fMRI data were acquired with the following parameters: 30 slices, TR = 2000 ms, TE = 25 ms, slice thickness = 3 mm, flip angle = 90°, and FOV = 192 × 192 mm2. Also the data which contain the options for reducing the spatial distortion of EPI images was received.