Multivariate information theory reveals directed information structure in fMRI data

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Publications

- **J.T. Lizier**\(^{1,2,6}\), J. Heinzle\(^3\), A. Horstmann\(^4\), J.-D. Haynes\(^{3,4,5}\), **M. Prokopenko**\(^{1,6}\), “Multivariate information-theoretic measures reveal directed information structure and task relevant changes in fMRI connectivity”, *Journal of Computational Neuroscience*, **30**, pp. 85-107, 2011.

- **J. T. Lizier**\(^{1,6}\), M. Rubinov\(^7\), Multivariate construction of effective computational networks from observational data, *Max Planck Institute for Mathematics in the Sciences* Preprint 25/2012.

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Application domain: Computational neuroscience

Computational analysis of brain imaging data and models.

Two reasons to highlight this area:

1. Connectome and full-brain simulators won’t be the whole story – we need large-scale analysis of dynamics.
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Cellular automata
Rule 54:

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0 0 1 1 0 1 1 0
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Emergent structures in dynamics:
Application domain: Computational neuroscience

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Two reasons to highlight this area:

1. Connectome and full-brain simulators won’t be the whole story – we need large-scale analysis of dynamics.

2. Mutually beneficial big data analysis:
   - **Neuroscientist**: “How can we analyse data to understand how brain regions interact? What does this tell us about, e.g. disease?”
   - **Computer scientist**: “How can we describe computation in the brain? What does this tell us about computation in natural systems, and use this information to design self-organised distributed computation?”
Interregional directed information structure inference

• **Task:** establish directed interregional information structure from multivariate time-series
  – Also known as effective networks;
  – Applying to brain imaging data here.
• **Method:** directed information transfer
  – Plus enhancements including multivariate analysis and statistical significance measurements
• **Application:** a visuomotor tracking task
  – Directed interregional structure, with movement planning regions driving visual and motor control
Directed information structure task

1. Take a multivariate time series measured across different regions (e.g. across brain regions during a cognitive task). Each region contains many measured variables (e.g. voxels in fMRI).

2. Infer the directed information structure between the regions that supports this task.
Directed information structure task – requirements

1. Take a multivariate time series measured across different regions (e.g. across brain regions during a cognitive task). Each region contains many measured variables (e.g. voxels in fMRI).
2. Infer the directed information structure between the regions that supports this task.

Challenges/requirements

- Don’t assume an underlying model
- Explicitly examines info transfer
- Capture directionality
- Capture non-linear interactions
- Capture collective interactions
- Infer at the regional level
- Handle small amounts of data
- Distinguish weak relationships
- Remain computationally tractable
**Directed information structure task – information transfer**

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**Our approach has properties to meet these requirements:**

- Information-theoretic
- Uses transfer entropy
- Asymmetric analysis
- Information-theoretic
Information transfer

Information dynamics studies computation of next state of a target variable in terms of information storage, transfer and modification.

Transfer entropy:
\[ T_{Y \rightarrow X} = I(Y; X | M) = \langle i(x_{n+1}; y_n | x_n^{(k)}) \rangle \]

Info from source that helps to predict destination value in the context of destination’s past state.

(Higher order) conditional and multivariate extensions are available.
Directed information structure task – regional level

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- Multivariate
- Infers at the regional level
Directed information structure task – statistical tests

1. Take a multivariate time series measured across different regions (e.g. across brain regions during a cognitive task). Each region contains many measured variables (e.g. voxels in fMRI).

2. Infer the directed information structure between the regions that supports this task.

Challenges/requirements
- Don’t assume an underlying model
- Explicitly examines info transfer
- Capture directionality
- Capture non-linear interactions
- Capture collective interactions
- Infer at the regional level
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Our approach has properties to meet these requirements:
- Information-theoretic
- Uses transfer entropy
- Asymmetric analysis
- Information-theoretic
- Multivariate
- Infers at the regional level
- Uses dynamic kernel width
- Statistical significance testing
Directed information structure task – tractability

1. Take a multivariate time series measured across different regions (e.g. across brain regions during a cognitive task). Each region contains many measured variables (e.g. voxels in fMRI).

2. Infer the directed information structure between the regions that supports this task.

Challenges/requirements

- Don’t assume an underlying model
- Explicitly examines info transfer
- Capture directionality
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Our approach has properties to meet these requirements:

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- Multivariate
- Infers at the regional level
- Uses dynamic kernel width
- Statistical significance testing
- Uses sampling / greedy approaches
Regions encompassing: Movement planning, visual perception and control, and execution
Undirected structure (MI technique)

Clusters identified by spectral reordering

Cortical group with motor and pre-motor regions

Visual perception and control

Use of HPC cluster
Interesting hierarchical structure revealed which correlates well with experiment.

 Neither univariate analysis nor averages across regions capture this structure.

 Beware of limitations of fMRI data (e.g. no feedback links observed).
Conclusion and Future prospects

Contribution of algorithm to infer directed interregional information structure in multivariate time-series.

In later work:

- Addition of multivariate / conditional interactions, in order to remove redundancies and include synergies.
- Shift to inference at individual variable level: use for causal network inference.
- Space-time dynamics of information flow.
- Adaptation of the algorithm for feature selection in machine learning (SIEF Health Diagnostics project).
Thank You

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