Hybrid multivariate morphology using lattice auto-associative memories for resting-state fMRI network discovery

Manuel Graña, Darya Chyzhyk

Computational Intelligence Group
Dept. CCIA, UPV/EHU, Apdo. 649, 20080 San Sebastian, Spain
www.ehu.es/ccwintco

December 5, 2012

Abstract

Analysis of resting-state fMRI data,

- hybrid Multivariant Mathematical Morphology
  - induced by a supervised *h*-ordering
    - defined by the response of Lattice Auto-associative Memories built from specific fMRI voxels.
- a morphological top-hat allows to to identify brain networks.
- Results show differences in networks fiund in schizophrenia patients and healthy controls

contents

Introduction

- Definition of morphological operators on multi-variate images needs the definition of appropriate ordering in the vector space.
  - *LAAM-supervised h*-ordering based on Lattice Auto-Associative Memories (LAAMs),
- Brain networks in resting state fMRI data.
  - Morphological filters correspond to the correlation based approaches.

Introduction

- LAAMs are auto-associative neural networks
  - functional neurons perform morphological (lattice) operations.
- LAAMs present interesting properties such as perfect recall, unlimited storage and one-step convergence.
- LAAM-supervised ordering keeps multivariate morphology under the general framework of Lattice algebra $(\vee, \wedge, +)$
  - LAAM-supervised ordering is faster and imposes less computational burden than the supervised orderings previously proposed.

Resting state fMRI

- Resting state fMRI data has been used to study brain functional connectivity
  - correlation of low frequency oscillations in diverse areas of the brain reveal their functional relations.
  - connections discovered are a brain fingerprint, the so-called default-mode network.
- do not impose constraints on the cognitive abilities of the subjects.
  - in the study of brain maturation there is no single cognitive task which is appropriate across the aging population.

Resting state fMRI

- machine learning and data mining approaches:
  - hierarchical clustering,
  - independent component analysis (ICA),
  - fractional amplitude of low frequency analysis,
  - multivariate pattern analysis (MVPA).
- Graph analysis to study the connectivity structure of the brain.

Schizophrenia

Schizophrenia is a severe psychiatric disease that is characterized by delusions and hallucinations, loss of emotion and disrupted thinking.

Functional disconnection between brain regions is suspected to cause these symptoms, because of known aberrant effects on gray and white matter in brain regions that overlap with the default mode network.

Resting state fMRI studies have indicated aberrant default mode functional connectivity in schizophrenic patients.

Goal of our work is to find differences in connectivity betwee patients with and without auditory hallucinations

LAAM definitions

- input/output pairs of patterns

$$(X, Y) = \left\{ \left(\mathbf{x}^{\xi}, \mathbf{y}^{\xi} \right); \xi = 1, .., k \right\}$$

- a linear heteroassociative neural network

$$W = \sum_{\xi} \mathbf{y}^{\xi} \cdot \left(\mathbf{x}^{\xi} \right)' .$$

- erosive and dilative LAMs, respectively

$$W_{XY} = \bigwedge_{\xi=1}^{k} \left[\mathbf{y}^{\xi} \times \left(-\mathbf{x}^{\xi} \right)' \right] \text{ and } M_{XY} = \bigvee_{\xi=1}^{k} \left[\mathbf{y}^{\xi} \times \left(-\mathbf{x}^{\xi} \right)' \right],$$

where $\times$ is any of the $\boxed{\vee}$ or $\boxed{\wedge}$ operators,

LAAM definitions

- operator $\boxed{\vee}$ denotes the max matrix product

$$C = A \boxed{\vee} B = [c_{ij}] \Leftrightarrow c_{ij} = \bigvee_{k=1..n} \{a_{ik} + b_{kj}\},$$

- operator $\boxed{\wedge}$ denotes the min matrix product

$$C = A \boxed{\wedge} B = [c_{ij}] \Leftrightarrow c_{ij} = \bigwedge_{k=1..n} \{a_{ik} + b_{kj}\}.$$

LAAM definitions and properties

Definition

When $X = Y$ then W_{XX} and M_{XX} are called Lattice Auto-Associative Memories (LAAMs).

- perfect recall for an unlimited number of stored patterns

$$W_{XX} \boxed{\vee} X = X = M_{XX} \boxed{\wedge} X$$

- convergence in one step for any input pattern
  - if $W_{XX} \boxed{\vee} \mathbf{z} = \mathbf{v}$ then $W_{XX} \boxed{\vee} \mathbf{v} = \mathbf{v}$
  - if $M_{XX} \boxed{\vee} \mathbf{z} = \mathbf{u}$ then $M_{XX} \boxed{\wedge} \mathbf{u} = \mathbf{u}$.

Multivariate Mathematival Morphology

Morphological operations are mappings between complete lattices, denoted $\mathbb{L}$ or $\mathbb{M}$,

erosion is a mapping $\varepsilon : \mathbb{L} \to \mathbb{M}$ conmuting with the infimum operation, $\varepsilon\left(\bigwedge Y\right) = \bigwedge_{y \in Y} \varepsilon\left(y\right)$; $\forall Y \subseteq \mathbb{L}$

dilation is a mapping $\delta : \mathbb{L} \to \mathbb{M}$ conmuting with the supremum operation, $\delta\left(\bigvee Y\right) = \bigvee_{y \in Y} \delta\left(y\right)$.

gradient $g\left(Y\right) = \delta\left(Y\right) - \varepsilon\left(Y\right)$,

top-hat $t\left(Y\right) = Y - \delta\left(\varepsilon\left(Y\right)\right)$.

Multivariate ordering

Definition

A h-ordering is defined by a surjective map of the original partially ordered set onto a complete lattice $h : X \rightarrow \mathbb{L}$,

- the order defined in $\mathbb{L}$ induces a total order in X,

$$r \leq_h r' \Leftrightarrow h(r) \leq h(r') \tag{1}$$

Definition

A h-supervised ordering is a h-ordering satisfying $h(b) = \perp$, $\forall b \in B$, and $h(f) = \top$, $\forall f \in F$,

- for background and foreground $B, F \subset X$, $B \cap F = \emptyset$,
- $\perp$ and $\top$ are the bottom and top elements of $\mathbb{L}$

LAAM h-function

Definition

Given $\mathbf{c} \in \mathbb{R}^n$ and $X = \{\mathbf{x}_i\}_{i=1}^{K}$, $\mathbf{x}_i \in \mathbb{R}^n$; the LAAM based h_X-function is

$$h_X(\mathbf{c}) = \zeta\left(\mathbf{x}^{\#}, \mathbf{c}\right), \tag{2}$$

- $\mathbf{x}^{\#} \in \mathbb{R}^n$ is a LAAM recall result

$$\mathbf{x}^{\#} = M_{xx} \boxed{\wedge} \mathbf{c}$$

or

$$\mathbf{x}^{\#} = W_{xx} \boxed{\vee} \mathbf{c}$$

- $\zeta(\mathbf{a}, \mathbf{b})$ is the Chebyshev distance $\zeta(\mathbf{a}, \mathbf{b}) = \bigvee_i |a_i - b_i|$.

One sided ordering

Definition

one-side LAAM-supervised ordering:

$$\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n,\ \mathbf{x} \leq_X \mathbf{y} \Longleftrightarrow h_X(\mathbf{x}) \leq h_X(\mathbf{y})\,. \tag{3}$$

- $h_X : \mathbb{R}^n \to \mathbb{L}_X$, where $\mathbb{L}_X = \left(\mathbb{R}_0^+, <\right)$, $\perp_X = 0$
- the Background set B s.t. $h_X(\mathbf{b}) = \perp_X = 0$
  - is the set of fixed points of the LAAM $B = \mathcal{F}(X)$

B/F ordering

Definition

The relative background/foreground supervised h-function:

$$h_r(\mathbf{c}) = h_F(\mathbf{c}) - h_B(\mathbf{c}), \tag{4}$$

Given training sets B and F

Definition

relative LAAM-supervised ordering denoted $\leq_r$:

$$\forall \mathbf{x}, \mathbf{y} \in \mathbb{R}^n,\ \mathbf{x} \leq_r \mathbf{y} \Longleftrightarrow h_r(\mathbf{x}) \leq h_r(\mathbf{y}) \tag{5}$$

B/F ordering

- $h_r(\mathbf{c}) : \mathbb{R}^n \to \mathbb{L}_{B/F}$ where $\mathbb{L}_{B/F} = (\mathbb{R}, <)$,
  - $h_r(\mathbf{b}) > 0$; $\mathbf{b} \in \mathcal{F}(B)$
  - $h_r(\mathbf{f}) < 0$; $\mathbf{f} \in \mathcal{F}(F)$
  - no proper bottom and top elements
  - $h_r(\mathbf{c}) = 0$; decision boundary $\mathbf{c} \in C_r$

aim
: of the experiments is a proof of concept of the approach

  - discrimination of **healthy** control subjects, **schizophrenia** patients **with** and **without** auditory hallucinations.

results
: find different brain networks depending on the subject using the **same** *h*-function built from selected voxel seeds.

Materials

- resting state fMRI data obtained from 1 HC, 1SCNH, 1SCWH
- F 240 BOLD volumes and one T1-weighted
  - skull extraction
  - manually AC-PC transformed.
  - The functional images coregistered to the T1-weighted anatomical image.
  - slice timing,
  - head motion correction
  - smoothing (FWHM=4mm)
  - spatial normalization to (MNI) template
  - temporal filtering (0.01-0.08 Hz)
  - linear trend removing
  - All the subjects have less than 1mm maximum displacement and less than 1º of angular motion.

Results

aim to obtain network correlated with an the auditory cortex voxel: effect related to the auditory hallucinations.

seed voxel time series X extracted from HC.

same LAAM M_{XX} applied to HC and patients

computing both h_X and $h_{B/F}$ maps

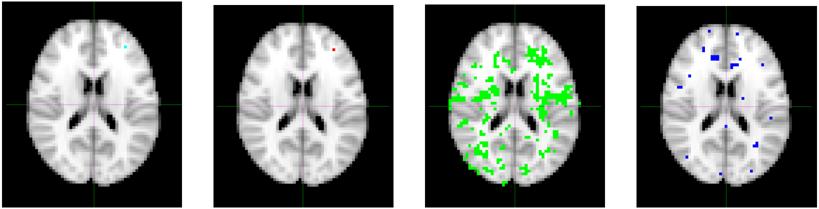
network_1: most similar voxels according to the h-function map

network_2: peaks of the top-hat transformation

One-side supervised h-ordering

- results of two seeds gray matter
  - one in the frontal lobe
  - in the auditory cortex.
- independently of the seed voxel used to build h_X, we find a strong discordance between the network_1 of Schizophrenic patients with and without AH.

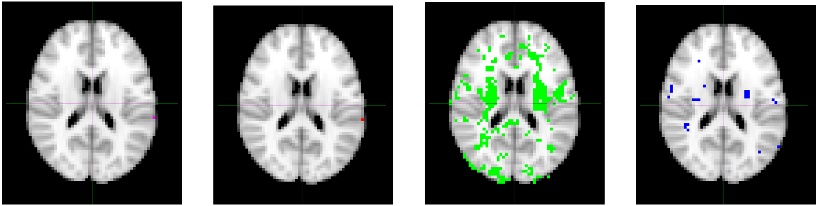
network_1



(a) (b) (c) (d)

Figure : Seed from the **frontal lobe**. (a) location of the seed voxel in the HC, **network_1** in in HC (b), SCWH (c), and SCNH (d).

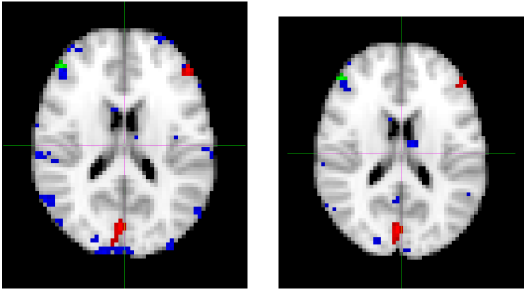
network_1



(a) (b) (c) (d)

Figure : Seed from the **auditory** cortex. (a) location of the seed voxel in the HC, **network_1** in in HC (b), SCWH (c), and SCNH (d).

network_2



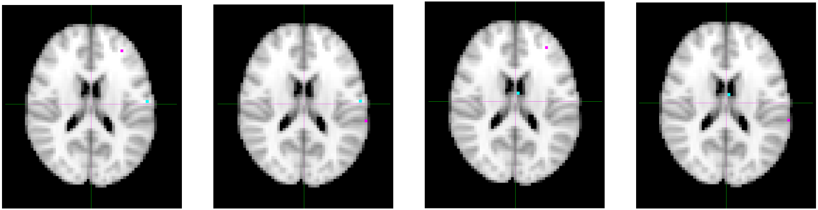
(a) (b)

Figure : **network_2** computed on front lobe (a) and auditory cortex (b). Red, green, blue voxel colors correspond to HC, SCNH, and SCWH, respectively.

Background/foreground supervised ordering

- background voxels (1) WM in the Temporal Lobe and (2) CSF in the ventricles,
- foreground voxels GM: (1) in the Auditory Cortex and (2) in Frontal Lobe,
- compute the h_r map for all combinations
- strong difference between the network locations detected in the three subjects from the same map.

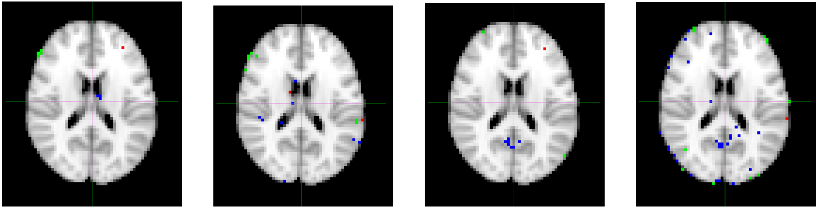
B/F seed voxels



(a) (b) (c) (d)

Figure : Two voxel seeds: (a) **B** from WM and **F** from GM of Frontal Lobe, (b) **B** from WM anfd **F** from GM of Auditory Cortex, (c) **B** from CSF of the ventricule and **F** from GM of Frontal Lob, (d) **B** from CSF of the ventricule and **F** from GM of Auditory Cortex. Blue=**B**, pink=**F**.

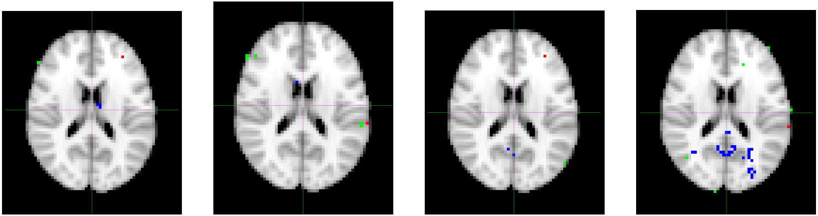
network_1



(e) (f) (g) (h)

Figure : **network_1** from two voxel seed pairs in previous figure. Red, green, blue voxel colors correspond to HC, SCNH, and SCWH, respectively.

network_2



(a) (b) (c) (d)

Figure : **network_2** from two voxel seed pairs in previous figure. Red, green, blue voxel colors correspond to HC, SCNH, and SCWH, respectively.

Conclusions

- new method for fMRI data analysis
  - on multivariate mathematical morphology and
  - supervised reduced ordering that needs the definition of seed voxels.
- this method does not involve statistical techniques, is model-free in a very extensive point of view.
  - the method relies only in lattice computing operators,
- Experimental results on healthy control and patient data show strongly different network according to subject class,
- discrimination that could further be exploited by machine learning approaches.
- Work in progress deals with the group level analysis