Independent Component Analysis of Electrophysiological Data

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The EEGLAB environment
(sccn.ucsd.edu/eeglab)
is now available in the
Neuroscience Gateway
(NSGportal.org)

... In future, optional
NSG computation of EEGLAB
pipelines will be available directly
via the EEGLAB menu itself
Each scalp EEG data channel sums the projected activities of multiple brain (and non-brain) source processes.
The very broad EEG point-spread function

Single simulated parietal source → Very broad projected scalp potentials

Akalin Acar & Makeig 2010
The very broad EEG point-spread function

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The very broad EEG point-spread function

Single simulated parietal source → Very broad projected scalp potentials
The very broad EEG point-spread function

Each EEG channel records variations in a double-ended voltage difference between (at least) two electrodes.

Each EEG channel thereby constitutes a particular spatial filter receptive to sources located all over the brain surface – but particularly receptive to a complex distribution of cortical areas – NOT only to one radially oriented bit of cortex located directly below one of the two (or more) channel electrodes!
One emerging, spatially coherent effective source region

1 million active minicolumns

Summed scalp projection of the 1M sources.

Local coherence change only – no change in spectrum or amplitude

The **effective sources** of the scalp EEG are emergent islands of cortical LFP synchrony or near synchrony.
Two spatially static cortical sources

Scalp projection

Scalp epiphenomena!
Two spatially stationary cortical effective sources

Summed scalp projection

 Phenomena

 9 Hz

 10 Hz

 Epiphenomenal

epiphenomena -- secondary effects or byproducts that arise from but do not causally influence a process.

Z. Akalin Acar & S. Makeig (2012)
Summed scalp projections of 13 effective brain sources

Epiphenomenal Impressions

Causal Phenomena
Electromagnetic source localization using realistic head models

Simple Map

Signal Processing

Source Estimate

Inverse Problem

Sensor Localization

EEG/MEG

Electromagnetic source localization using realistic head models

Zeynep Akalin Acar & Scott Makeig ‘06
But how to find EEG effective sources?
Blind EEG Source Separation by Independent Component Analysis

ICA can find distinct EEG source activities -- and their ‘simple’ scalp maps!

Tony Bell, developer of Infomax ICA

CSF
Skull
Scalp

S. Makeig, S. Enghoff (2000)
Infomax ICA learning approach

How to make the outputs statistical independent?
Minimize their redundancy or mutual information.

Consider the joint entropy of two components,

$$H(y_1, y_2) = H(y_1) + H(y_2) - I(y_1, y_2).$$

Maximizing $H(y_1, y_2)$ $\iff$ minimizing $I(y_1, y_2)$.

The learning rule:

$$\Delta W \propto \frac{\partial H(y)}{\partial W} W^T W$$

Infomax

Is 0 if the two variables are independent

Natural gradient normalization (Amari)
Blind EEG Source Separation by ICA

Information-based Signal Processing
ICA Assumptions

- Mixing is linear at electrodes  ✓
- Propagation delays are negligible  ✓
- Component locations are fixed  ?
- Component time courses are independent  ?
- # components <= # scalp channels  ?

Contribution to EEG

# Scalp channels

# Effective sources
Are EEG effective source signals independent?

Independent Domains of Local Synchrony

Freeman - phase cones
Plenz - avalanches

Cortex

Thalamus

S. Makeig (2007)
Properties of EEG Independent Components

- Maximally Temporally Independent
- Concurrently Active and Spatially Overlapping
- *Dipolar* Scalp Maps (Delorme et al., 2012)
- Functionally Distinct
- Between-Subject Similarity / Complexity
ICA in practice

Onton & Makeig, 2006
ICA finds Non-Brain Independent Component (IC) Processes ...

... separates them from the remainder of the data ...
Independent muscle signals

S. Makeig, J. Onton 2005
... and also separates cortical brain IC processes

- Single dipole component
- Dual-symmetric dipole component
- Equivalent dipoles
Single Session - Two Maximally Independent Alpha Processes

30%
Important Result (2012)

Those linear decompositions of multi-channel EEG data that find ICs whose time courses are more nearly temporally independent

Also find more ICs whose scalp maps are highly ‘dipolar’ – i.e., ICs compatible with the spatial projection of a source process in a single local cortical patch (or, a non-brain artifactual source) – whose location can be accurately estimated using a equivalent dipole model

More nearly independent component time courses

Larger number of dipolar component scalp projections

Hypothesis: Dipolar ICs = Localized effective source processes

Delorme et al., PLOS One, 2012
Delorme et al., *PLOS One*, 2012
Are locations of EEG effective sources similar across tasks?

Are effective source locations within task similar across participants?
Effective Source Density

Visual Working Memory

dipoledensity()

Sternberg letter memory task

Onton & Makeig, 2005
Effective Source Density

Eyes-closed emotion imagination

>> dipoledensity()
Effective Source Density

Letter twoback with feedback

Onton & Makeig, 2005
Effective Source Density

Auditory novelty oddball

Onton & Makeig, 2005
Effective Source Density

A. Old/new word memory

Onton et al., '05

Word memory (old/new) task
Effective Source Density

B. Visually cued selective response

Onton & Makeig, 2005
Are source dynamics similar across participants?
Example: frontal midline theta cluster

Individual Differences
‘EEG Biomarkers’
Can ICA reveal subject differences?

Multidimensional Landscape of Individual Differences
Auditory Deviance Response

The deepest mental trap in electrophysiology lurks in the word “THE” !!!
Nonpsychiatric Comparison Subjects (NCS)

Mean Map Dipole Density

7% ΔERP pvaf

x = 40 mm

R Superior Temporal

Schizophrenia Patients (SZ)

Dipole Density Mean Map

ΔERP pvaf

x = 40 mm

6%

R Inferior Frontal

13%

40 mm

Ventral Mid Cingulate

29%

0 mm

Anterior Cingulate

24%

0 mm

Medial Orbitofrontal

29%

0 mm

Dorsal Mid Cingulate

29%

0 mm

Rissling et al., 2014
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<th>PEAK AMPLITUDES</th>
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Low- and High-Resolution Source Localization
EEG Source Localization

LORETA = Low-Resolution Electrical Tomography
Arthur Tsai – Topological source clustering and measure projection

Arthur Tsai et al., *NeuroImage*, 2014
High-Resolution Distributed Source Localization using a multiscale patch basis

1. Compute a ‘dictionary’ of Gaussian patches conforming to the cortical surface centered at each cortical mesh voxel.

2. Use a ‘sparsifying’ approach to find the sum of the fewest of these patches that together produce the given source scalp or grid map.

0. Build a high-res. cortical surface mesh; give each voxel an oriented dipole.
High-resolution source localization requires an electrically accurate head model.
Handheld 3-D electrode position recording system software

sccn.ucsd.edu/wiki/Get_chanlocs

Currently by hand 1-by-1. Soon by machine learning.
Brain imaging during movement – How?

- Current advances in miniaturization, computer power, and information-based signal processing make possible a new imaging modality:

  → Mobile Brain/Body Imaging (MoBI)

Concept:

Combine whole-head EEG, eye gaze tracking, and whole-body motion capture recording in a real-world 3-D environment.

Scott Makeig, 2008
MoBI

Mobile Brain/Body Imaging

Record what the brain does,
What the brain experiences,
And what the brain organizes.
**Lab Streaming Layer** software for synchronous multi-stream, multi-platform recording and feedback – freely available online (paper in progress):

`github.com/labstreaminglayer`

**Extensible Data Format (xdf)** for multimodal data collection and storage.

**SNAP** – a python-based framework running on Unity for control of simple or complex MoBI experiments.

**MoBILAB** – a Matlab-based multimodal data browser and pre-processing app.
Now feasible – Low-cost MoBI Systems

Any EEG System

Low-Cost MoBI

< $100

Emotiv Neuroheadset

Touchscreen

Kinect motion capture

< $500

Eye Tribe eye tracker

< $1000

Full Body Wireless Inertial Motion Capture

Leap Motion hand/finger tracker

< $100

< $100

LSL software drivers exist for all these (and more) devices
Brain imaging of natural cognition -- actions & interactions

Imaging Human Agency and Social Interactions
Neuroelectromagnetic Forward Head Modeling Toolbox (NFT)

Invasively Monitored Head -- Forward Electrical Model

Electrical Brain Source Analysis for ECoG

Intact Head -- Forward Electrical Model

Independent Component Source of ECoG Data

Source Patch in Sulcus Estimated using the Forward Head Model

Akalin Acar, Palmer, Makeig, 2009
ECoG Data Source Decomposition by ICA

gyral source

sulcal source
Just as, currently, MRI & fMRI signals are only interpreted after transformation from sensor space to brain source space,

So too, in future, electrophysiological signals should (and will) be interpreted only after suitable transformation from EEG|ECoG|LFP sensor space to brain effective source space.

→ The dependence on spatially stable source dynamics forced by ICA is artificial; more general models of spatiotemporal field trajectories (e.g., using deconvolutive ICA or complex ICA).