Independent Component Analysis of Electrophysiological Data

Scott Makeig
Institute for Neural Computation
University of California San Diego

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

Tony Bell, developer of Infomax ICA

S. Makeig, S. Enghoff (2000)
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 vs. PCA

Principal Component Analysis

Independent Component Analysis

PCA simply decorrelates the outputs using an **orthogonal mixing matrix**.

PCA makes each successive component account for as much **variance** in the data as possible.

ICA makes each component account for as much **temporally independent information** in the data as possible, with no constraints on the mixing matrix.

**PCA lumps – ICA splits!**

Arnaud Delorme & S. Makeig, 2016
ICA in practice

Onton & Makeig, 2006
A P300' visual target response at electrode Cz (vertex)

Average ERP

No scalp response in these trials ... Why not?

What sources contribute to this potential?

The response (at Cz) sums 238 independent sources

Scalp EEG signals are strong mixtures of brain sources. In this sense scalp channel signals are epiphenomena. Source signals are the EEG phenomena of real interest! No more than ~30% of any scalp channel variance is produced by any one brain source!
Classifying ICs

Non-brain sources

Effective brain sources

EOG

EMG

Brain

Brain

J. Onton & S. Makeig, 2005
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 Session - Two Maximally Independent Alpha Processes
ICA is a linear data decomposition method

\[
\text{Act} = \mathbf{W} \ast \text{Data}
\]

\[
\text{Data} = \mathbf{W}^{-1} \ast \text{Act}
\]

\[
\text{Data} = \mathbf{W}^{-1} \ast (\mathbf{W} \ast \text{Data})
\]

Makeig & Onton, 2011
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\ minimizes \( I(y_1, y_2) \).

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)
Historical Remarks

- Bell & Sejnowski (1995): Information maximization (Infomax)
- Makeig, Bell, Jung, Sejnowski (1996); ICA decomposition of EEG
- Amari et al. (1996): Natural gradient learning
- Cardoso (1996): Joint approximate diagonalization (JADE)
- Hyvarinen (1999): (fastICA)
- Lee/Girolami (1999): Mixture model ICA (Extended Infomax)
- Palmer (2006): Adaptive mixture ICA (AMICA)

Applications of ICA to biomedical signals

- EEG/ERP analysis (Makeig, Bell, Jung & Sejnowski, *NIPS 1996*)
- fMRI analysis (McKeown et al., 1998)
- Fetal/mother ECG separation (Cardoso, 1998)
- Electrocorticography (ECoG) (Whitmer, 2010)
Important Recent Result (2012)

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

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

More independent time courses ↔ Larger number of dipolar ICs

Hypothesis: Dipolar ICs = Localized cortical source processes

Delorme et al., PLOS One, 2012
Delorme et al., *PLOS One*, 2012
Important Recent Result

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More independent time courses $\leftrightarrow$ Larger number of dipolar ICs

Dipolar ICs = Localized cortical source processes

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

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

Visual Working Memory

dipoledensity()
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
Effective Source Density

B. Visually cued selective response
Are source dynamics similar across participants?
Example: frontal midline theta cluster

Onton, Delorme & Makeig, NeuroImage (2005)
Goal: To cluster equivalent ICs across subjects
Why analyze sources instead of channel activities?
Auditory Deviance Response

The deepest mental trap in electrophysiology lurks in the word “THE” !!!
### PEAK AMPLITUDES

<table>
<thead>
<tr>
<th>Scalp Electrode (Fz)</th>
<th>PEAK%AMPLITUDE</th>
<th>ERP</th>
<th>r²</th>
</tr>
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<tbody>
<tr>
<td>Verbal IQ (WRAT)</td>
<td></td>
<td>P3a</td>
<td>0.11</td>
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<tr>
<td>Functional Capacity (UPSA)</td>
<td></td>
<td>RON</td>
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</table>

#### R Superior Temporal

<table>
<thead>
<tr>
<th>Scalp Electrode</th>
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<tbody>
<tr>
<td>Working Memory (LNS Reorder)</td>
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<tr>
<td>Verbal IQ (WRAT)</td>
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<td>RON</td>
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<tr>
<td>Immediate Verbal Memory (CVLT)</td>
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<td>RON</td>
<td>0.28</td>
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<tr>
<td>Delayed Verbal Memory (CVLT)</td>
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<td>RON</td>
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<tr>
<td>Functional Capacity (UPSA)</td>
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<td>MMN</td>
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<tr>
<td>Functional Capacity (UPSA)</td>
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#### R Inferior Frontal

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<tr>
<td>Negative Symptoms (SANS)</td>
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<tr>
<td>Psychosocial Functioning (SOF)</td>
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<td>RON</td>
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<tr>
<td>Auditory Attention (LNS Forward)</td>
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<td>MMN</td>
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<tr>
<td>Working Memory (LNS Reorder)</td>
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<td>Verbal IQ (WRAT)</td>
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#### Ventral Mid Cingulate

<table>
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<td>Positive Symptoms (SAPS)</td>
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<td>RON</td>
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<td>P3a</td>
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<tr>
<td>Immediate Verbal Memory (CVLT)</td>
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<td>0.41</td>
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<tr>
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<tr>
<td>Verbal IQ (WRAT)</td>
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<td>Executive Functioning (WCST)</td>
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#### Anterior Cingulate

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<tr>
<td>Functional Status (GAF)</td>
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<td>MMN</td>
<td>0.18</td>
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<tr>
<td>Functional Status (GAF)</td>
<td></td>
<td>RON</td>
<td>0.17</td>
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<td>0.25</td>
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<td>RON</td>
<td>0.17</td>
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#### Medial Subtorfrontal

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<tbody>
<tr>
<td>Positive Symptoms (SAPS)</td>
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<td>P3a</td>
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<tr>
<td>Negative Symptoms (SANS)</td>
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<td>P3a</td>
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<td>Psychosocial Functioning (SOF)</td>
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<td>P3a</td>
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<tr>
<td>Functional Capacity (UPSA)</td>
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<td>P3a</td>
<td>0.32</td>
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#### Dorsal Mid Cingulate

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### PEAK LATENCIES

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<tr>
<td>---n/a---</td>
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### R Superior Temporal
- Functional capacity (UPSA) MMN 0.25
- Delayed Verbal Memory (CVLT) MMN 0.17

### R Inferior Frontal
- **Negative Symptoms (SANS)** RON 0.51
- Psychosocial Functioning (SOF) RON 0.25
- **Executive Functioning (WCST)** MMN 0.30
- **Executive Functioning (WCST)** P3a 0.28

### Ventral Mid Cingulate
- **Negative Symptoms (SANS)** P3a 0.33
- **Negative Symptoms (SANS)** RON 0.33
- Psychosocial Functioning (SOF) P3a 0.31
- Verbal IQ (WRAT) MMN 0.25
- **Executive Functioning (WCST)** P3a 0.30

### Anterior Cingulate
- Functional Capacity (UPSA) RON 0.17
- Verbal IQ (WRAT) MMN 0.24
- Auditory Attention (LNS-Forward) MMN 0.17

### Medial Orbitofrontal
- **Negative Symptoms (SANS)** RON 0.41
- Positive Symptoms (SAPS) RON 0.40
- **Auditory Attention (LNS-Forward)** MMN 0.29
- **Executive Functioning (WCST)** P3a 0.32

### Dorsal Mid Cingulate
- Negative Symptoms (SANS) MMN 0.20
- Negative Symptoms (SANS) P3a 0.17
- Global Functioning (GAF) RON 0.24
- Functional Capacity (UPSA) P3a 0.13
Why don’t all subjects contribute to every IC cluster?
Subject differences?

Significant ITC differences (by bootstrap) between the LOC and fLOC clusters immediately follow Probe presentation (5-11 Hz).
Subject differences?
Subject differences?
Properties of EEG Independent Components

- Maximally Temporally Independent
- Concurrently Active and Spatially Overlapping
- Dipolar Scalp Maps
- Functionally Distinct
- Between-Subject Similarity / Complexity