Independent Component Analysis of Electrophysiological Data

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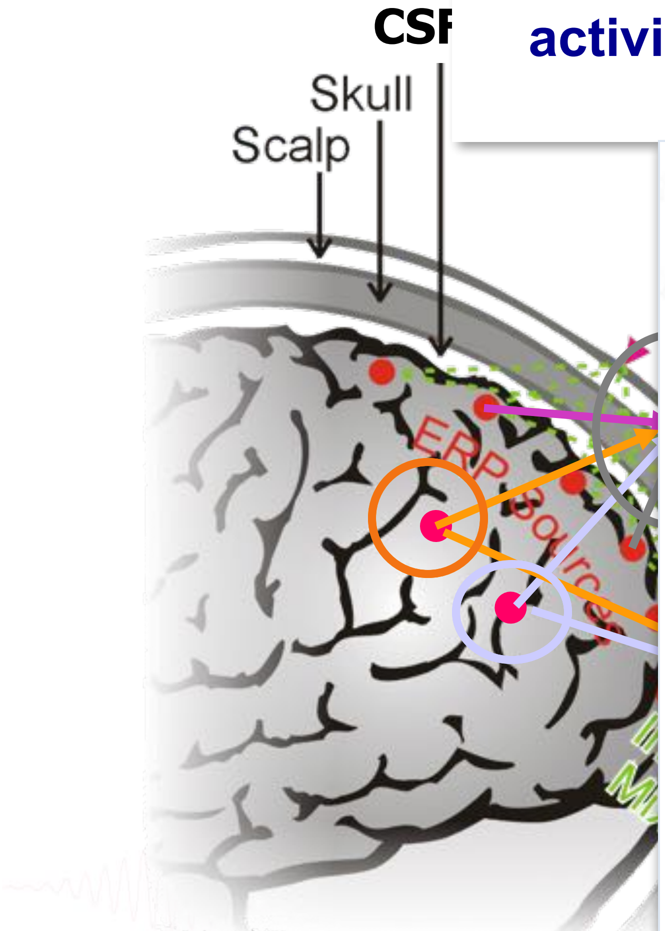
Blind EEG Source Separation by Independent Component Analysis

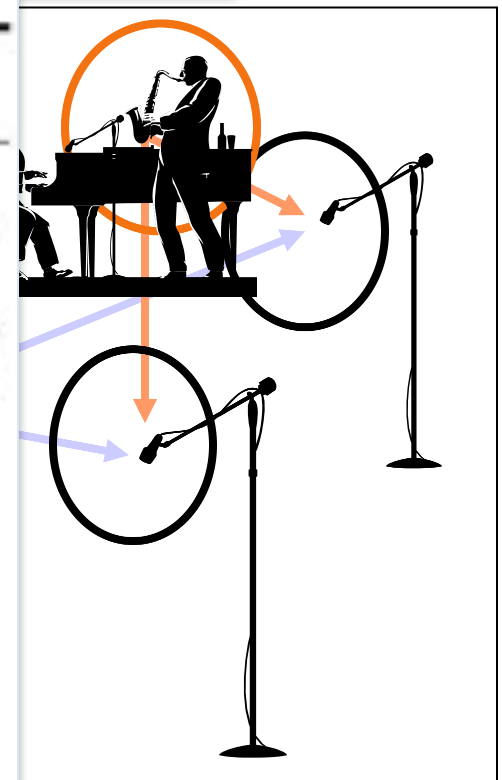
Tony Bell, developer of Infomax ICA

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



Independent Component Analysis of Electroencephalographic Data

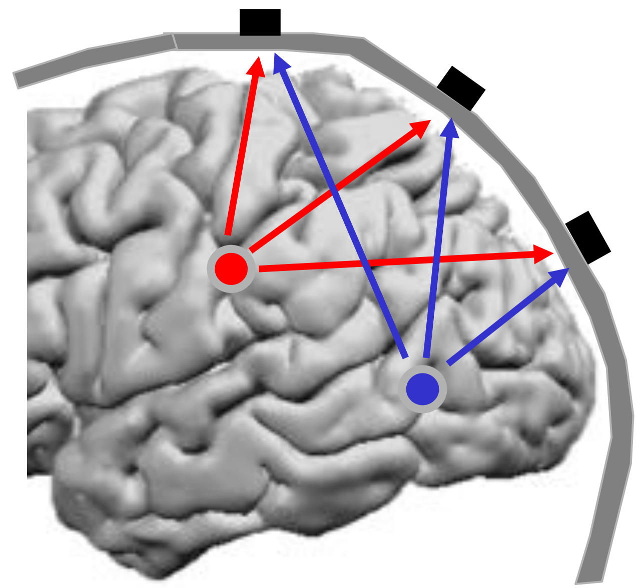
Abstract

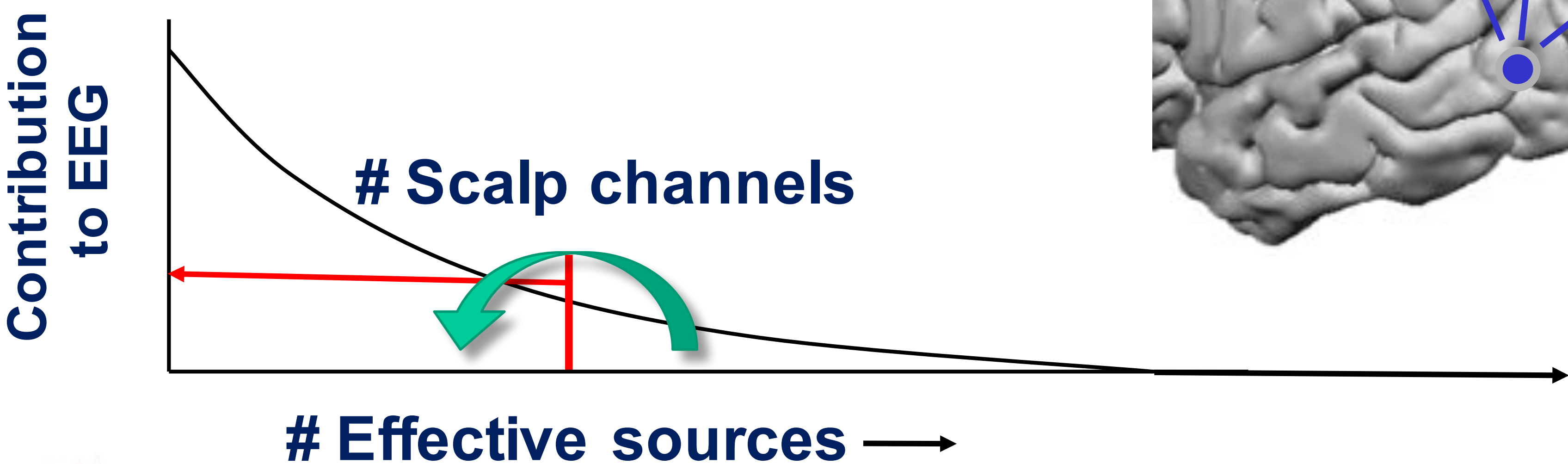


S. Makeig, S. Enghoff (2000)

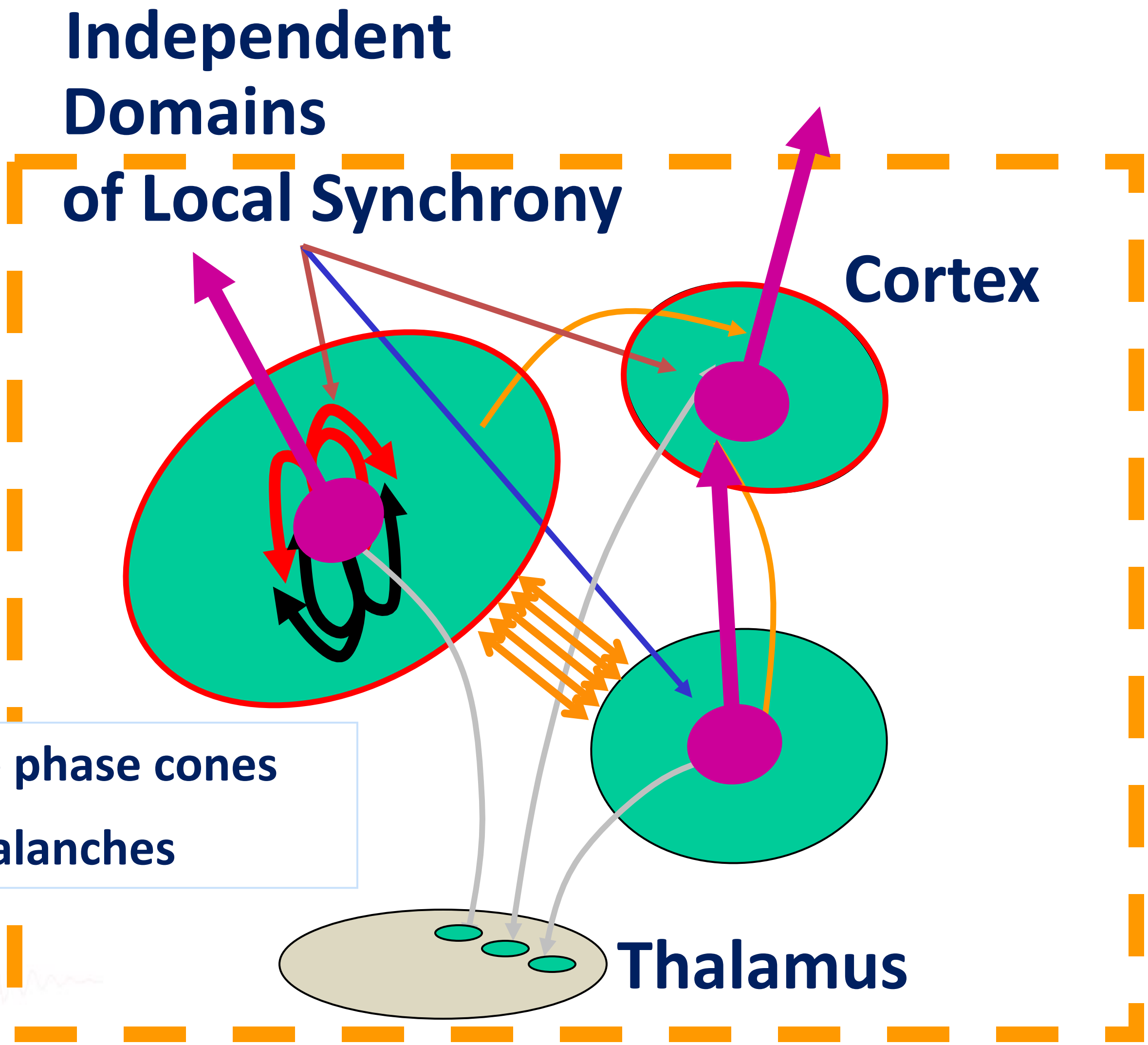
ICA Assumptions

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





Are EEG effective source signals independent?

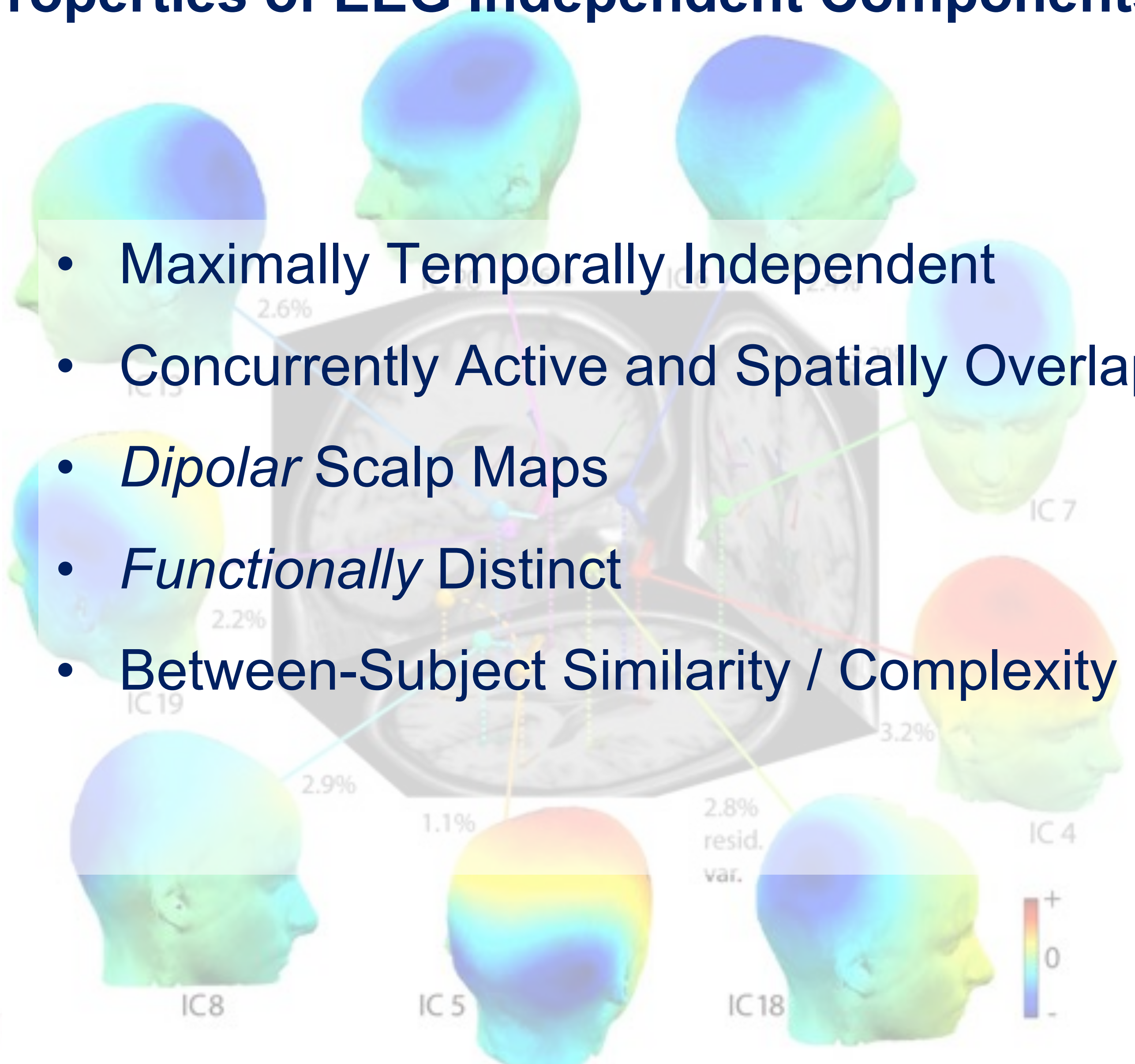


Freeman - phase cones

Plenz - avalanches

S. Makeig (2007)

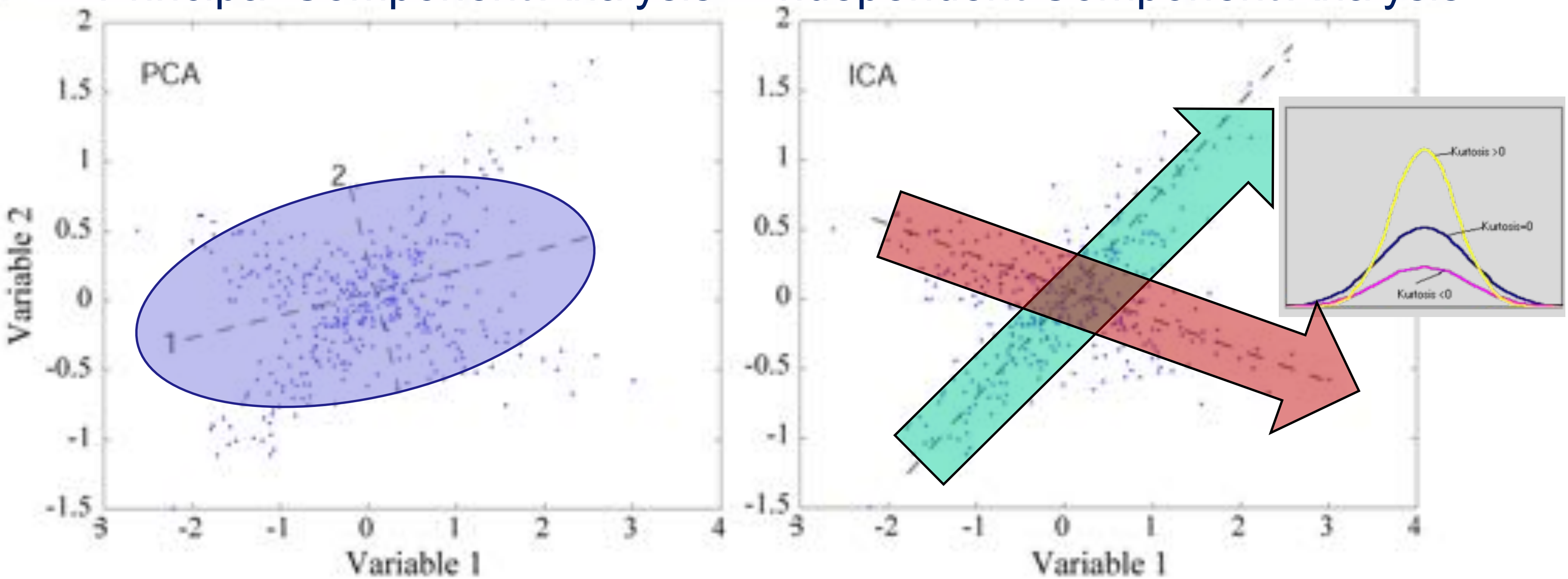
Properties of EEG Independent Components



- Maximally Temporally Independent
- Concurrently Active and Spatially Overlapping
- *Dipolar* Scalp Maps
- *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**.

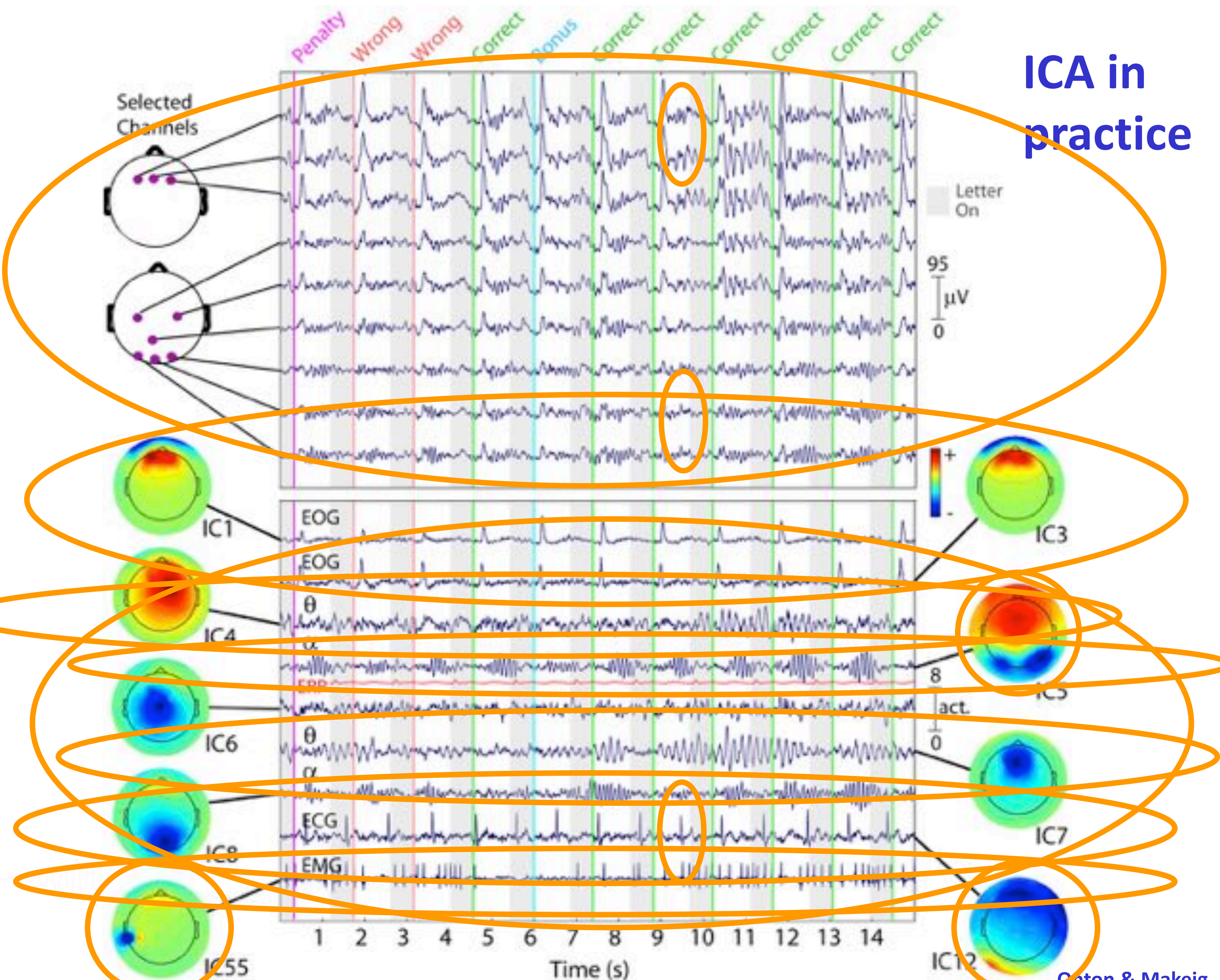
PCA makes each successive component account for as much **variance** in the data as possible.

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

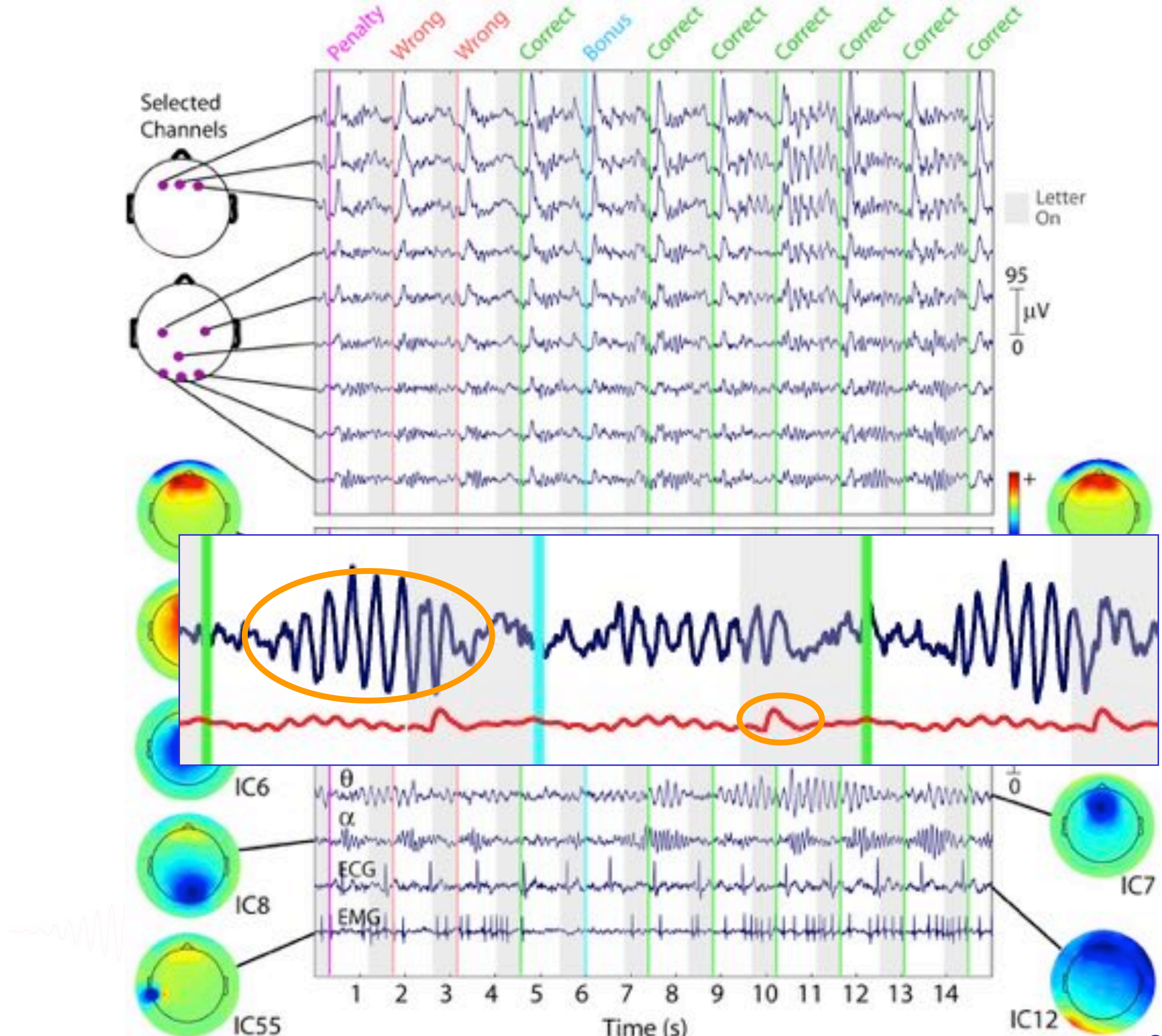
PCA lumps – ICA splits!

Arnaud Delorme & S. Makeig, 2016

ICA in practice

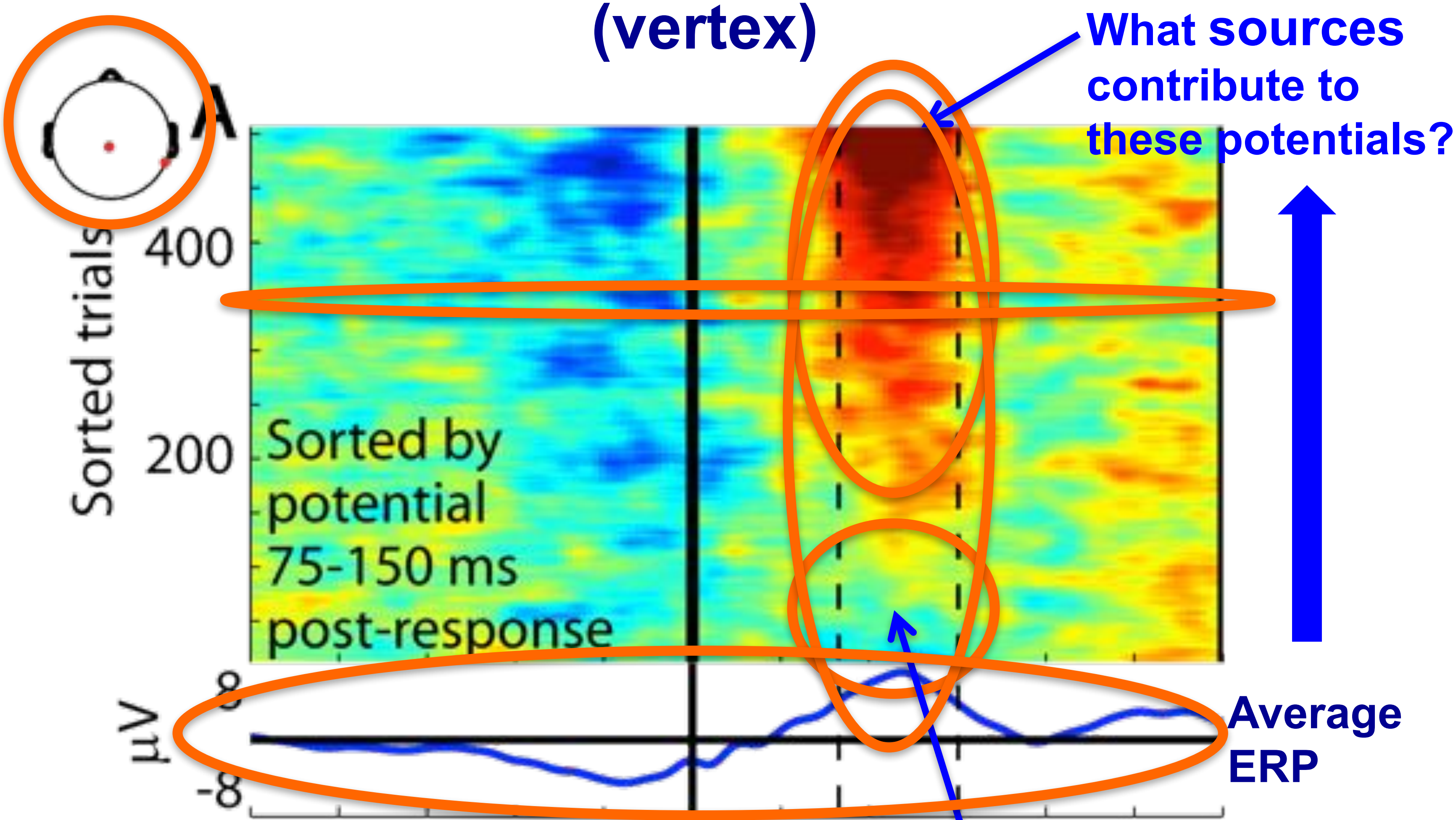


Onton & Makeig, 2006



Onton, Makeig (2006)

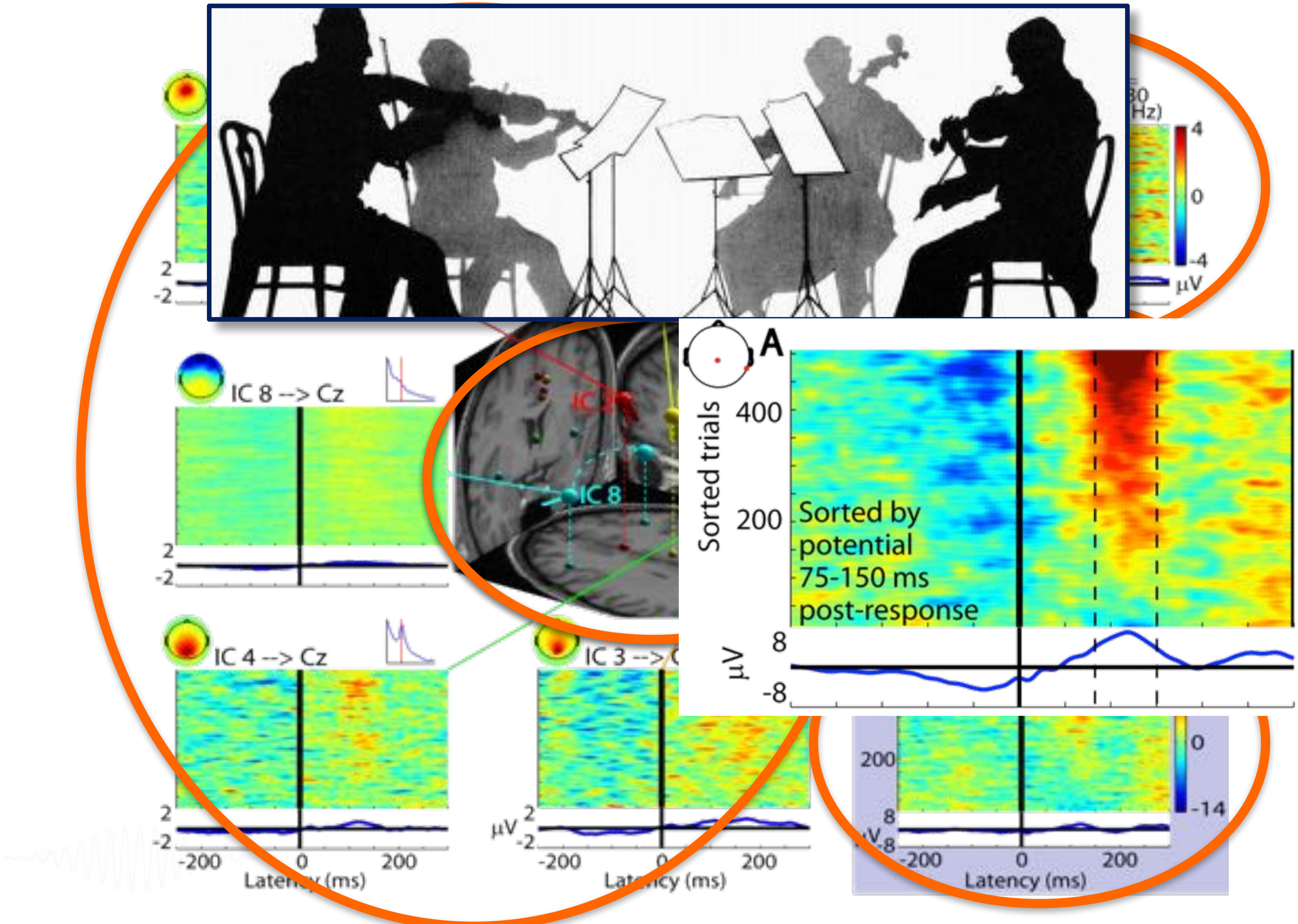
A P300' visual target response at electrode Cz (vertex)



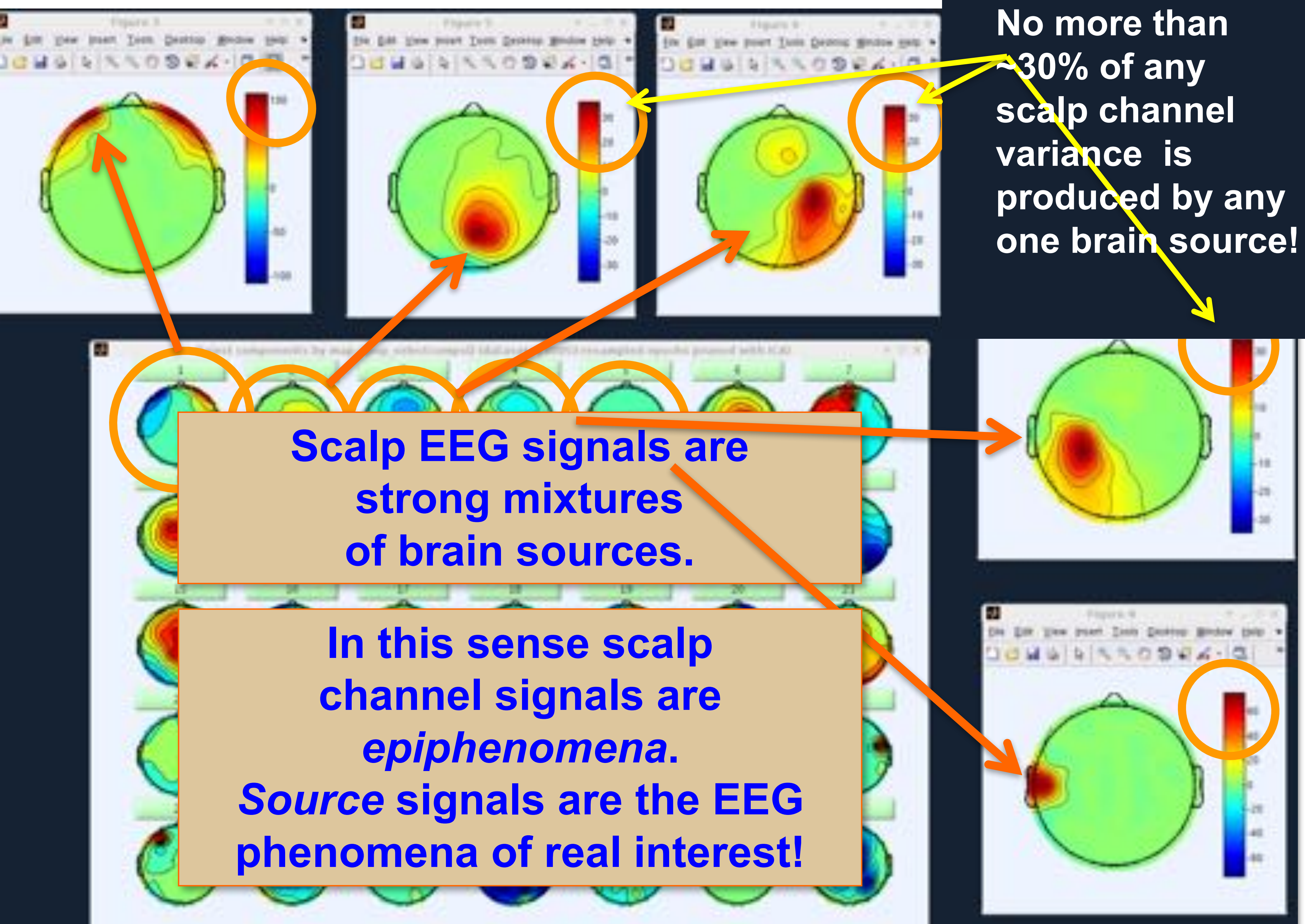
erpimage()

J. Onton & S. Makeig (2009)

The response (at Cz) sums 238 independent sources

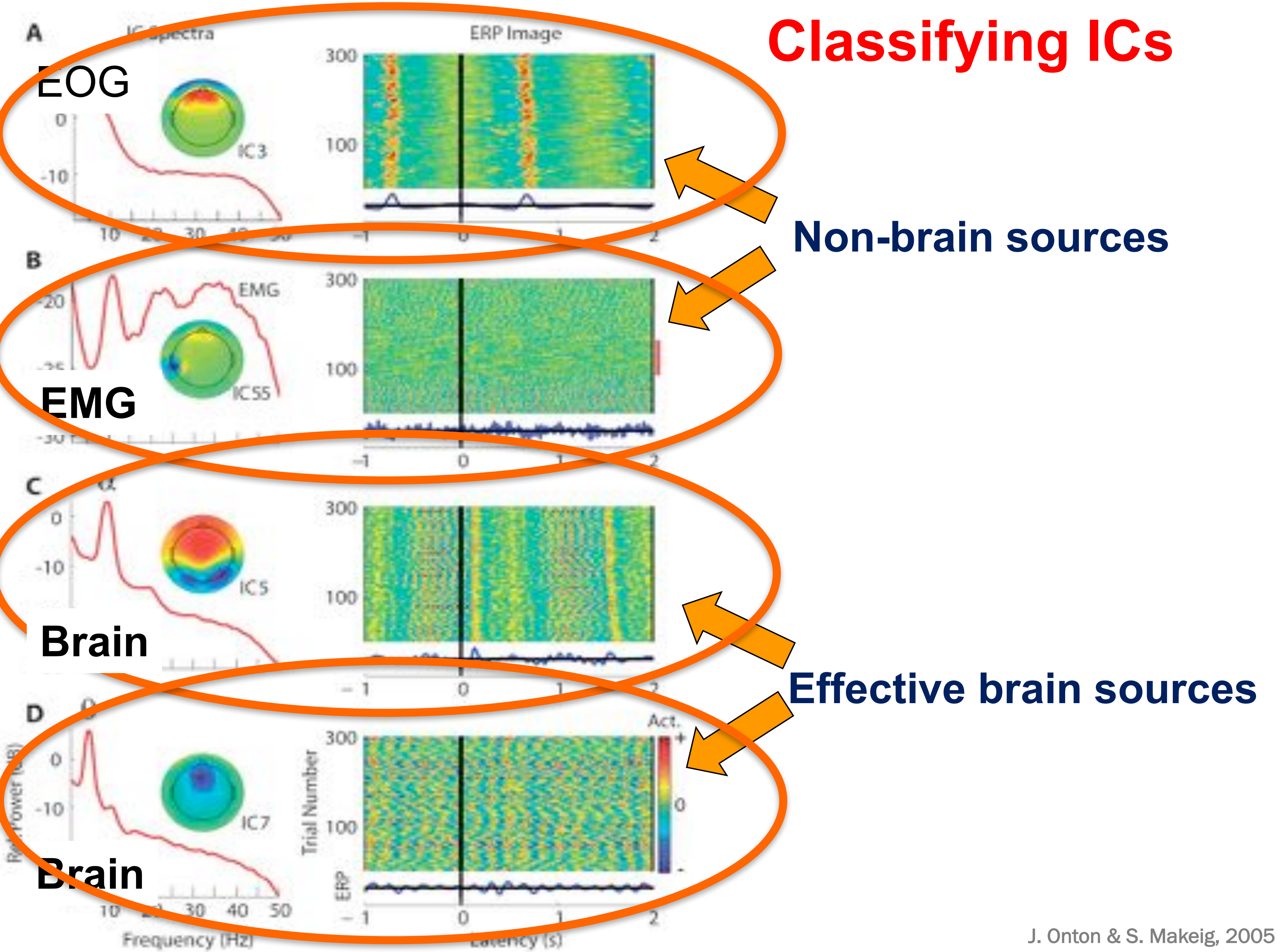


J. Onton & S. Makeig (2009)



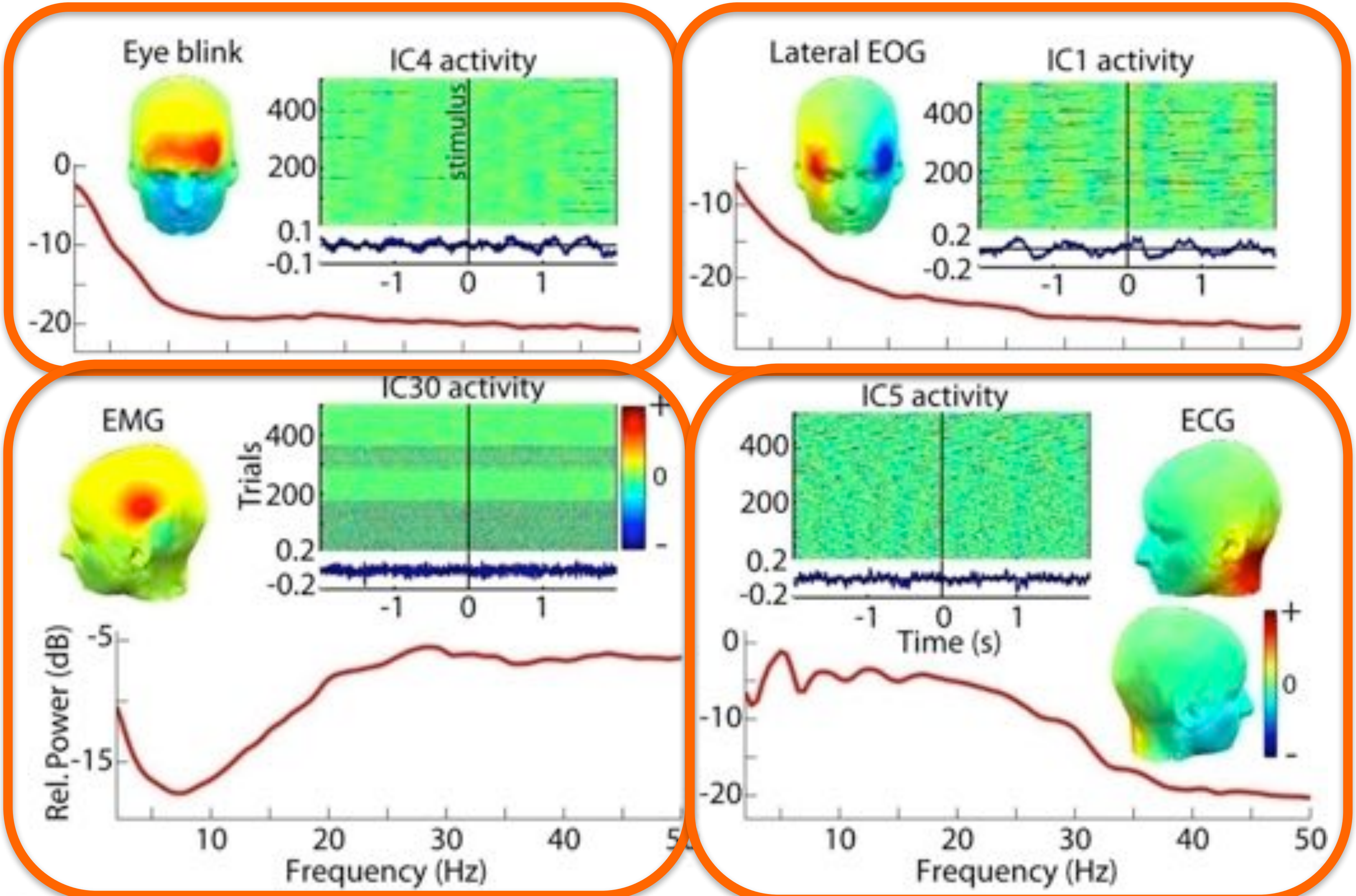
S. Makeig & M. Miyakoshi, 2015

Classifying ICs



J. Onton & S. Makeig, 2005

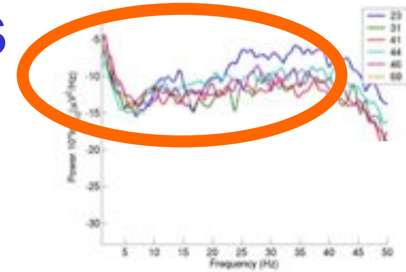
ICA finds Non-Brain Independent Component (IC) Processes …

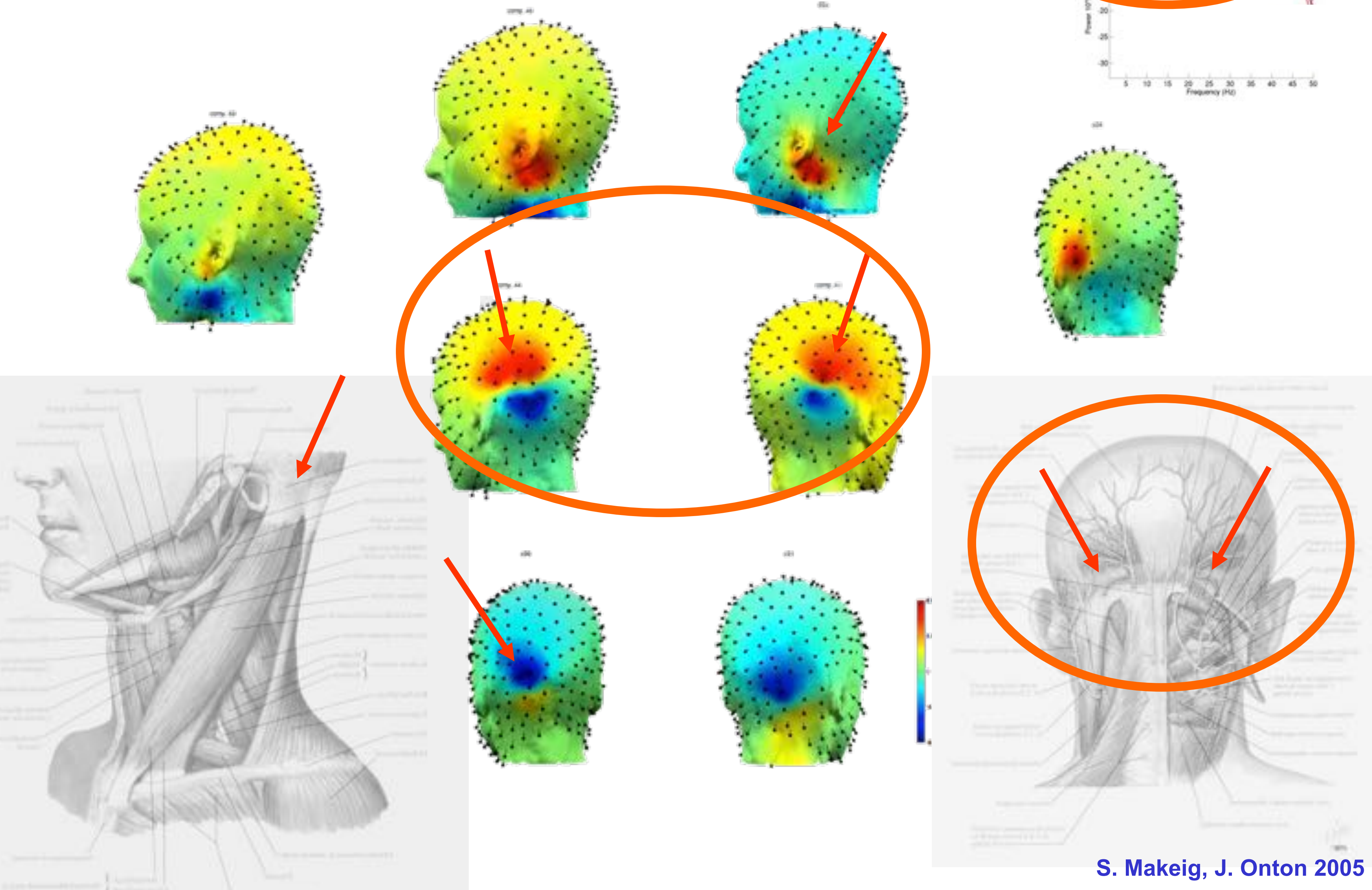


… separates them from the remainder of the data …

J. Onton & S. Makeig

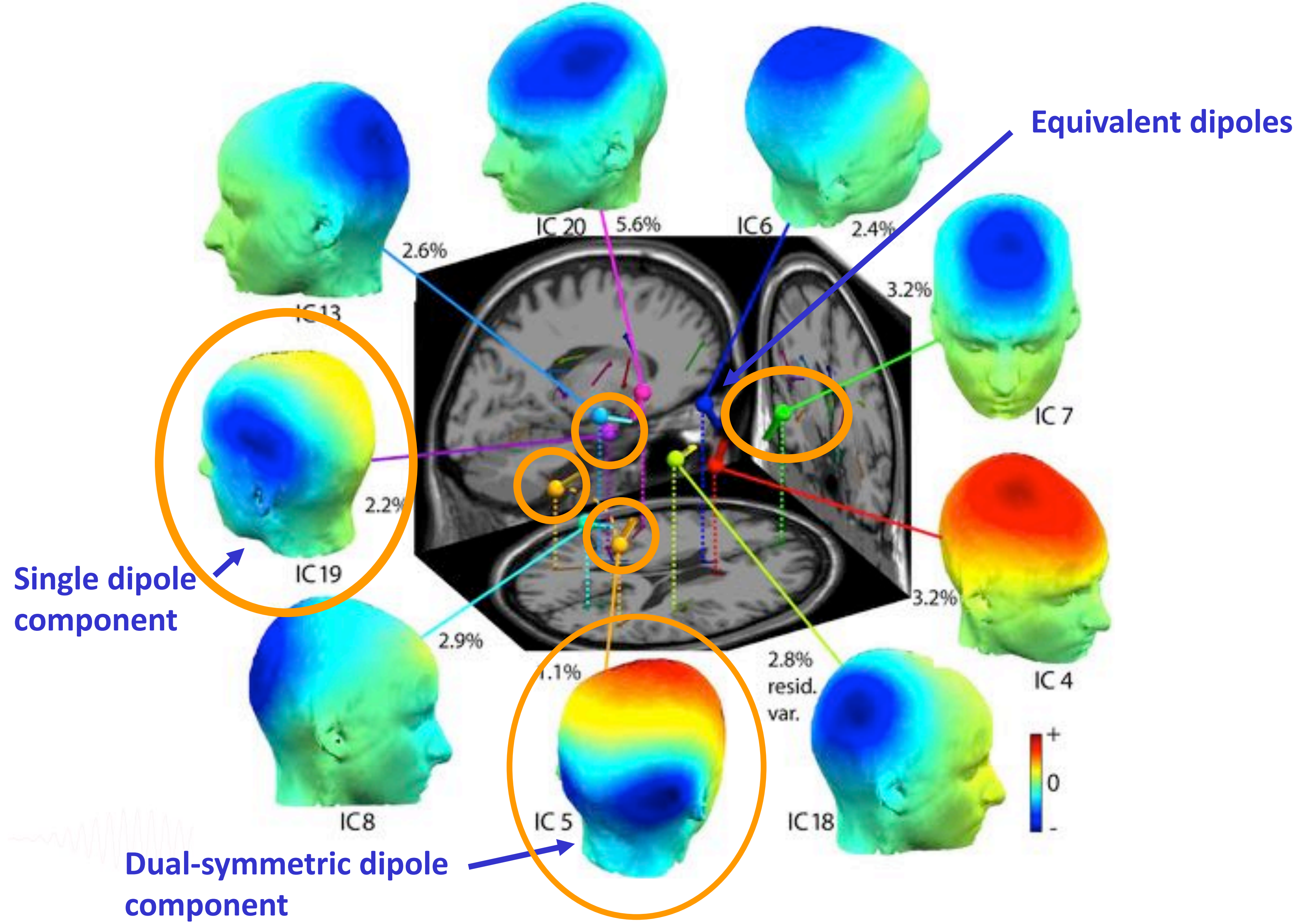
Independent muscle signals





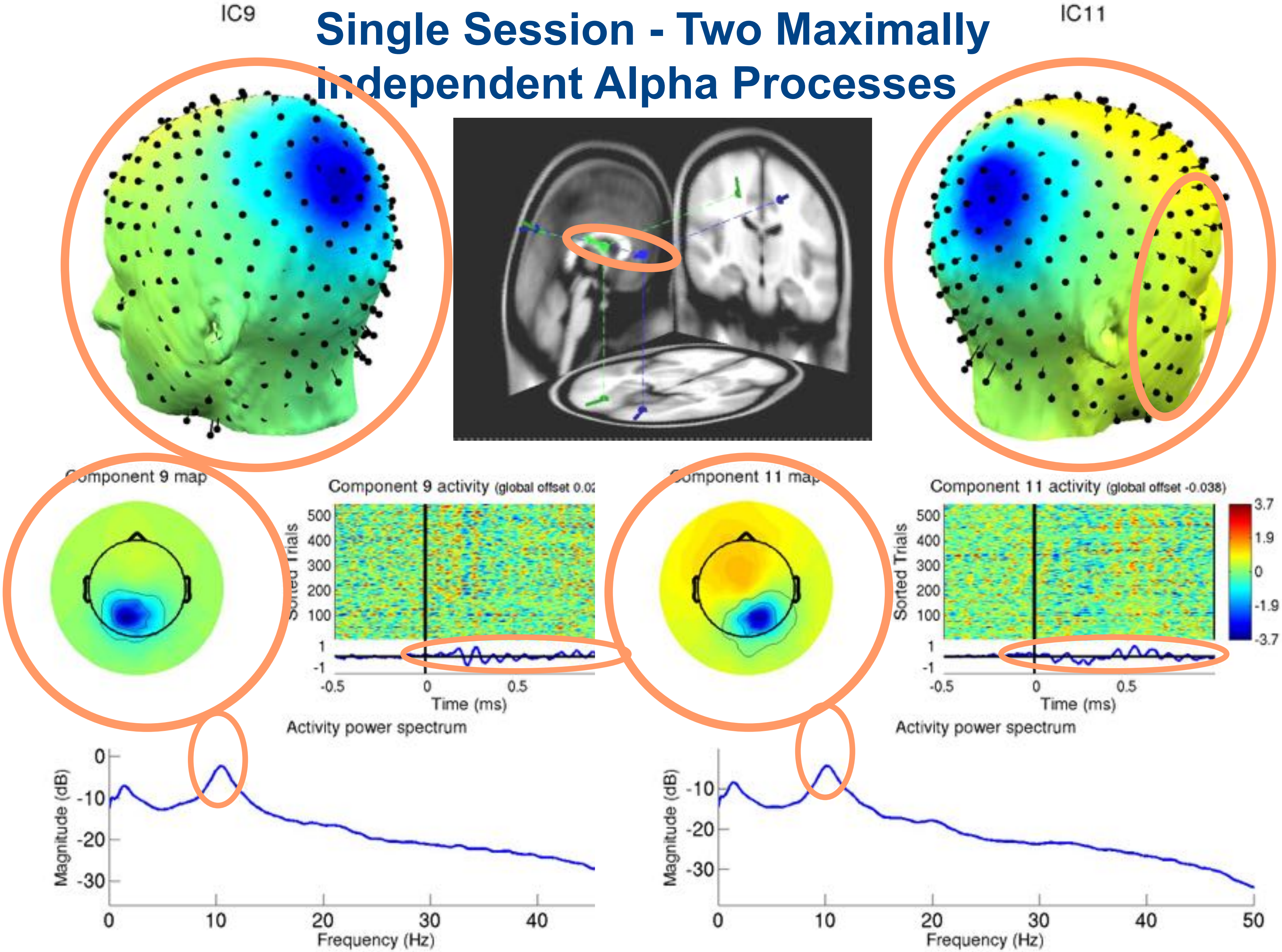
S. Makeig, J. Onton 2005

… and also separates cortical brain IC processes

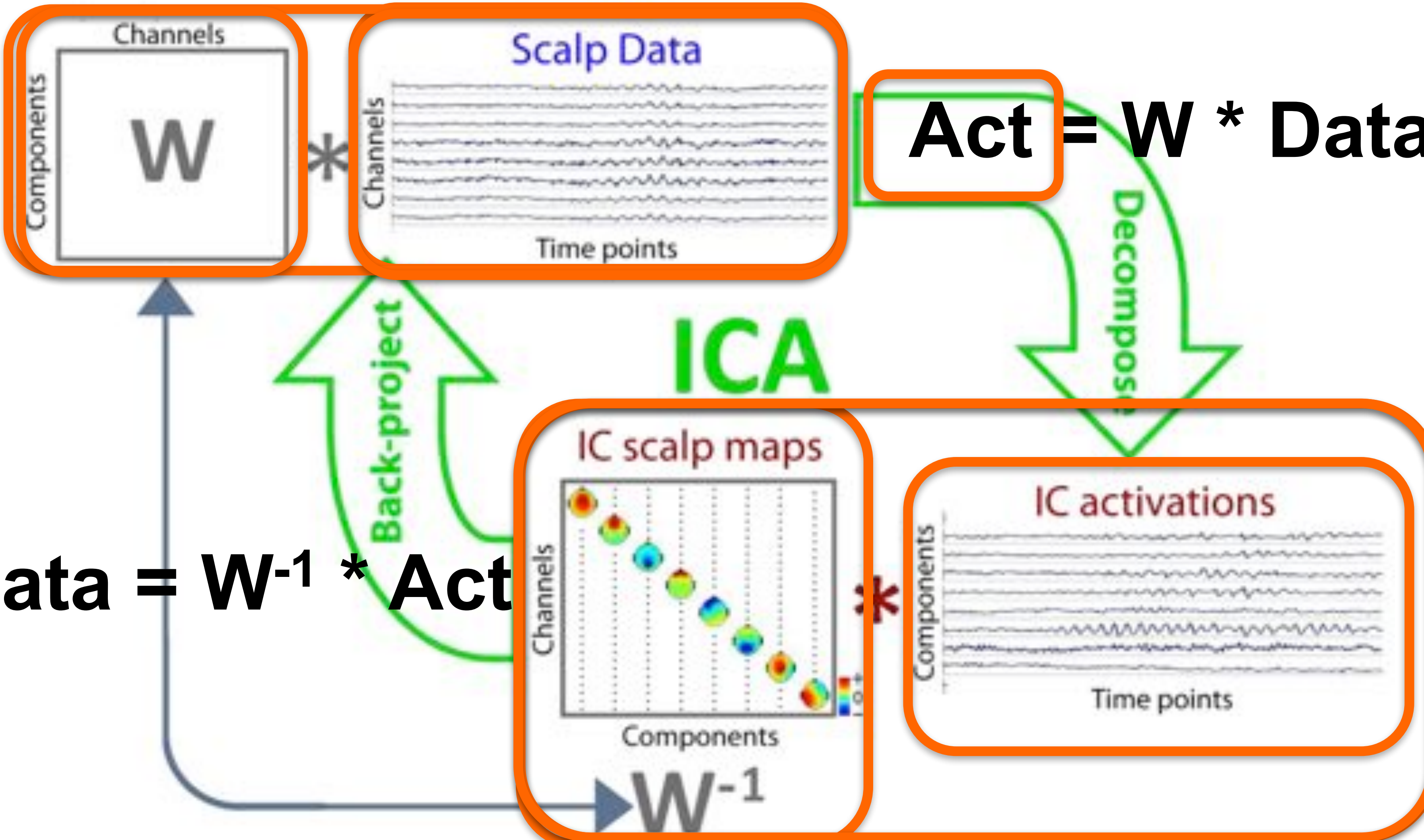


Julie Onton & S. Makeig (2006)

Single Session - Two Maximally Independent Alpha Processes



ICA is a linear data decomposition method



$$Act = W * Data$$

$$Data = W^{-1} * Act$$

$$Data = W^{-1} * (W * Data)$$

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,

$$\boxed{H(y_1, y_2) = H(y_1) + H(y_2) - I(y_1, y_2).}$$

$$\boxed{\text{Maximizing } H(y_1, y_2)} \Longrightarrow \boxed{\text{minimizing } I(y_1, y_2).}$$

Infomax

Is 0 if the two variables are independent

The learning rule:

$$\boxed{\Delta \mathbf{W}} \propto \boxed{\frac{\partial H(\mathbf{y})}{\partial \mathbf{W}}} \underbrace{\mathbf{W}^T \mathbf{W}}_{\substack{\text{Natural gradient} \\ \text{normalization} \\ \text{(Amari)}}}$$

Historical Remarks

- Herault & Jutten ("Space or time adaptive signal processing by neural network models“, *Neural Nets for Computing Meeting*, Snowbird, Utah, 1986): Seminal paper
- 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)

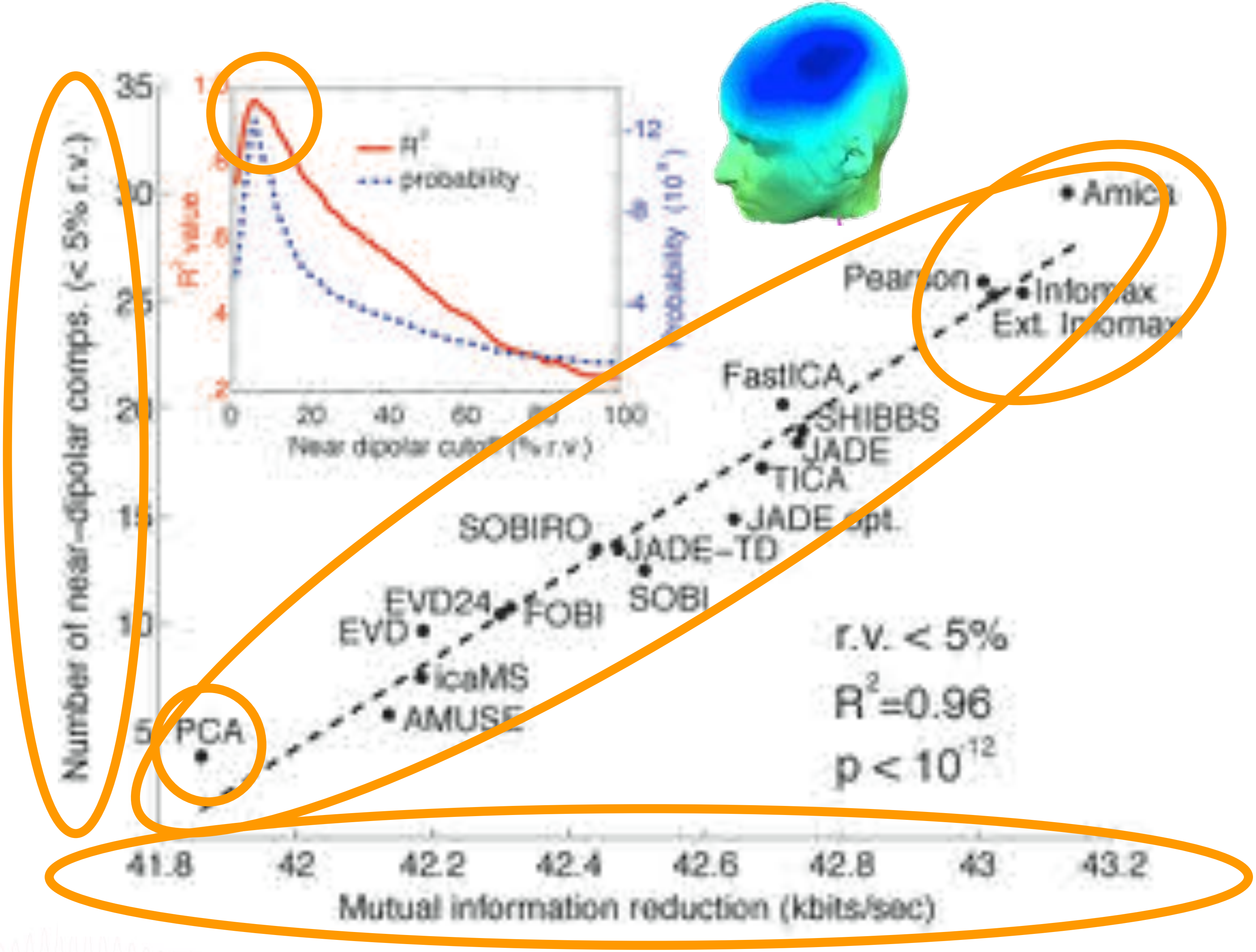
Those linear decompositions of multi-channel EEG data that find ICs whose time courses are **more** temporally **independent …**

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

S. Makeig, 2011

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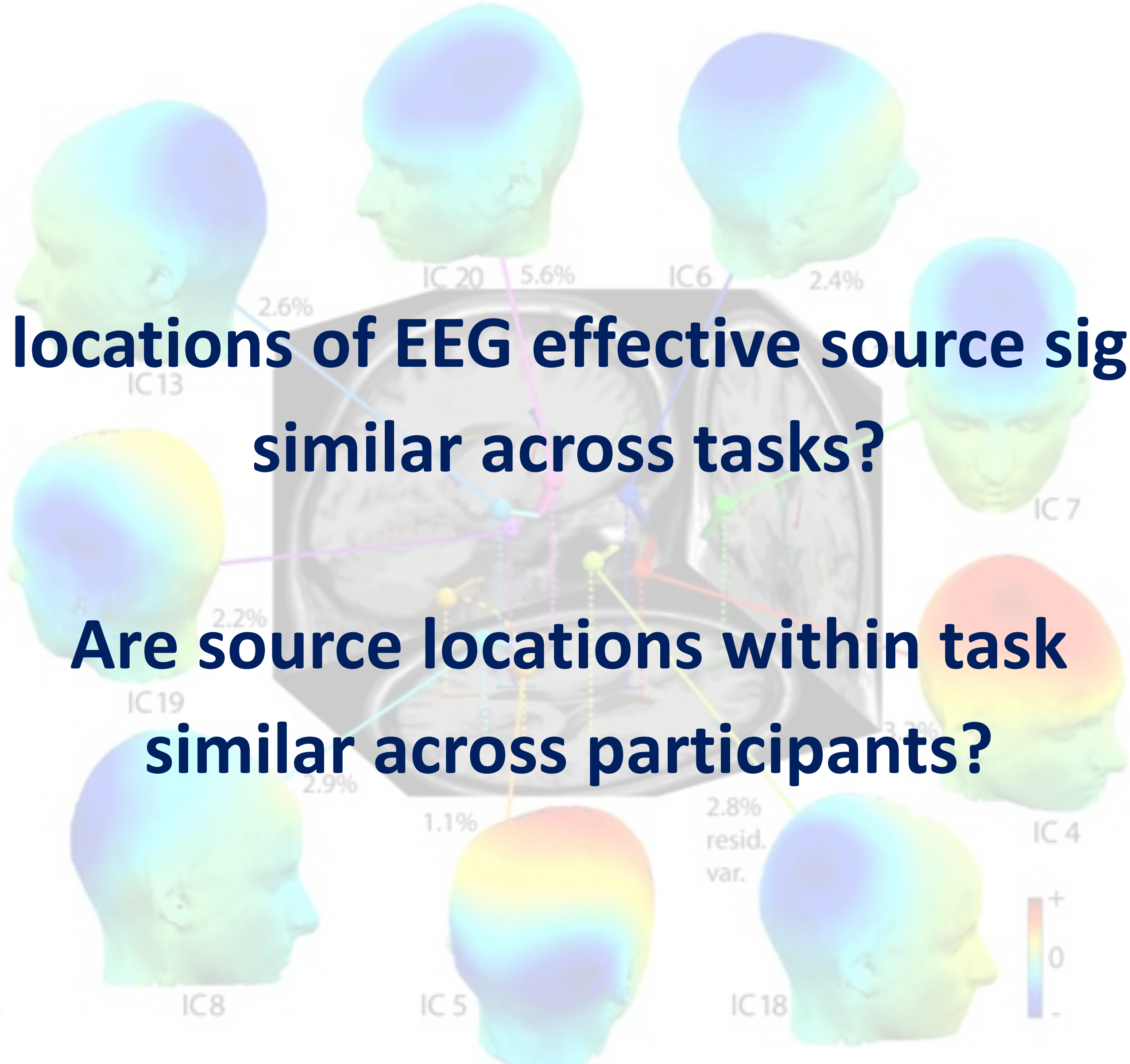


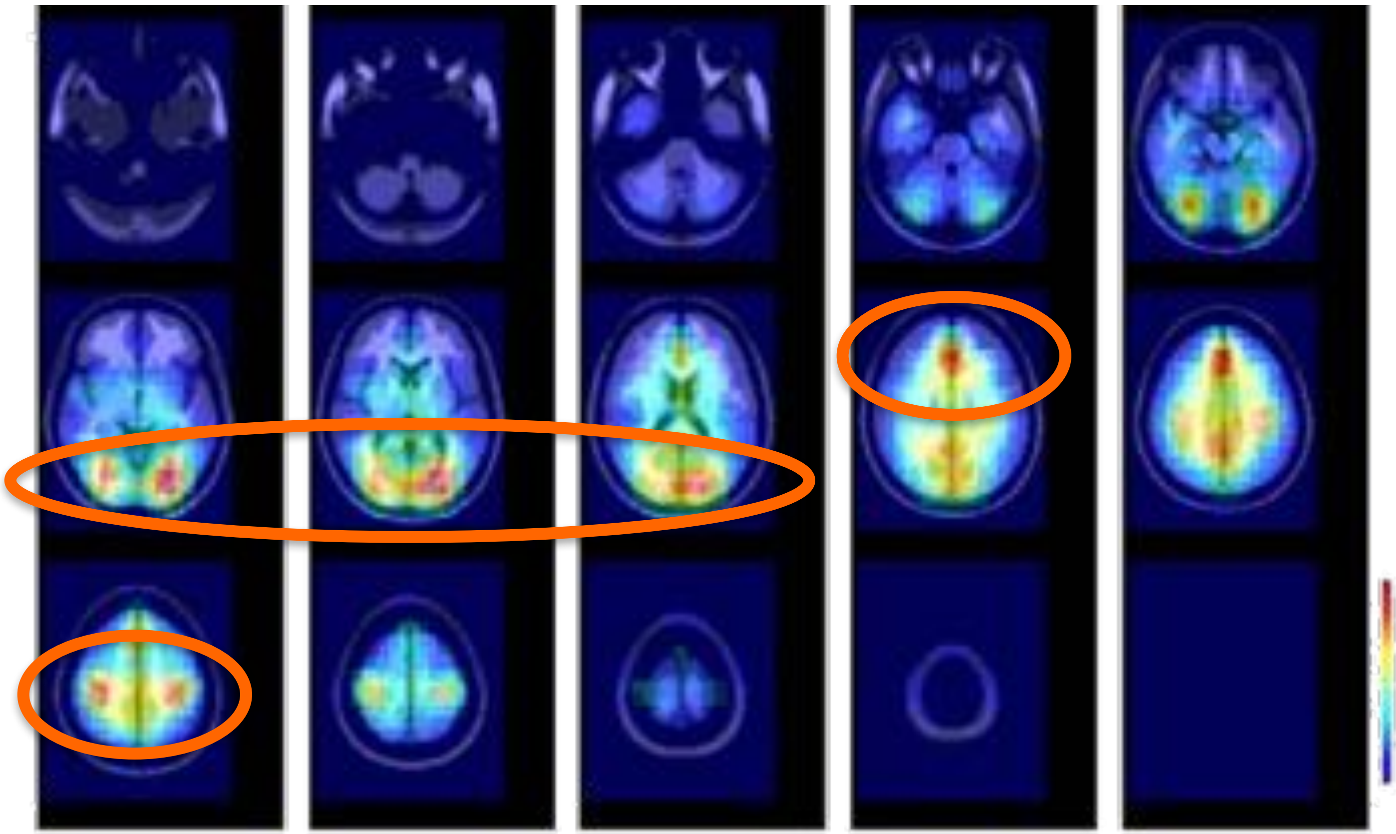
Are locations of EEG effective source signals similar across tasks?

Are source locations within task similar across participants?

S. Makeig (2007)

Effective Source Density

Visual Working Memory



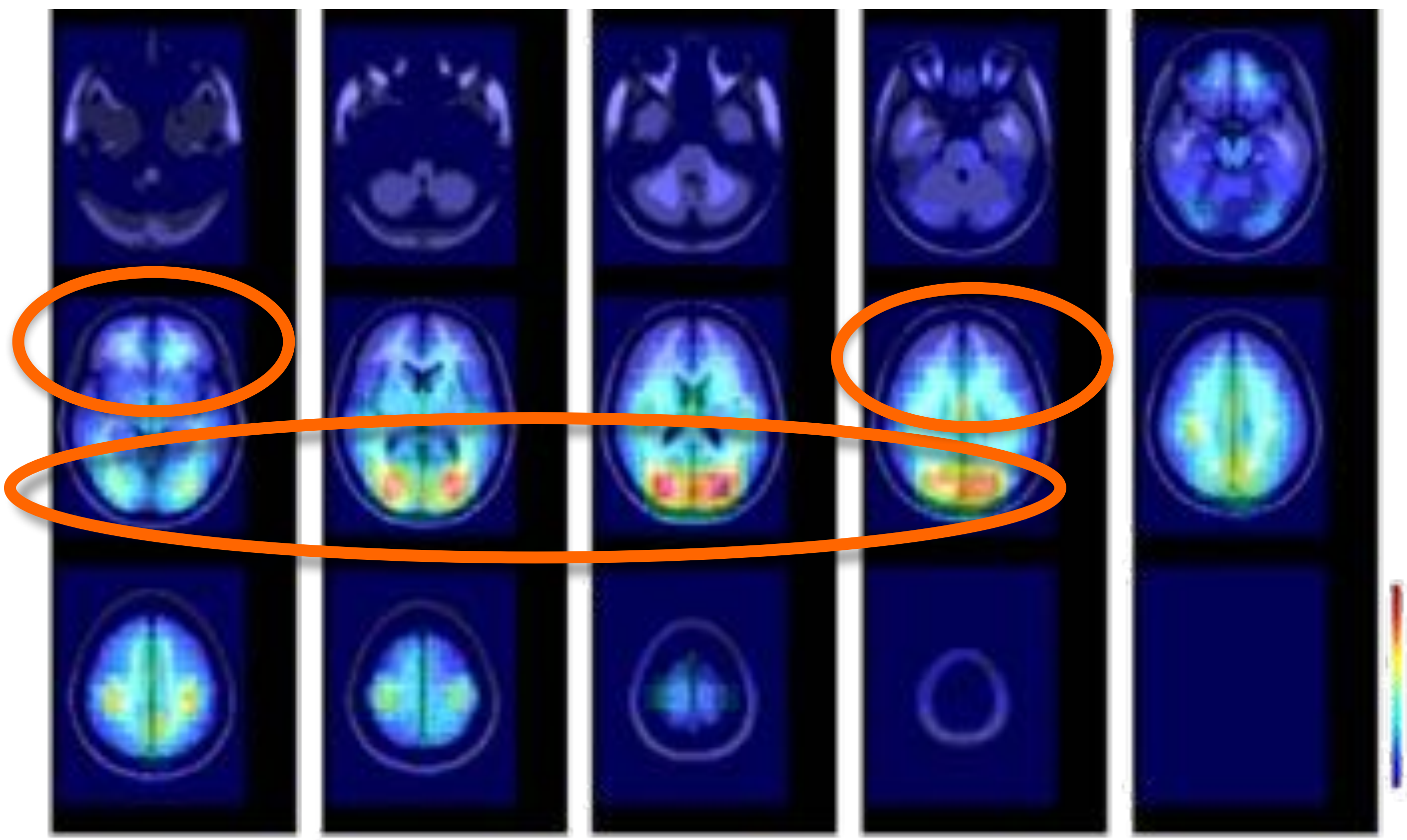
Sternberg letter memory task

dipoledensity()

Onton & Makeig, 2005

Effective Source Density

Eyes-closed emotion imagination

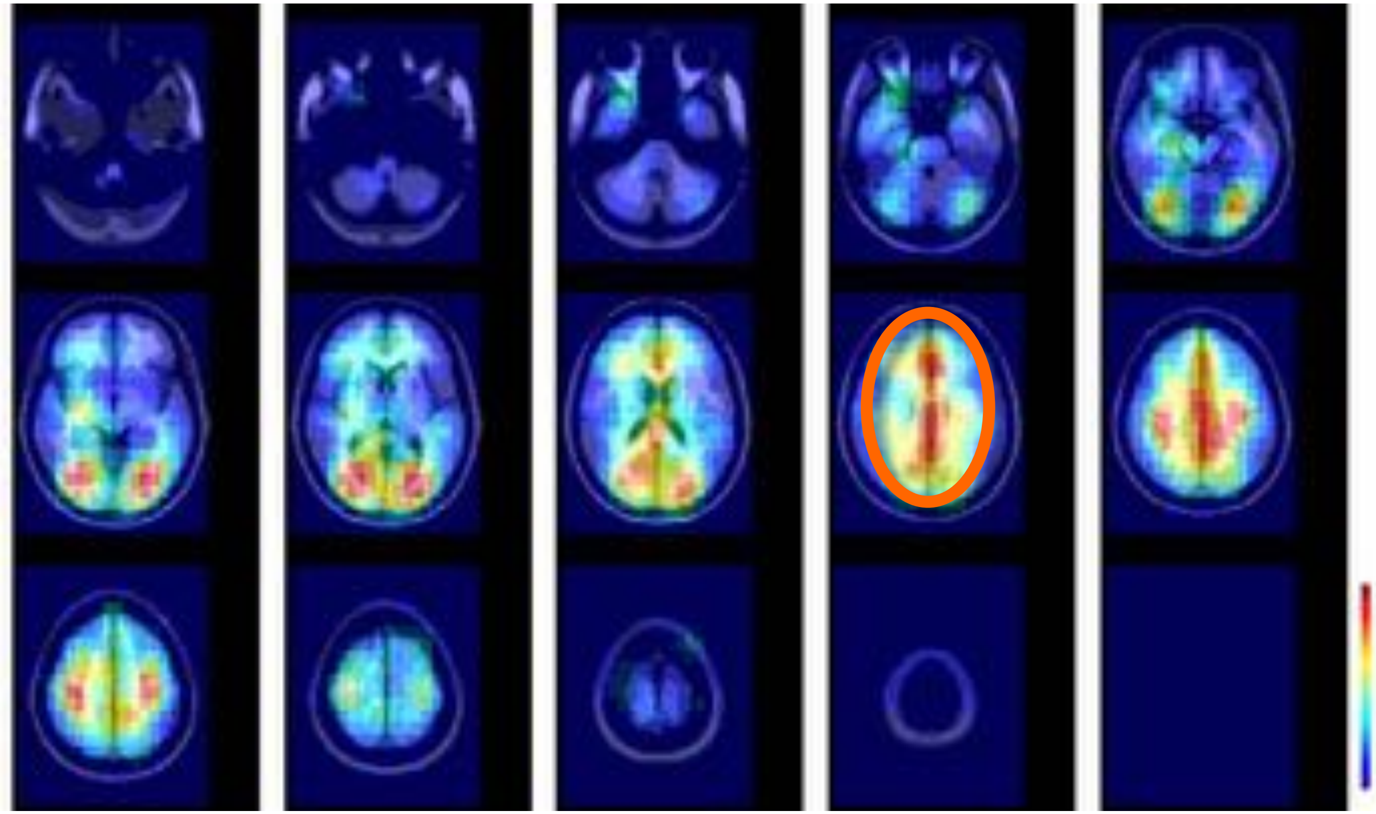


>> dipoledensity()

Onton & Makeig, 2005

Effective Source Density

Letter twoback with feedback

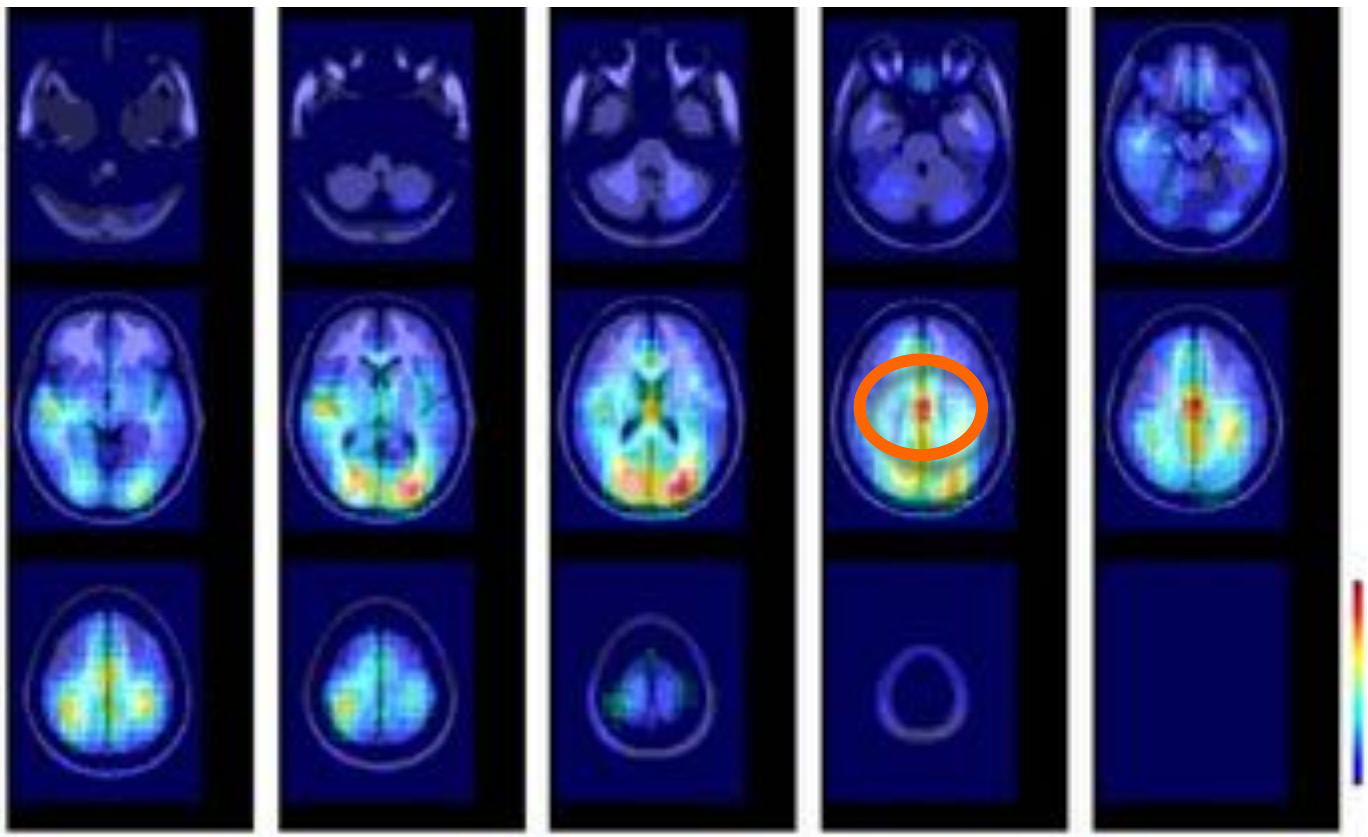


Letter twoback with feedback

Onton & Makeig, 2005

Effective Source Density

Auditory novelty oddball

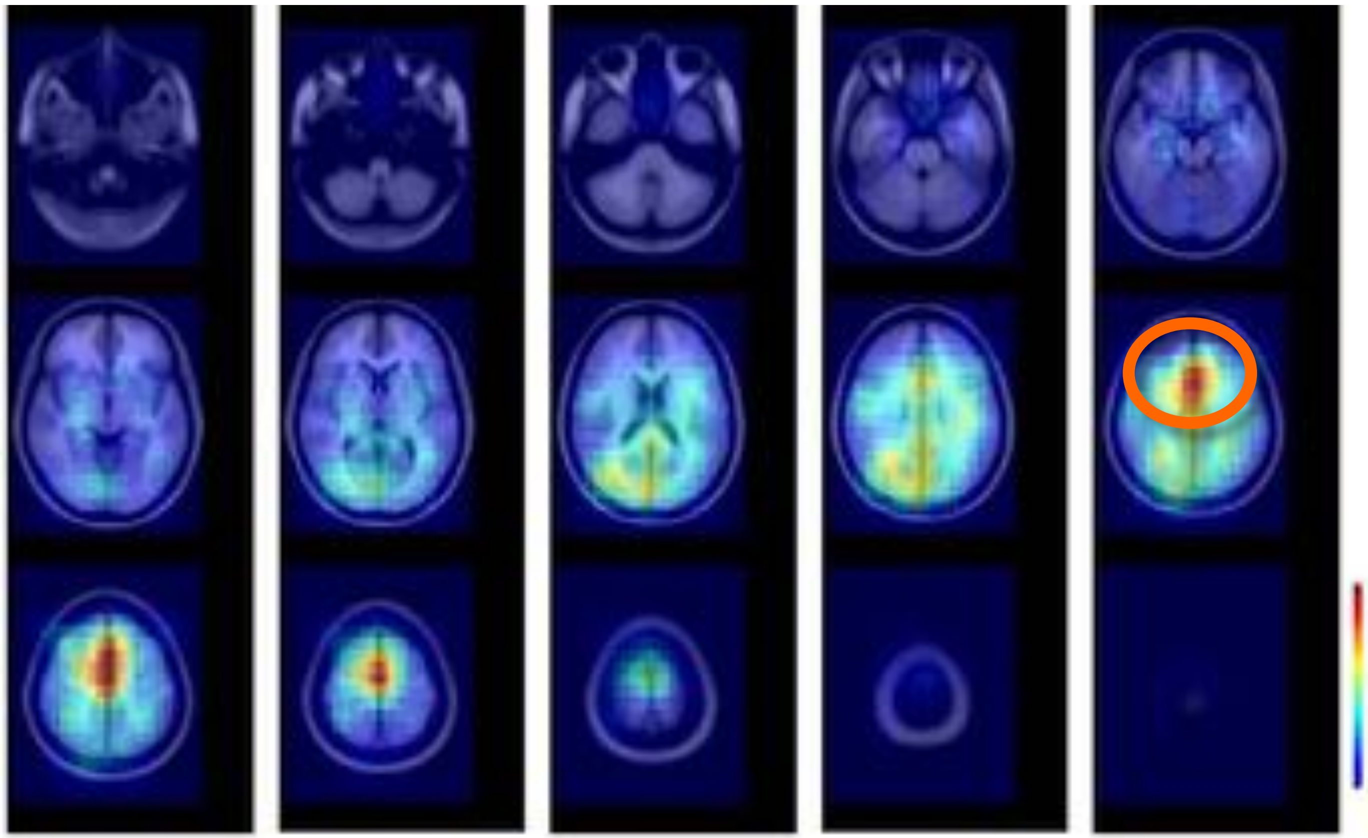


Auditory oddball plus novel sounds

Onton & Makeig, 2005

Effective Source Density

A. Old/new word memory

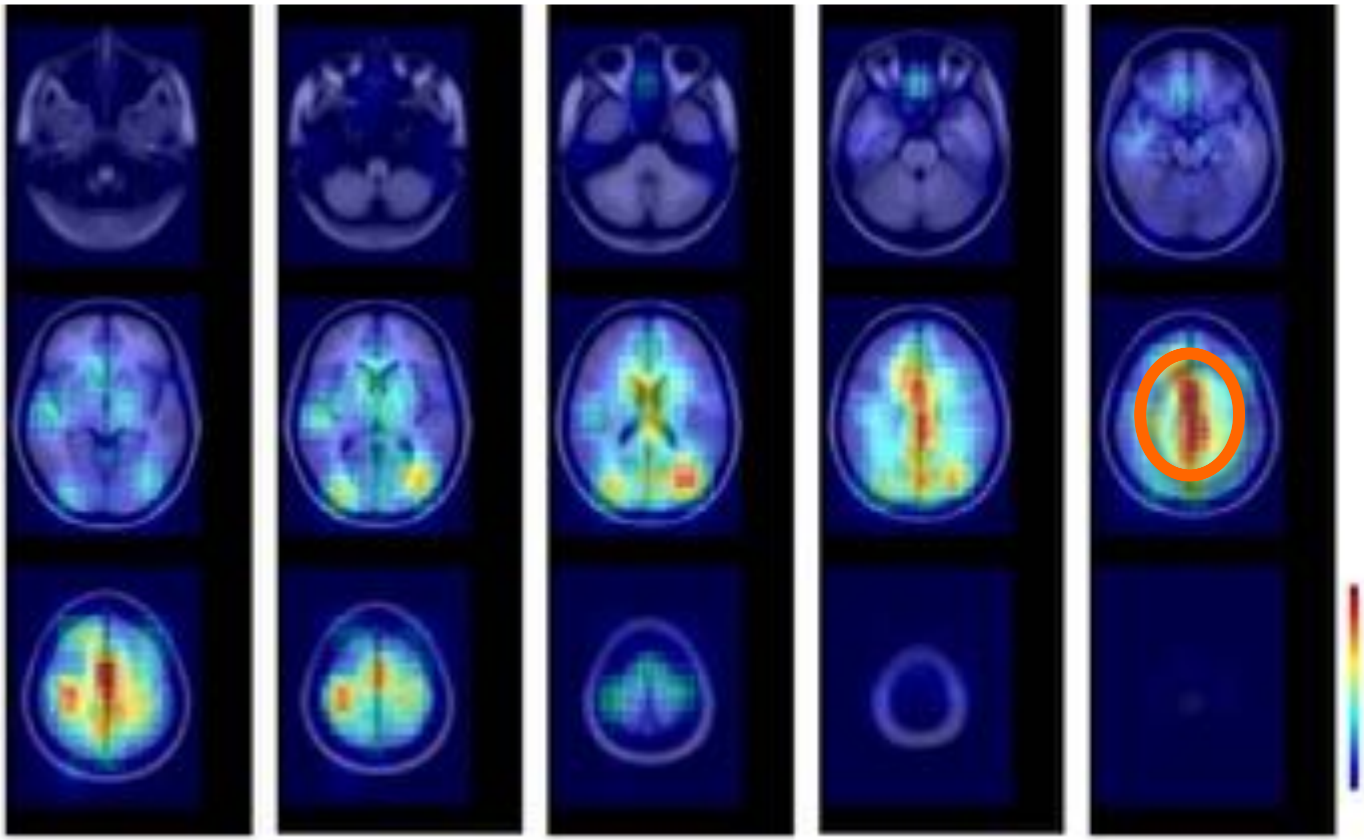


Word memory (old/new) task

Onton & Makeig, 2005

Effective Source Density

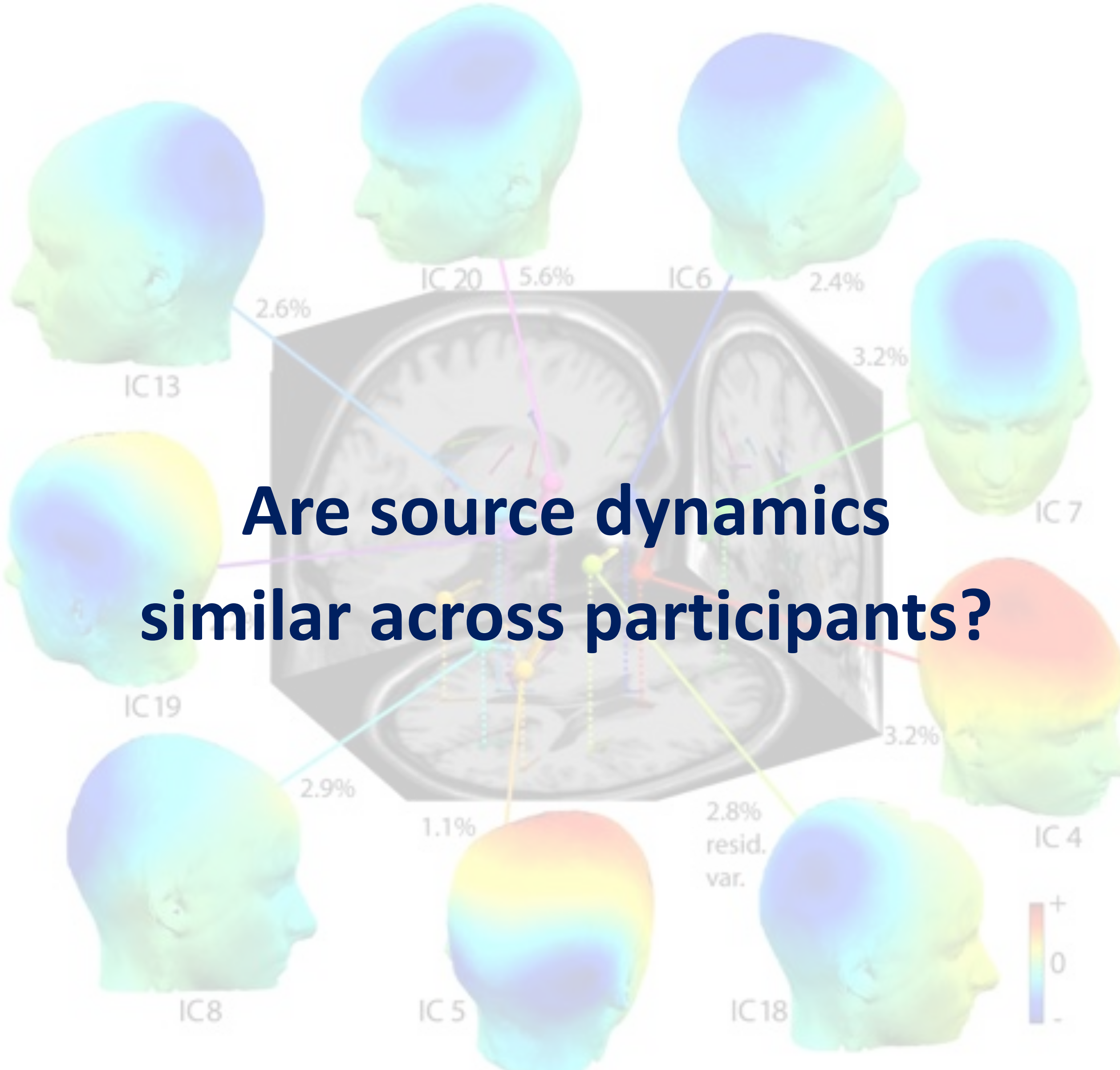
B. Visually cued selective response



Visually
cued
button
press
task

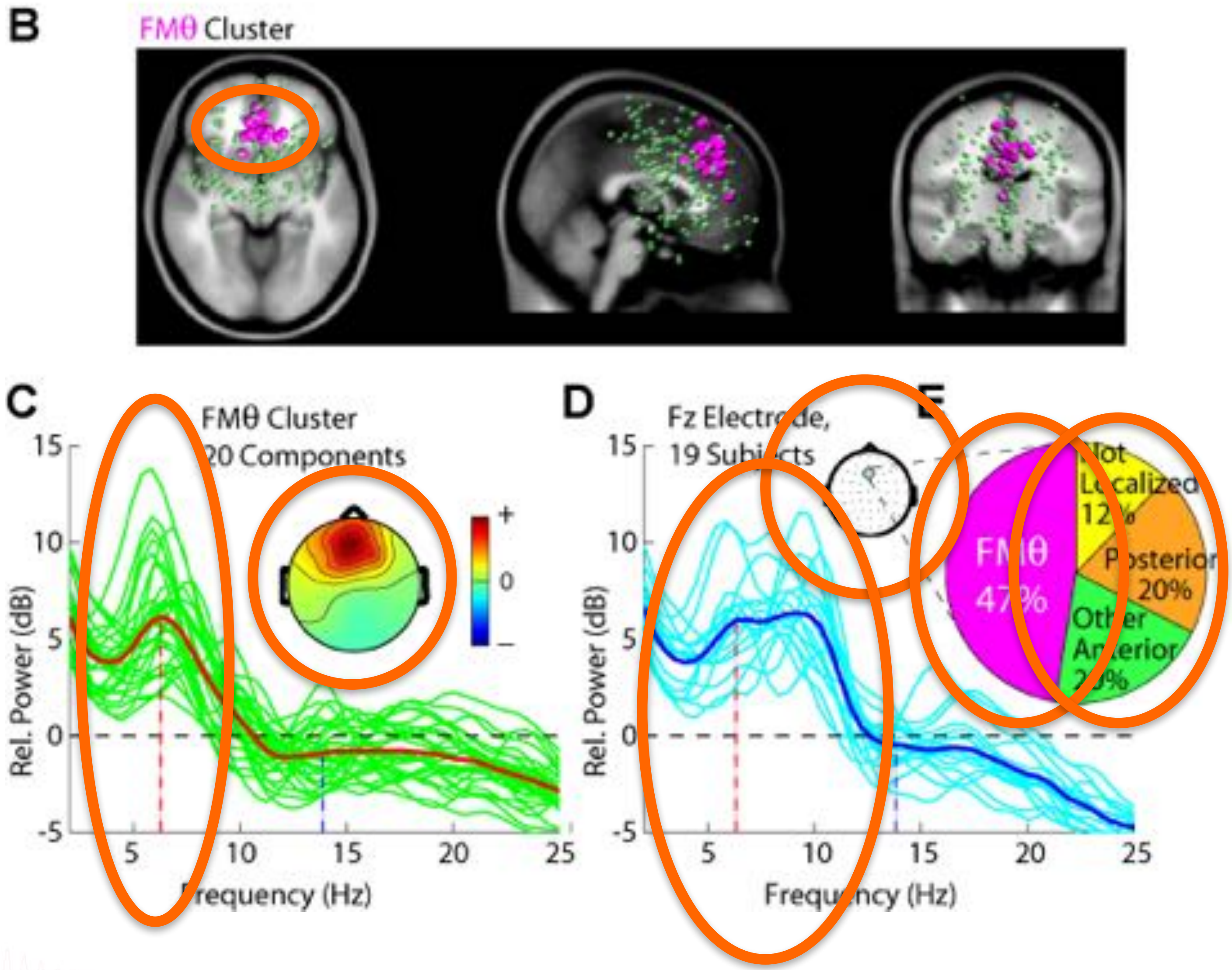
Onton & Makeig, 2005

Are source dynamics similar across participants?



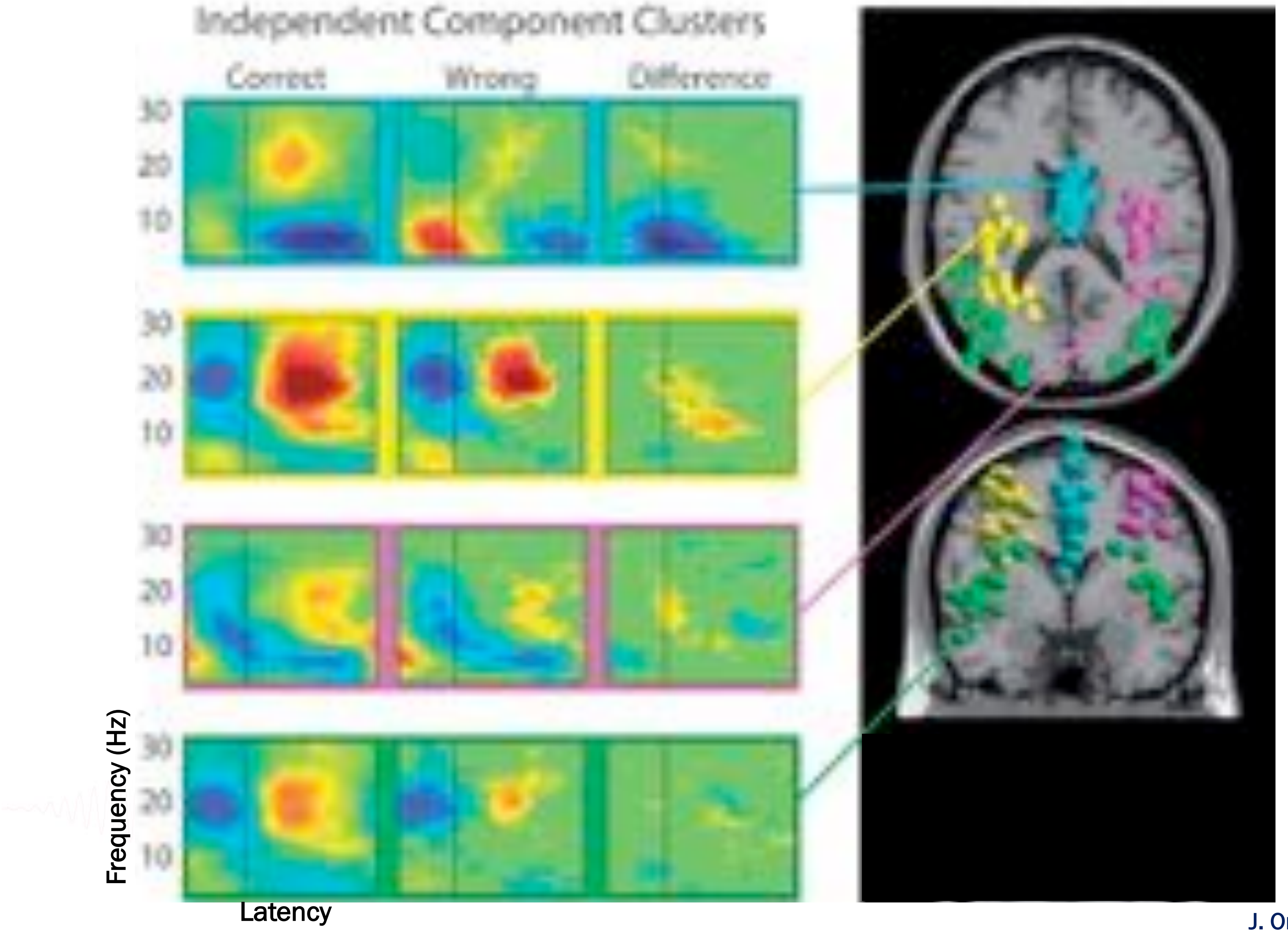
S. Makeig (2007)

Example: frontal midline theta cluster



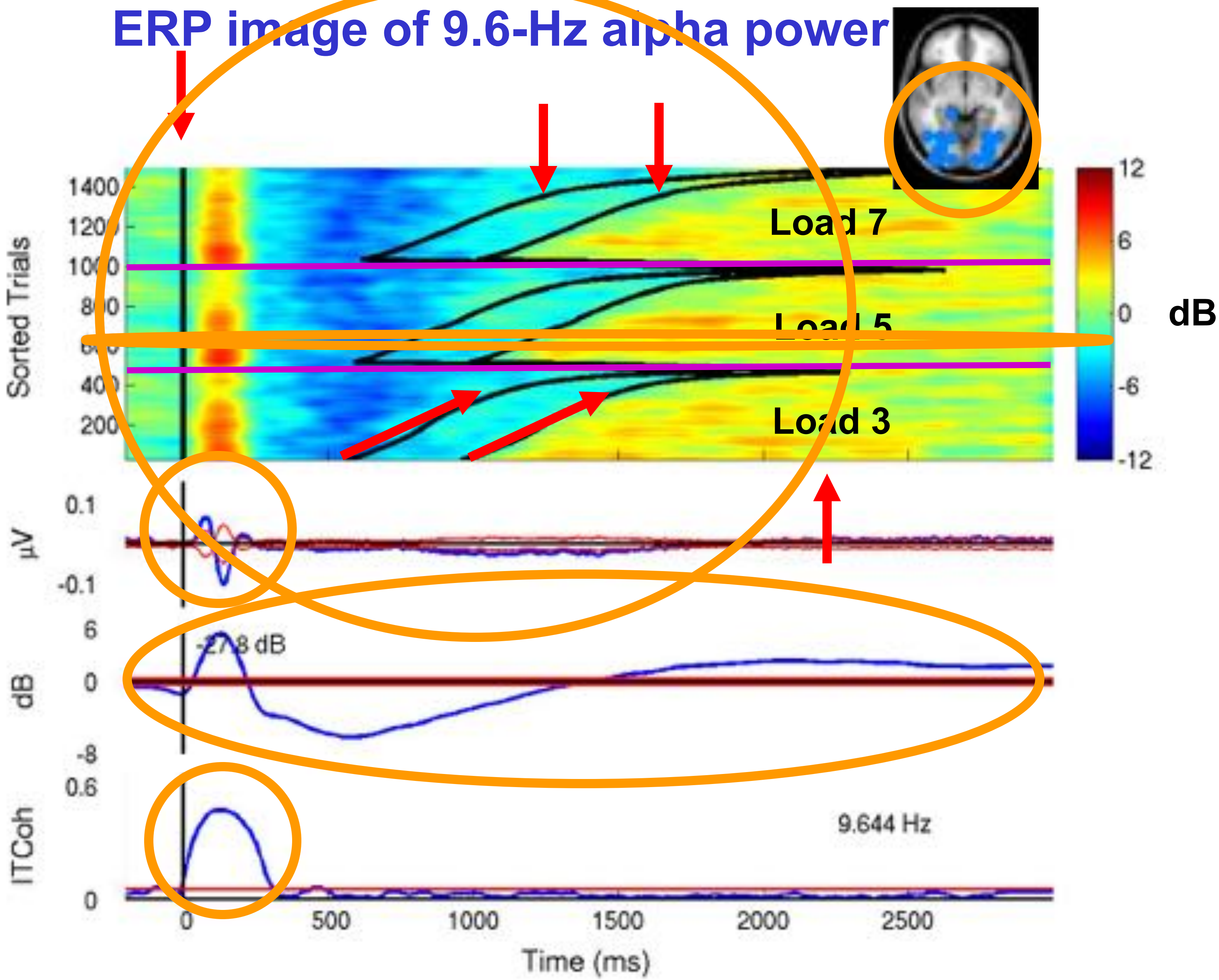
Onton, Delorme & Makeig, *NeuroImage* (2005)

Goal: To cluster equivalent ICs across subjects



J. Onton, 2005

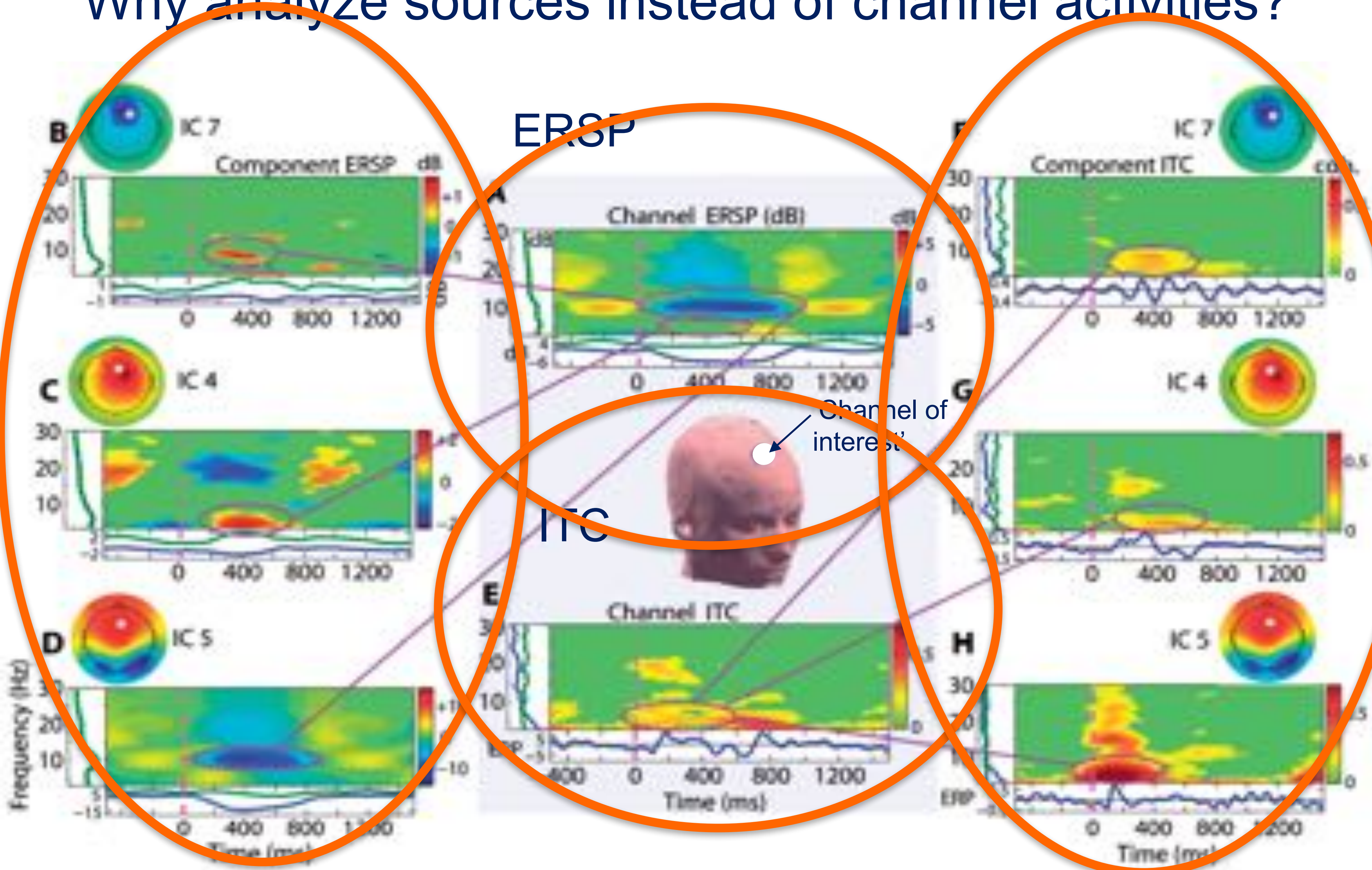
ERP image of 9.6-Hz alpha power



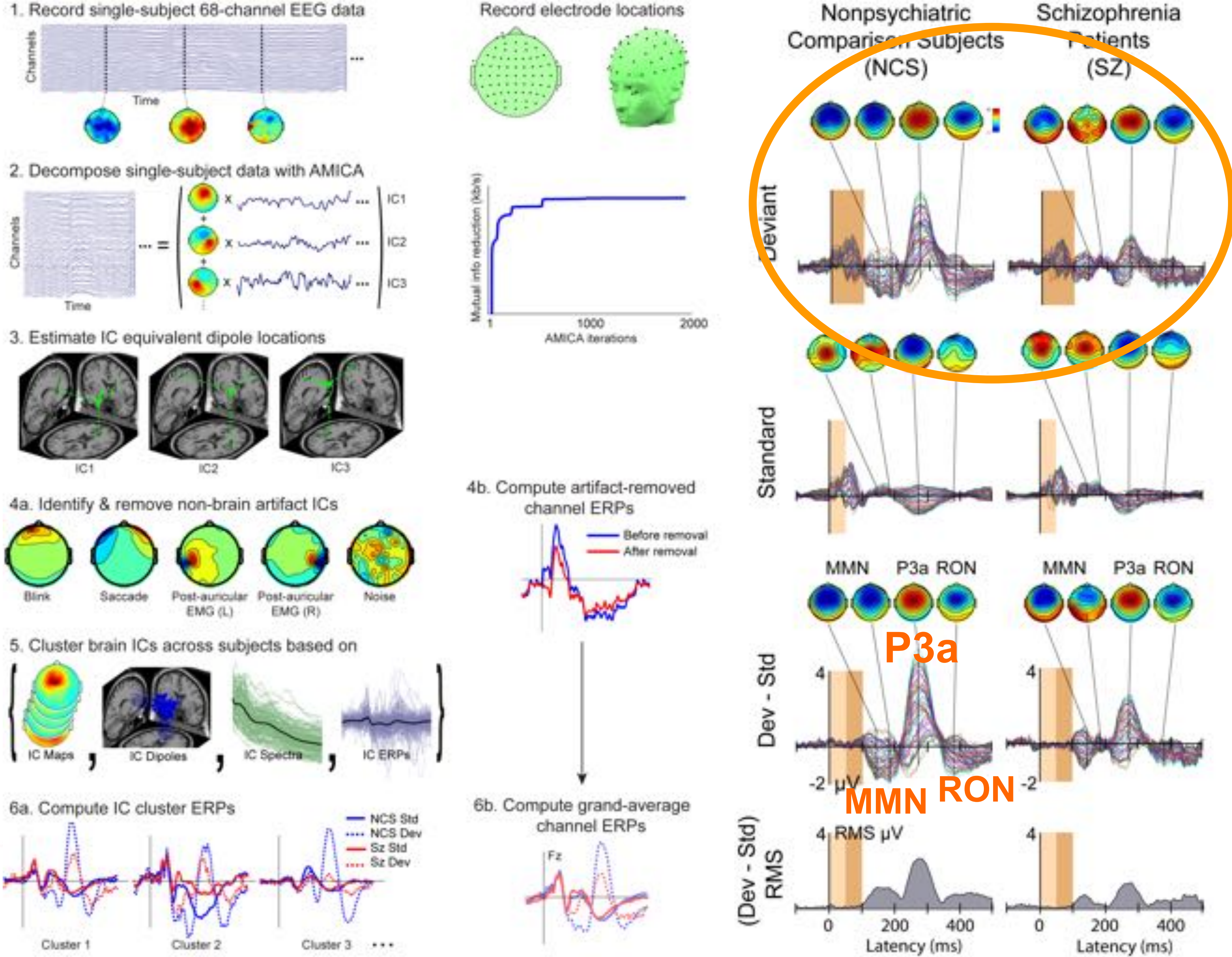
erpimage()

Onton, Delorme & Makeig, 2005.

Why analyze sources instead of channel activities?

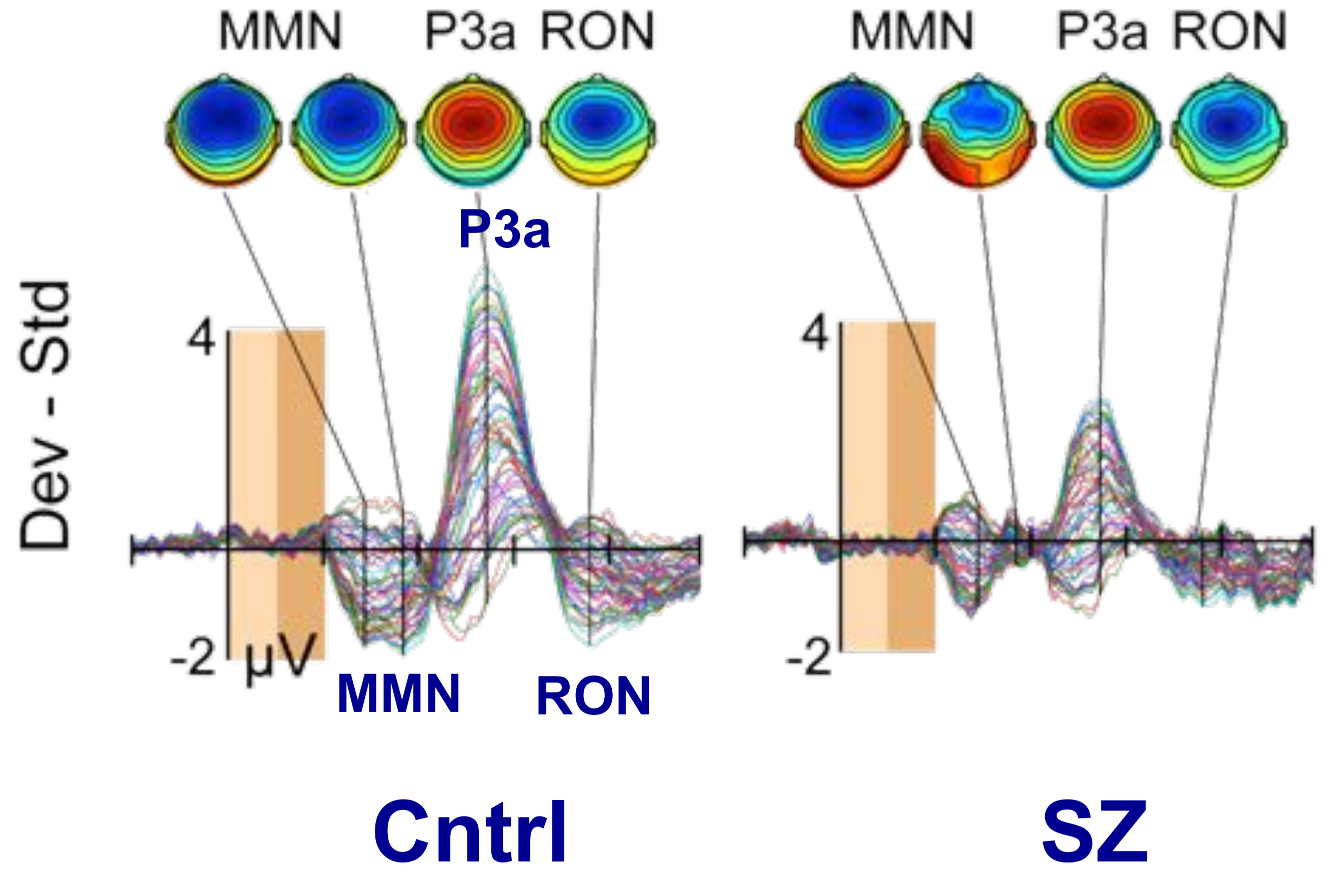


J. Onton & S. Makeig, 2005

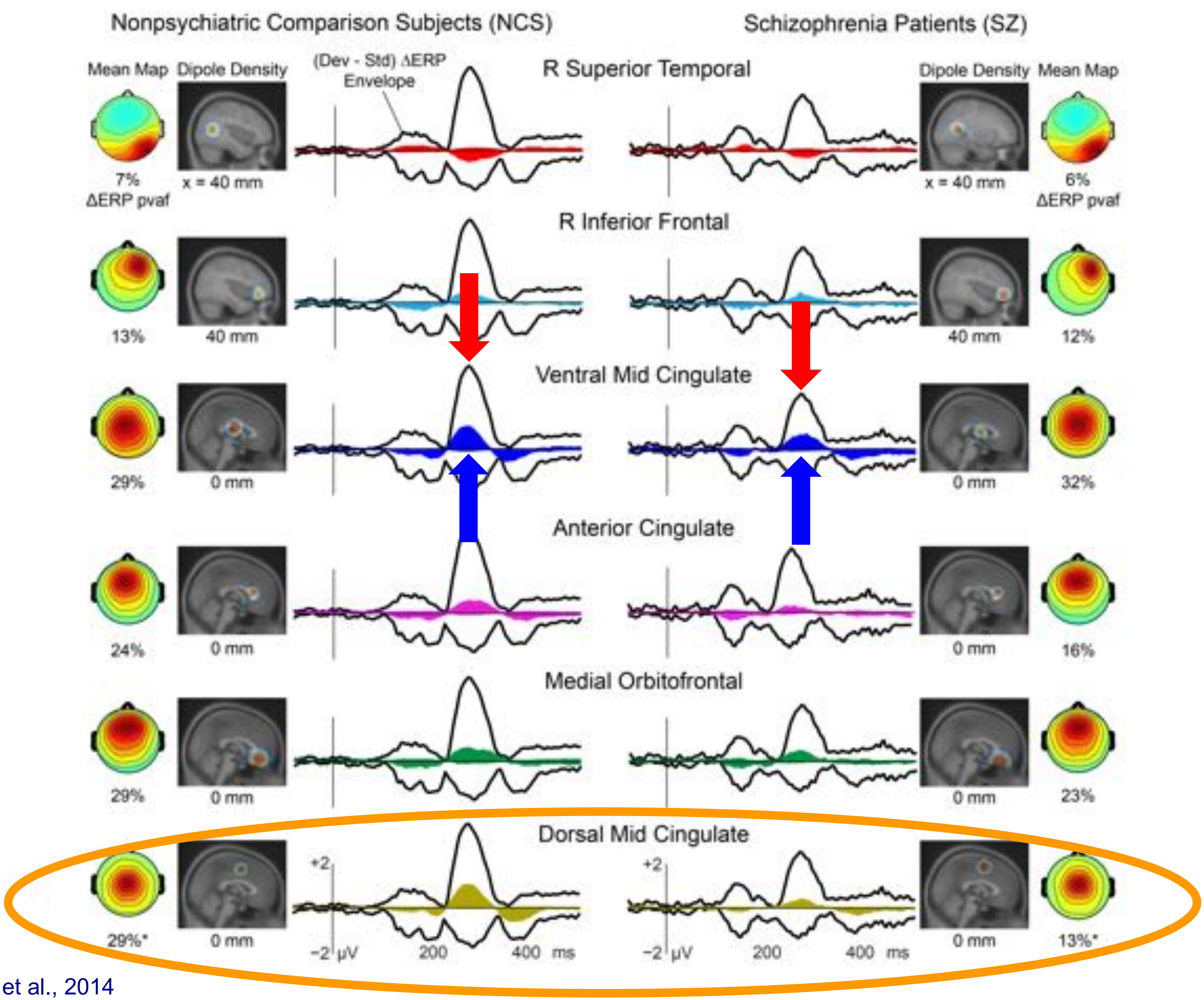


1. Record single-subject 68-channel EEG data
Channels
Time
Record electrode locations
2. Decompose single-subject data with AMICA
IC1
IC2
IC3
Mutual info reduction (kb/s)
AMICA iterations
1
1000
2000
3. Estimate IC equivalent dipole locations
4a. Identify & remove non-brain artifact ICs
Blink
Saccade
Post-auricular EMG (L)
Post-auricular EMG (R)
Noise
4b. Compute artifact-removed channel ERPs
Before removal
After removal
5. Cluster brain ICs across subjects based on
IC Maps
IC Dipoles
IC Spectra
IC ERPs
6a. Compute IC cluster ERPs
NCS Std
NCS Dev
Sz Std
Sz Dev
Cluster 1
Cluster 2
Cluster 3
6b. Compute grand-average channel ERPs
Fz
Nonpsychiatric Comparison Subjects (NCS)
Schizophrenia Patients (SZ)
Deviant
Standard
MMN P3a RON
MMN P3a RON
Dev - Std
P3a
4
-2 μV
MMN
RON
-2
(Dev - Std) RMS
4 RMS μV
0
200
400
Latency (ms)

Auditory Deviance Response



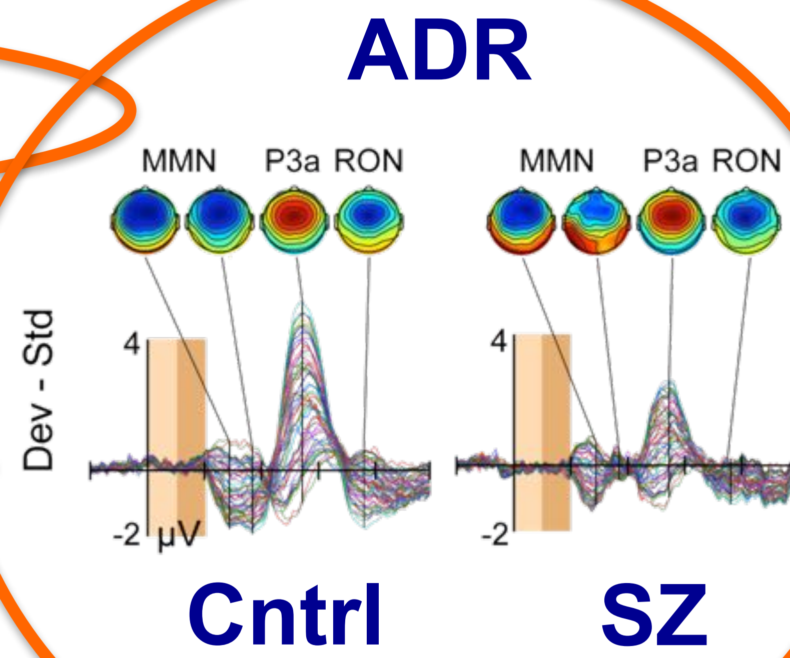
The deepest mental trap in electrophysiology lurks in the word "THE" !!!



Rissling et al., 2014

PEAK AMPLITUDES	ERP	r^2
Scalp Electrode (Fz)		
Verbal IQ (WRAT)	P3a	0.11
Functional Capacity (UPSA)	RON	0.12
R Superior Temporal		
Working Memory (LNS Reorder)	RON	0.15
Verbal IQ (WRAT)	RON	0.15
Immediate Verbal Memory (CVLT)	**RON**	**0.28**
Delayed Verbal Memory (CVLT)	RON	0.26
Functional Capacity (UPSA)	**MMN**	**0.48**
Functional Capacity (UPSA)	RON	0.26
R Inferior Frontal		
Negative Symptoms (SANS)	**RON**	**0.36**
Psychosocial Functioning (SOF)	RON	0.24
Auditory Attention (LNS Forward)	**MMN**	**0.38**
Working Memory (LNS Reorder)	**MMN**	**0.30**
Verbal IQ (WRAT)	**MMN**	**0.46**
Ventral Mid Cingulate		
Positive Symptoms (SAPS)	**RON**	**0.29**
Negative Symptoms (SANS)	**P3a**	**0.36**
Immediate Verbal Memory (CVLT)	**RON**	**0.41**
Delayed Verbal Memory (CVLT)	RON	0.24
Verbal IQ (WRAT)	**RON**	**0.29**
Executive Functioning (WCST)	RON	0.24
Anterior Cingulate		
Functional Status (GAF)	MMN	0.18
Functional Status (GAF)	RON	0.17
Immediate Verbal Memory (CVLT)	RON	0.25
Delayed Verbal Memory (CVLT)	RON	0.17
Medial Orbitofrontal		
Positive Symptoms (SAPS)	**P3a**	**0.40**
Negative Symptoms (SANS)	**P3a**	**0.54**
Psychosocial Functioning (SOF)	**P3a**	**0.37**
Functional Capacity (UPSA)	**P3a**	**0.32**
Dorsal Mid Cingulate		
Verbal IQ (WRAT)	P3a	0.15
Executive Functioning (WCST)	MMN	0.18

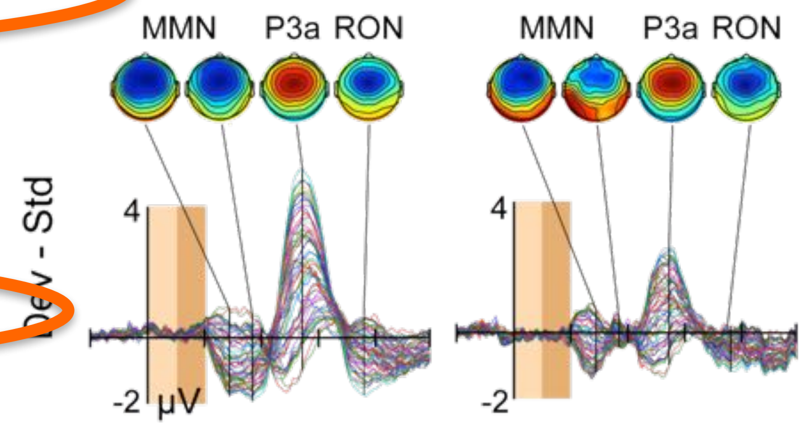
X



PEAK LATENCIES

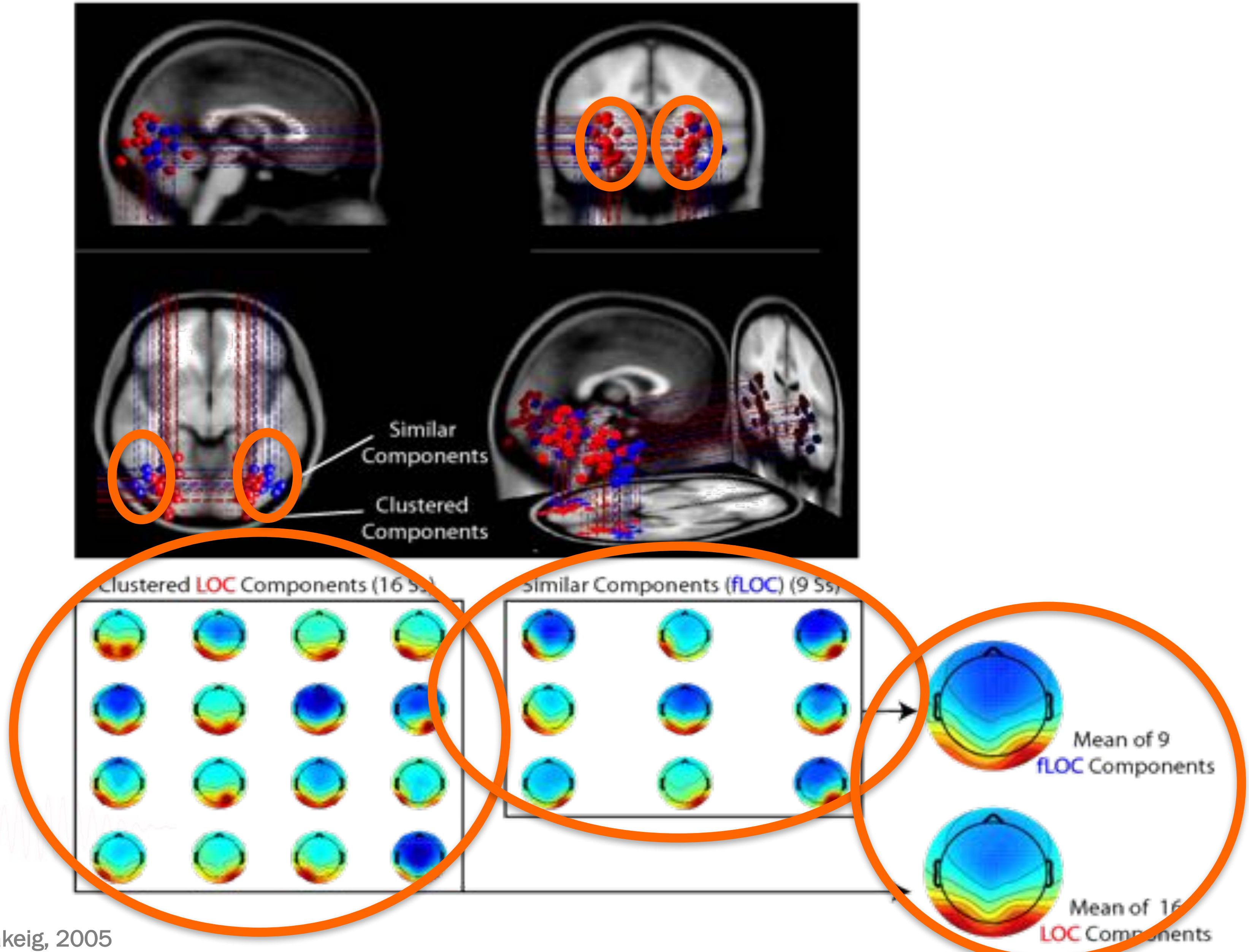
	ERP	r^2
Scalp Electrode (Fz)		
---n/a---	---	---
R Superior Temporal		
Functional capacity (UPSA)	MMN	0.25
Delayed Verbal Memory (CVLT)	MMN	0.17
R Inferior Frontal		
Negative Symptoms (SANS)	**RON**	**0.51**
Psychosocial Functioning (SOF)	RON	0.25
Executive Functioning (WCST)	**MMN**	**0.30**
Executive 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

ADR



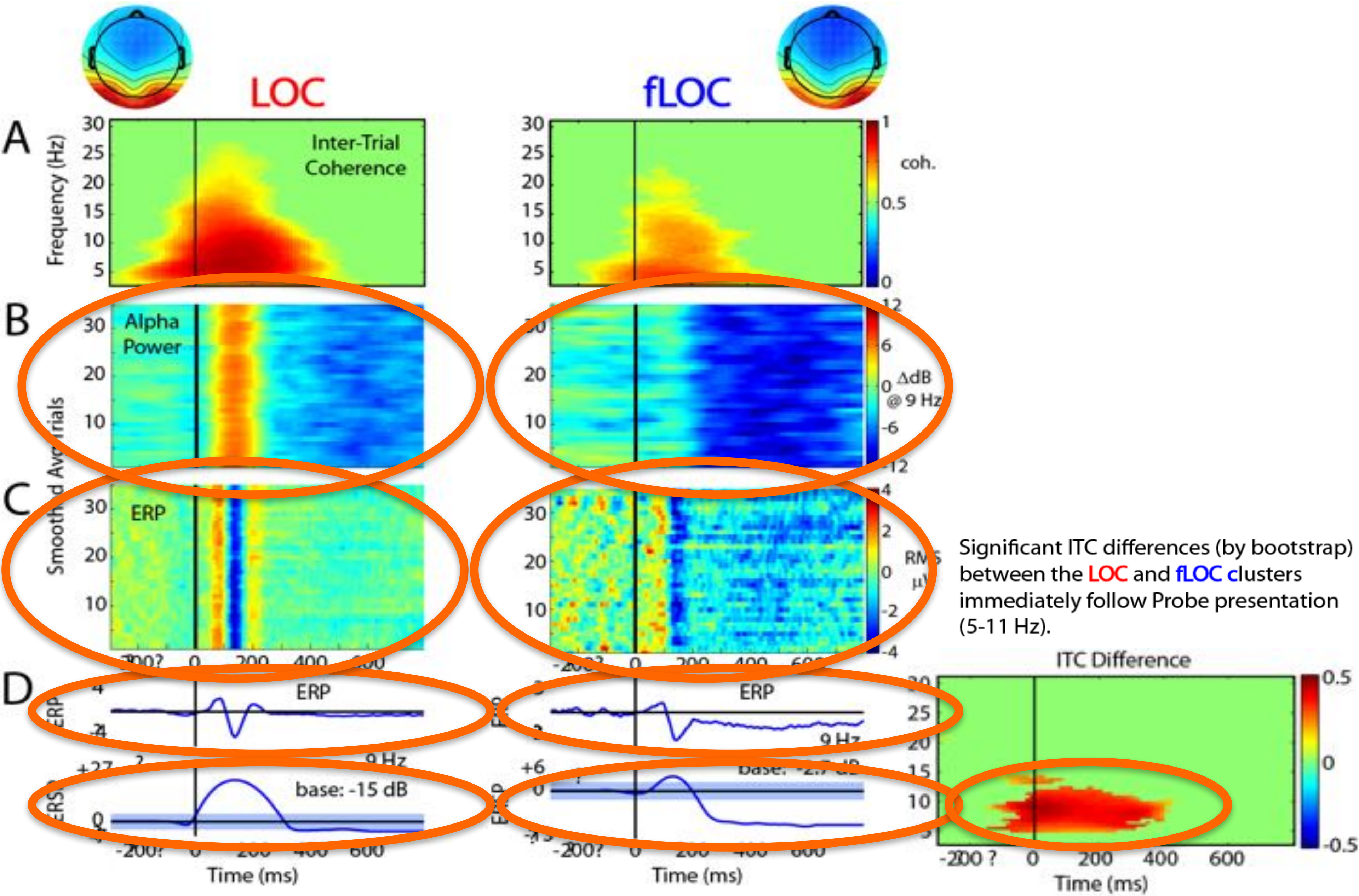
Cntrl **SZ**

Why don't all subjects contribute to every IC cluster?



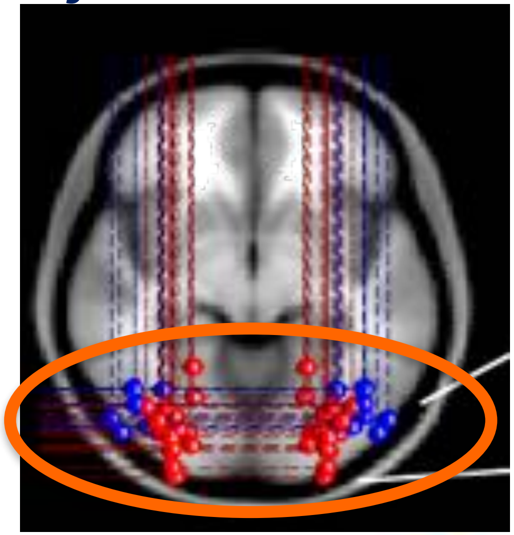
Onton & Makeig, 2005

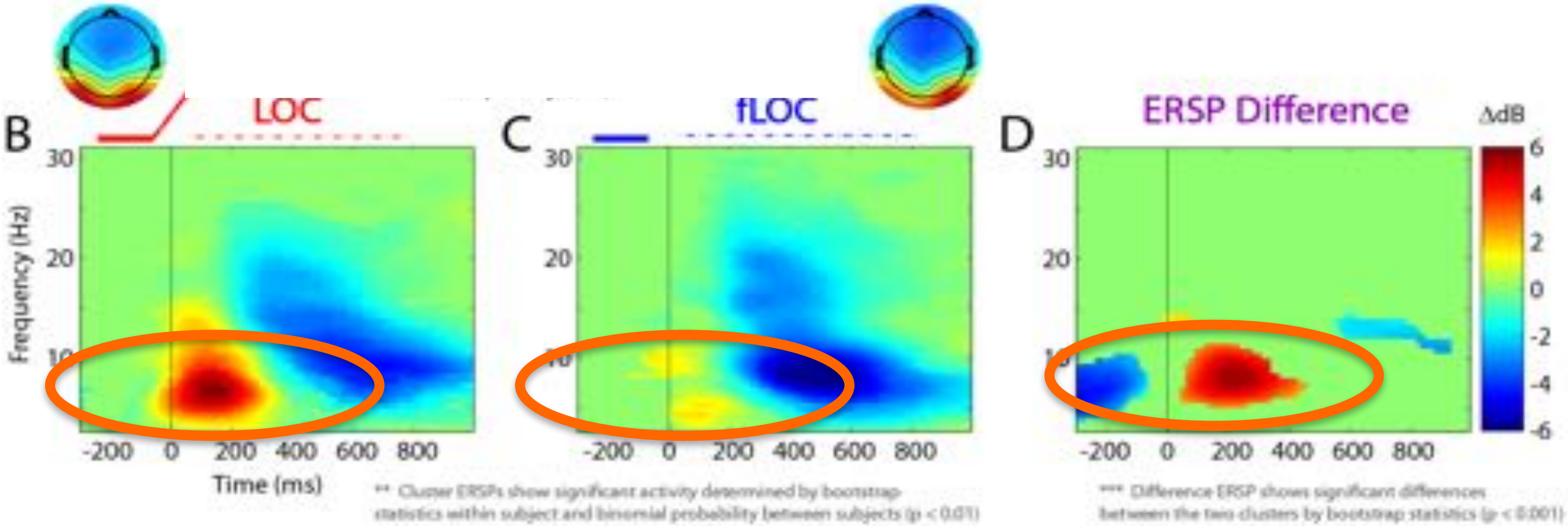
Subject differences?



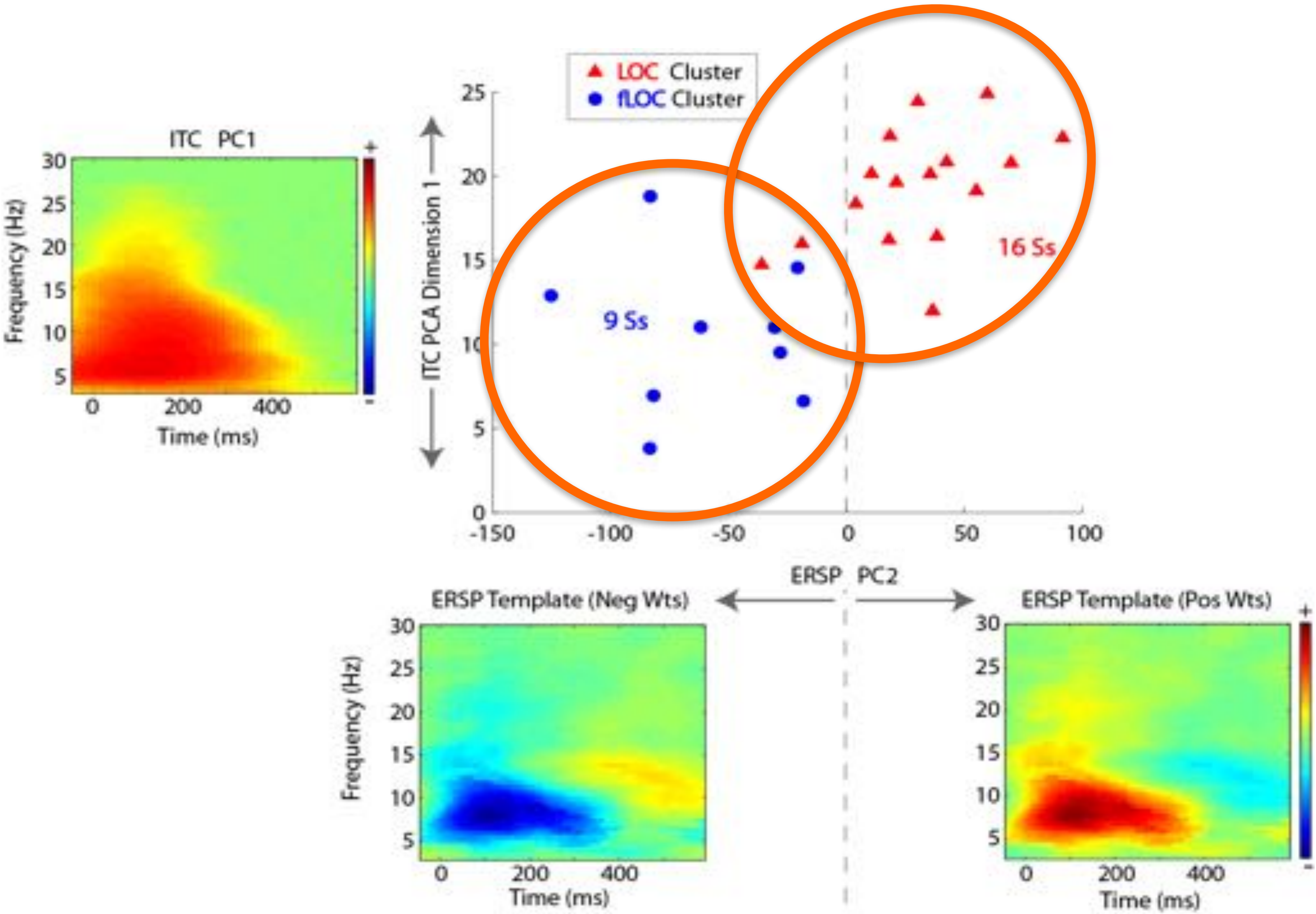
Significant ITC differences (by bootstrap) between the LOC and fLOC clusters immediately follow Probe presentation (5-11 Hz).

Subject differences?





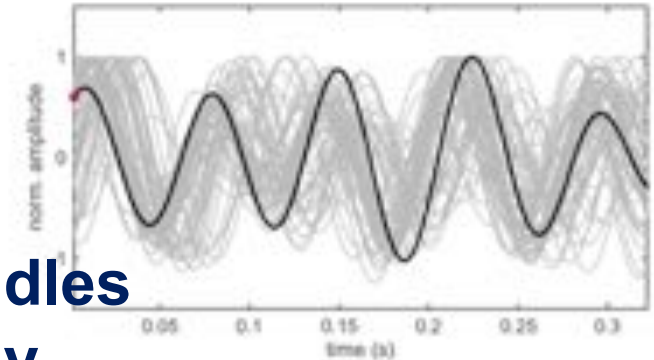
Subject differences?



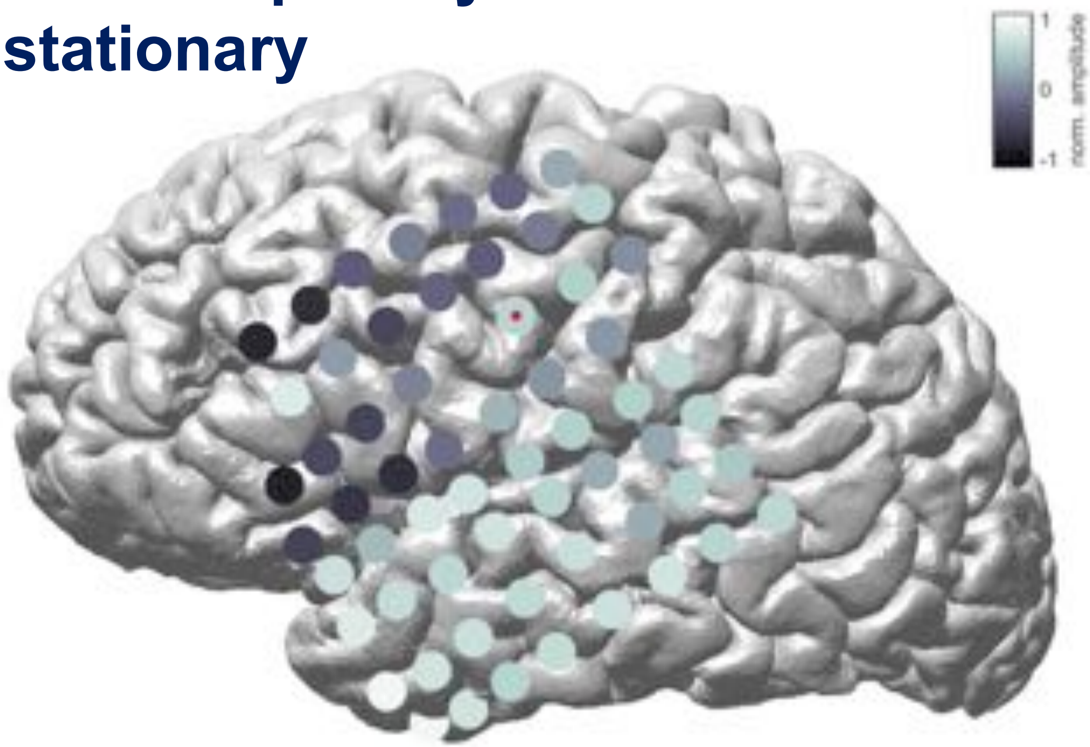
Properties of EEG Independent Components

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

But …



NB: Sleep spindles are *not* spatially stationary



Muller et al., 2014

More …