Independent Component Analysis of Electrophysiological Data

Scott Makeig
Institute for Neural Computation
University of California San Diego

58th Cracow School of Theoretical Physics
Zakopane, Poland

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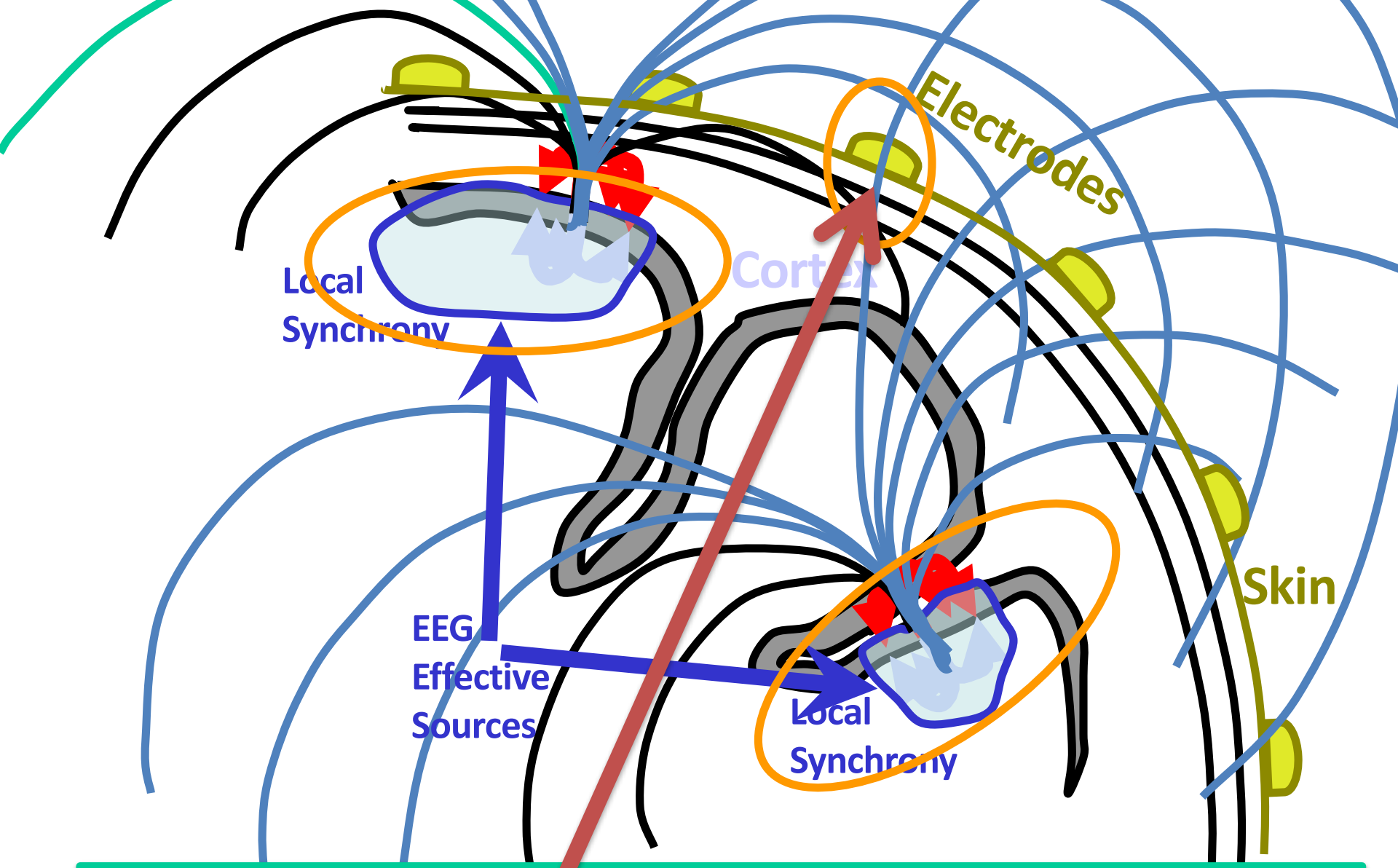
The EEGLAB environment

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

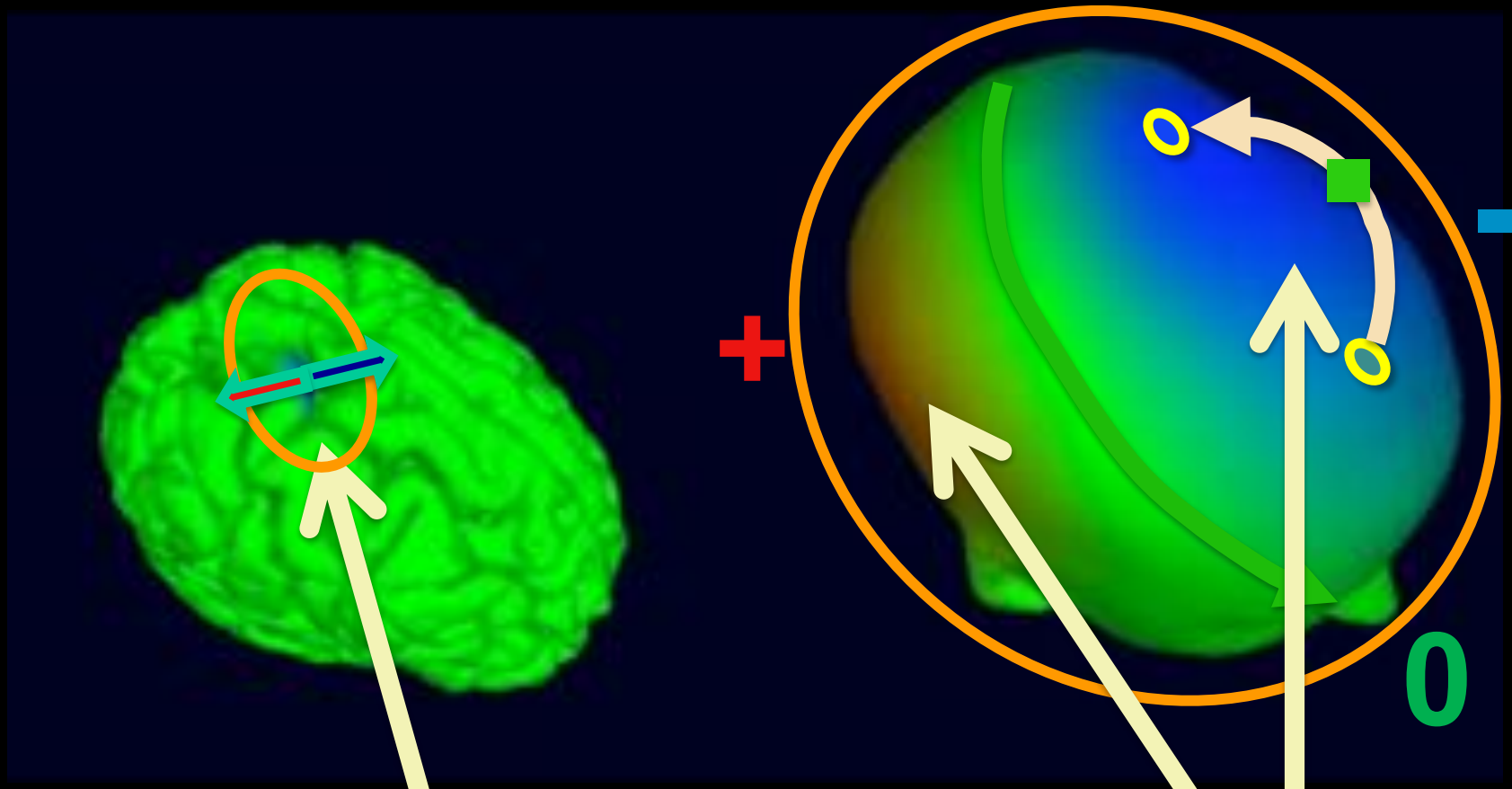
… In future, optional
NSG computation of EEGLAB
pipelines will be available directly
via the EEGLAB menu itself



Each scalp EEG data channel sums the projected activities of multiple brain (and non-brain) source processes.

S. Makeig 2007

The very broad EEG point-spread function

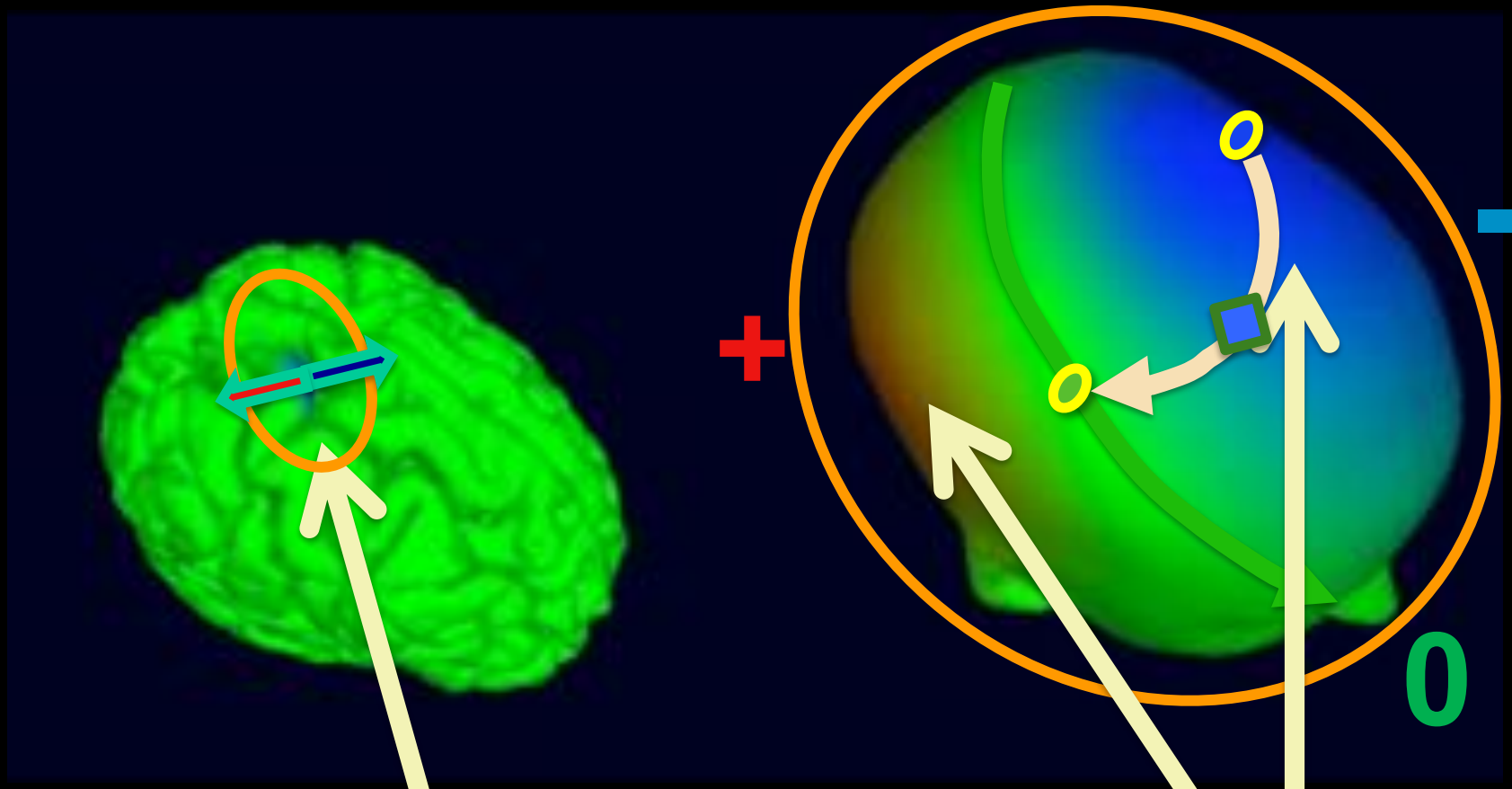


Single simulated parietal source →

Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The very broad EEG point-spread function

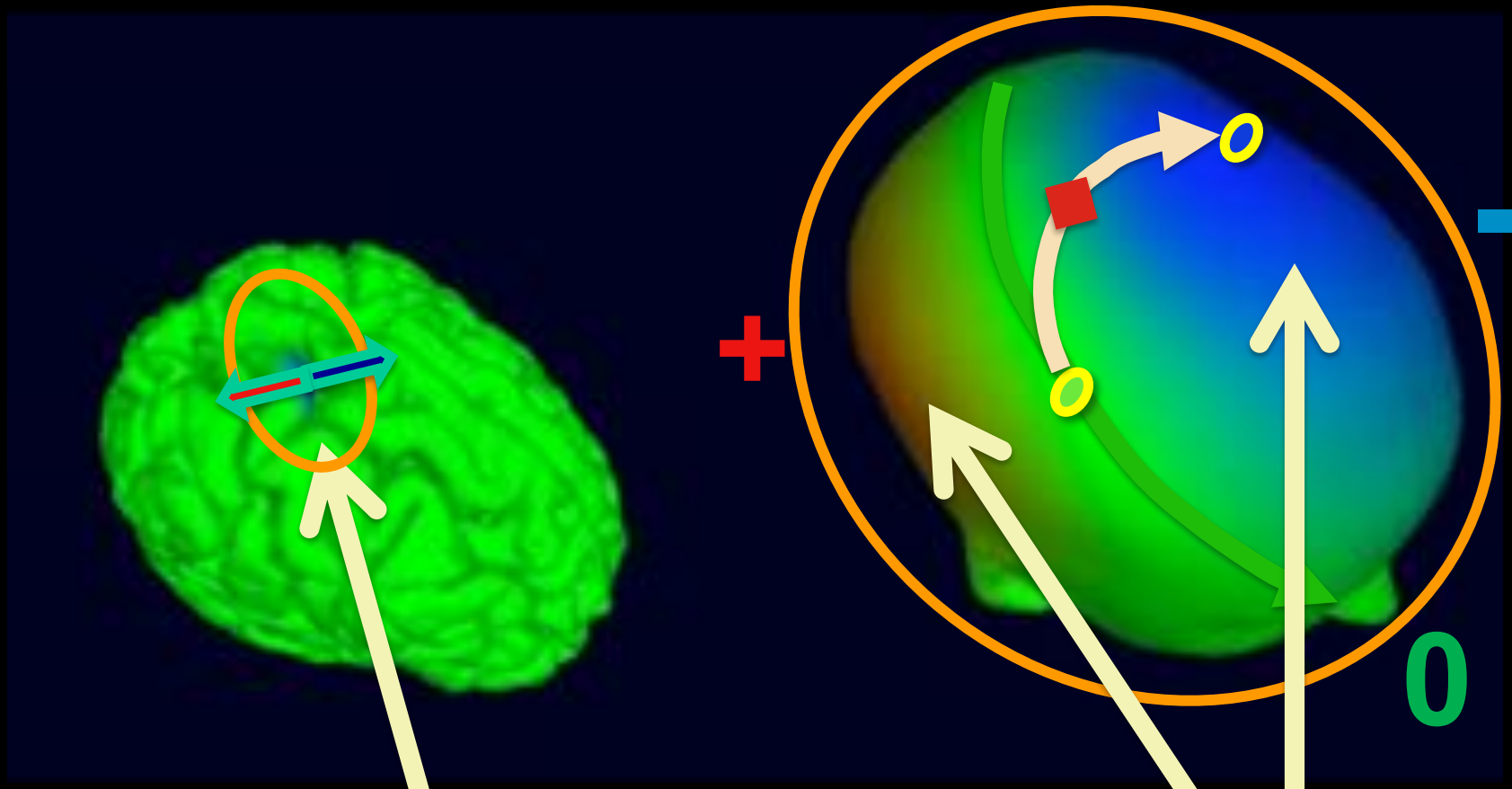


Single simulated parietal source →

Very broad projected scalp potentials

Akalin Acar & Makeig 2010

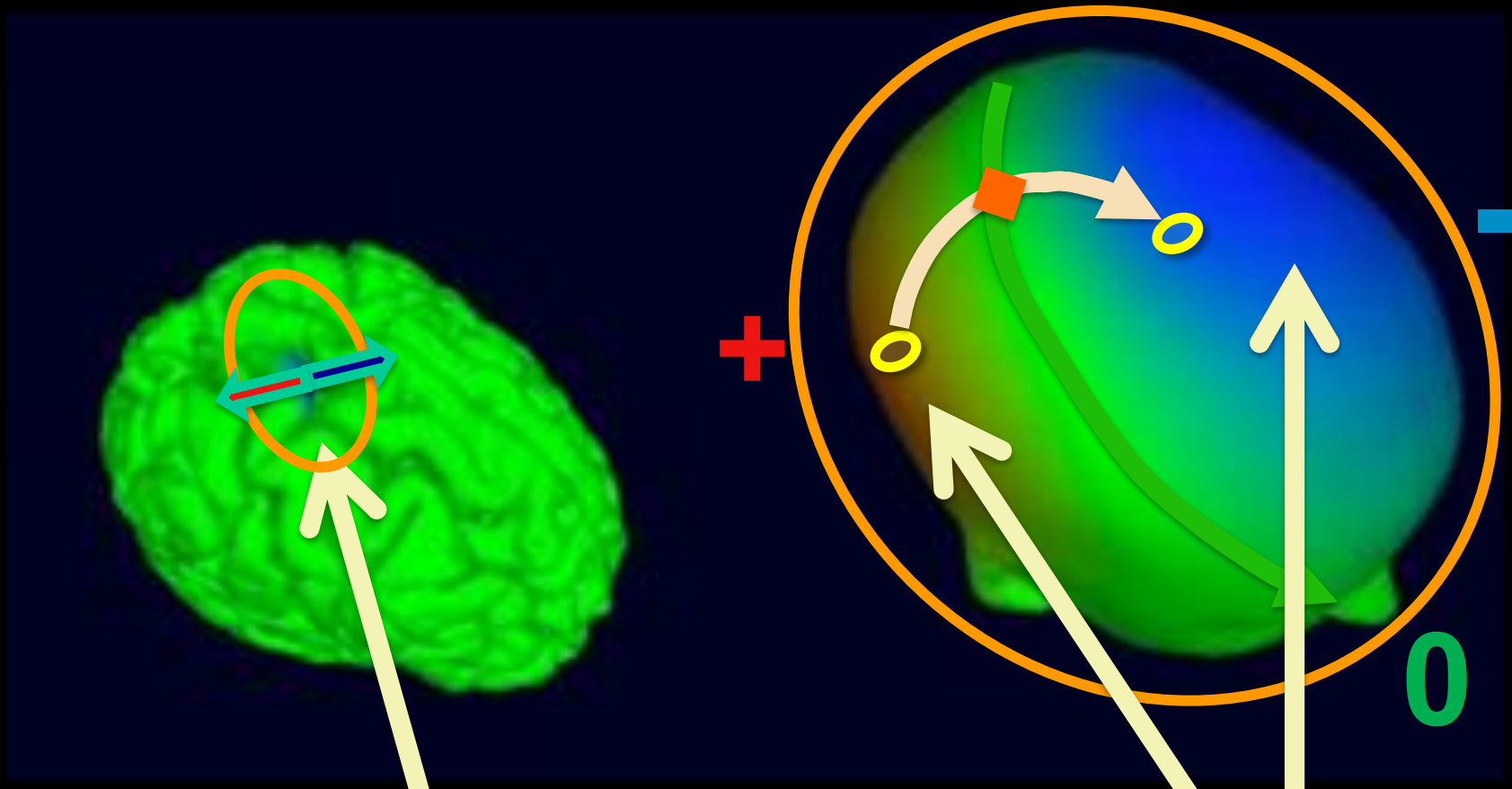
The very broad EEG point-spread function



Single simulated parietal source → Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The very broad EEG point-spread function

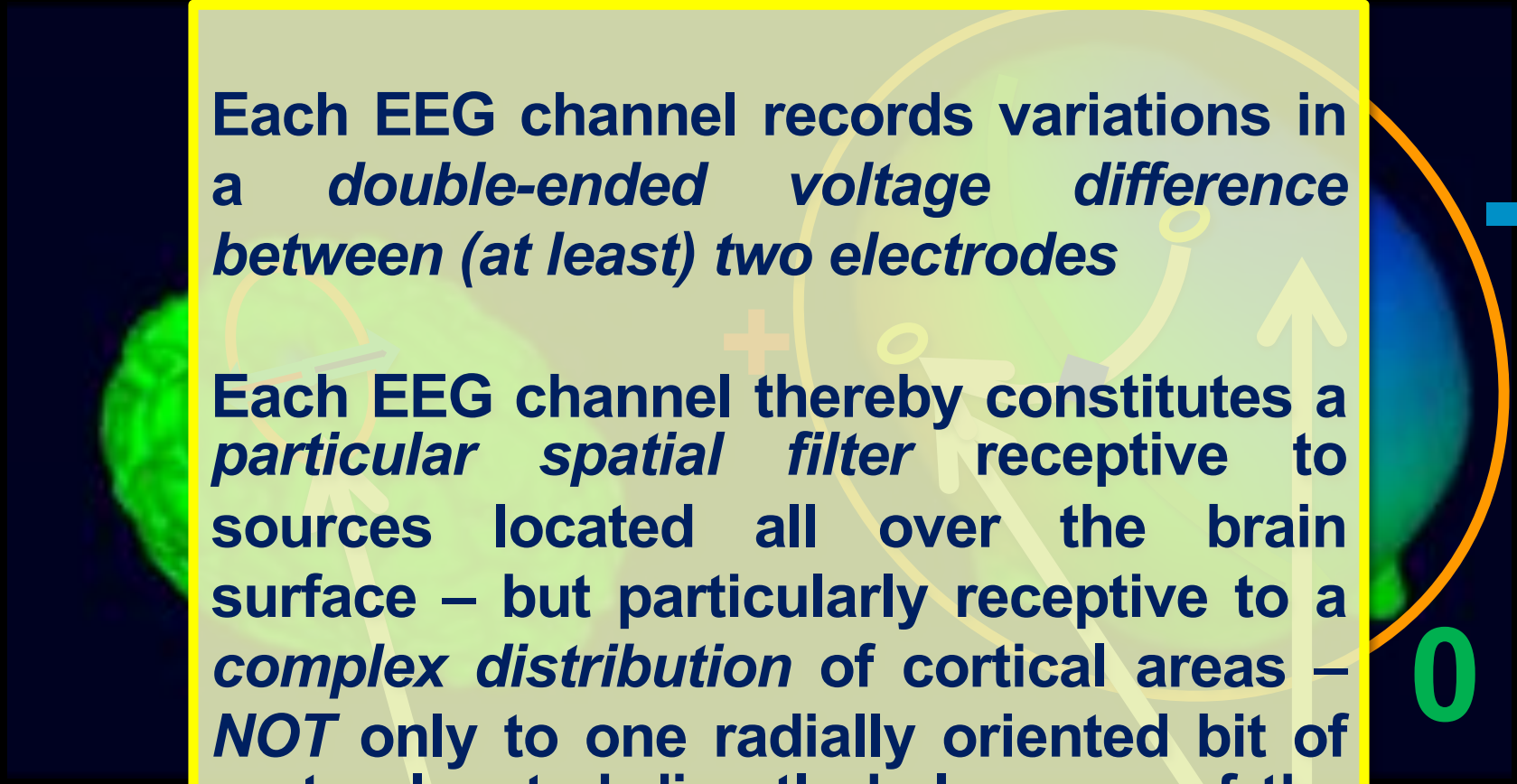


Single simulated parietal source →

Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The very broad EEG point-spread function

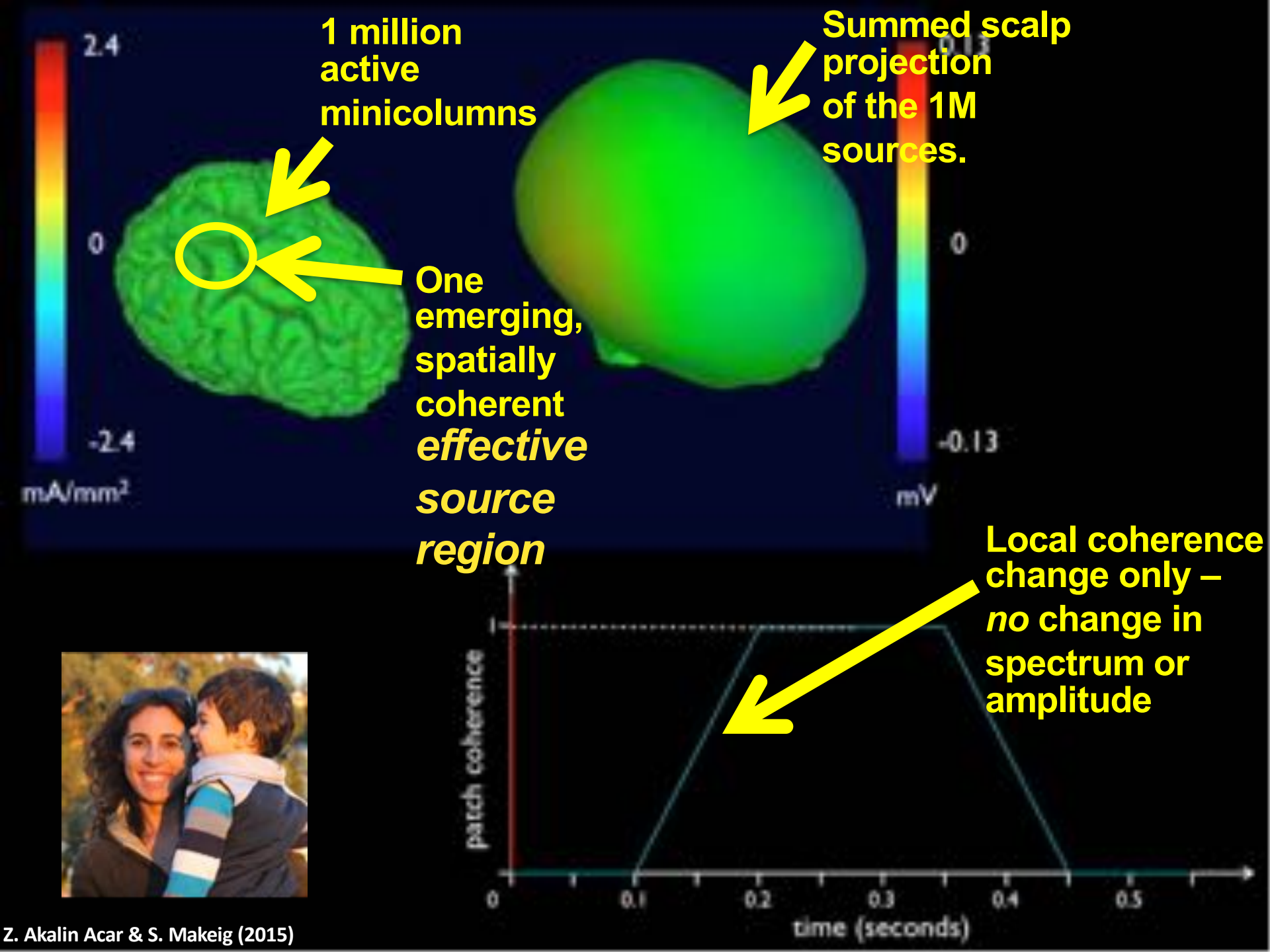


Each EEG channel records variations in a *double-ended voltage difference between (at least) two electrodes*

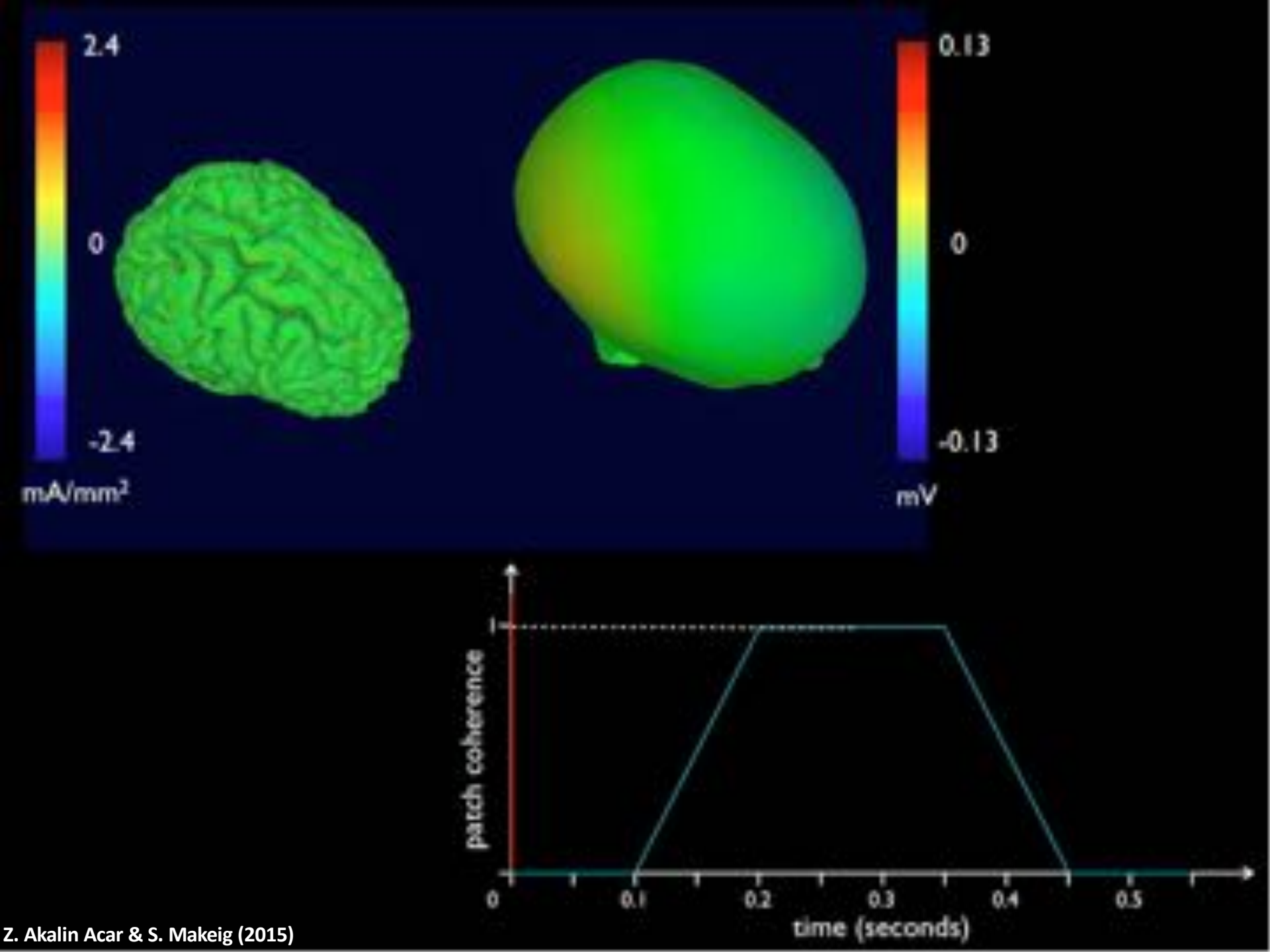
Each EEG channel thereby constitutes a *particular spatial filter* receptive to sources located all over the brain surface – but particularly receptive to a *complex distribution* of cortical areas – *NOT* only to one radially oriented bit of cortex located directly below *one* of the *two* (or more)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

Single simulated parietal source → Very broad projected scalp potentials

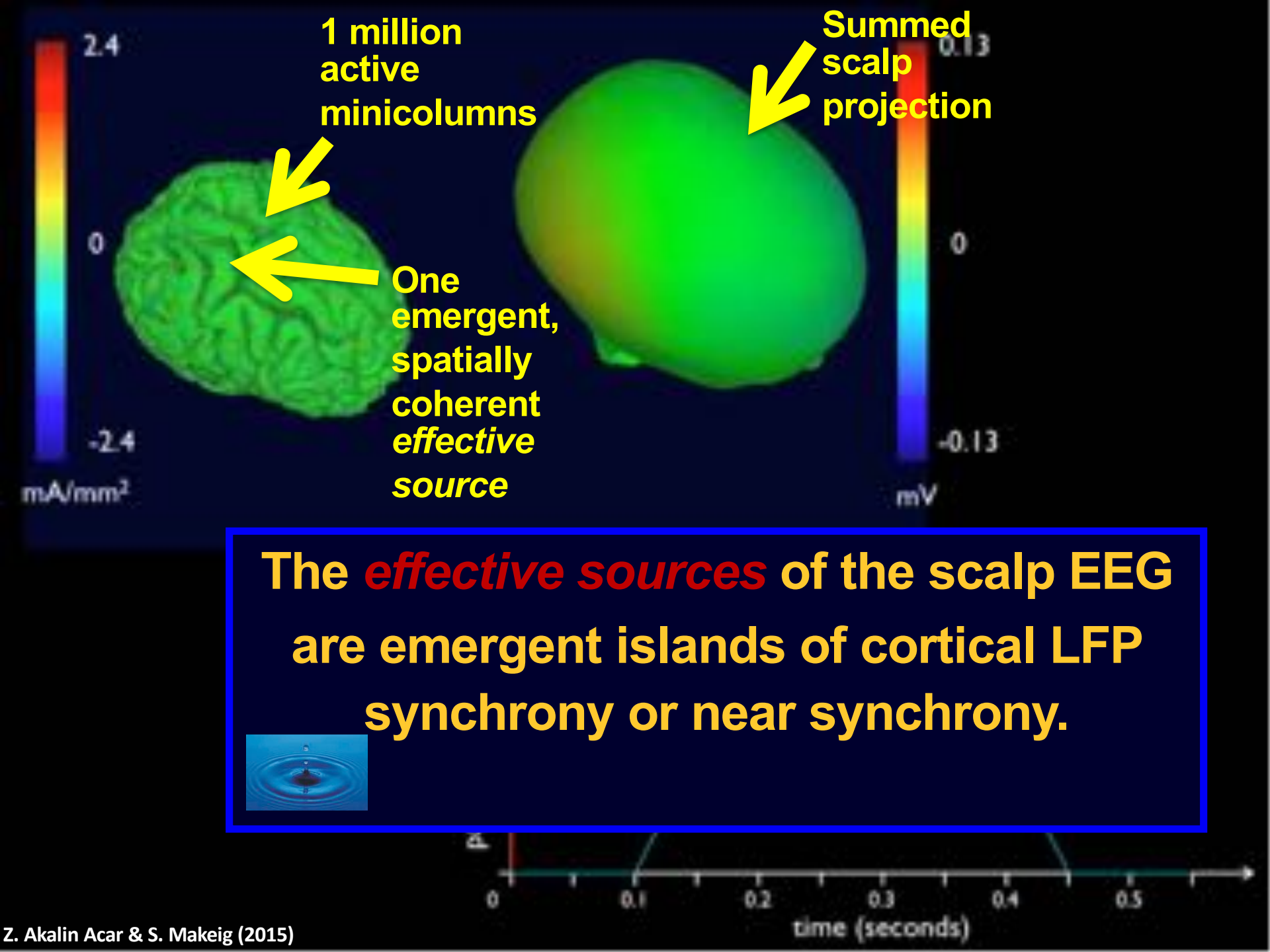
Akalin Acar & Makeig 2010



Z. Akalin Acar & S. Makeig (2015)



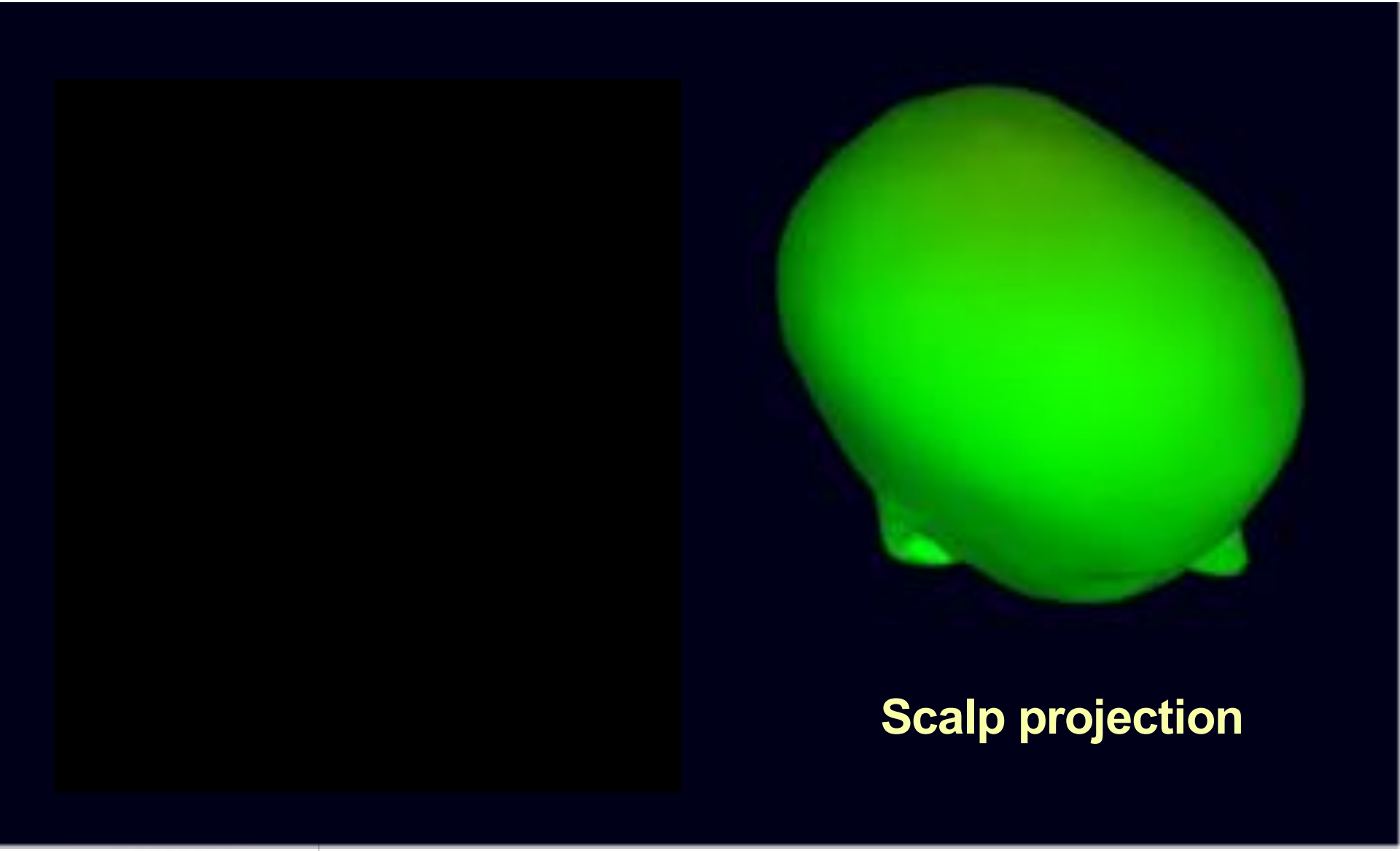
Z. Akalin Acar & S. Makeig (2015)



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

Z. Akalin Acar & S. Makeig (2015)

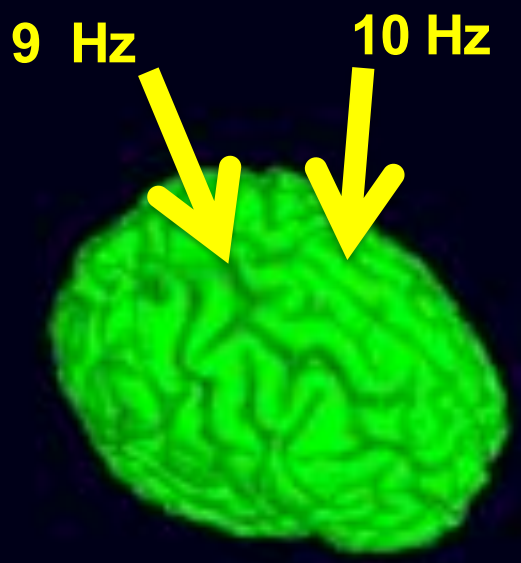
Scalp epiphenomena !



Z. Akalin Acar & S. Makeig (2012)

Scalp epiphenomena !

Phenomena



Two spatially stationary cortical effective sources

Epiphenomenal

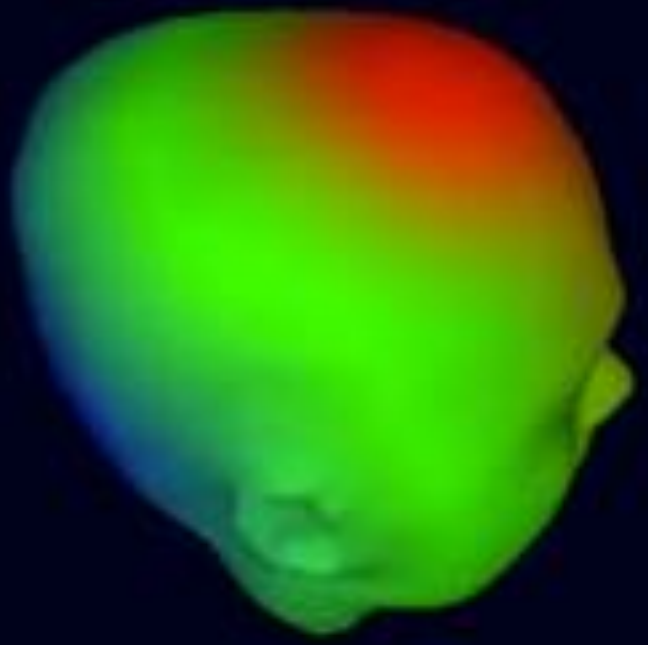
epiphenomena --

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

Summed scalp projection

Z. Akalin Acar & S. Makeig (2012)

Summed scalp projections of 13 effective brain sources



Epiphenomenal Impressions

Causal Phenomena

Z. Akalin Acar & S. Makeig (2016)

Electromagnetic source localization using realistic head models

Zeynep Akalin Acar & Scott Makeig '06

Cloud art: Berndnaut Smilde

S. Makeig, 2016

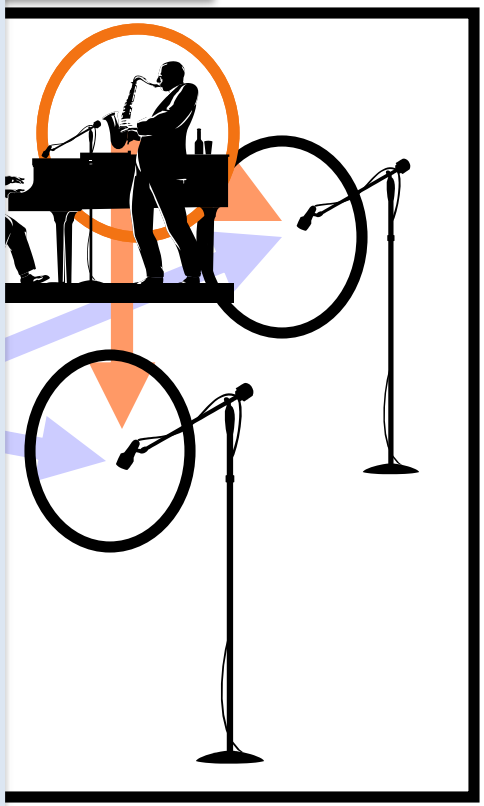
Blind EEG Source Separation by Independent Component Analysis

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)

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 $H(y_1, y_2)$ $\Longrightarrow$ minimizing $I(y_1, y_2)$.

Infomax

Is 0 if the two variables are independent

The learning rule:

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

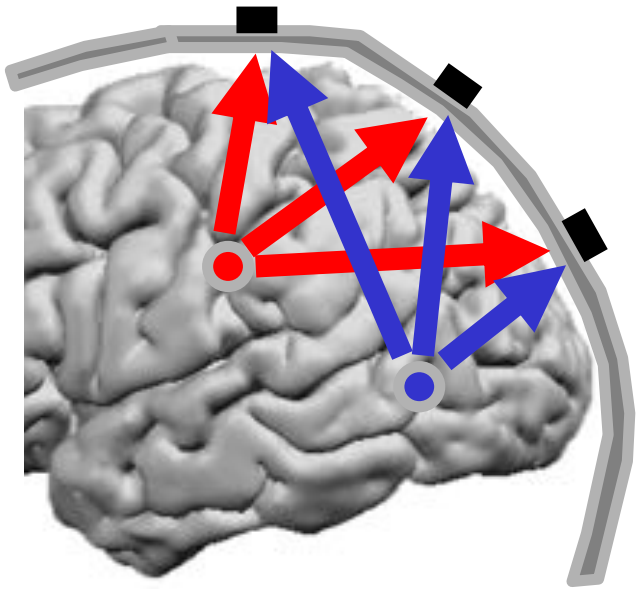
Natural gradient normalization (Amari)

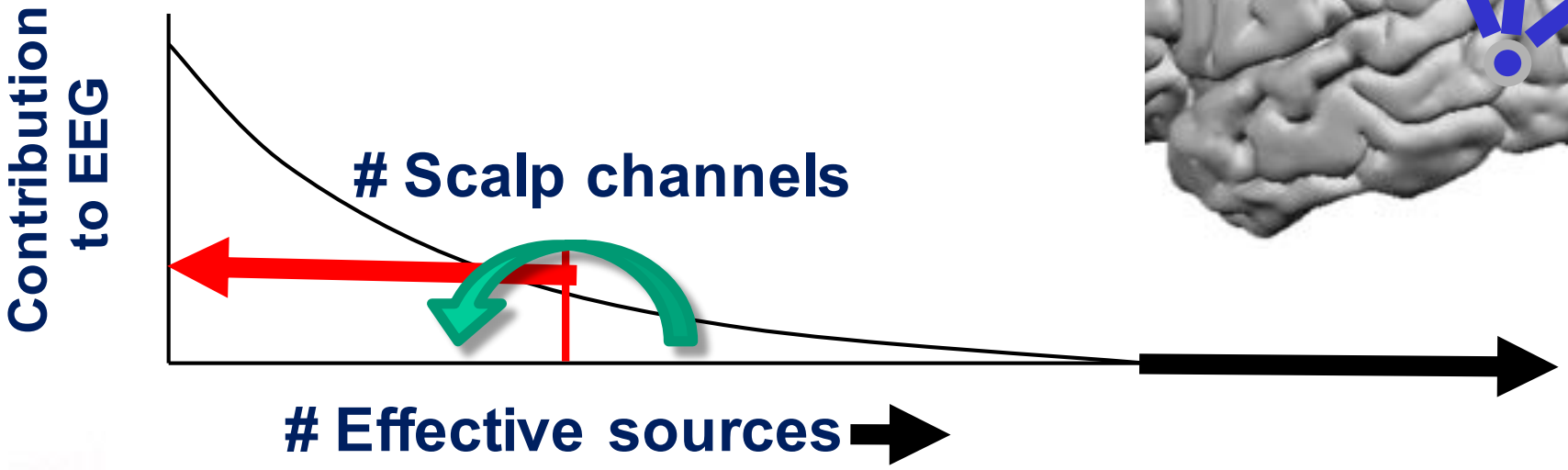
Blind EEG Source Separation by ICA

Information-based Signal Processing

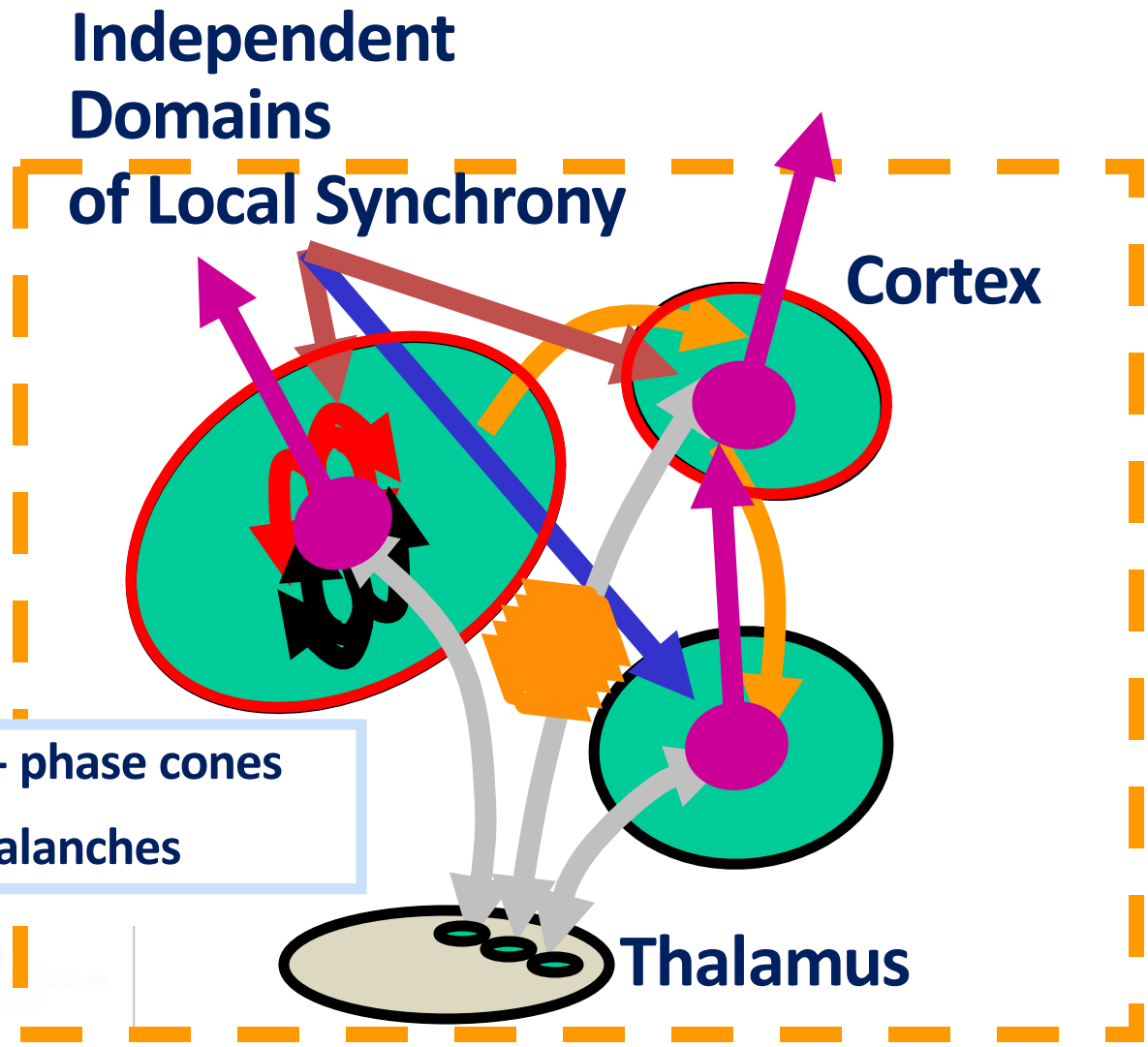
ICA Assumptions

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





Are EEG effective source signals independent?



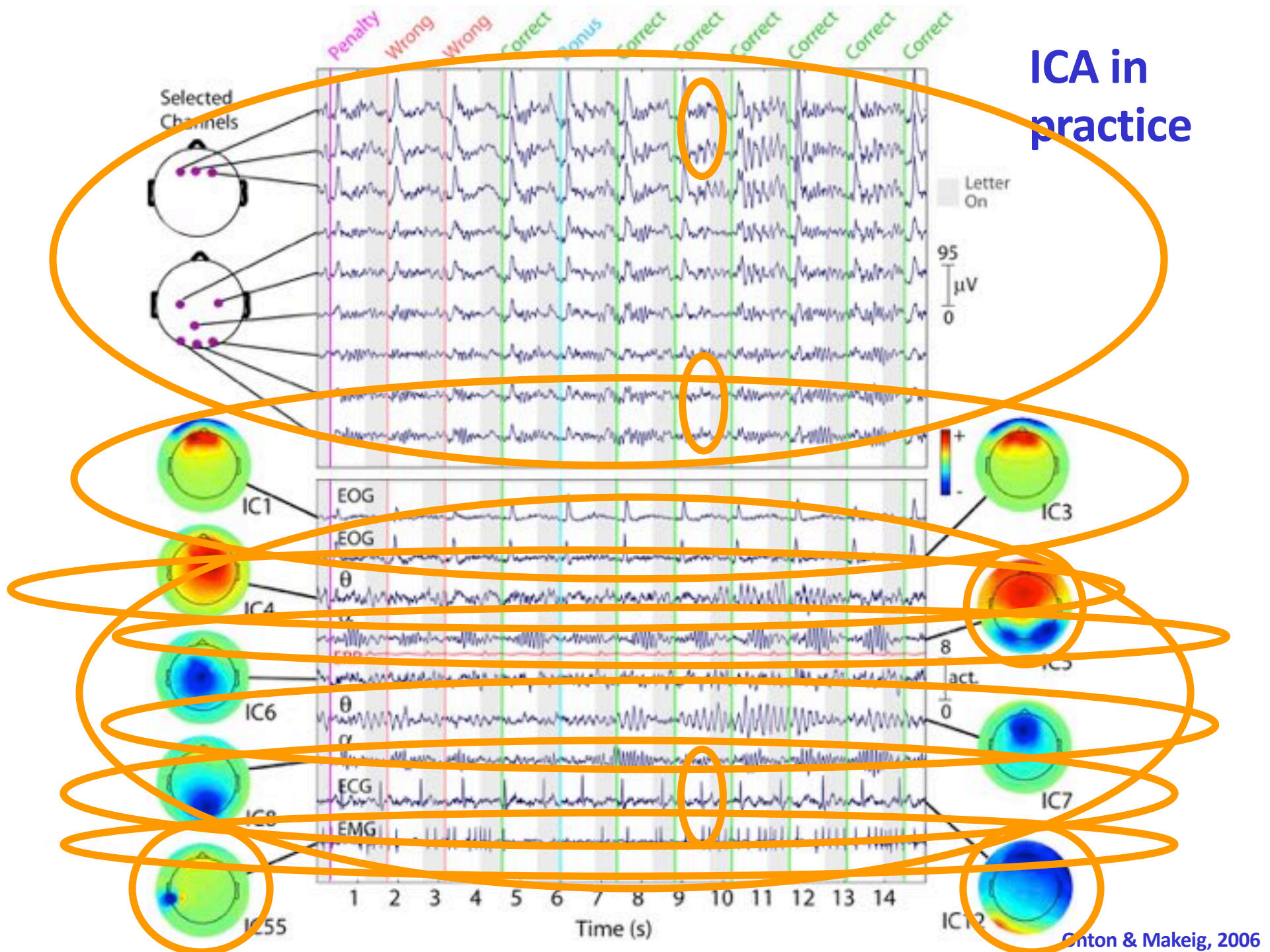
Freeman - phase cones

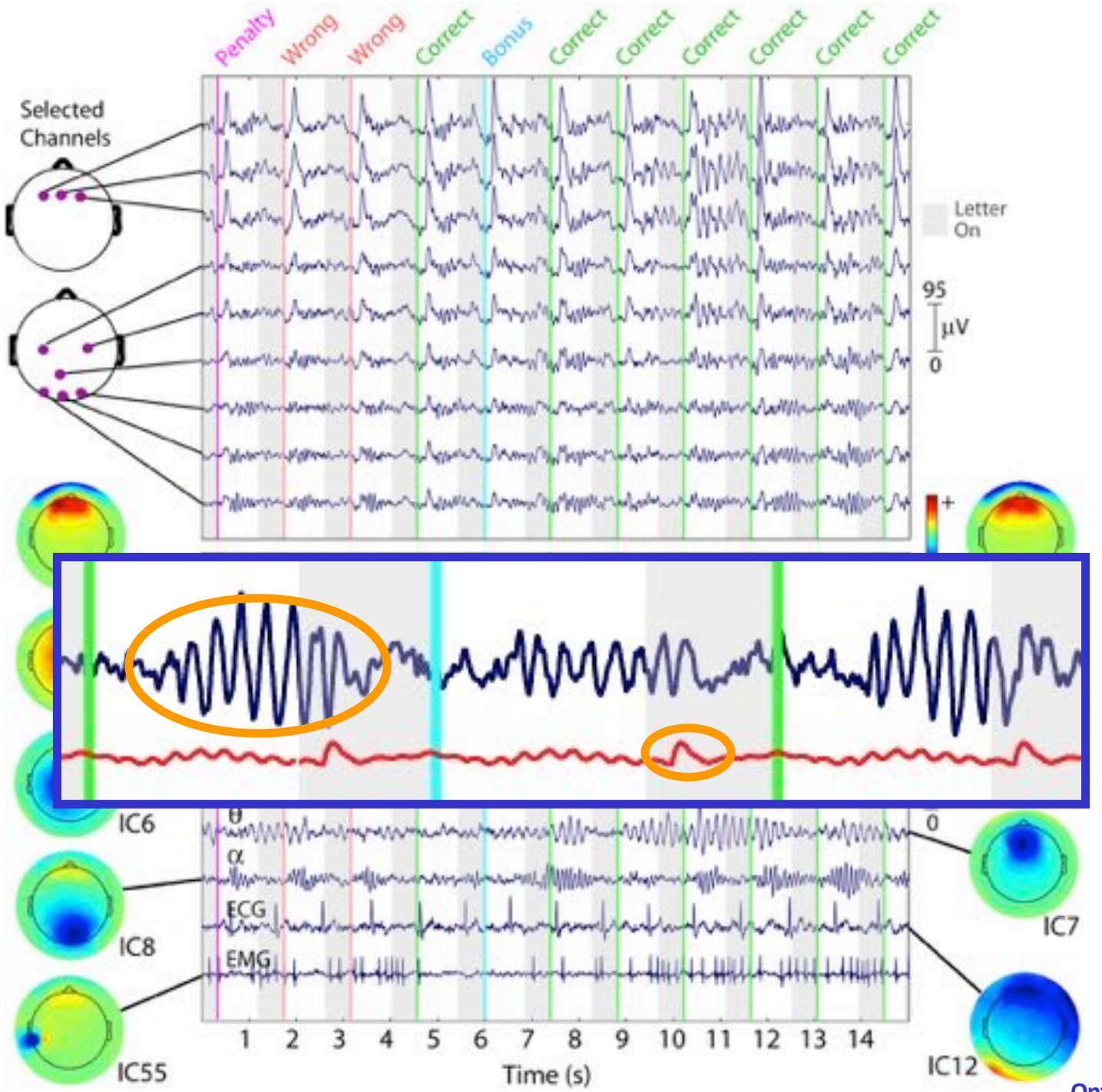
Plenz - avalanches

S. Makeig (2007)

Properties of EEG Independent Components

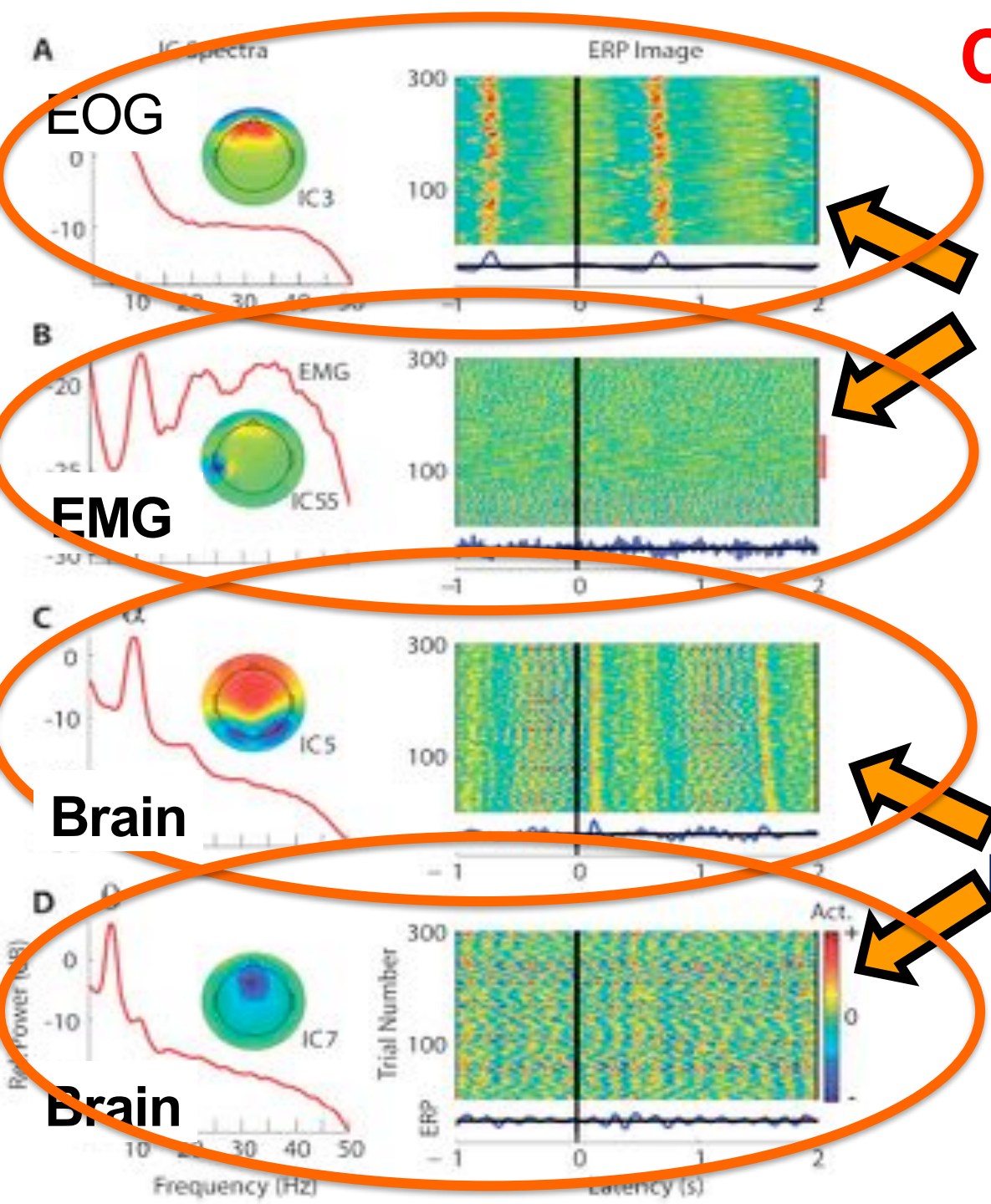
- Maximally Temporally Independent
- Concurrently Active and Spatially Overlapping
- *Dipolar* Scalp Maps (Delorme et al., 2012)
- *Functionally* Distinct
- Between-Subject Similarity / Complexity


ICA in practice
Penalty
Wrong
Wrong
Correct
Bonus
Correct
Correct
Correct
Correct
Correct
Correct
Selected Channels
Letter On
95
µV
0
IC1
IC3
EOG
EOG
θ
IC4
IC5
8
act.
0
IC6
θ
α
ECG
EMG
IC7
IC8
IC55
IC12
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Time (s)
Onton & Makeig, 2006



Onton, Makeig (2006)

Classifying ICs

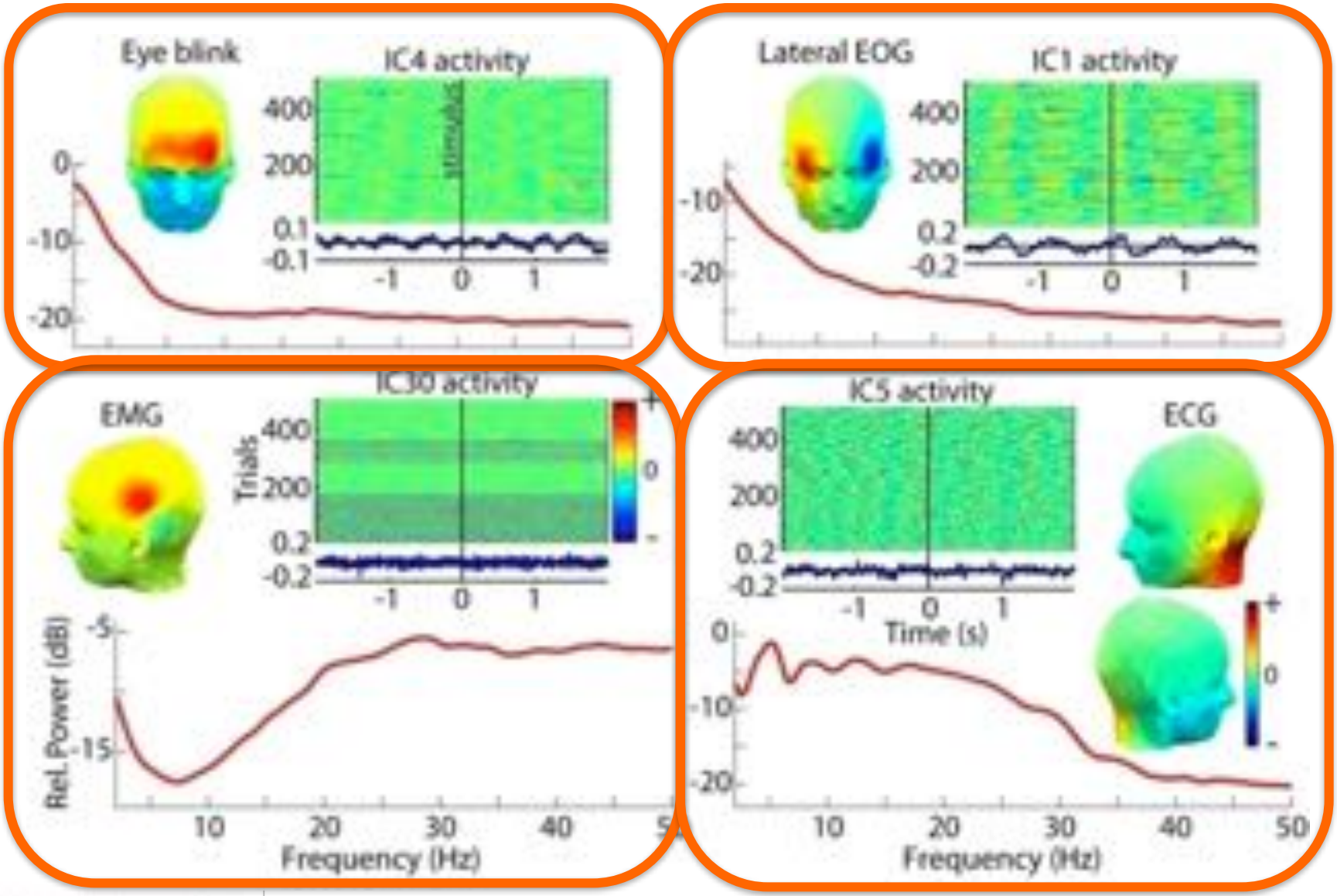


Non-brain sources

Effective brain sources

J. Onton & S. Makeig, 2005

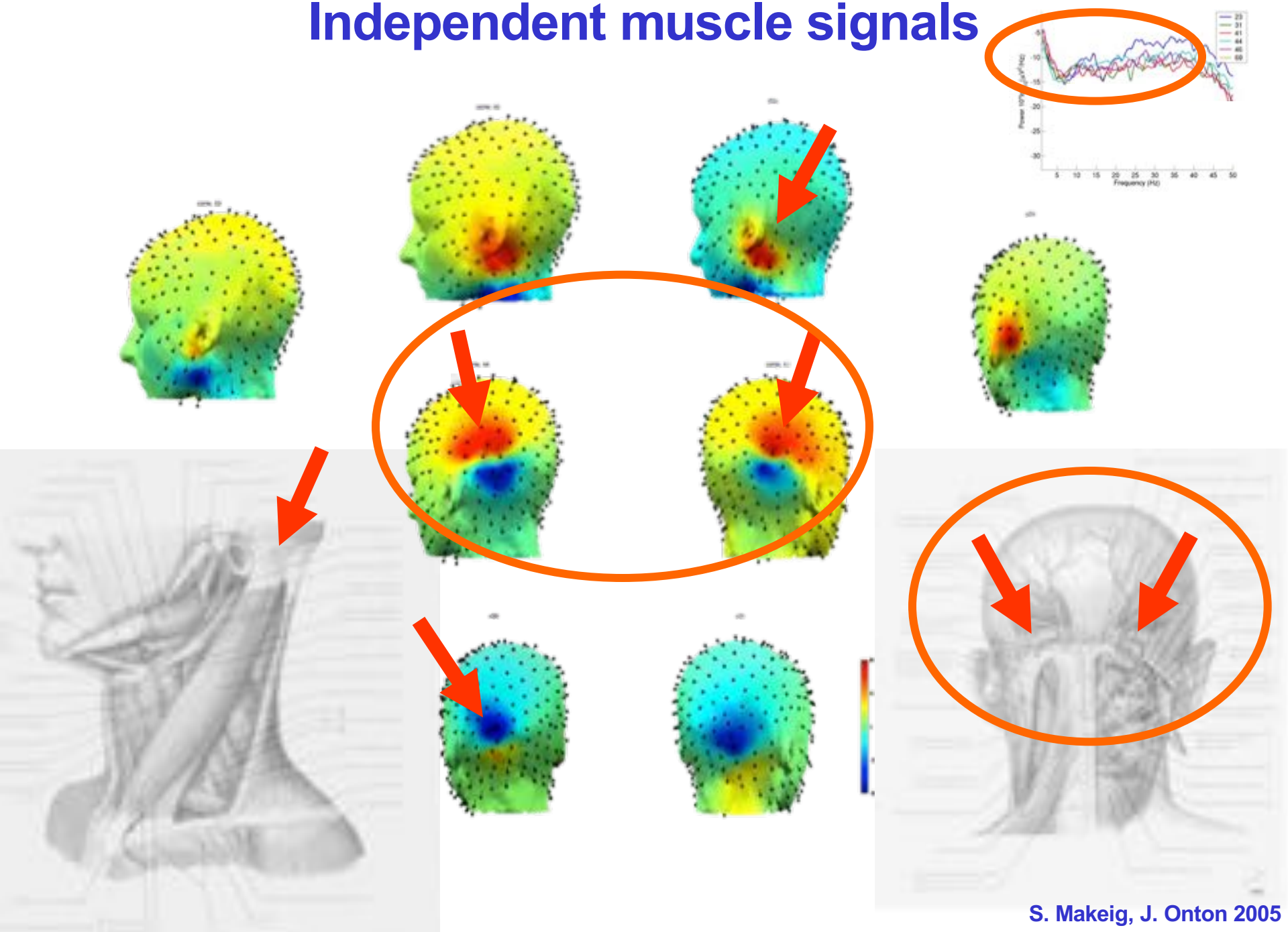
ICA finds Non-Brain Independent Component (IC) Processes …



… separates them from the remainder of the data …

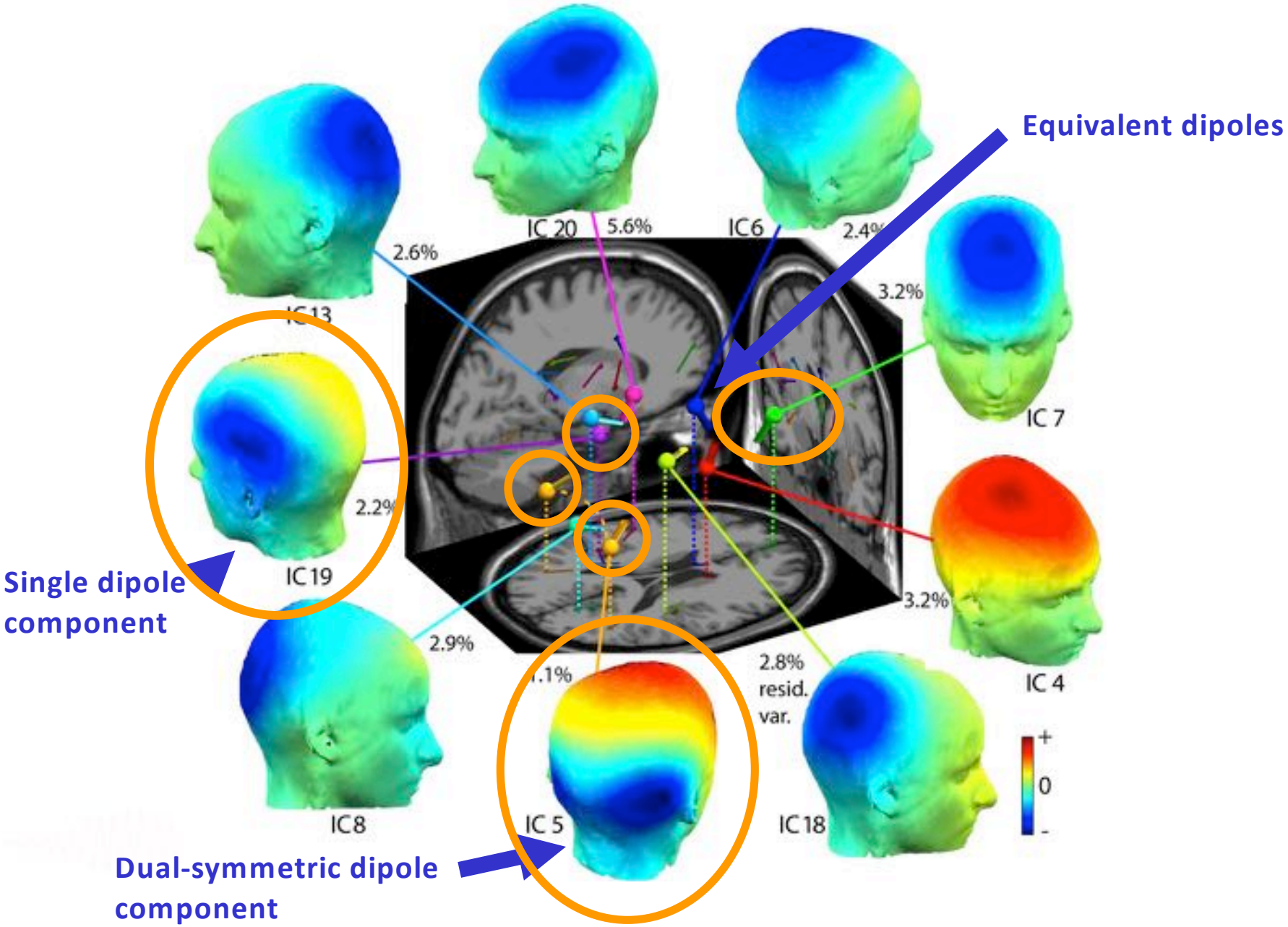
J. Onton & S. Makeig

Independent muscle signals



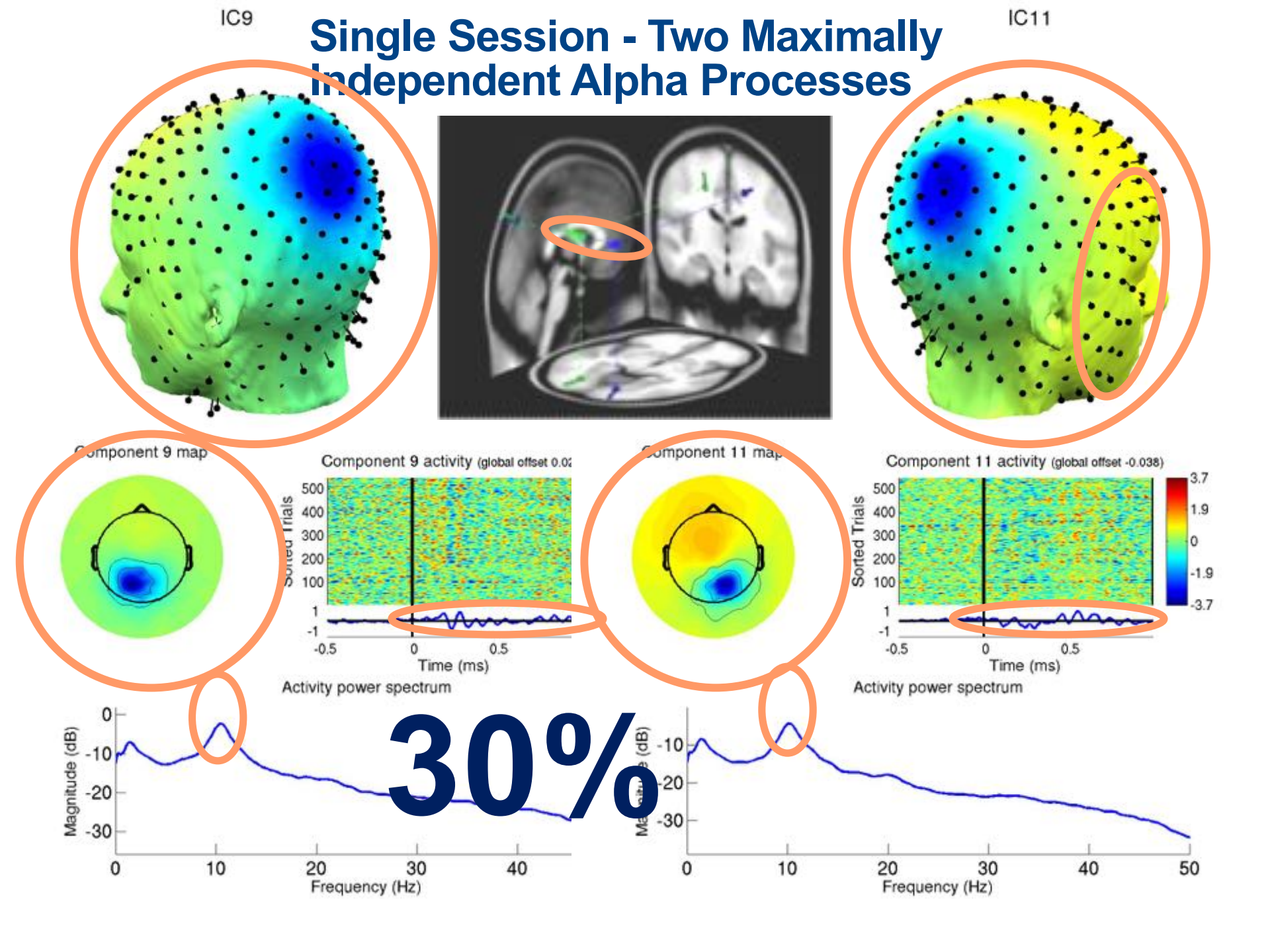
S. Makeig, J. Onton 2005

… and also separates cortical brain IC processes



Julie Onton & S. Makeig (2006)

Single Session - Two Maximally Independent Alpha Processes



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

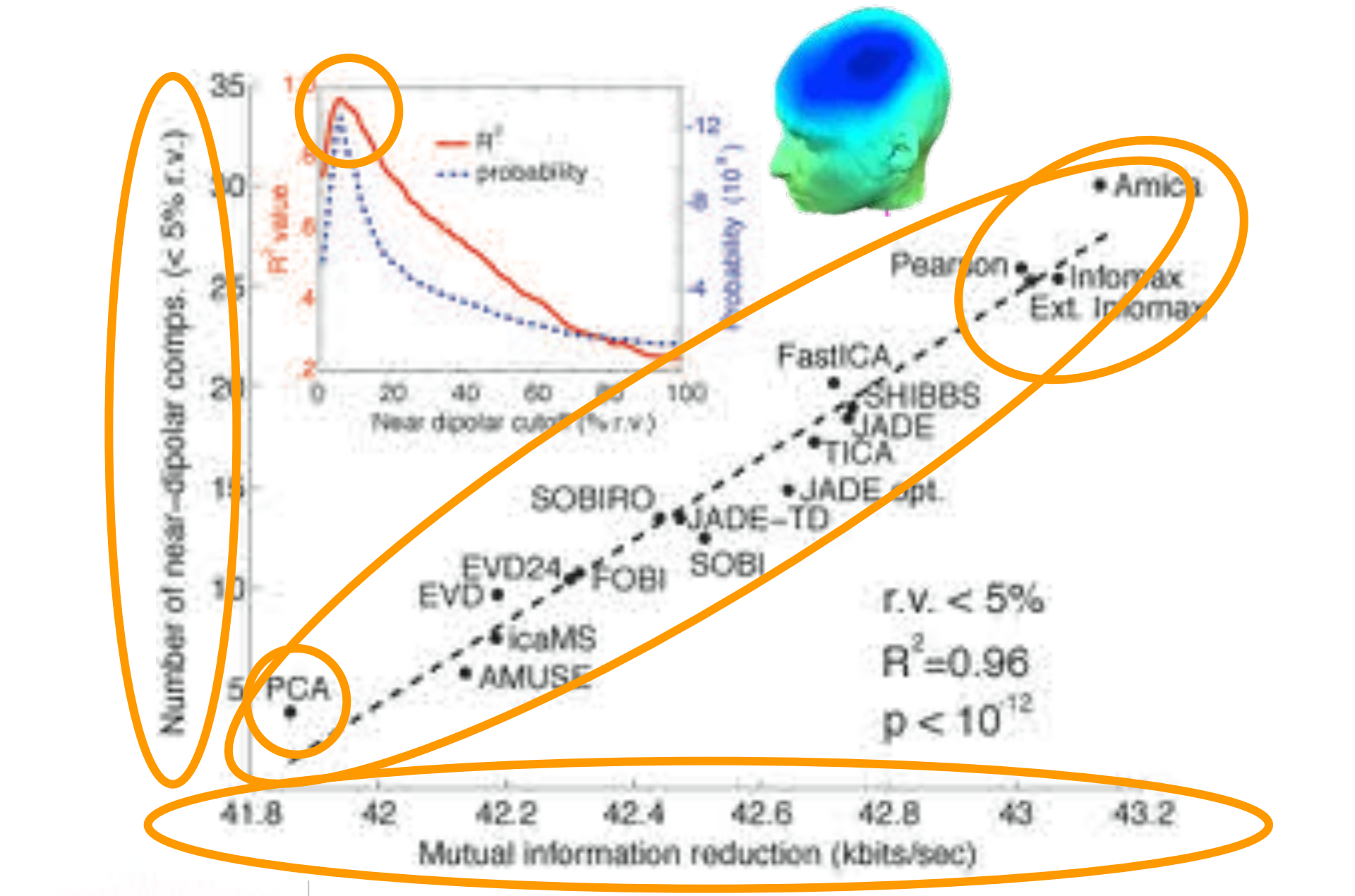
More nearly *independent* component time courses

↔

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

S. Makeig, 2011

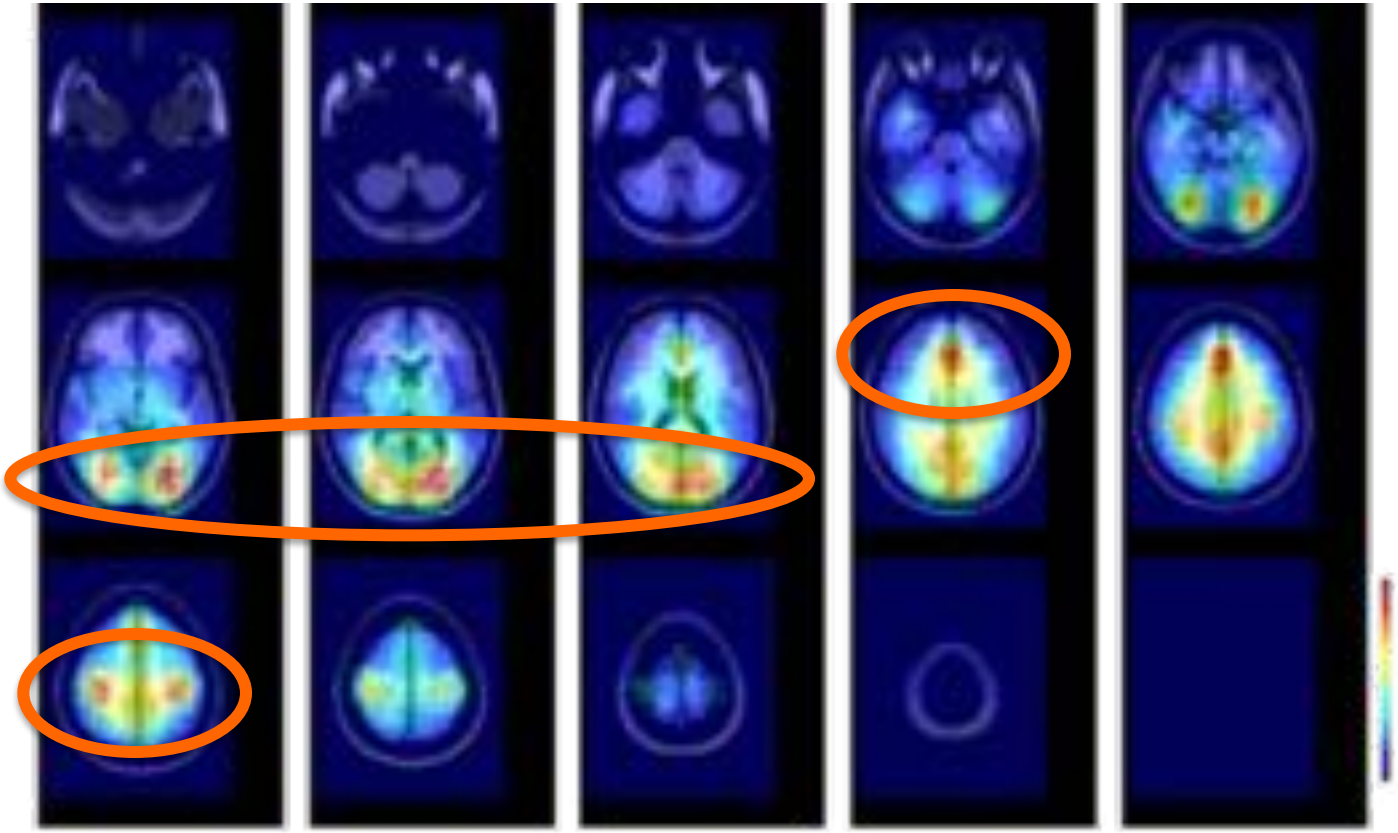
Are locations of EEG *effective sources* similar across tasks?

Are *effective source* locations within task similar across participants?

S. Makeig (2007)

Effective Source Density

Visual Working Memory



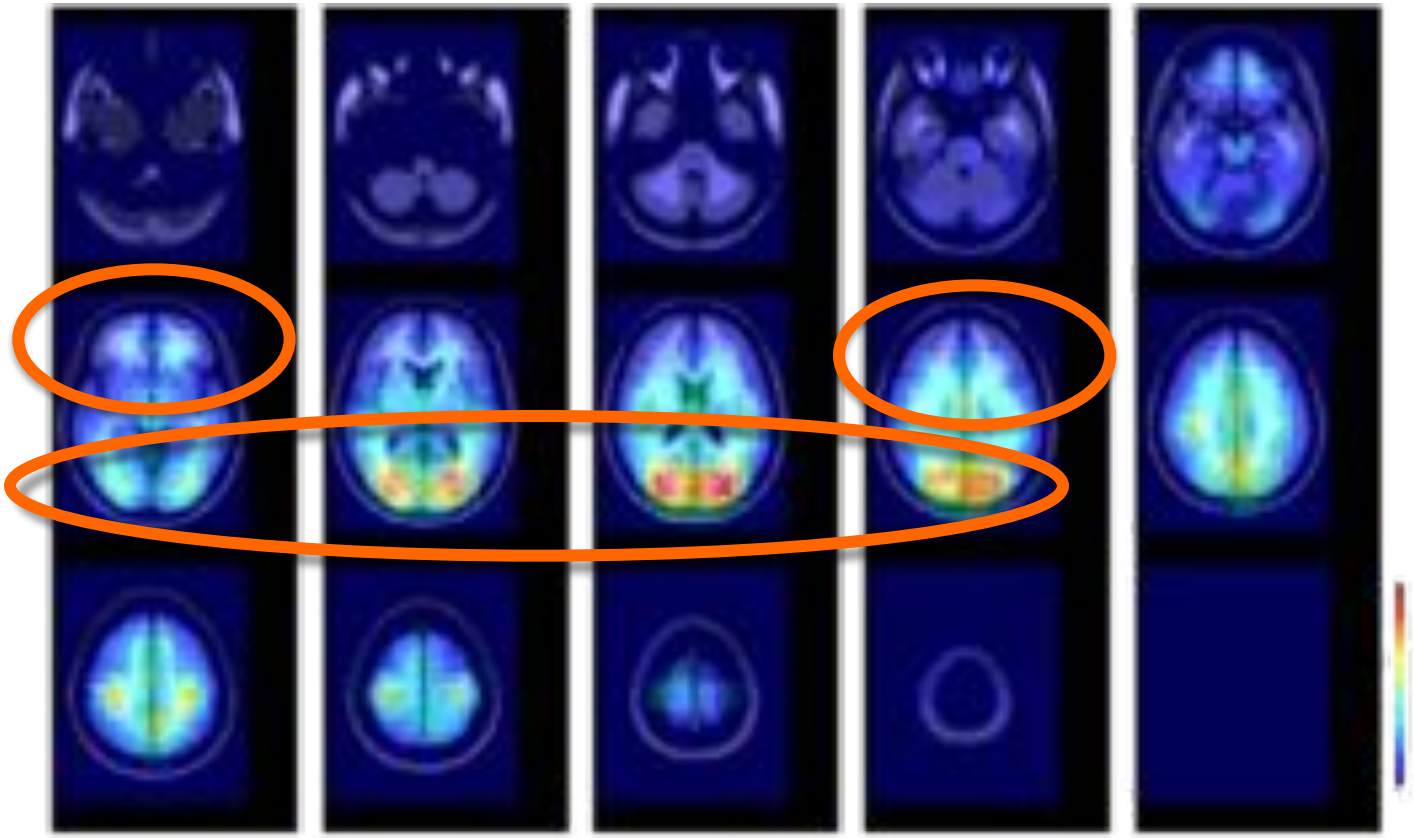
Sternberg letter memory task

dipoledensity()

Onton & Makeig, 2005

Effective Source Density

Eyes-closed emotion imagination

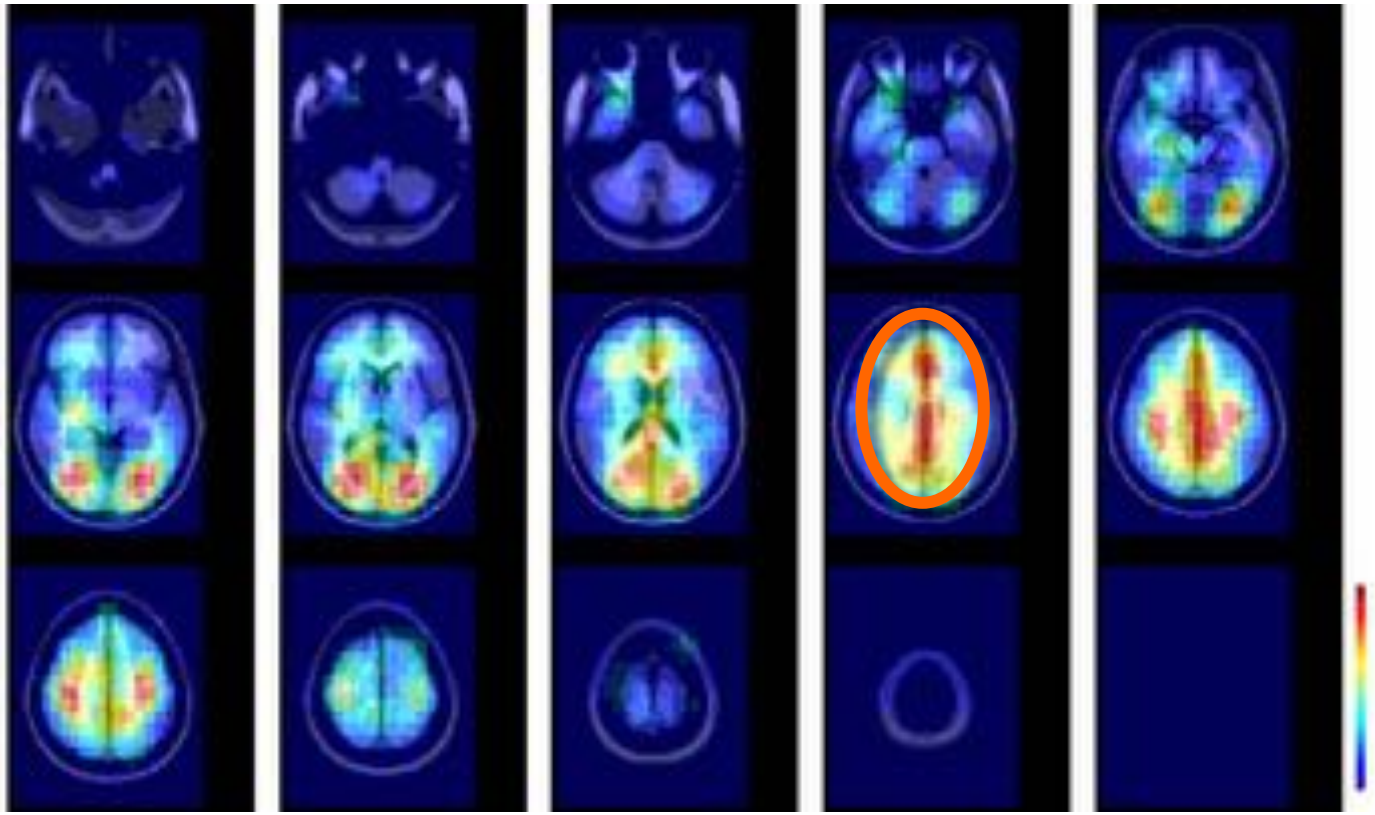


>> dipoledensity()

Onton & Makeig, 2005

Effective Source Density

Letter twoback with feedback

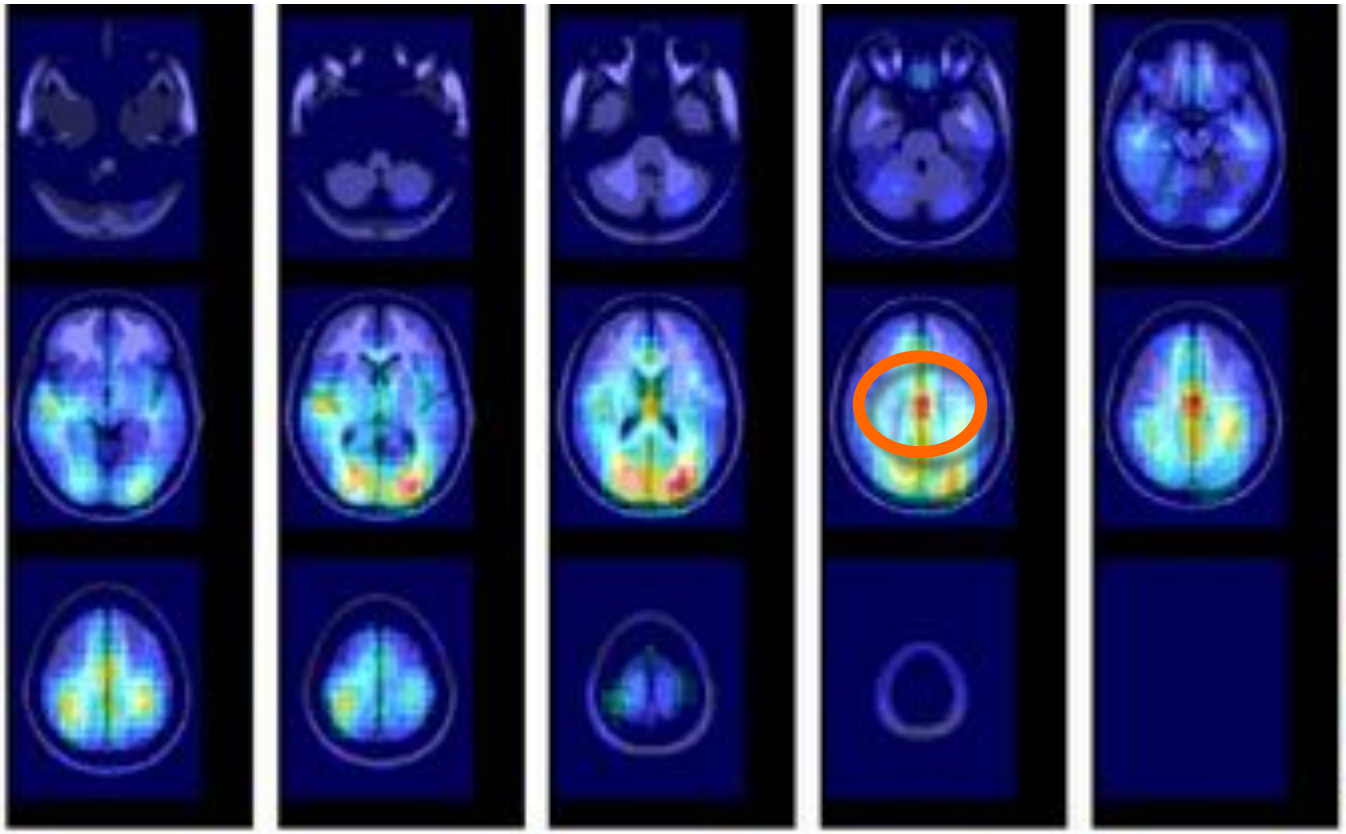


Letter twoback with feedback

Onton & Makeig, 2005

Effective Source Density

Auditory novelty oddball

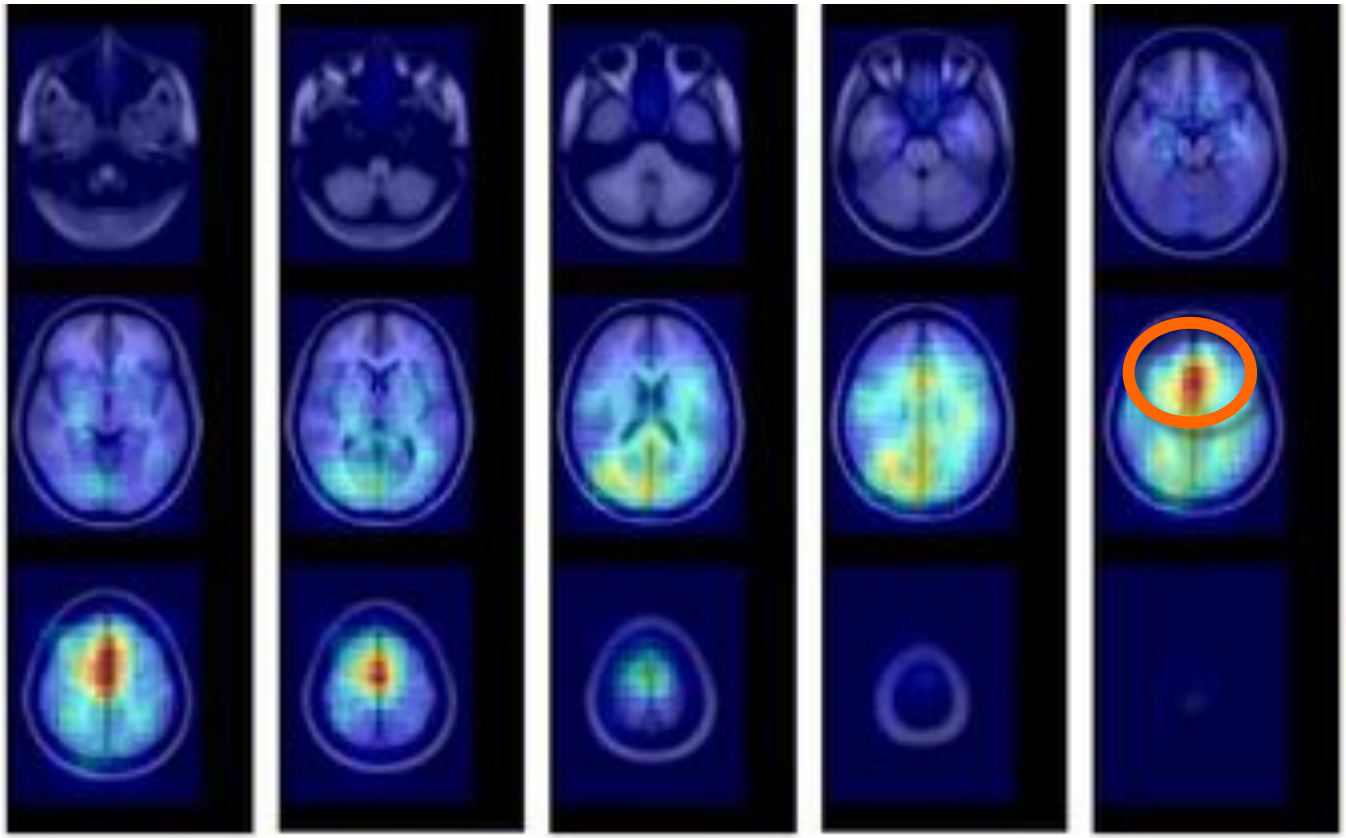


Auditory oddball plus novel sounds

Onton & Makeig, 2005

Effective Source Density

A. Old/new word memory

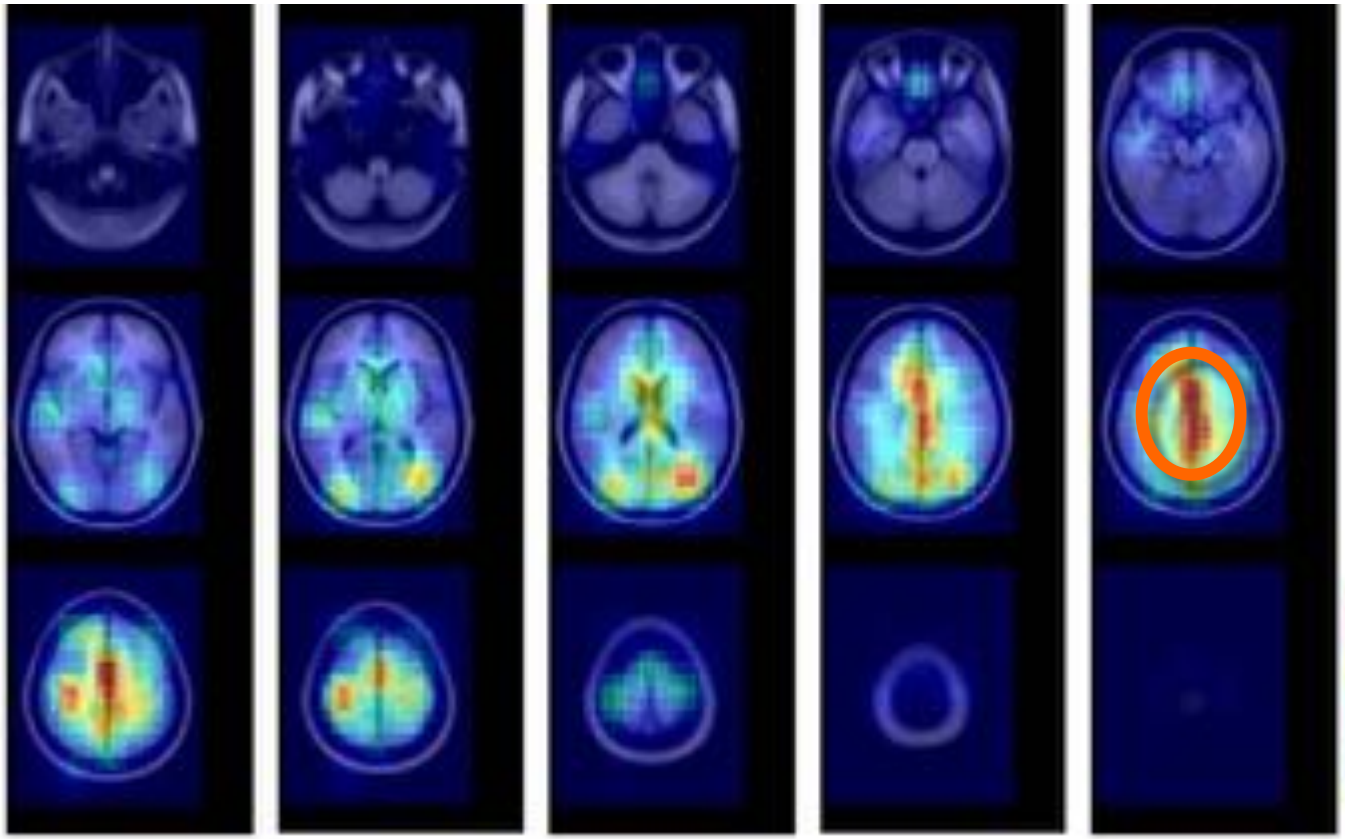


Word memory (old/new) task

Onton & Makeig, 2005

Effective Source Density

B. Visually cued selective response



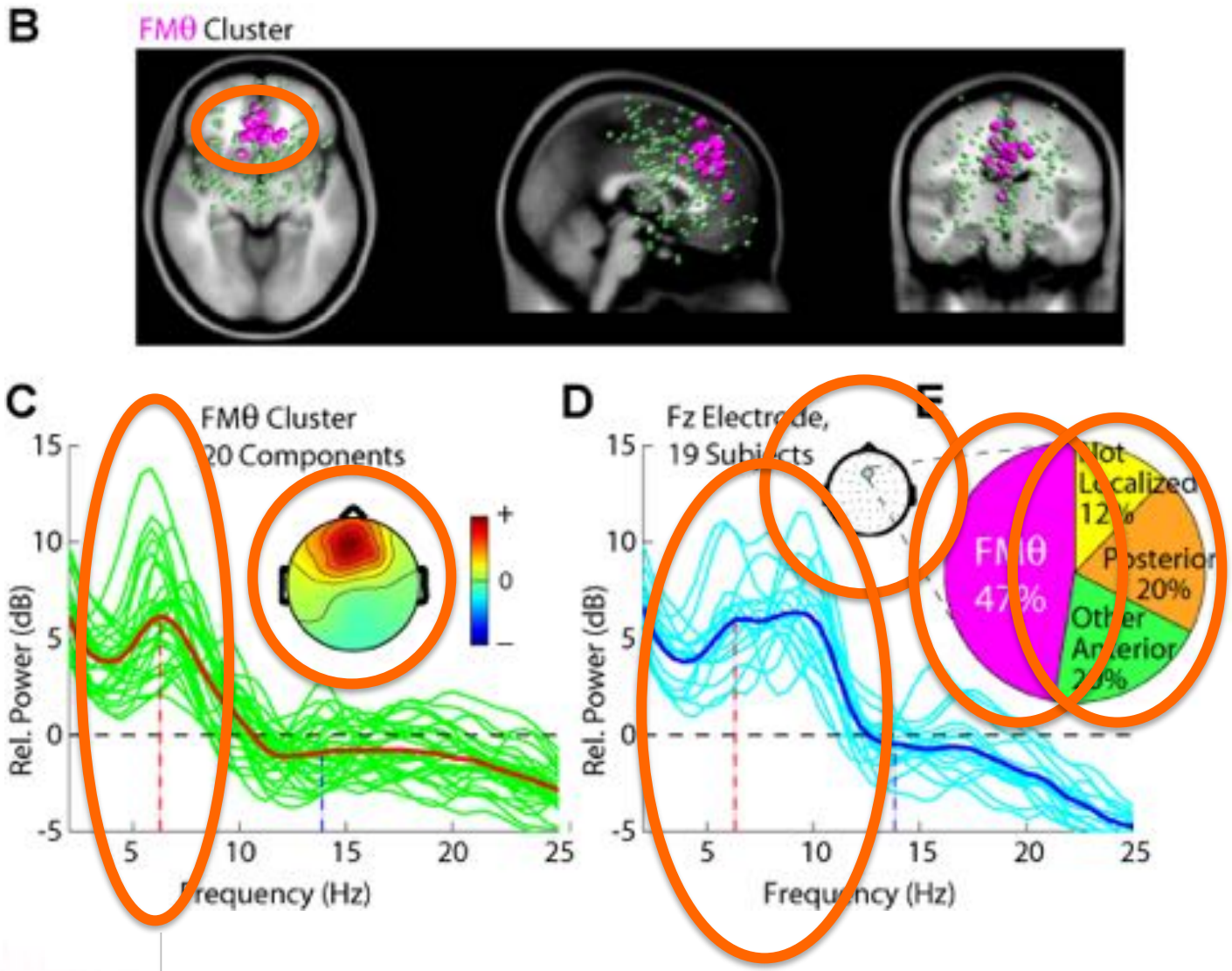
Visually cued button press task

Onton & Makeig, 2005

Are source dynamics similar across participants?

S. Makeig (2007)

Example: frontal midline theta cluster



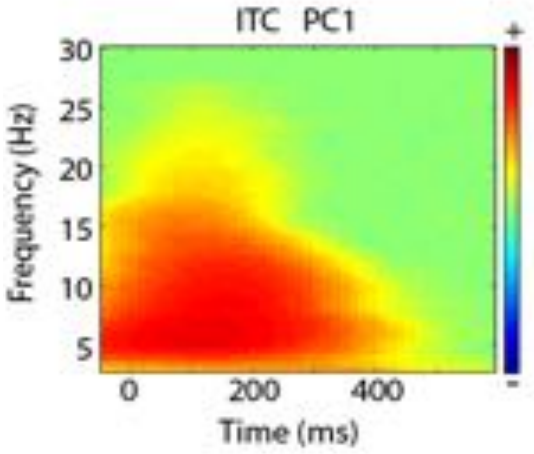
Onton, Delorme & Makeig, *NeuroImage* (2005)

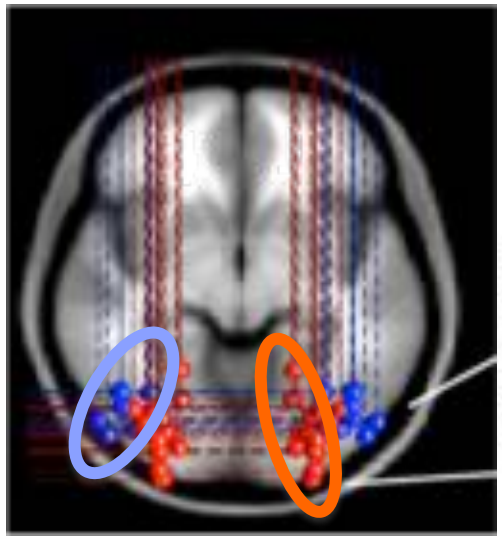
Individual Differences

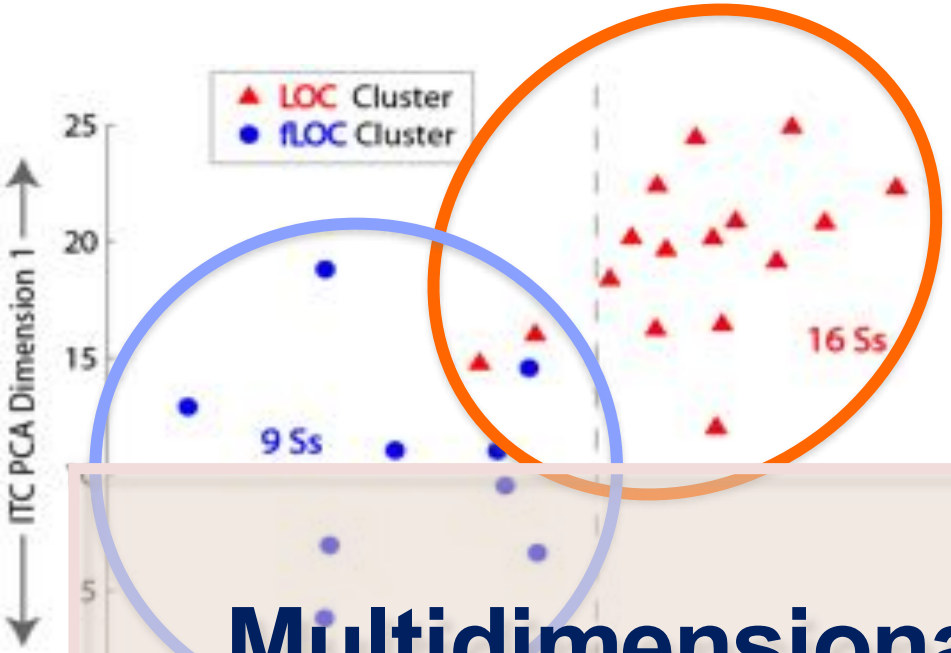
‘EEG Biomarkers’

Rissling et al., 2014

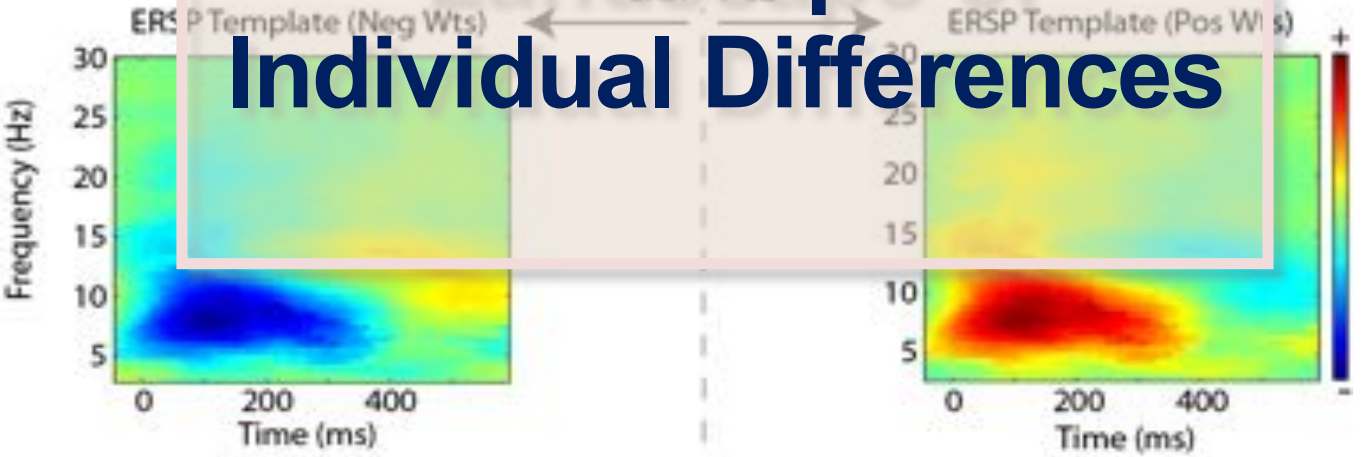
Can ICA reveal subject differences?

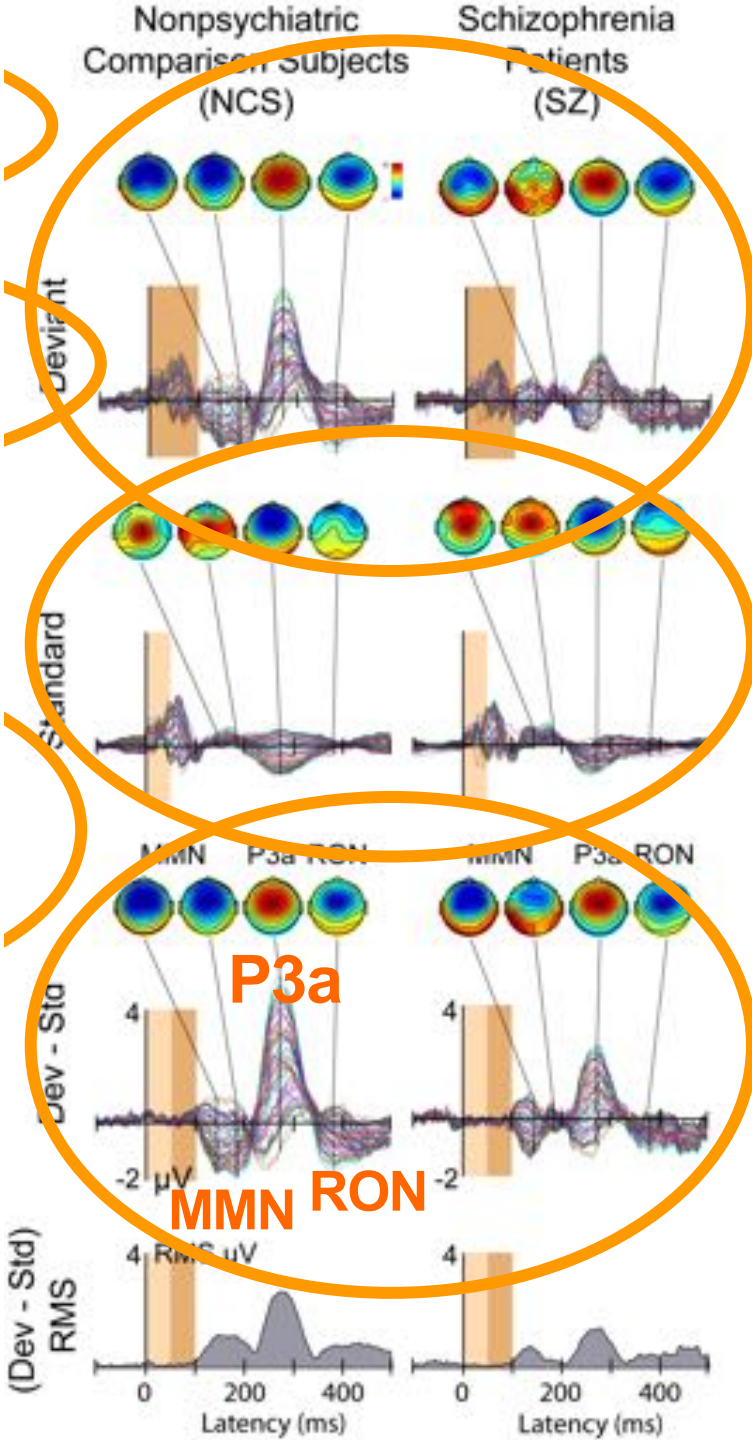




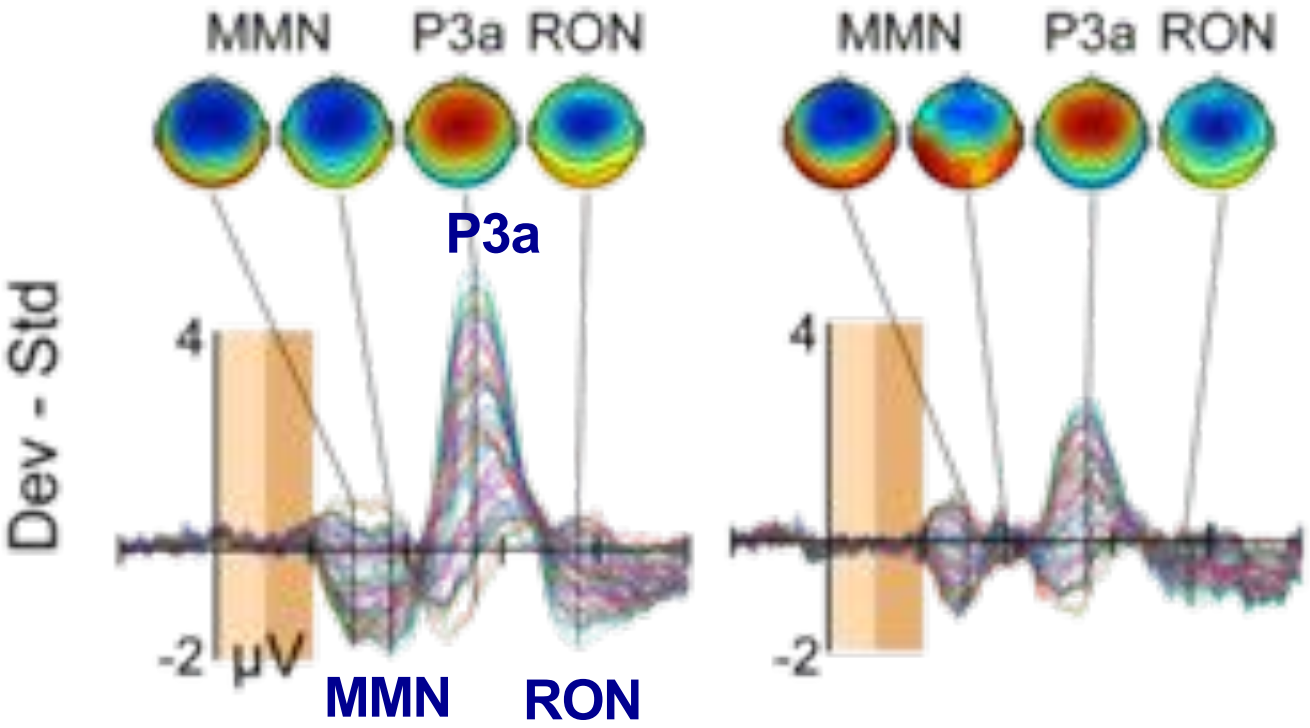


Multidimensional Landscape of Individual Differences



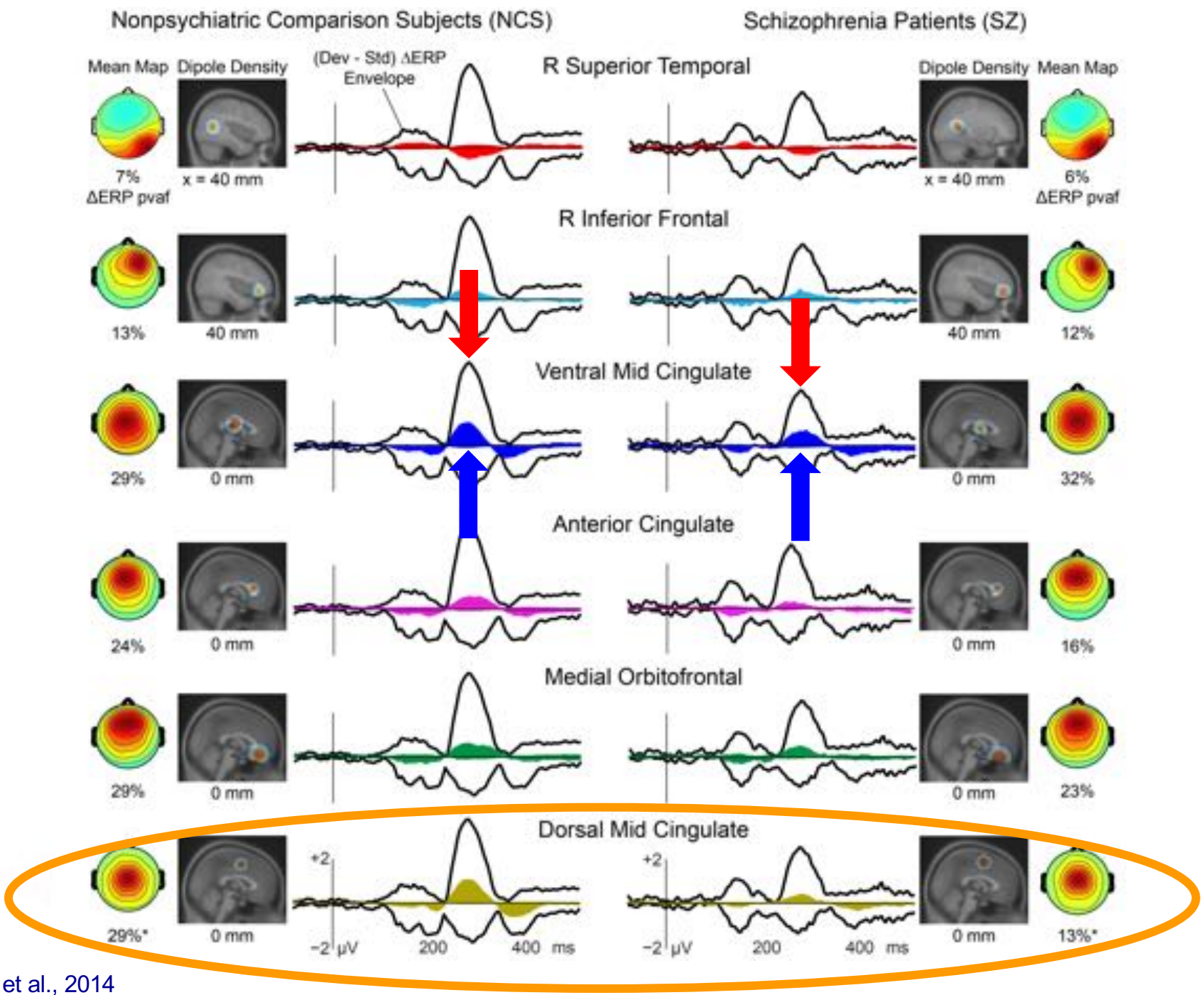

Nonpsychiatric
Comparison Subjects
(NCS)
Schizophrenia
Patients
(SZ)
Deviant
Standard
MMN
P3a
RON
MMN
P3a
RON
Dev - Std
4
-2 μV
4
-2
(Dev - Std)
RMS
4 RMS μV
4
0
200
400
Latency (ms)
0
200
400
Latency (ms)

Auditory Deviance Response



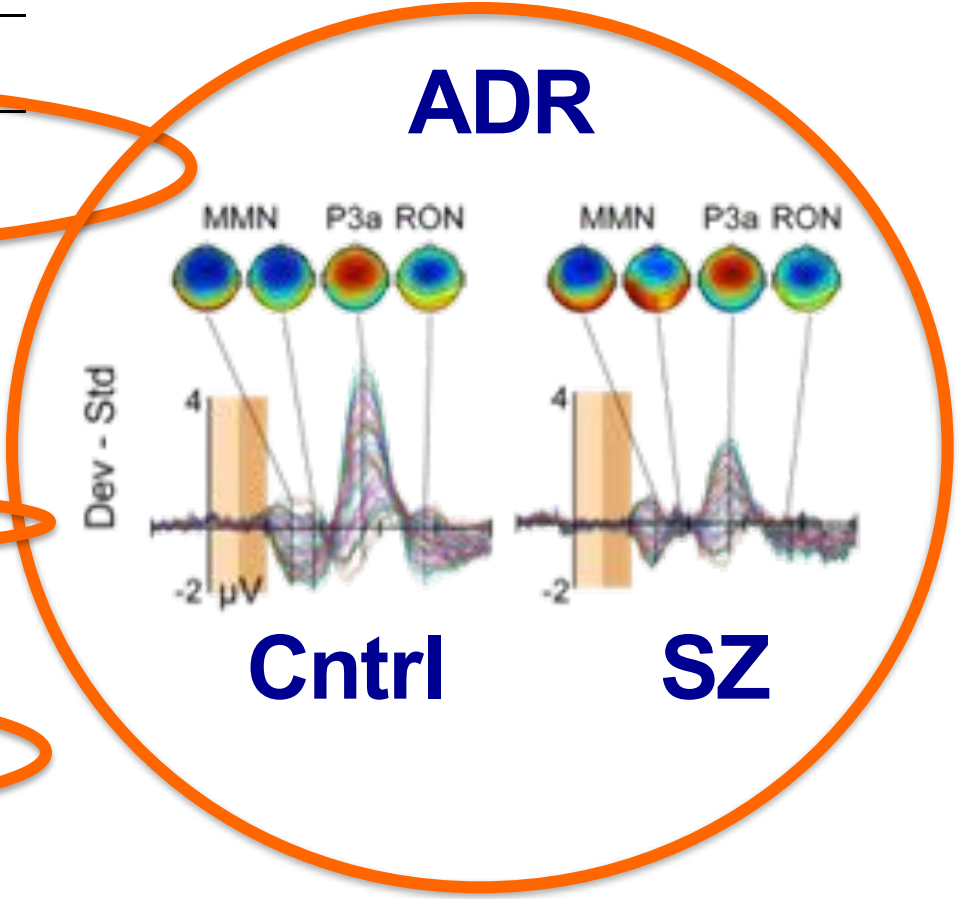
Cntrl **SZ**

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



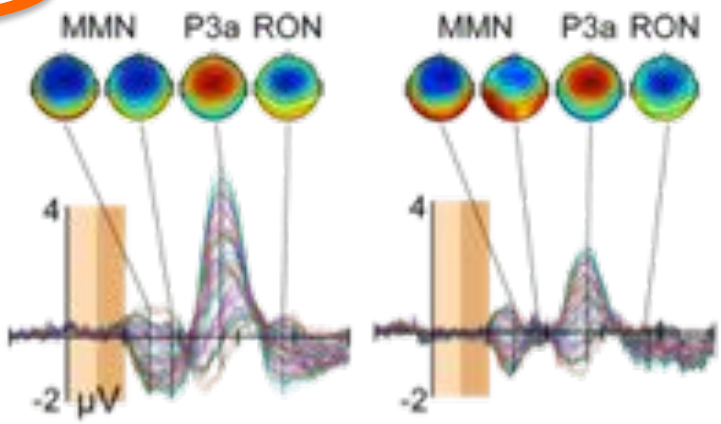
Rissling et al., 2014

PEAK AMPLITUDES	ERP	r^2
Scalp Electrode (Fz)		
Verbal IQ (WRAT)	P3a	0.11
Functional Capacity (UPS	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



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



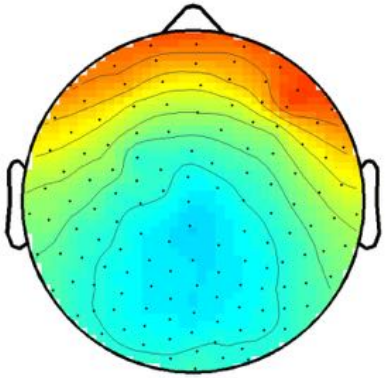
Cntrl SZ

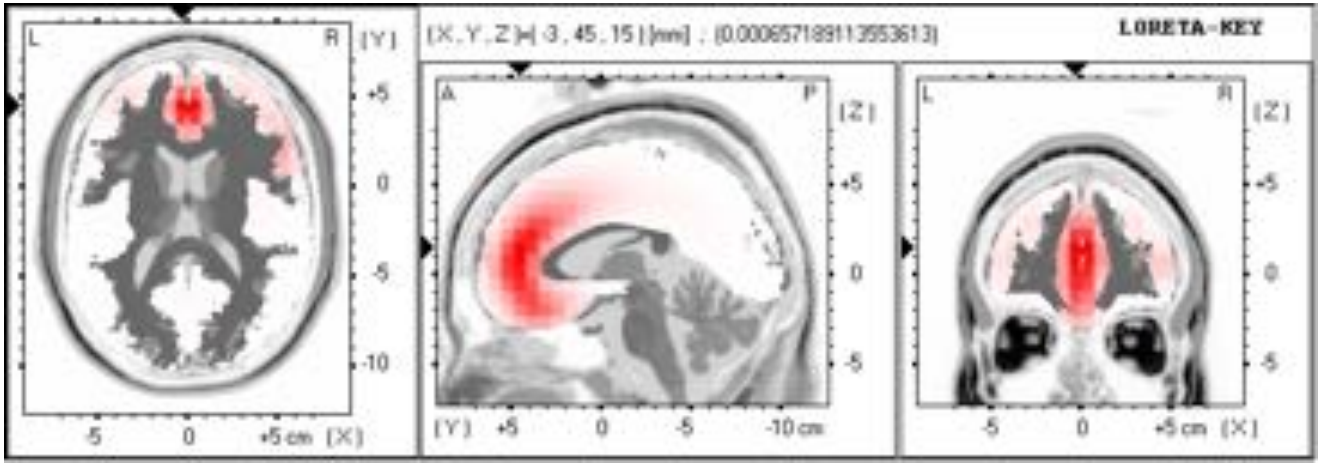
Low- and High-Resolution Source Localization

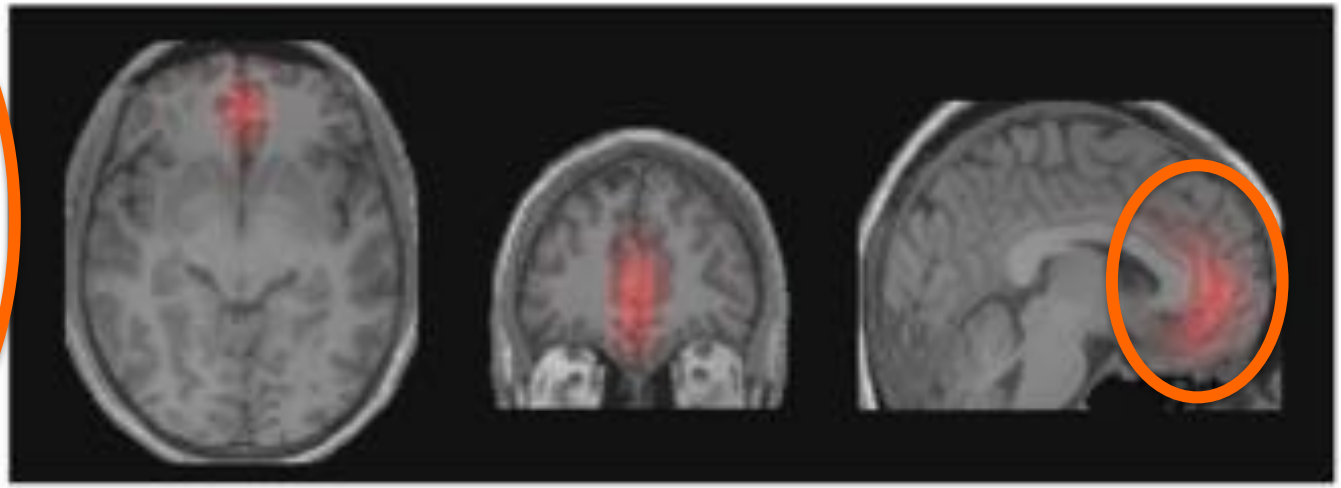
Rissling et al., 2014

EEG Source Localization

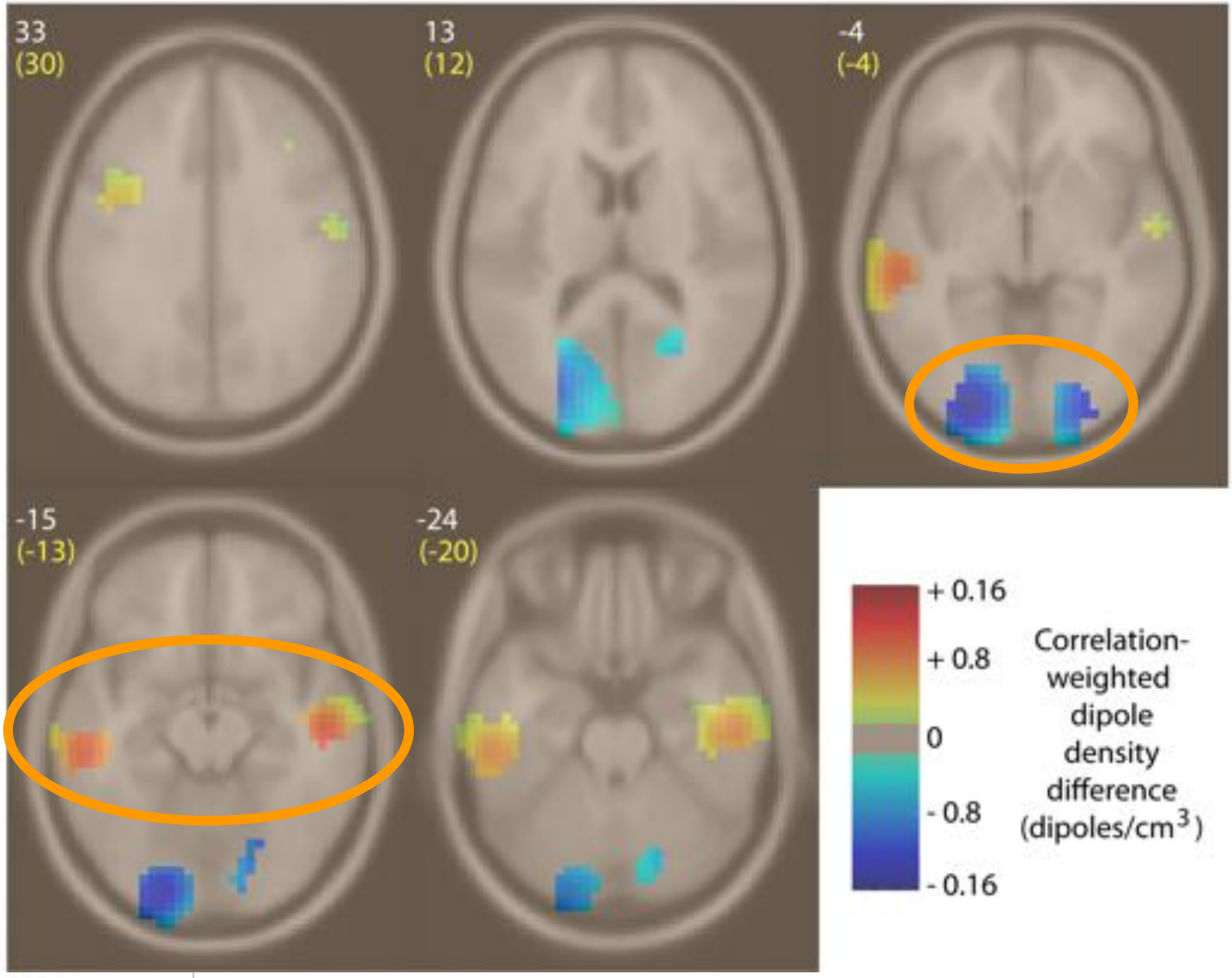
LORETA = **Low-Resolution** Electrical Tomography







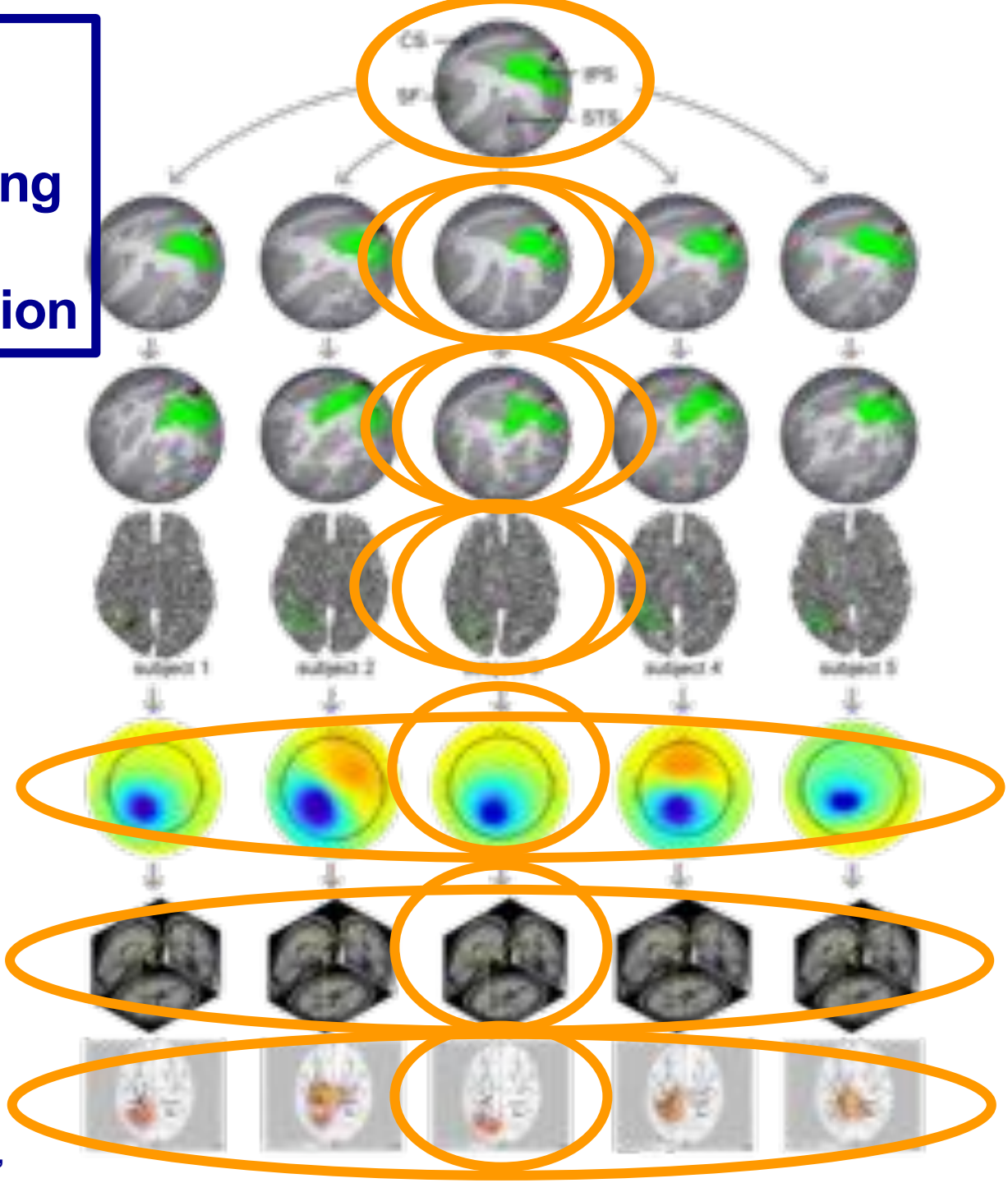
A. Delorme



Onton & Makeig, *Frontiers in Human Neuroscience* '09

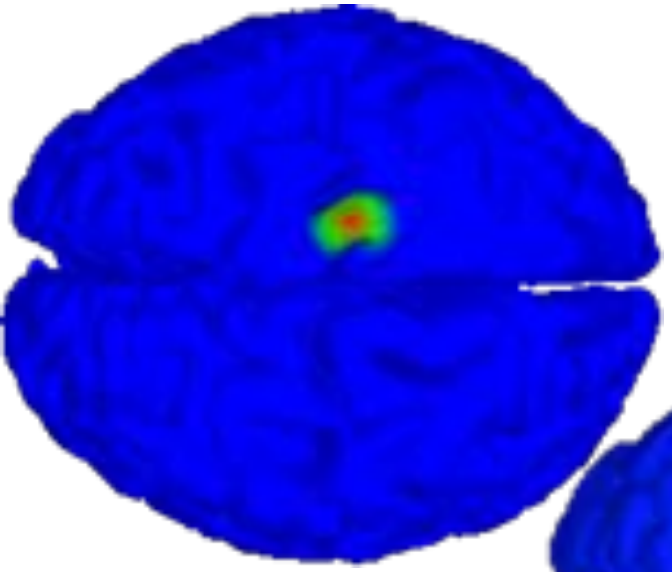
Arthur Tsai – Topological source clustering and measure projection

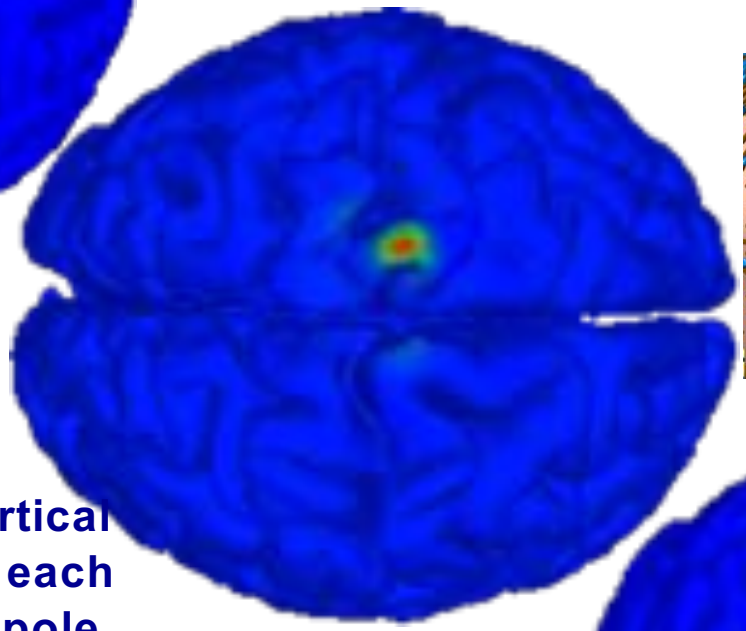
Arthur Tsai et al., *NeuroImage*,

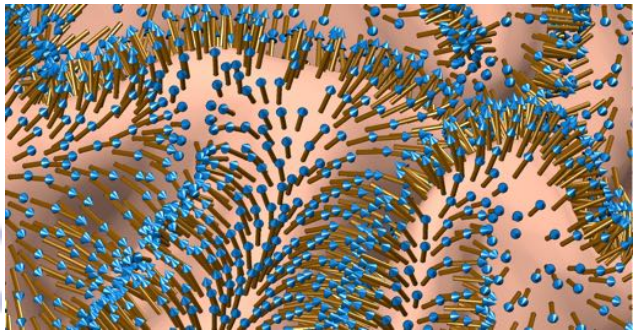


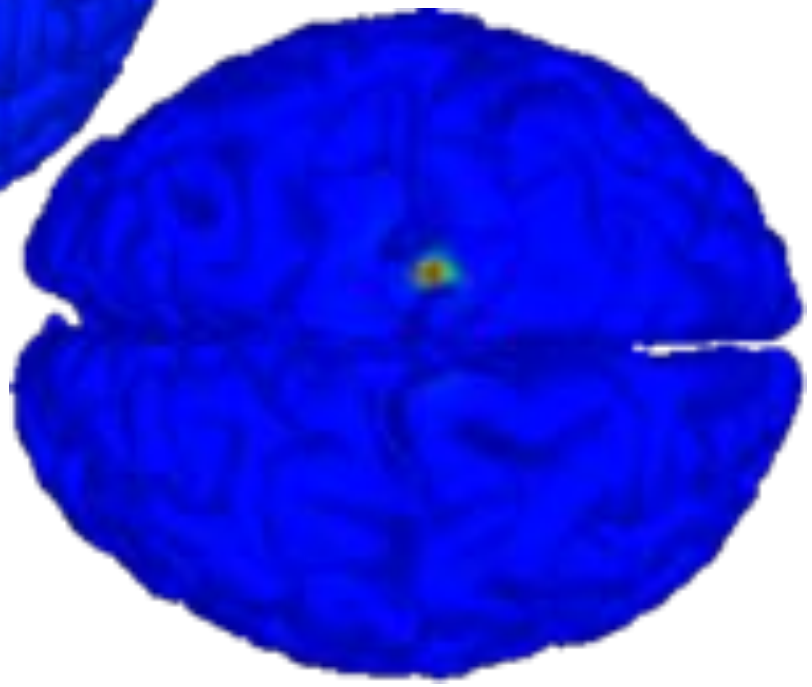
High-Resolution Distributed Source Localization

using a multiscale patch basis





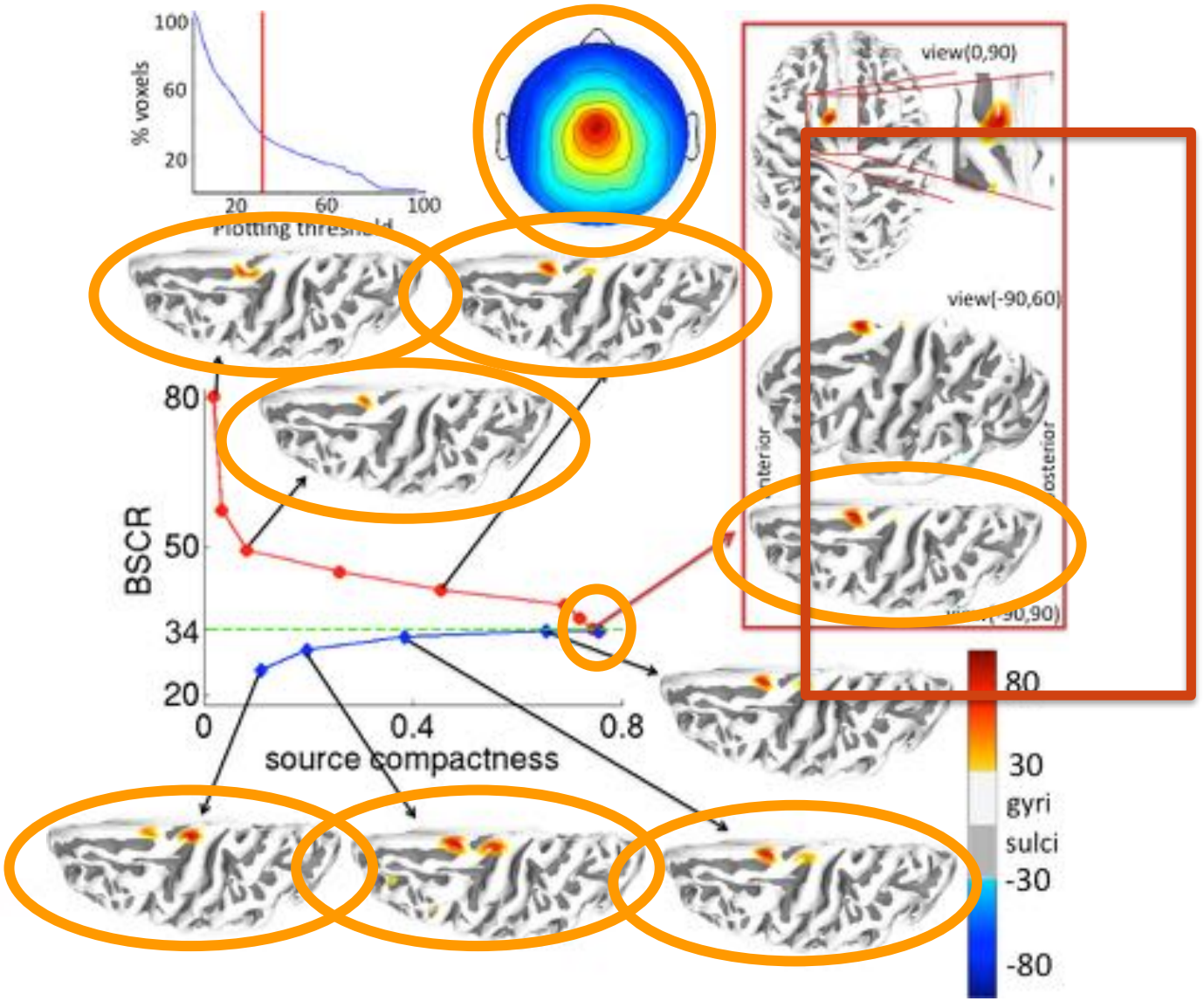




0. Build a high-res. cortical surface mesh; give each voxel an oriented dipole.
1. Compute a 'dictionary' of Gaussian patches conforming to the cortical surface centered at each cortical mesh voxel.
2. Use a 'sparsifying' approach to find the sum of the *fewest* of these patches that together produce the given source scalp or grid map.

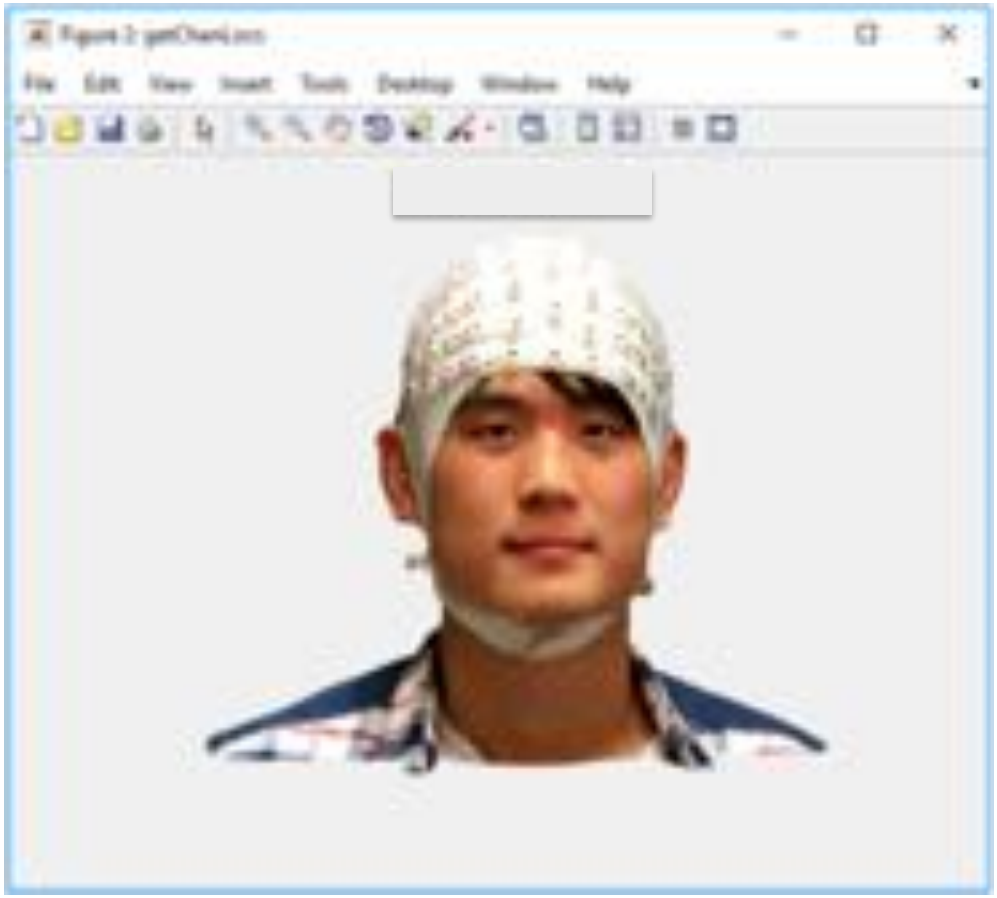
Zeynep Akalin Acar,, S. Makeig, G. Worrell, '09-'16

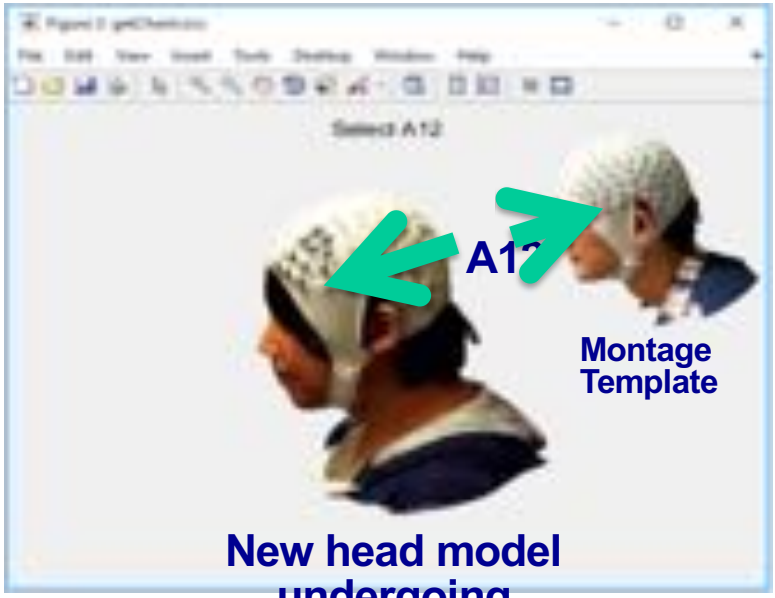
High-resolution source localization requires an *electrically* accurate head model



Handheld
3-D electrode position recording system software

sccn.ucsd.edu/wiki/Get_chanlocs





New head model undergoing electrode localization

Currently by hand 1-by-1.
Soon by machine learning.

Cl. Lee & S. Makeig, 2014

Mobile Brain/body Imaging (MoBI)

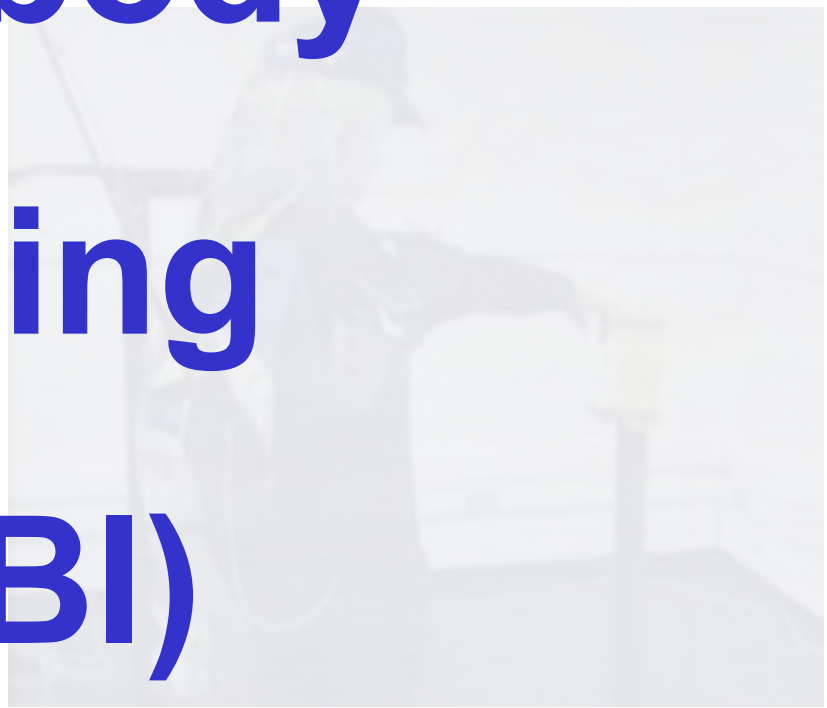
Brain imaging during movement – How?

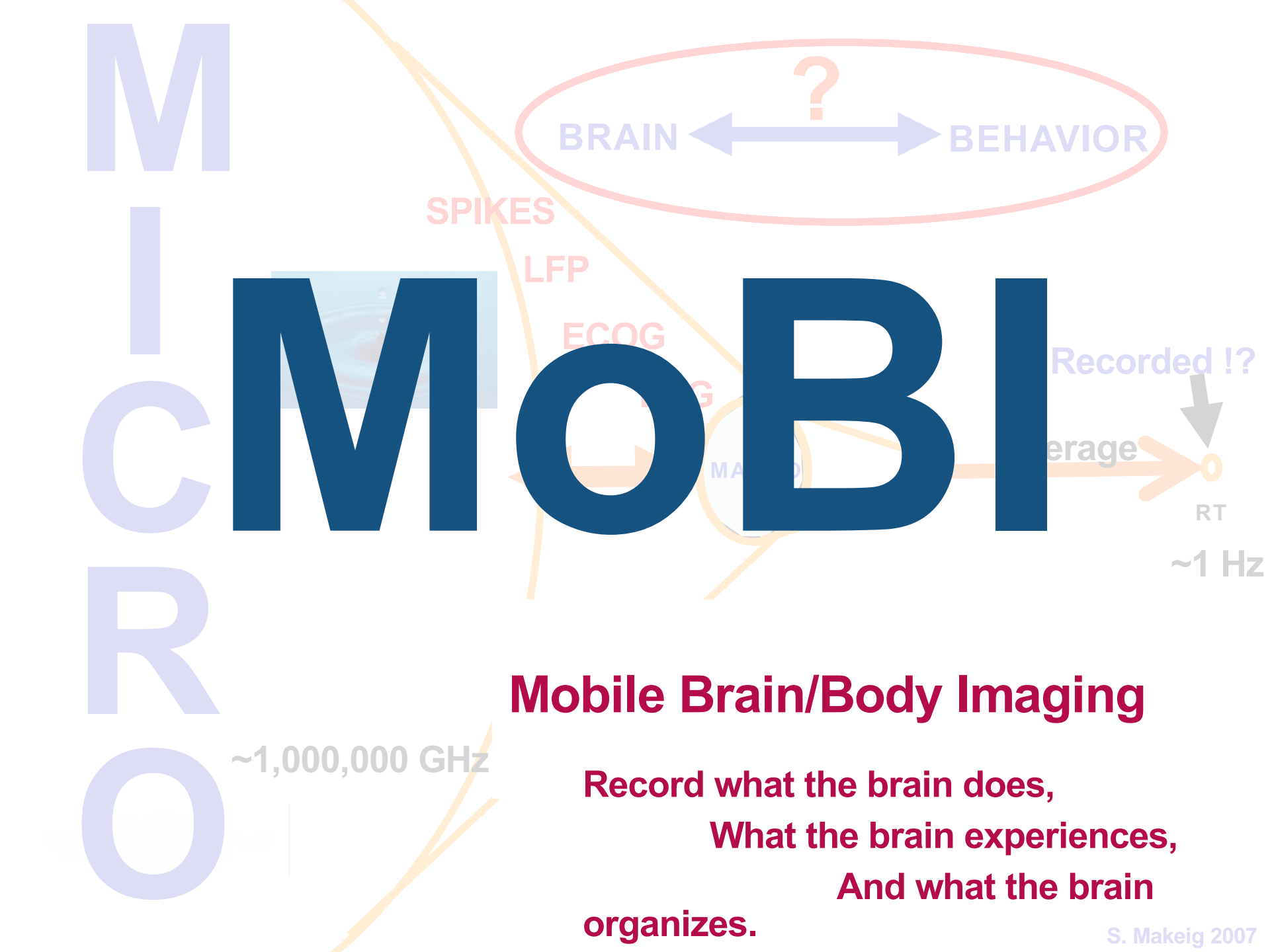
- Current advances in miniaturization, computer power, and information-based signal processing make possible a new imaging modality:

→ **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.





MoBI

Mobile Brain/Body Imaging

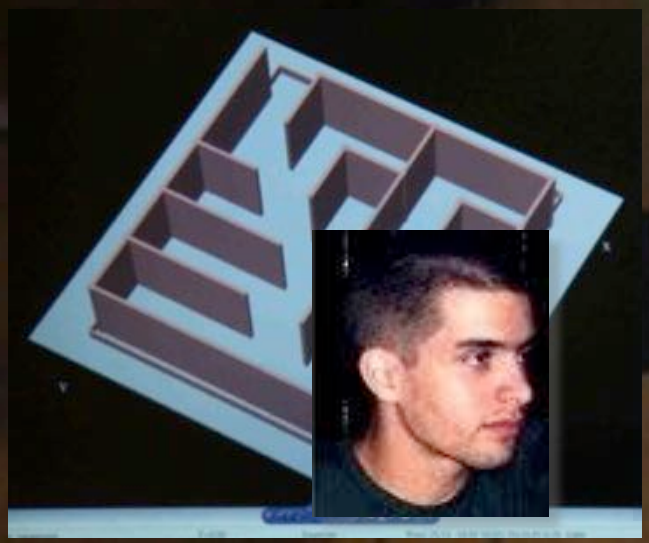
Record what the brain does,
What the brain experiences,
And what the brain organizes.

S. Makeig 2007

MoBI Lab at SCCN, UCSD

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.

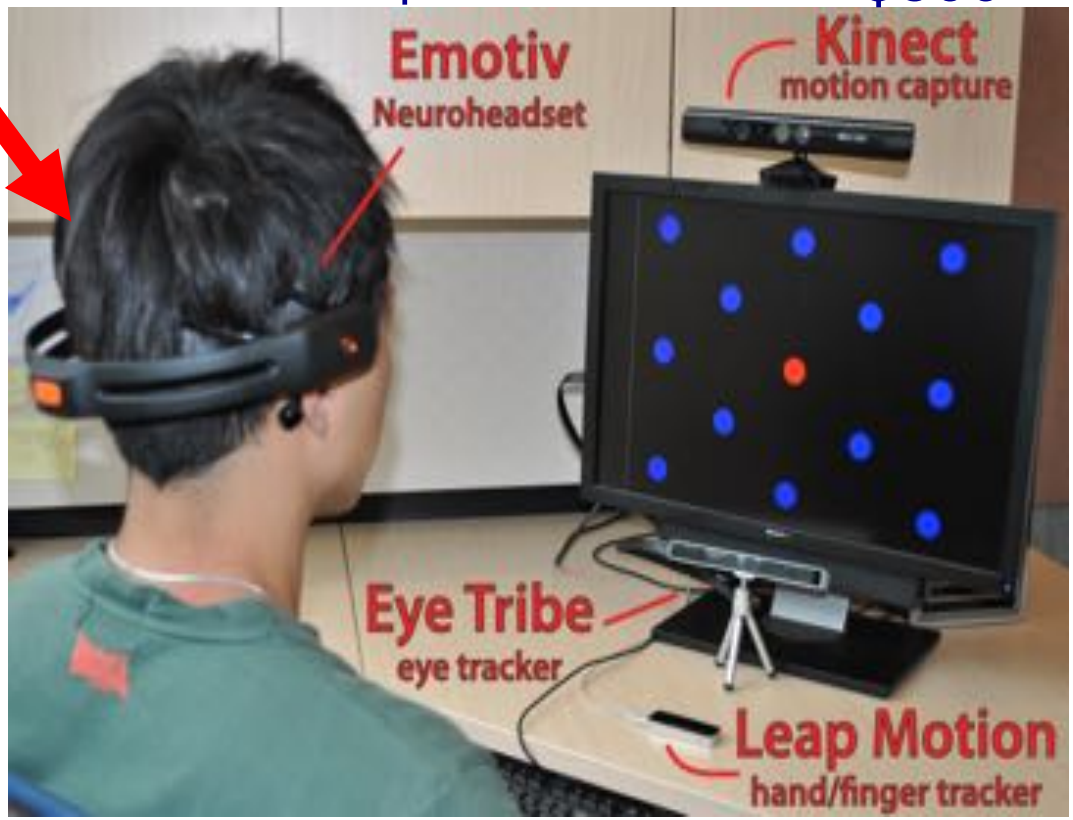
Now feasible – Low-cost MoBI Systems

Low-Cost MoBI

Any EEG System

< $500

< $500



< $500 Touchscreen

< $1000 Full Body Wireless Inertial Motion Capture

< $100

< $100

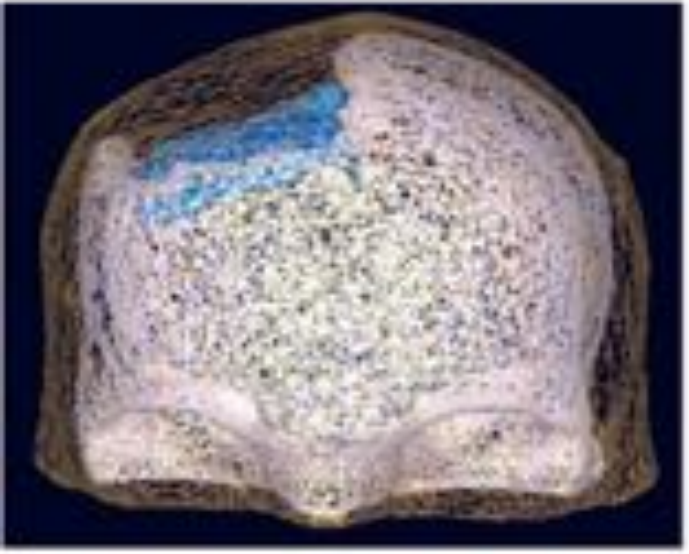
LSL software drivers exist for all these (and more) devices

Brain imaging of natural cognition -- actions & interactions

Imaging Human Agency and Social Interactions

S . Makeig, 2007

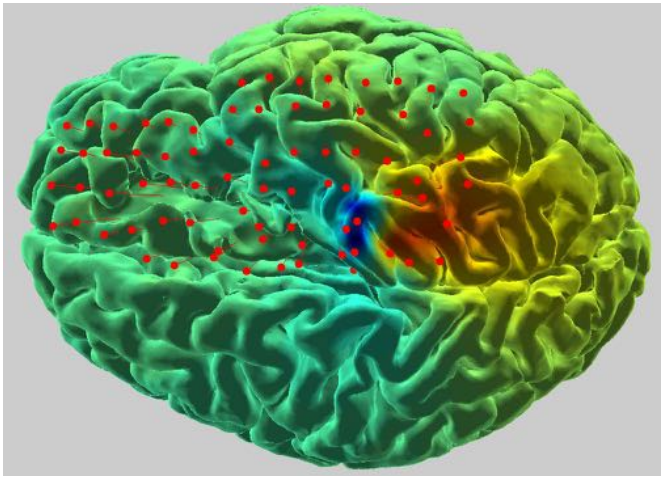
ECoG Source Analysis

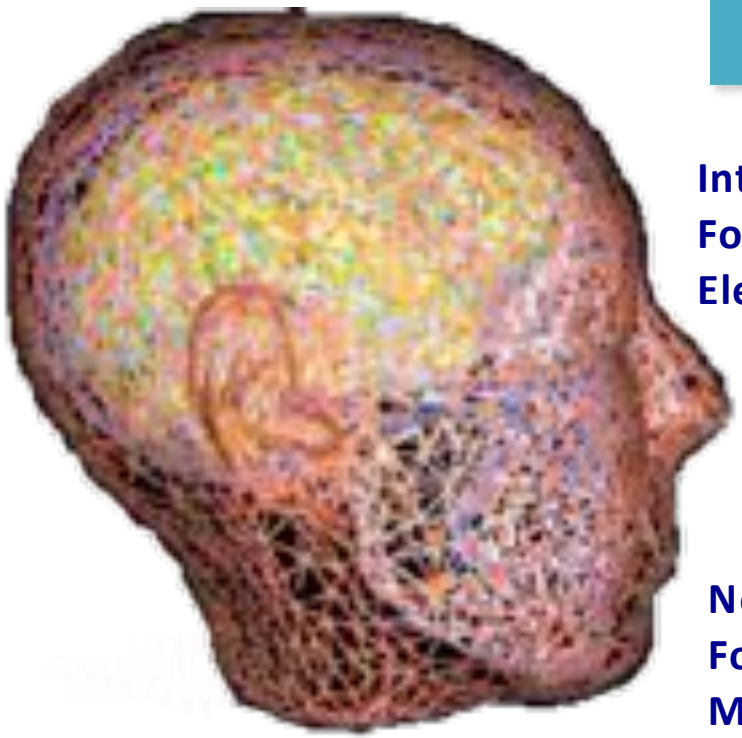


Invasively Monitored Head -- Forward Electrical Model

Electrical Brain Source Analysis for ECoG

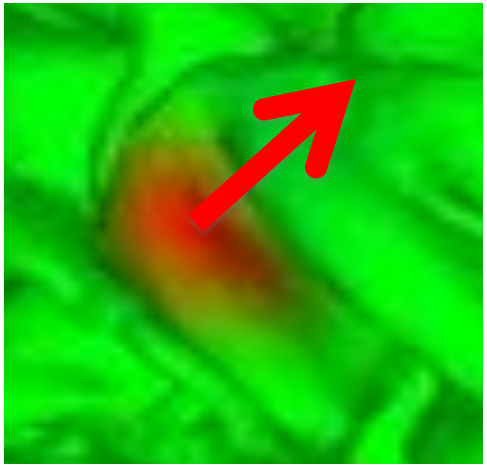
Independent Component Source of ECoG Data





Intact Head -- Forward Electrical Model

Neuroelectromagnetic Forward Head Modeling Toolbox (NFT)

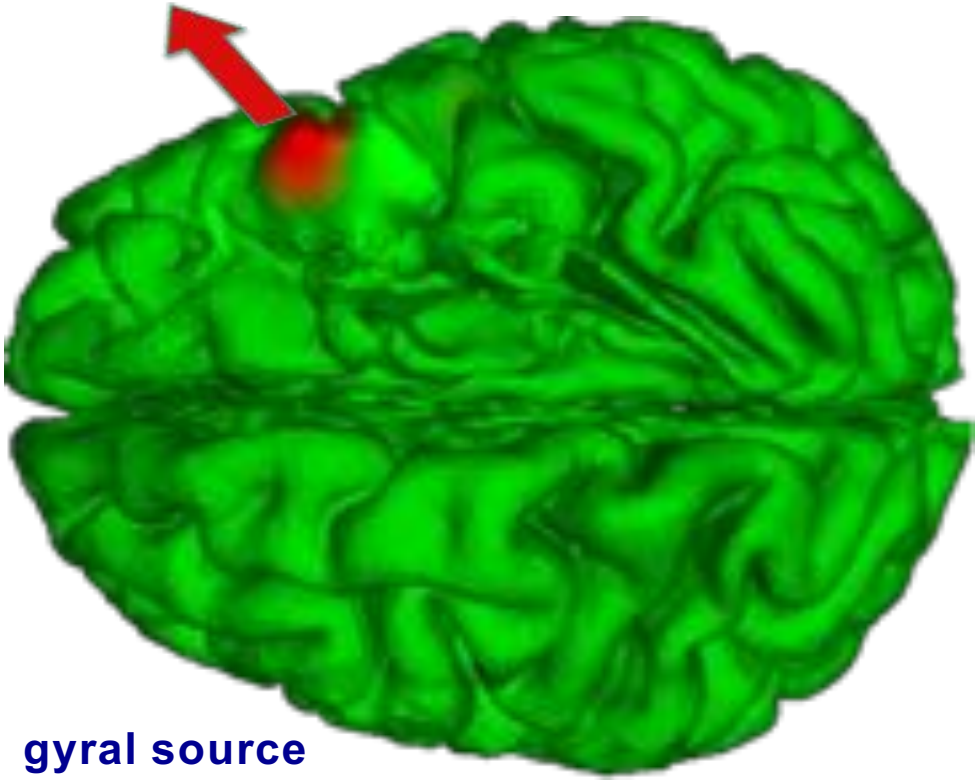


Source Patch in Sulcus Estimated using the Forward Head Model

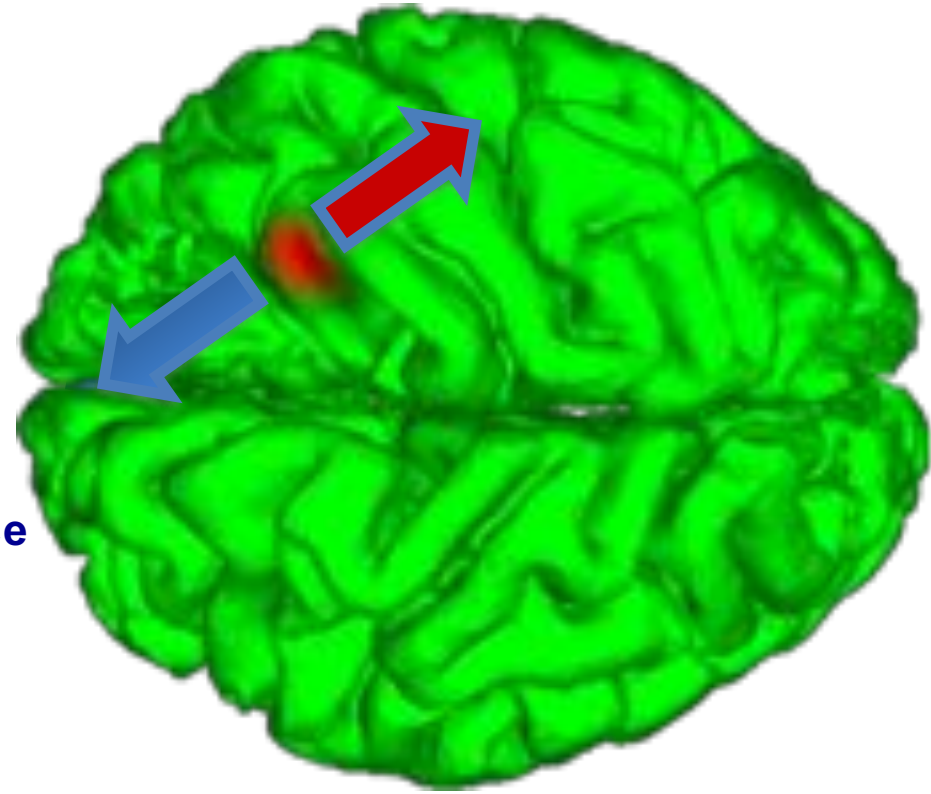
Akalin Acar, Palmer, Makeig, 2009

Akalin Acar, Palmer, Makeig, 2009

ECoG Data Source Decomposition by ICA



gyral source



sulcal source

Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16

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).