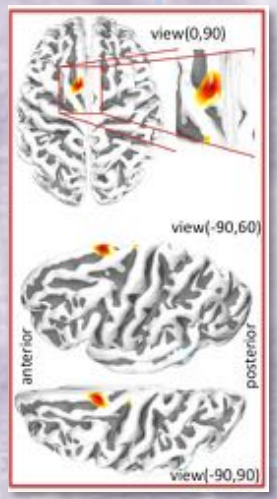
EEG Data Mining I:
Toward High-Resolution EEG Source Imaging



Scott Makeig

Institute for Neural Computation

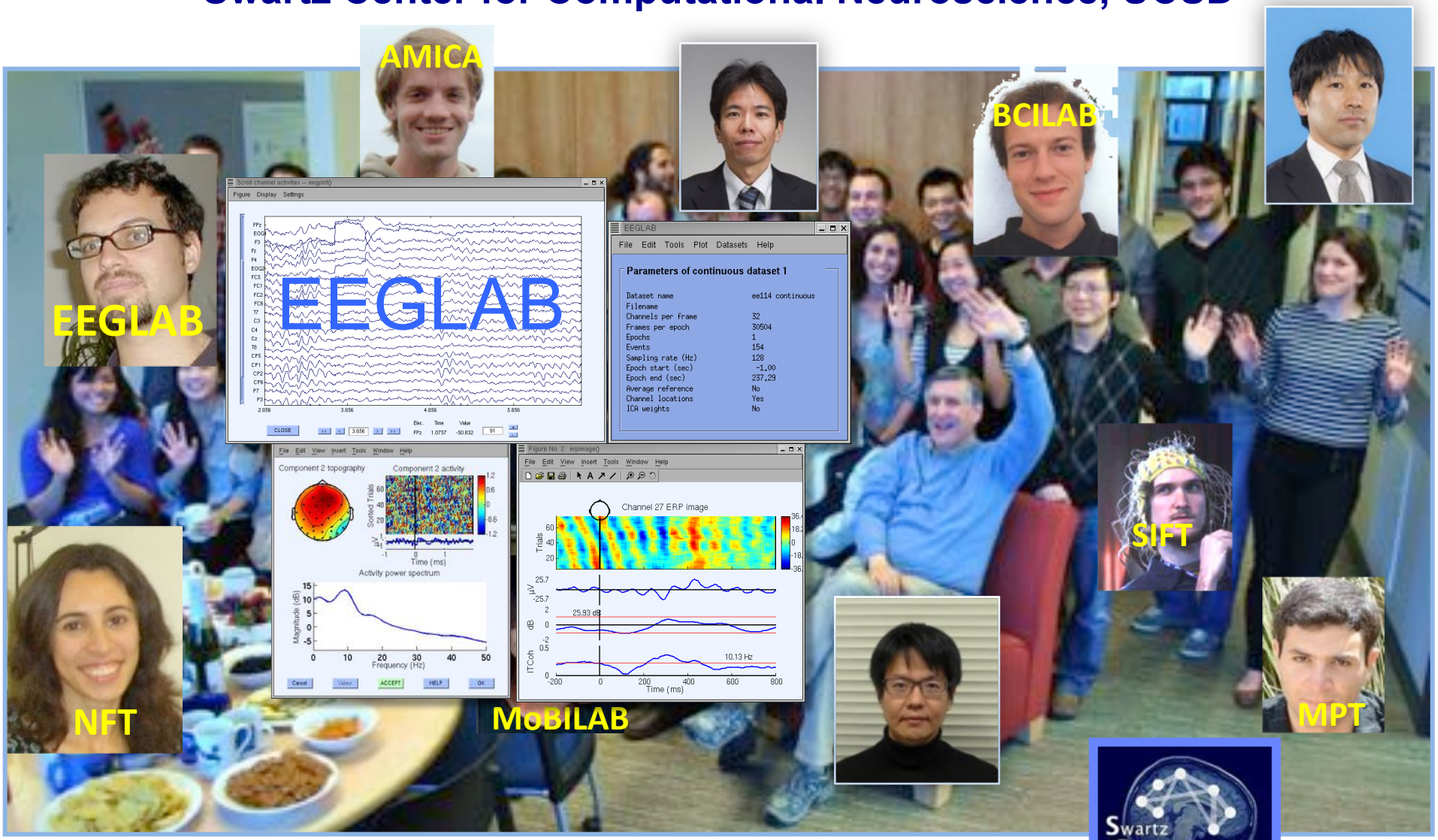
University of California San Diego

27th EEGLAB Workshop

Pittsburgh PA
September , 2018

smakeig@ucsd.edu, 2018

Swartz Center for Computational Neuroscience, UCSD



10th Anniversary SCCN Impromptu celebration 1/2/12

Functional Brain Imaging

Hemodynamic imaging

= imaging local brain **Energy**

Direct 3-D inverse model,

but quite slow & indirect

as well as expensive,

very heavy & non-portable.

1993 -

Electromagnetic imaging

= imaging local cortical **field *synchrony***

3-D imaging needs head model,

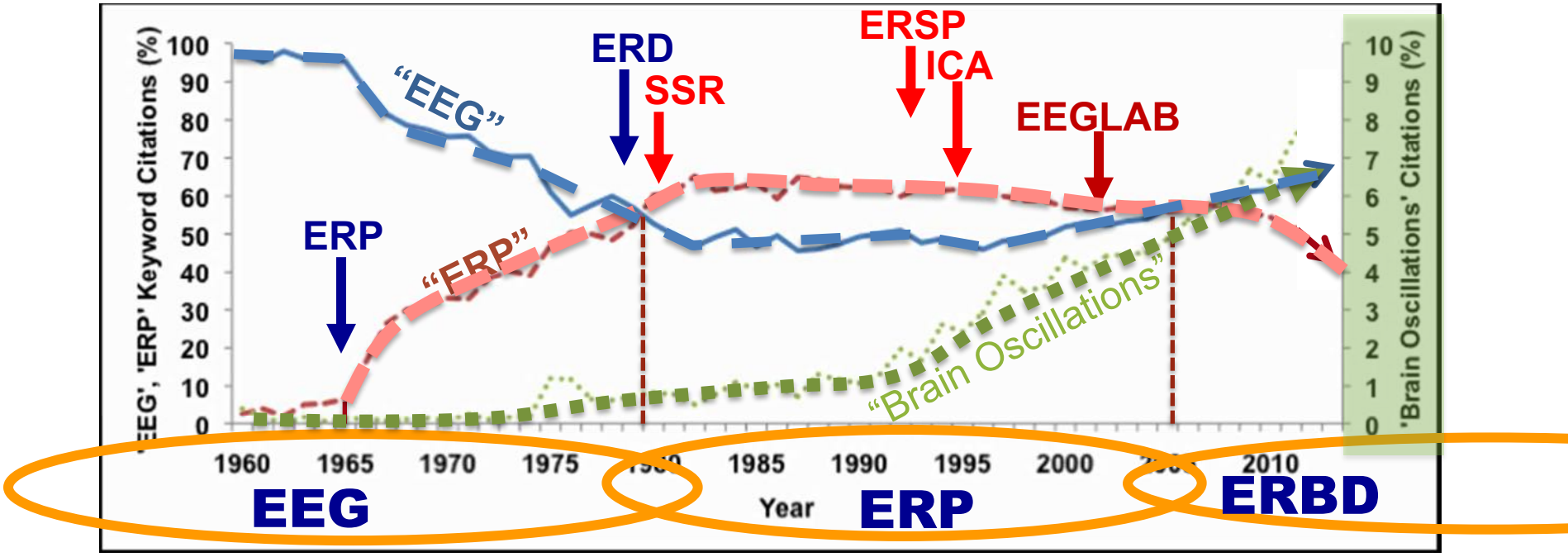
but a quite fast & direct measure

of *one aspect* of cortical activity –

local spatial field coherence.

1926 -

Three Modern Eras of EEG Research

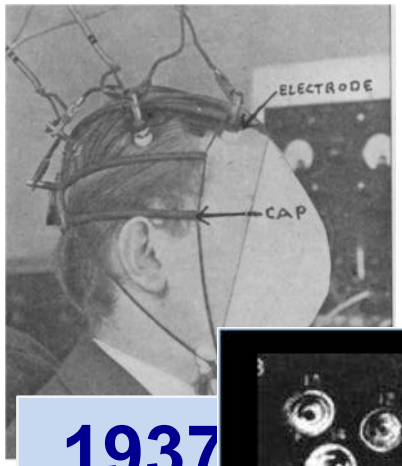


Loo, Lenartowicz & Makeig, 2015

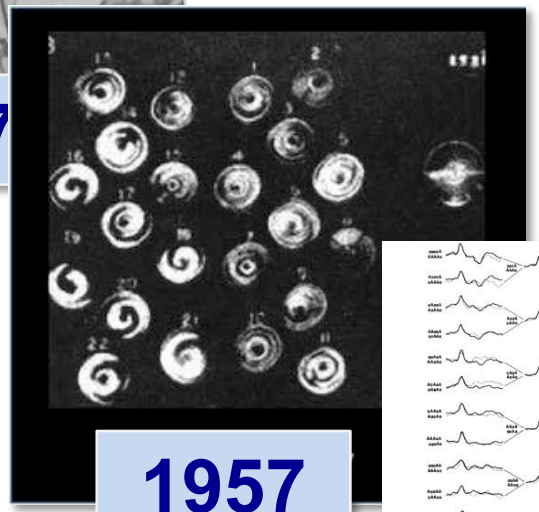
Figure 1. Relative number of PubMed citations retrieved by 'All Fields' search terms: 'EEG,' 'ERP,' and 'Brain Oscillations.' The percent of citations for each search term relative to the total number of citations returned by a search for any of the three terms is plotted relative to the other two search terms. For visual clarity, 'Brain Oscillations' citations are graphed with a green dotted line according to the Y-axis labels on the right; 'EEG' with a blue solid line and 'ERP' with a red dashed line according to the Y-axis labels on the left.

S. Makeig, 2016

Development of EEG brain Imaging …

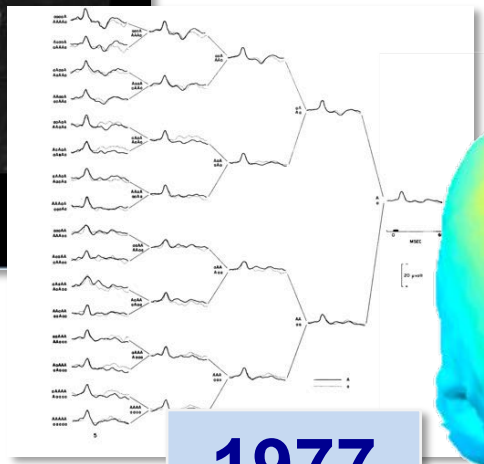


1937



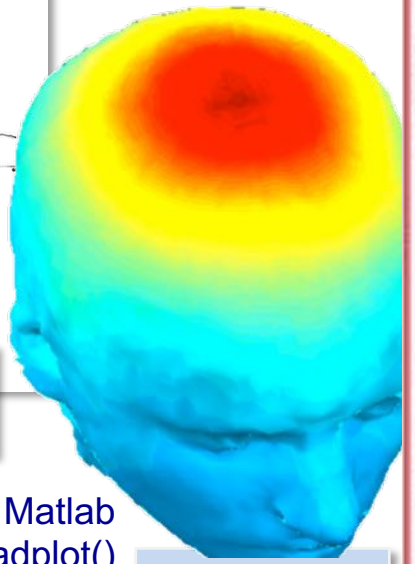
1957

Toposcope
Grey Walter



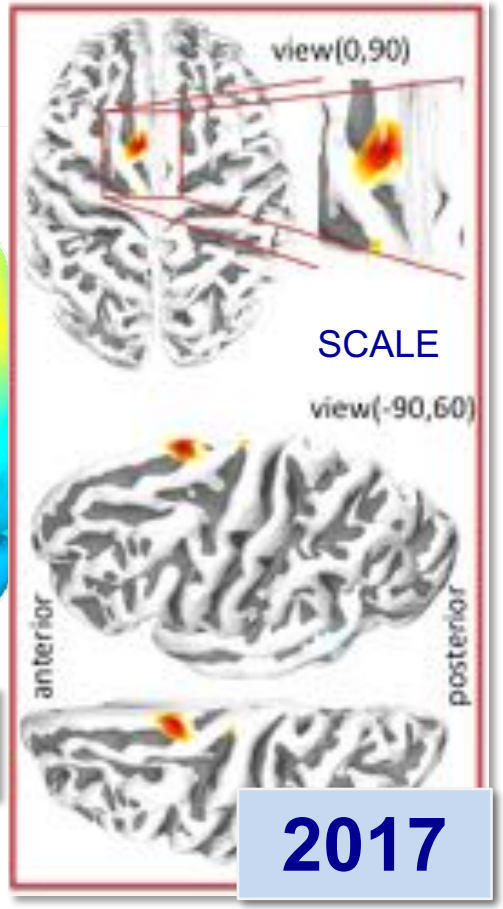
Oddball ERPs
K. Squires et al.

1977



Matlab
headplot()
→ EEGLAB

1997



2017

Z. Akalin Acar et al.

Functional Brain Imaging using EEG

- EEG imaging is noninvasive → little ethical concern
- EEG imaging can be tolerated by most subjects
- EEG imaging has fine time resolution
- EEG imaging is lightweight / mobile / wearable
- EEG imaging is inexpensive → scalable
- EEG source imaging requires a *good* forward-problem electrical head model and inverse localization method.
- Historically, much inertia in EEG methods development

Three Aspects of Human Consciousness

Knowing - I perceive, recall, believe

Feeling - I feel, experience as feeling

Willing - I act, aim, intend

"[Humans] have *full consciousness* of the [physical] world
in **all the aspects of knowing, feeling and willing**."

Meher Baba

S. Makeig (2017)

EEG & Cognitive Neuroscience

EEG can be used to learn and monitor
how the brain and nervous system
supports human consciousness
in all its aspects --

Knowing

Feeling

Willing

S. Makeig (2017)

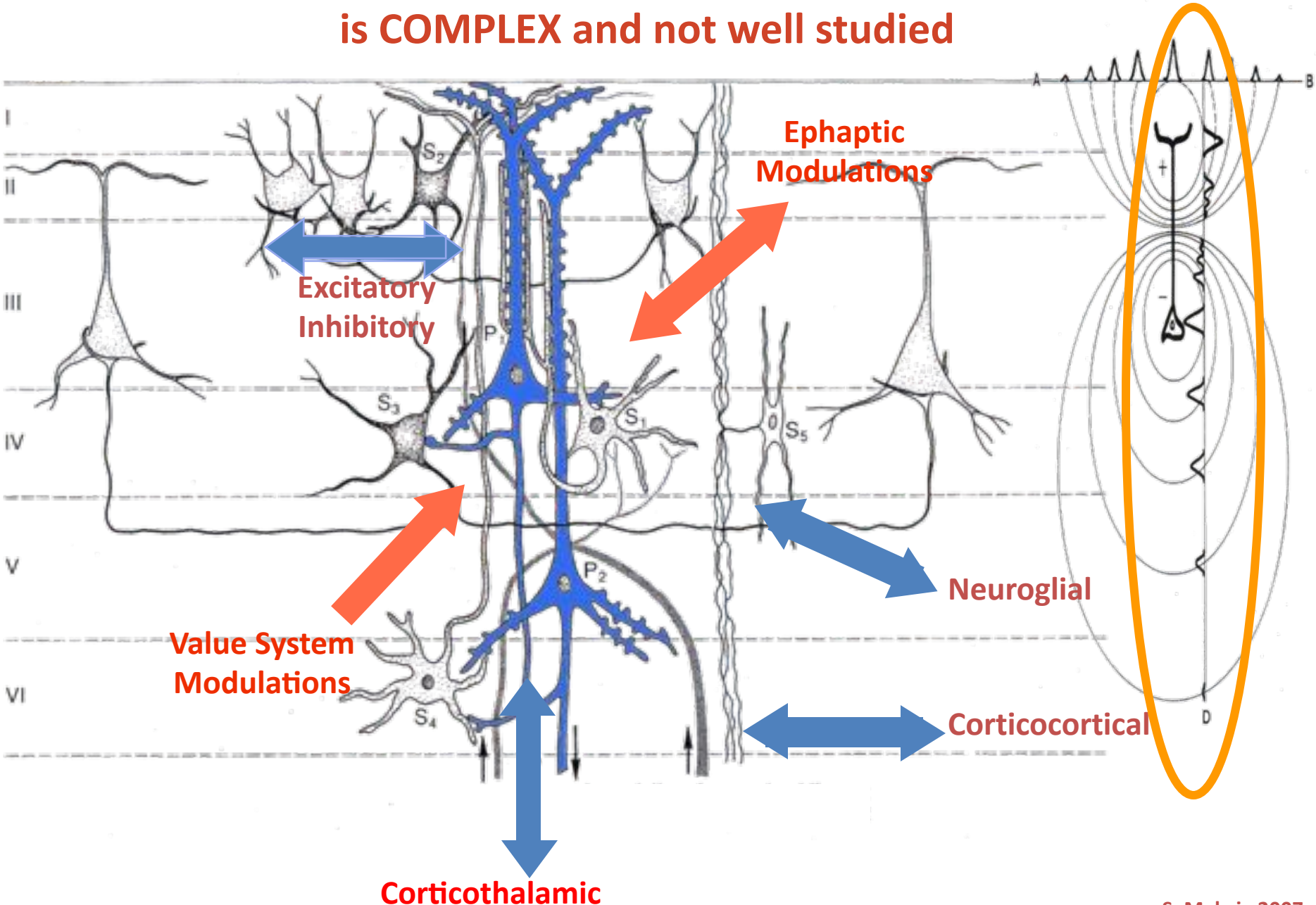
What is scalp EEG?

- A small portion of *cortical* electrical activity
- An even smaller portion of *total* brain electrical activity

- **But *which* portion?**
- **Triggered and modulated *how*?**
- **With *what* functional significance?**

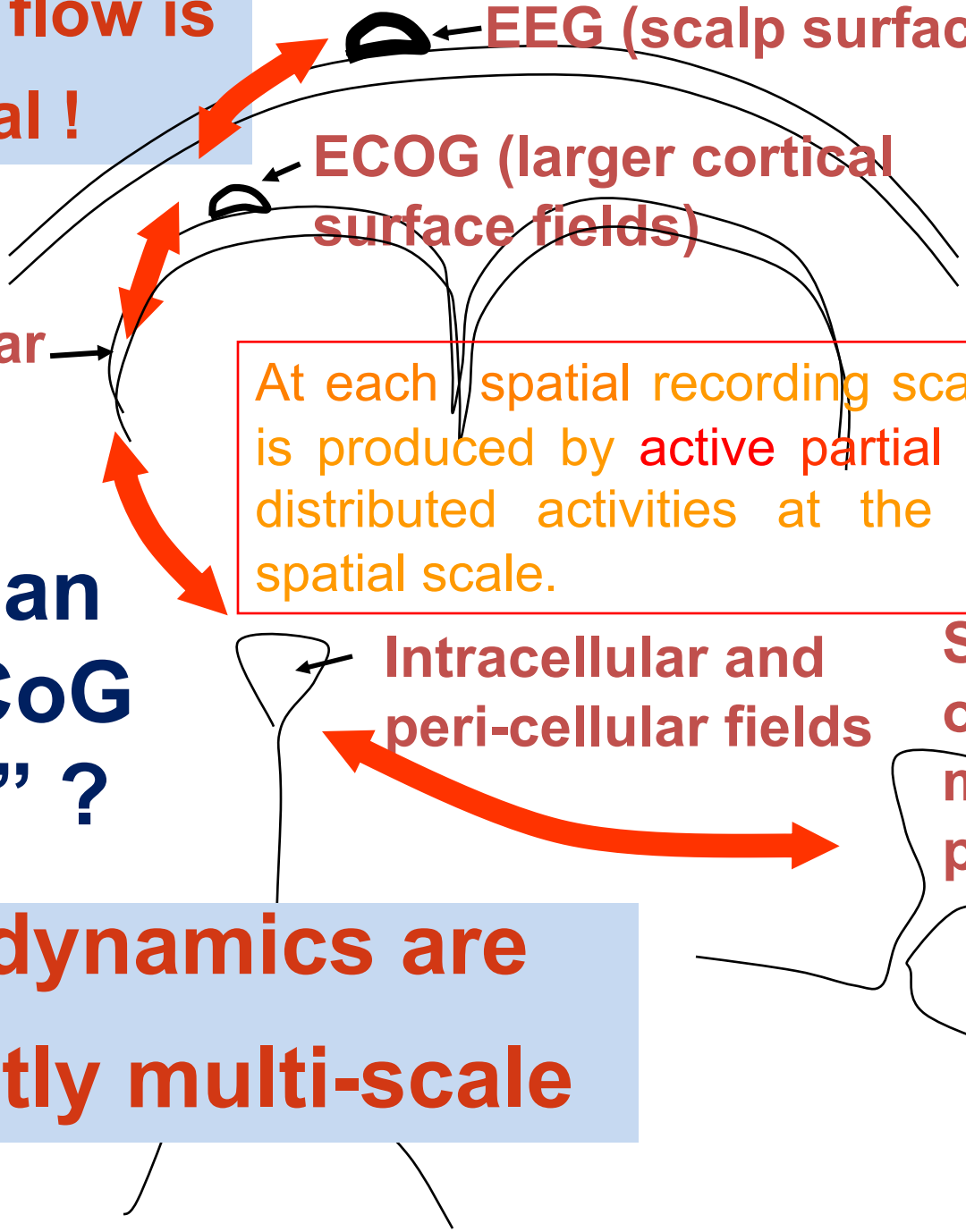
Cloud art: Berndnaut Smilde

The generation and modulation of local field potentials is COMPLEX and not well studied



S. Makeig 2007

Information flow is bi-directional !



At each spatial recording scale, the signal is produced by active partial coherence of distributed activities at the next smaller spatial scale.

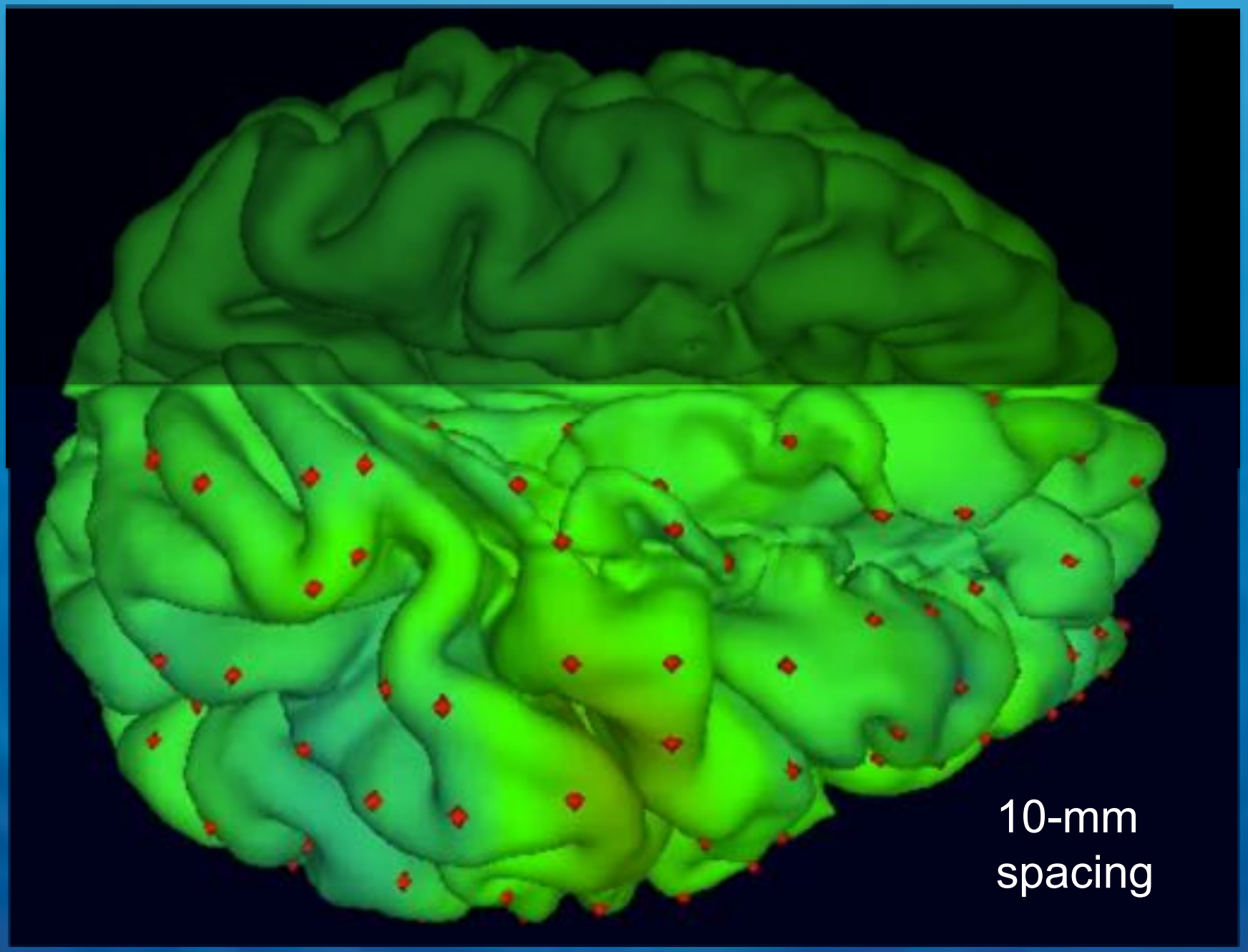
What is an EEG / ECoG "source" ?

Brain dynamics are inherently multi-scale

Scott Makeig 2007

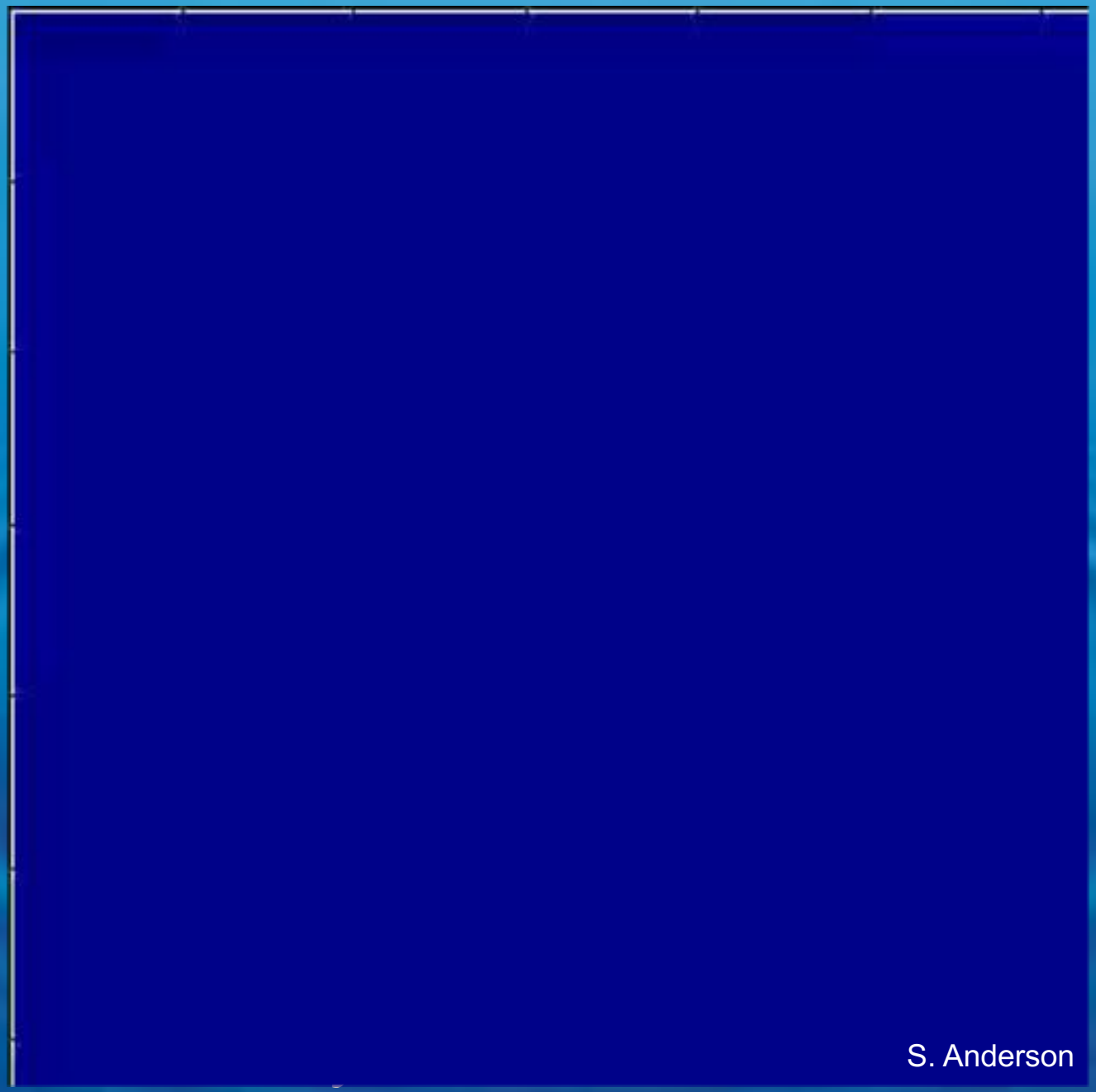
The spatiotemporal dynamics of cortex & brain have not yet been imaged on multiple spatial scales!

Alan Friedman



Z Akalin Acar, 2017

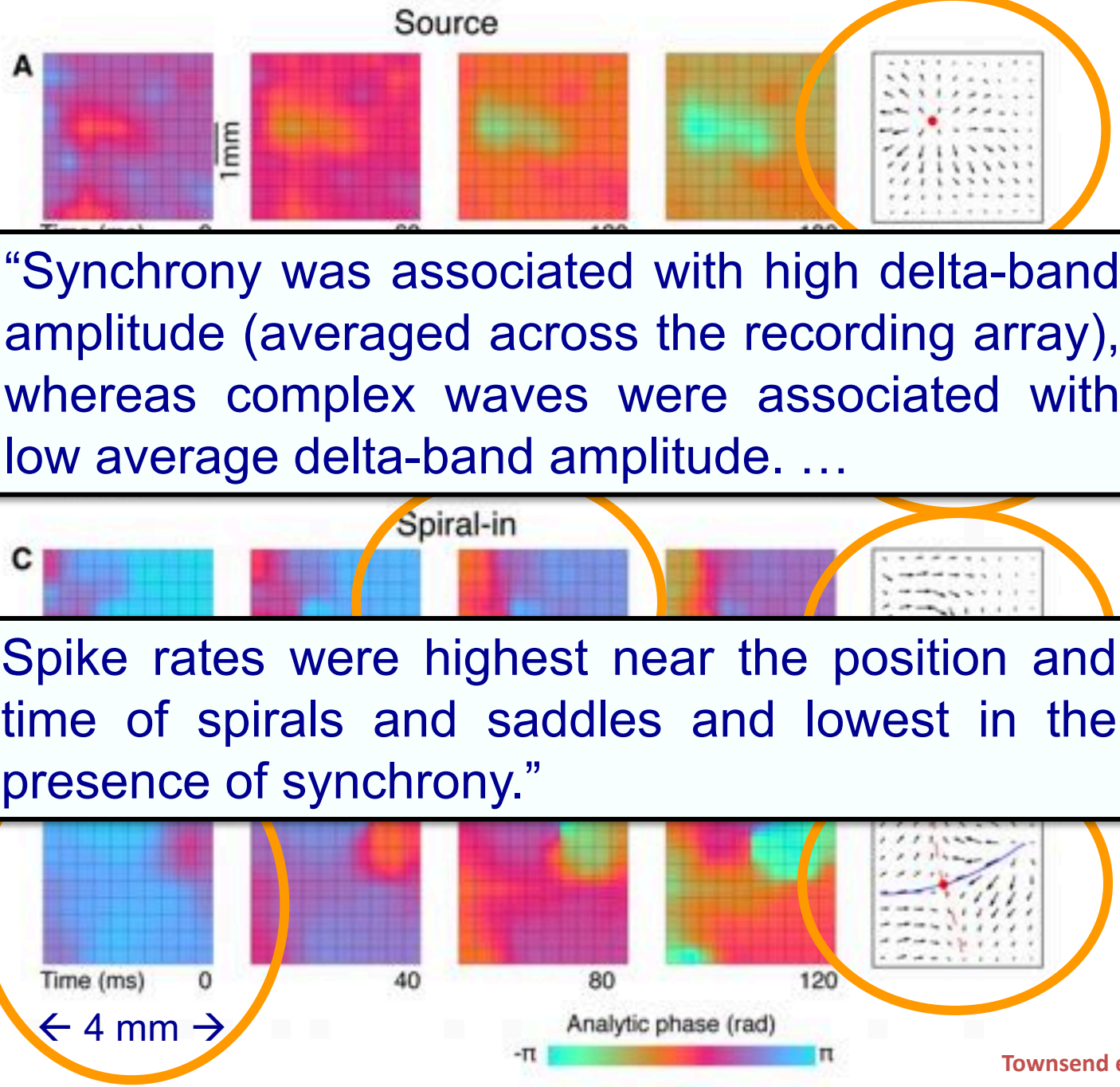
Phase cones (Freeman)



RS Anderson, 2007

J. Neurosci., March 18, 2015 • 35(11):4657–4662

Delta band (1-4 Hz) in anesth. animals



"Synchrony was associated with high delta-band amplitude (averaged across the recording array), whereas complex waves were associated with low average delta-band amplitude. …

Spike rates were highest near the position and time of spirals and saddles and lowest in the presence of synchrony."

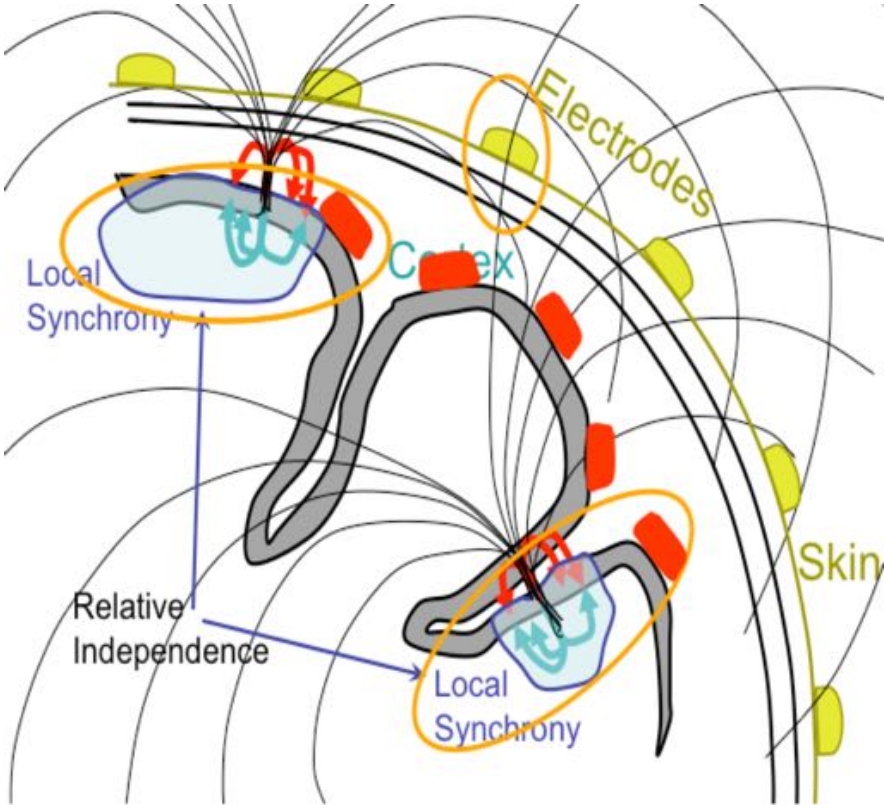
Simple patterns

Complex patterns

Townsend et al., 2015

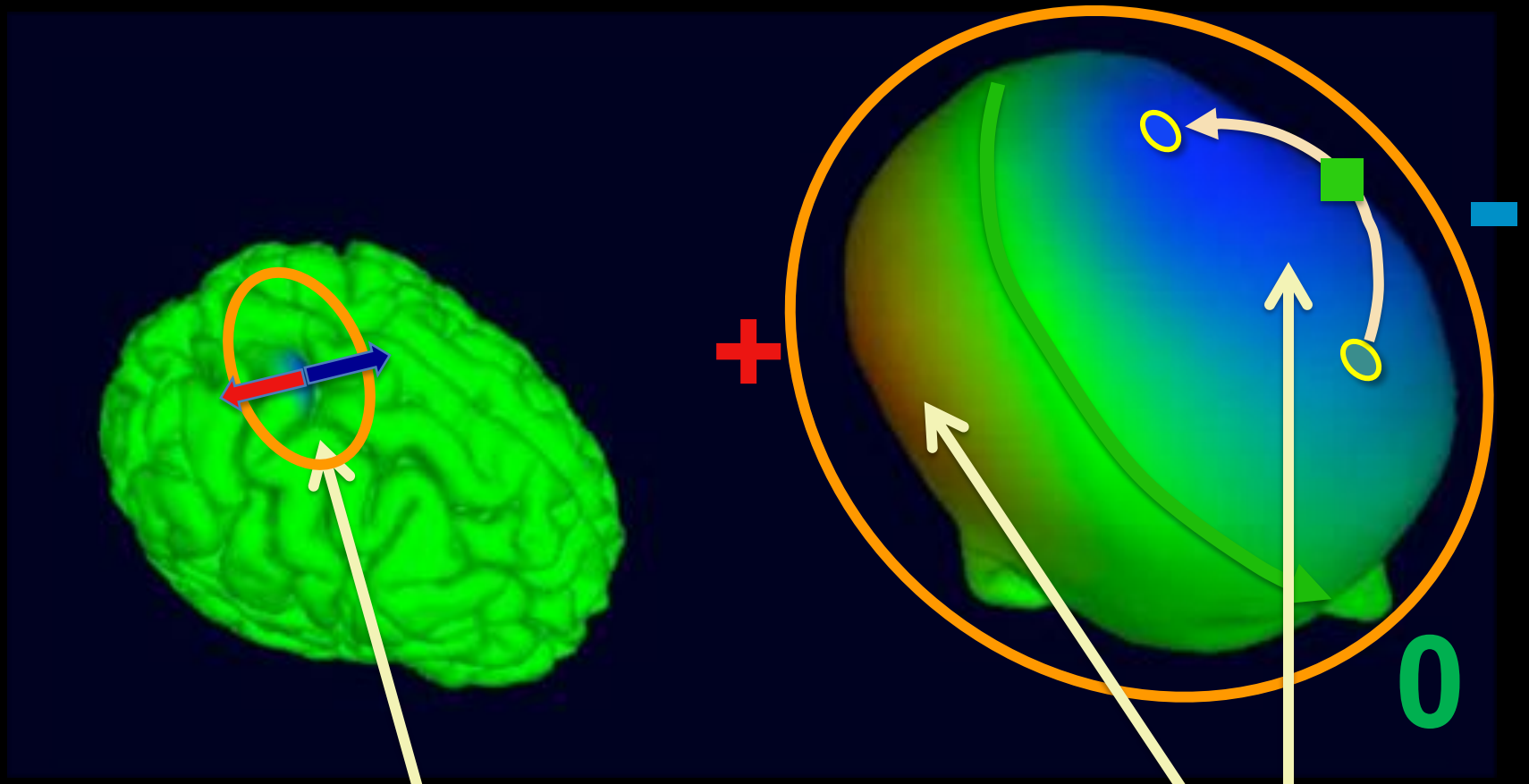
Naïve 2-D interpretation of EEG signals?

Cortical EEG signal projection patterns as point processes



Cortical source current volume conduction patterns

The very broad EEG point-spread function

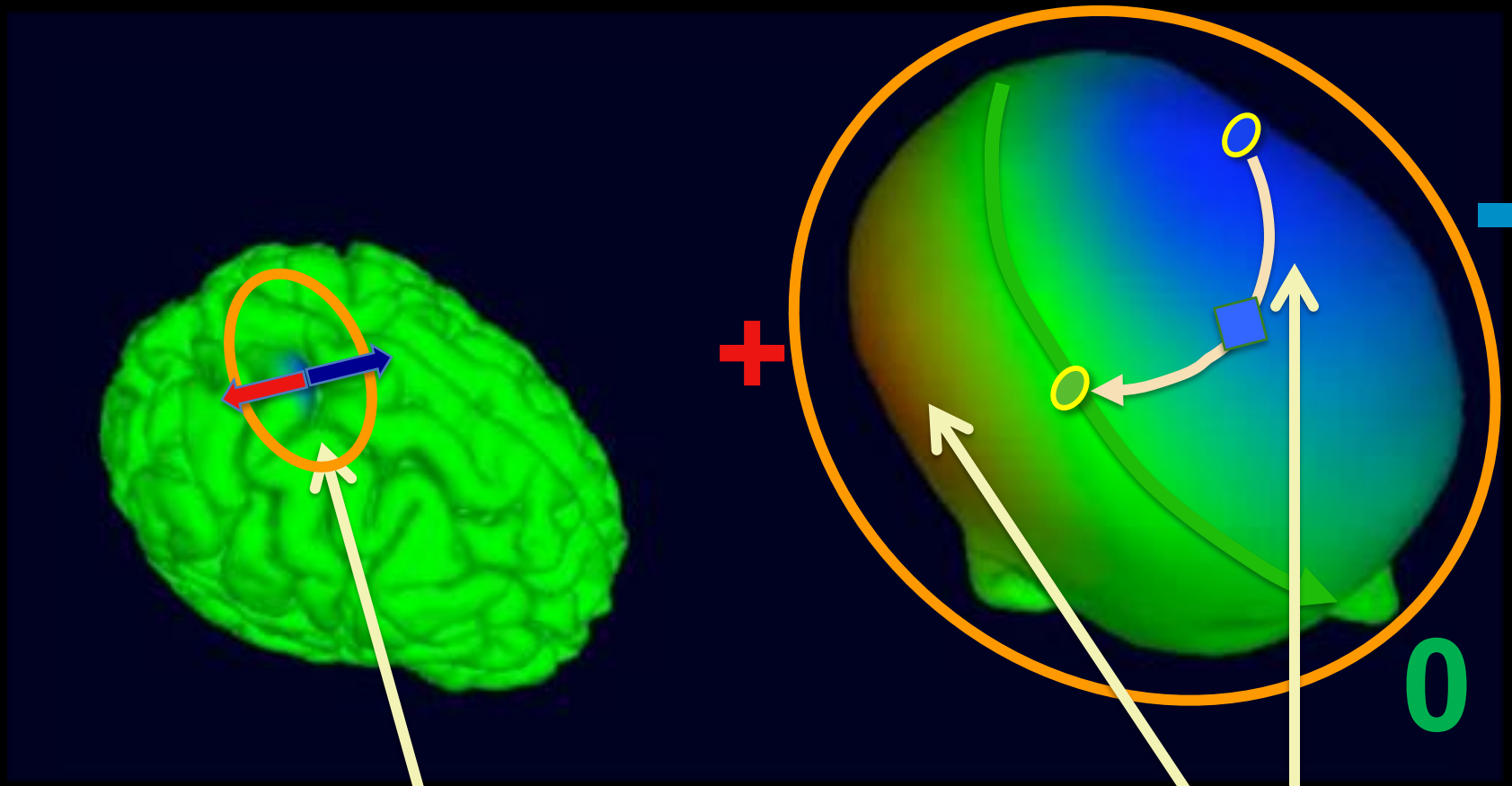


Single simulated parietal source →

Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The very broad EEG point-spread function



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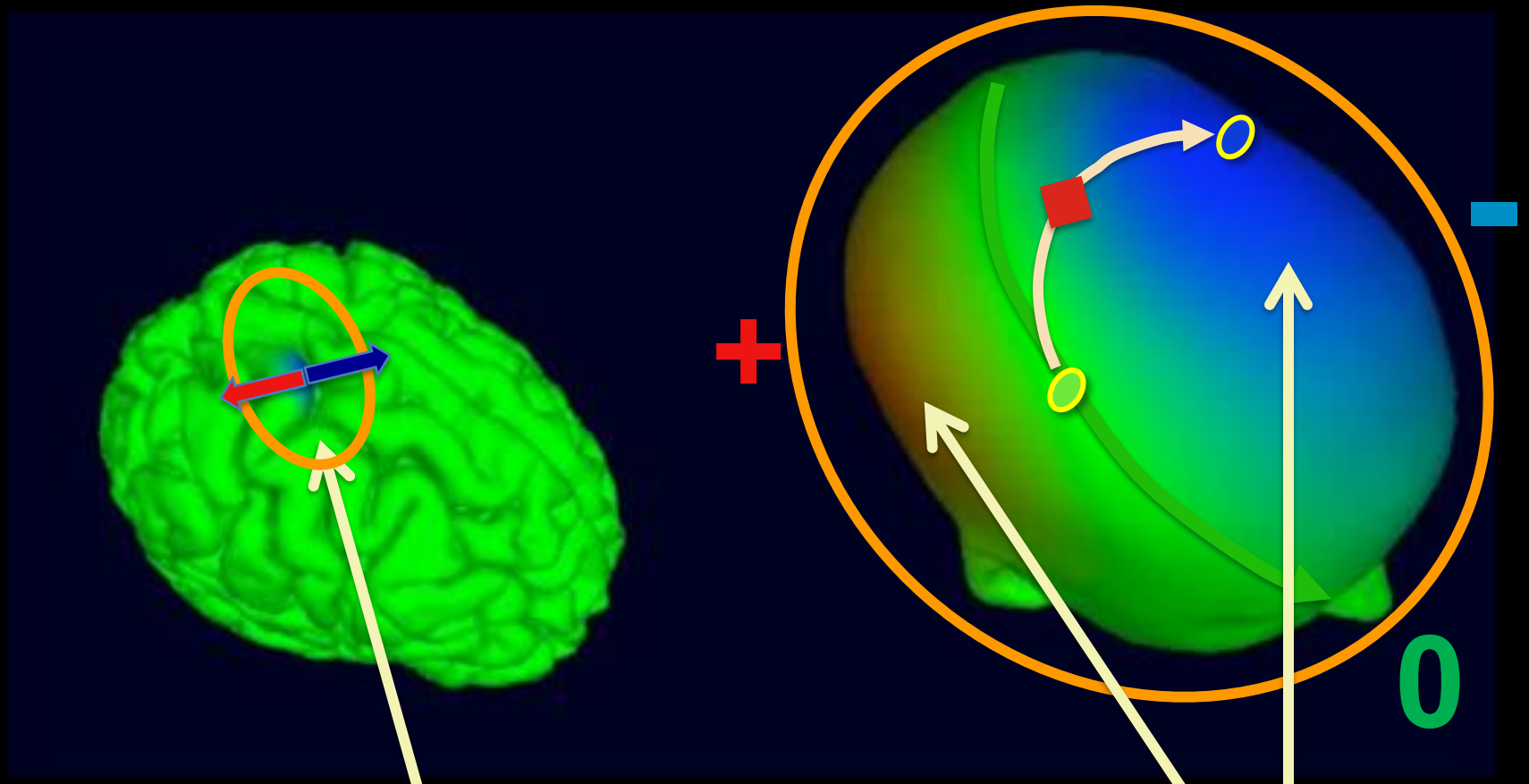
Akalin Acar & Makeig 2010

The very broad EEG point-spread function



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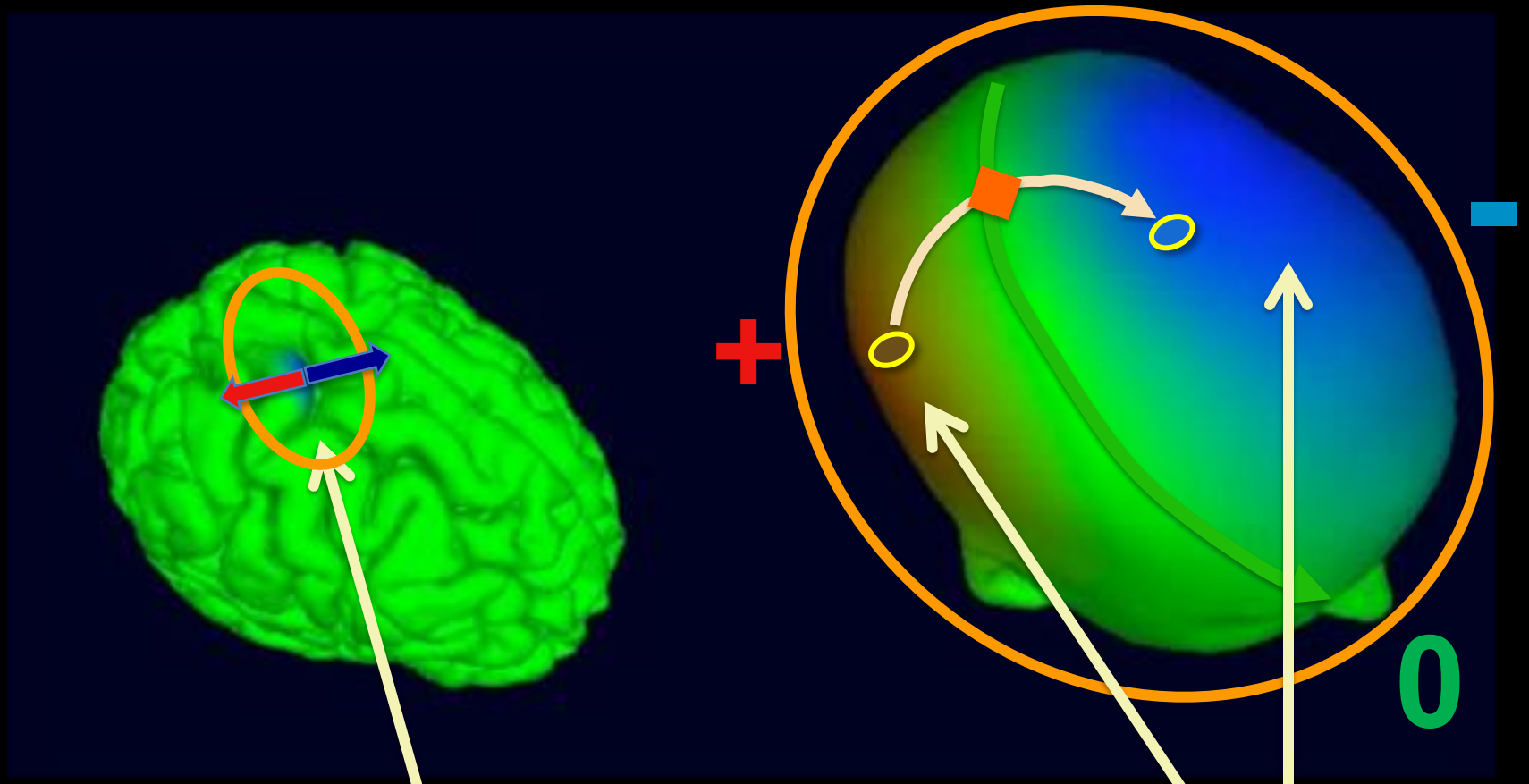
Akalin Acar & Makeig 2010

The very broad EEG point-spread function

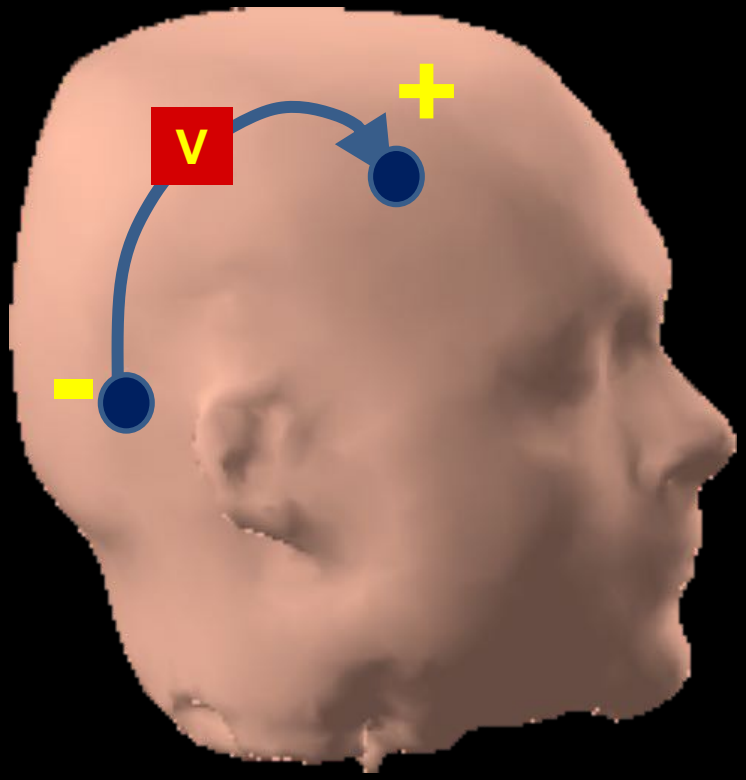


Single simulated parietal source →

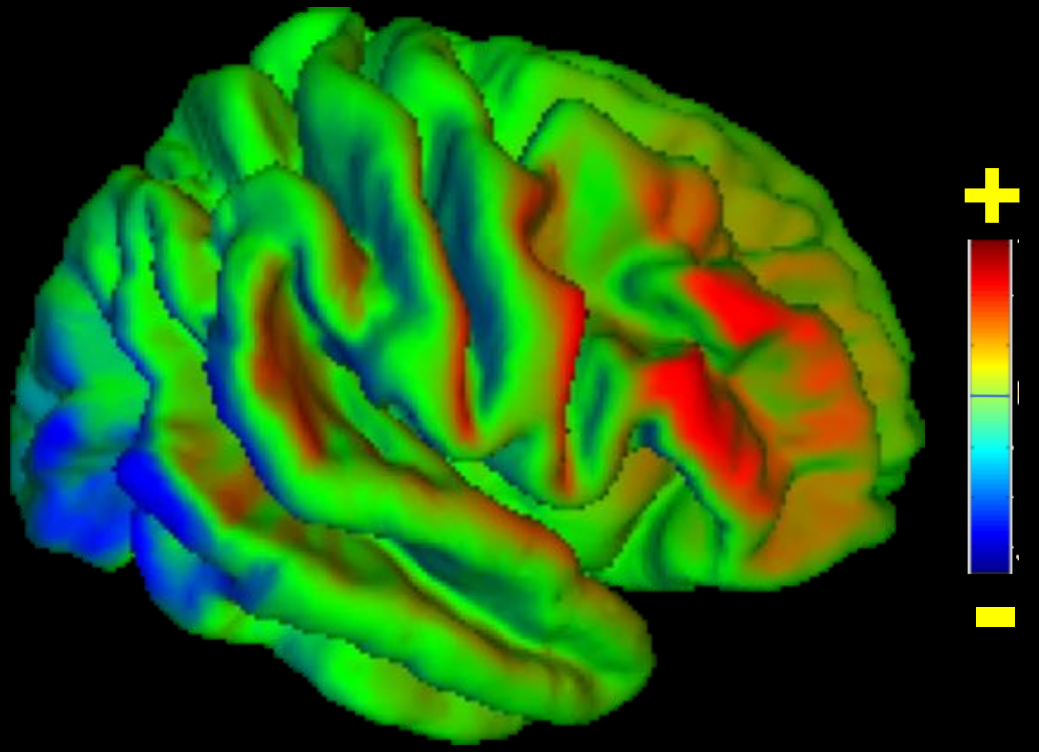
Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The ‘receptive field’ of a bipolar EEG channel



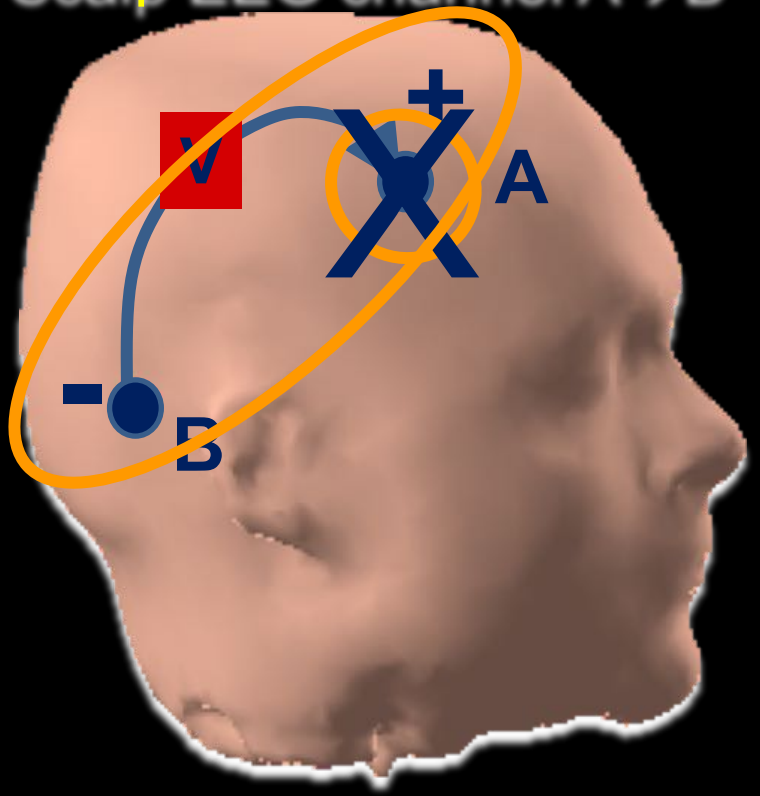
Scalp EEG channel

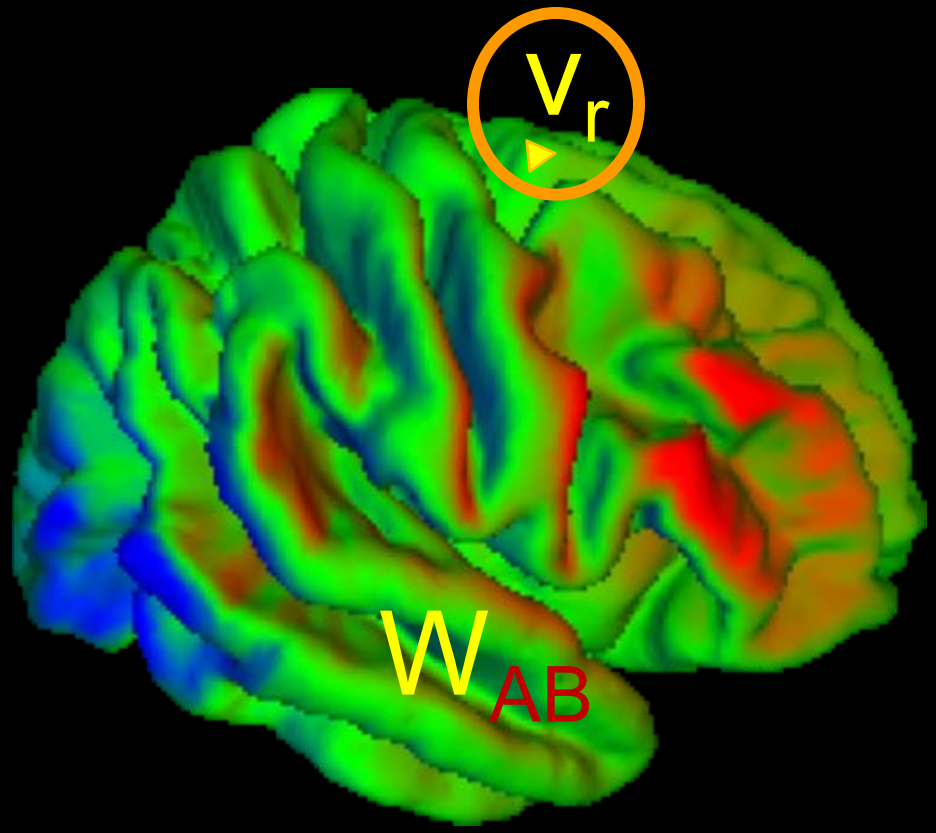


Its cortical ‘receptive field’

The ‘receptive field’ of a bipolar EEG channel!

Scalp EEG channel A→B





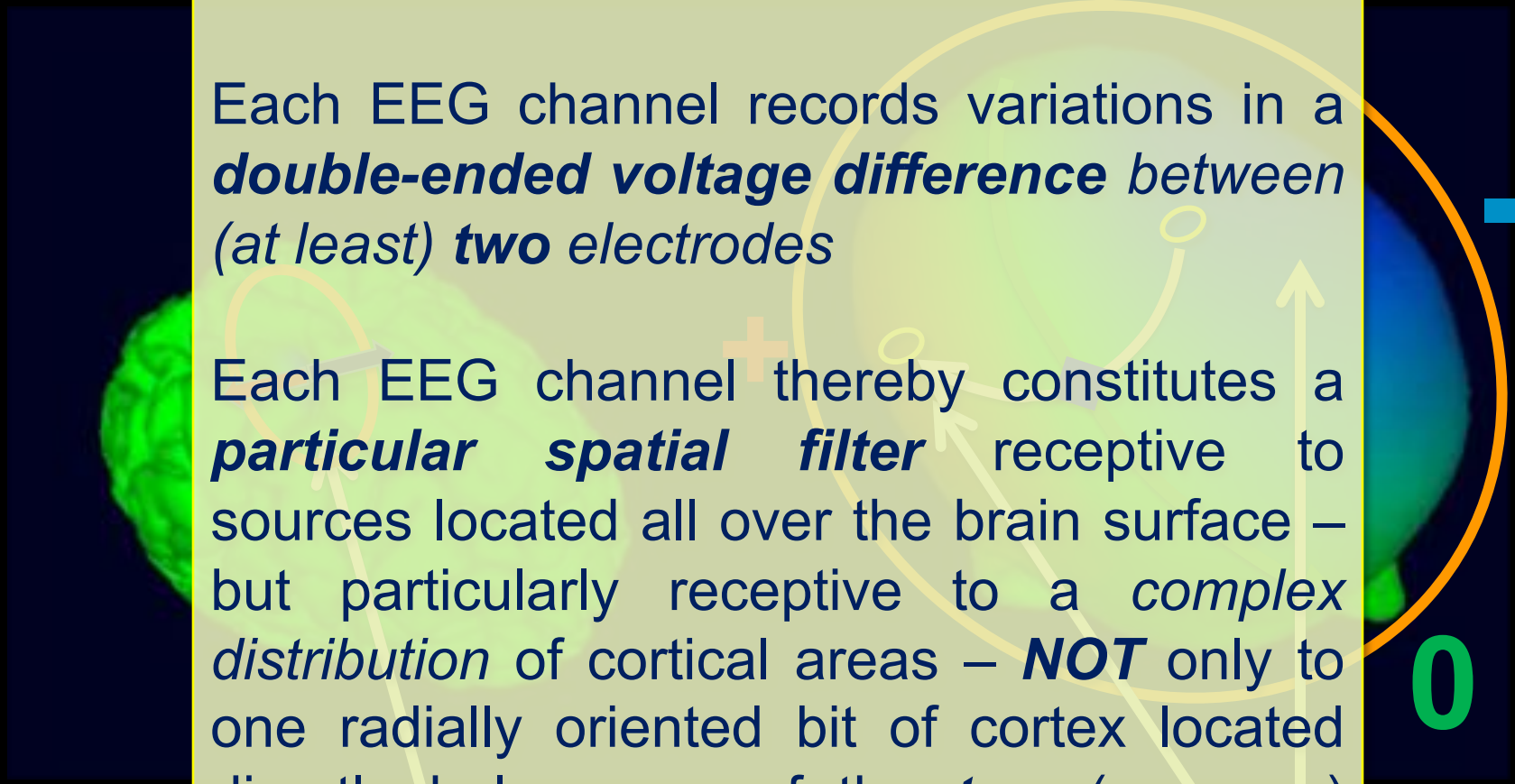
Its cortical ‘receptive field’

At time t,

$$V_{AB} = \sum_{r \text{ in Cortex}} v_r \times W_{AB}(r)$$

S. Makeig & Z. Akalin Acar, 2017

The very broad EEG point-spread function



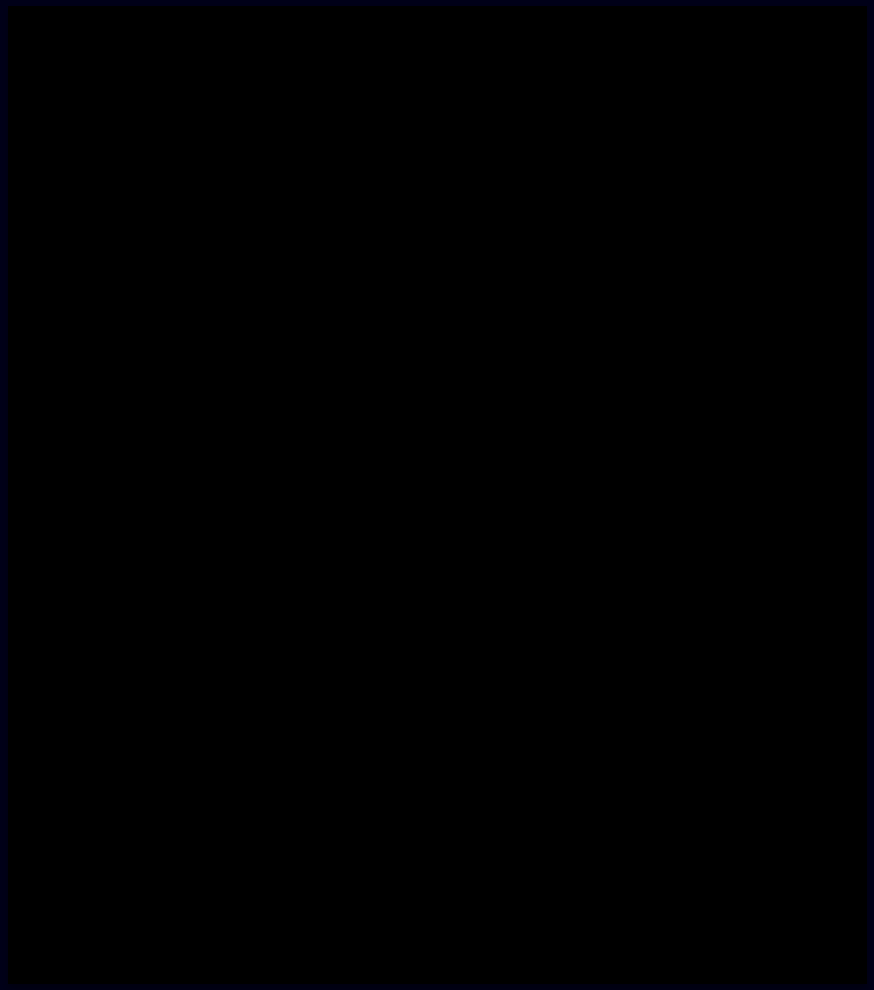
Each EEG channel records variations in a ***double-ended voltage difference*** *between (at least)* ***two*** *electrodes*

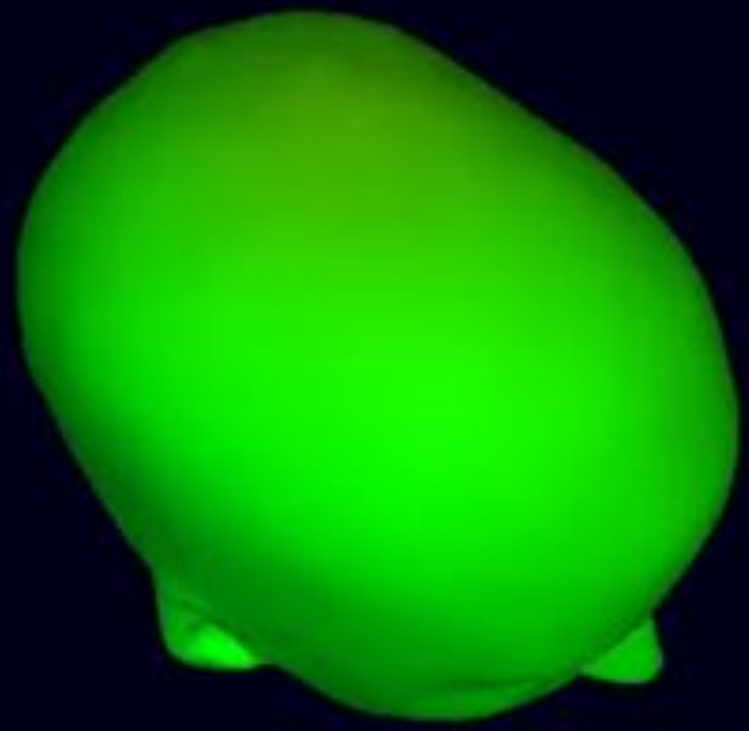
Each EEG channel thereby constitutes a ***particular spatial filter*** receptive to sources located all over the brain surface – but particularly receptive to a *complex distribution* of cortical areas – ***NOT*** only to one radially oriented bit of cortex located directly below ***one*** of the ***two***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

Single simulated parietal source → Very broad projected scalp potentials

Akalin Acar & Makeig 2010

What are the cortical ‘sources’?



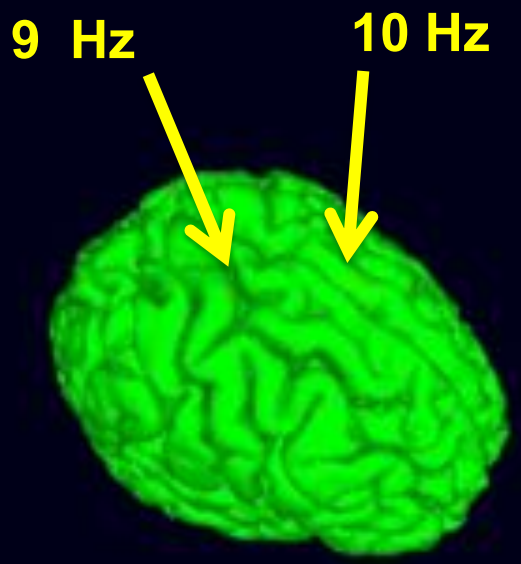


Scalp projection

Z. Akalin Acar & S. Makeig (2012)

Scalp epiphenomena !

Phenomena



Two spatially stationary cortical effective sources

Epiphenomenal

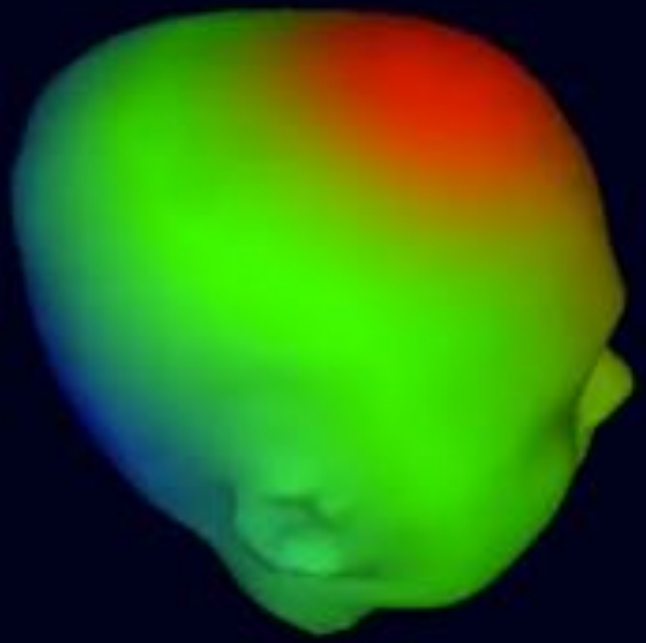
epiphenomena --

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

Summed scalp projection

Z. Akalin Acar & S. Makeig (2012)

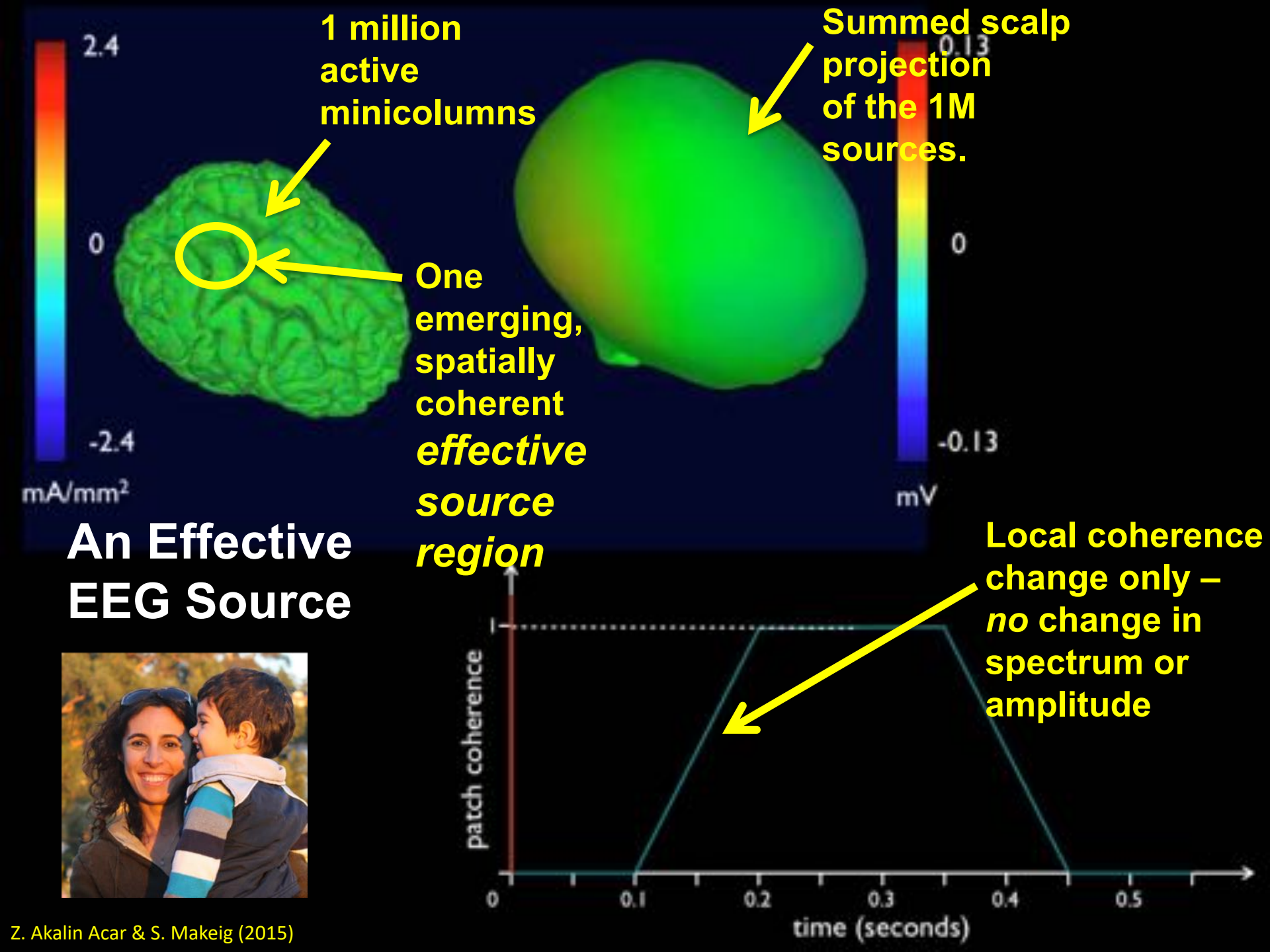
Summed scalp projections of 13 effective brain sources



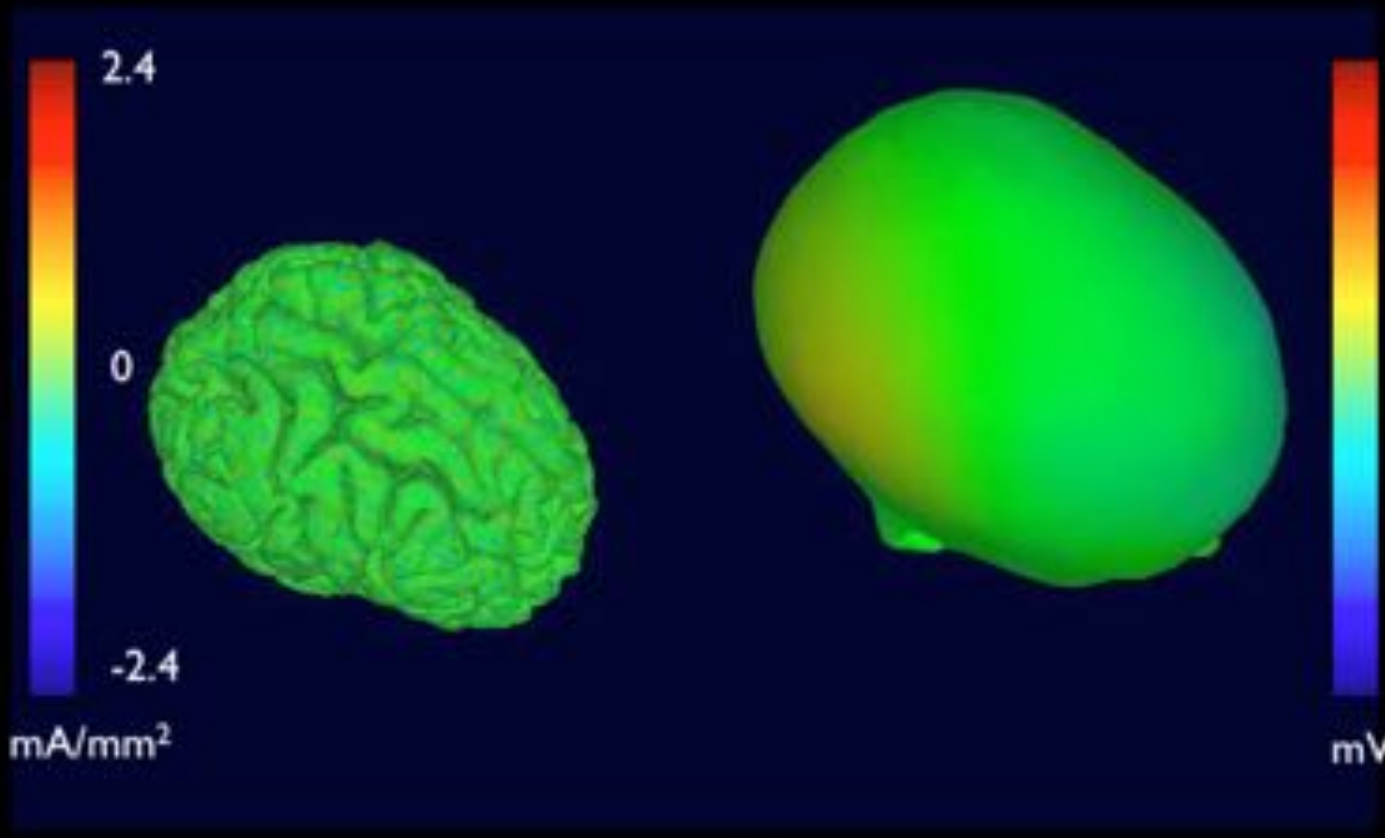
Epiphenomenal Impressions

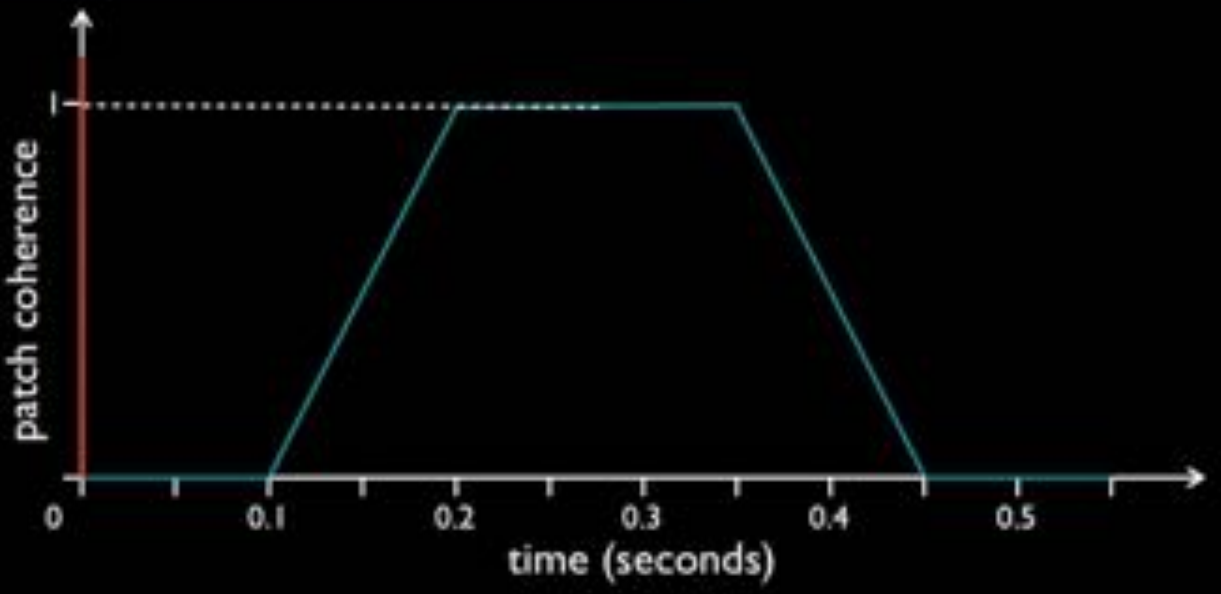
Causal Phenomena

Z. Akalin Acar & S. Makeig (2016)

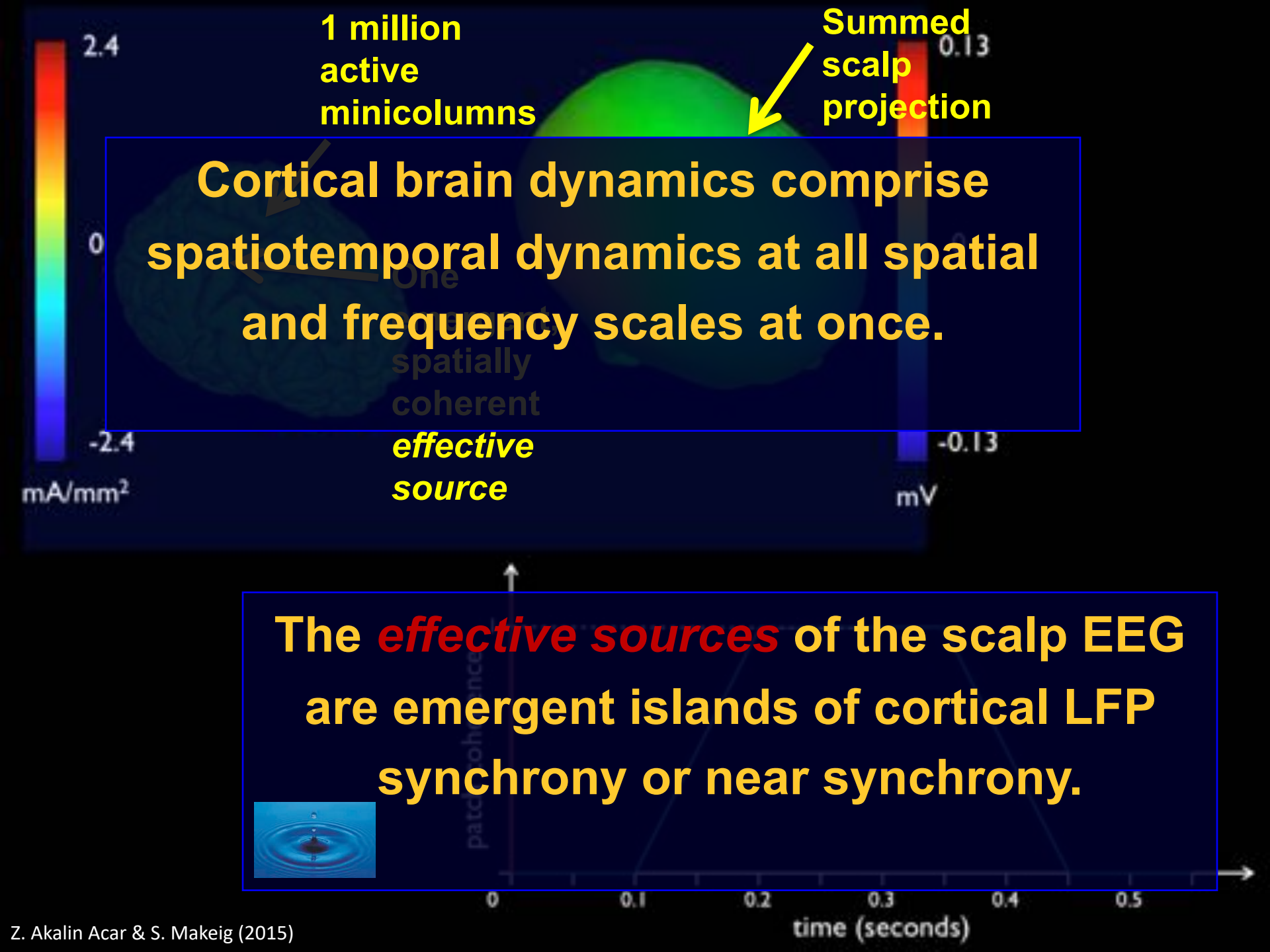


Z. Akalin Acar & S. Makeig (2015)

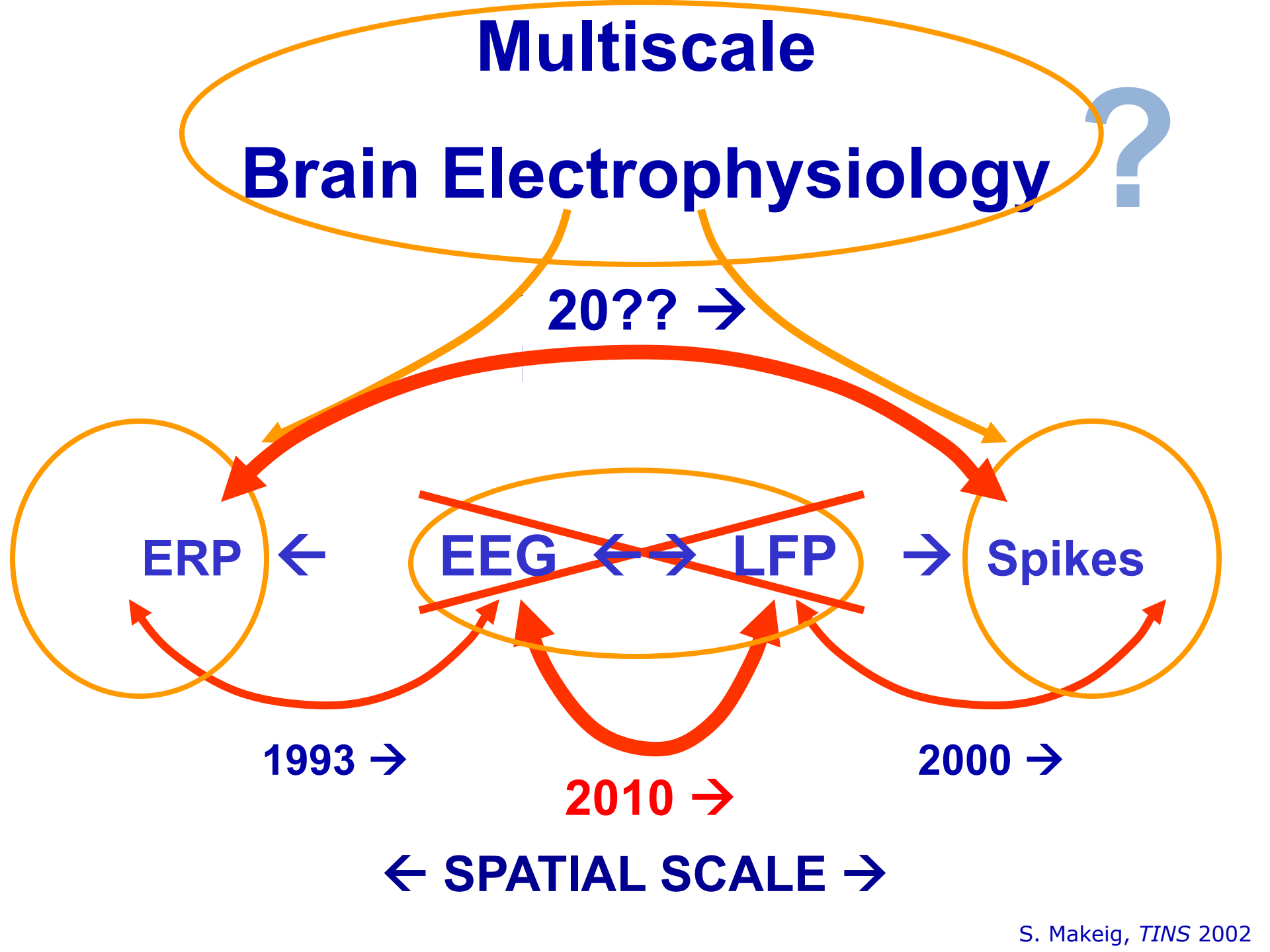




Z. Akalin Acar & S. Makeig (2015)



Z. Akalin Acar & S. Makeig (2015)



S. Makeig, *TINS* 2002

Electromagnetic source localization using realistic head models

NFT

Solve
forv
prc
using
head
(B

T1-weighte

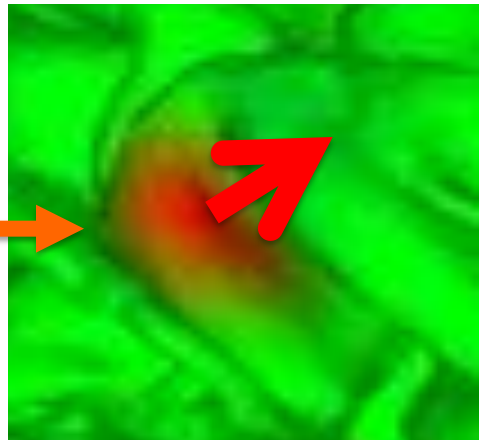
MRI

Proto

Segmentation

Simple Map

Signal Processing



Source Estimate

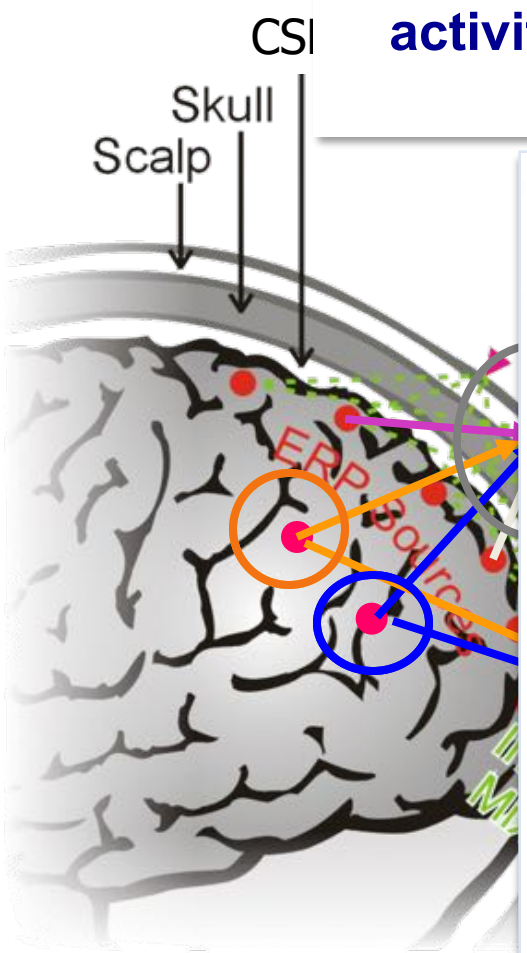
EEG/MEG

Zeynep Akalin Acar & Scott Makeig ‘06

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

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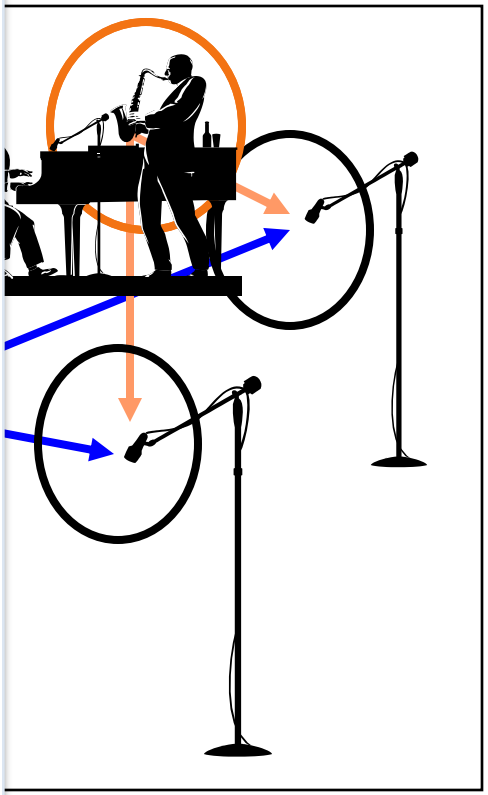
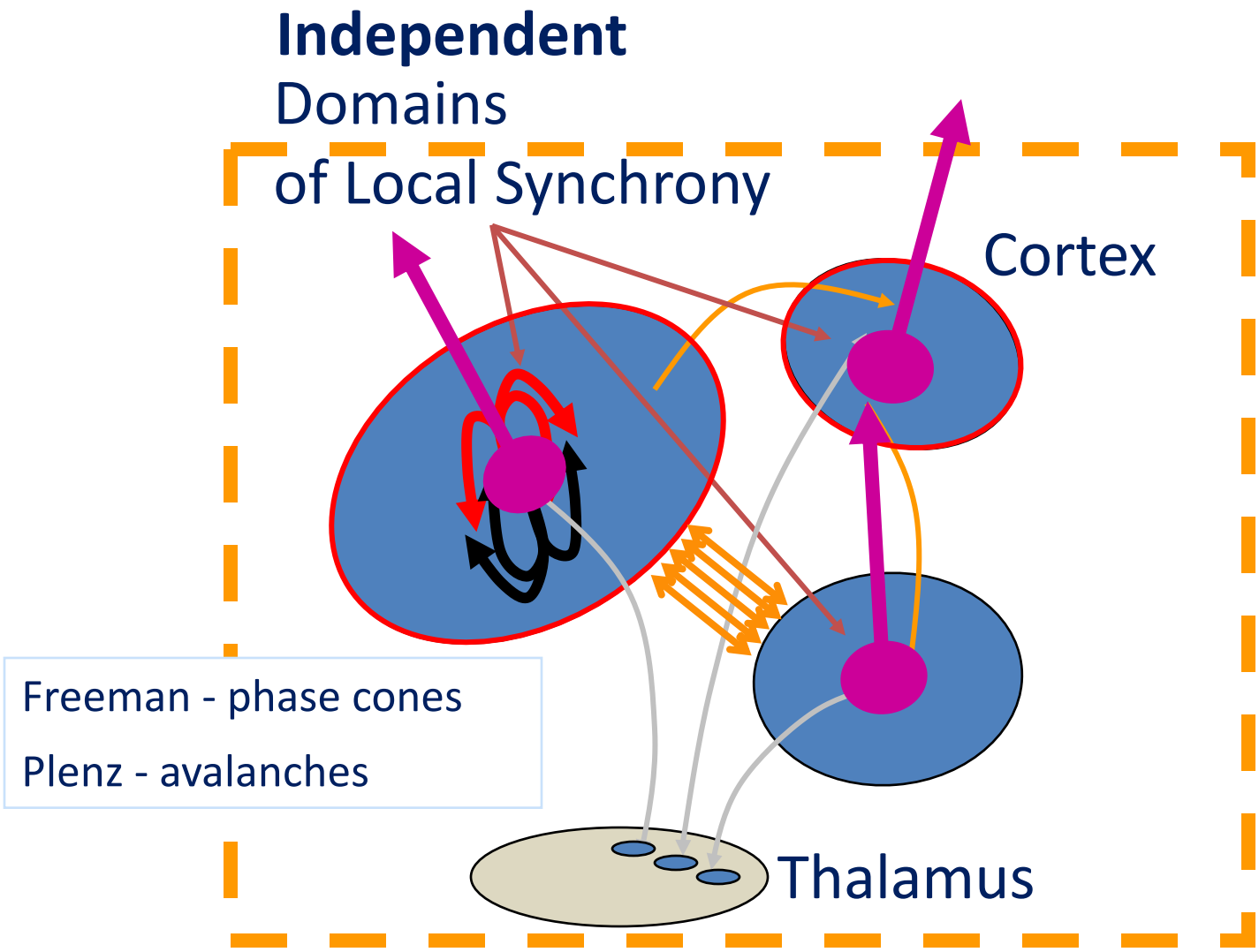
Abstract

Because of the distance between the skull and brain and their different resistivities, electroencephalographic (EEG) data collected from any point on the human scalp includes activity generated within a large brain area. This spatial smearing of EEG data by volume conduction does not involve significant time delays, however, suggesting that the Independent Component Analysis (ICA) algorithm of Bell and Sejnowski [1] is suitable for performing blind source separation on EEG data. The ICA algorithm separates the problem of source identification from that of source localization. First results of applying the ICA algorithm to EEG and event-related potential (ERP) data collected during a sustained auditory detection task show: (1) ICA training is insensitive to different random seeds. (2) ICA may be used to segregate obvious artifactual EEG components (line and muscle noise, eye movements) from other sources. (3) ICA is capable of isolating overlapping EEG phenomena, including alpha and theta bursts and spatially-separable ERP components, to separate ICA channels. (4) Nonstationarities in EEG and behavioral state can be tracked using ICA via changes in the amount of residual correlation between ICA-filtered output channels.



S. Makeig, S. Enghoff (2000)

Are EEG effective source signals independent?



S. Makeig (2007)

The EEG Inverse Problem is Twofold

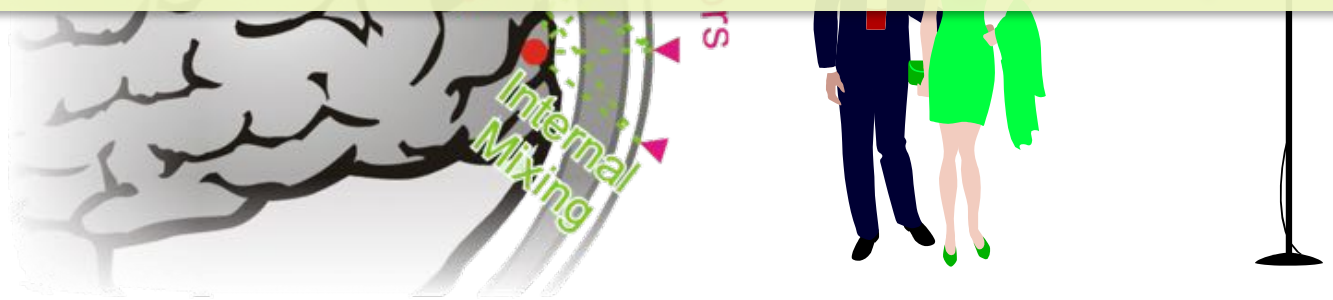
Effective source
Identification → Localization

ICA gives a model-based response to the first question:

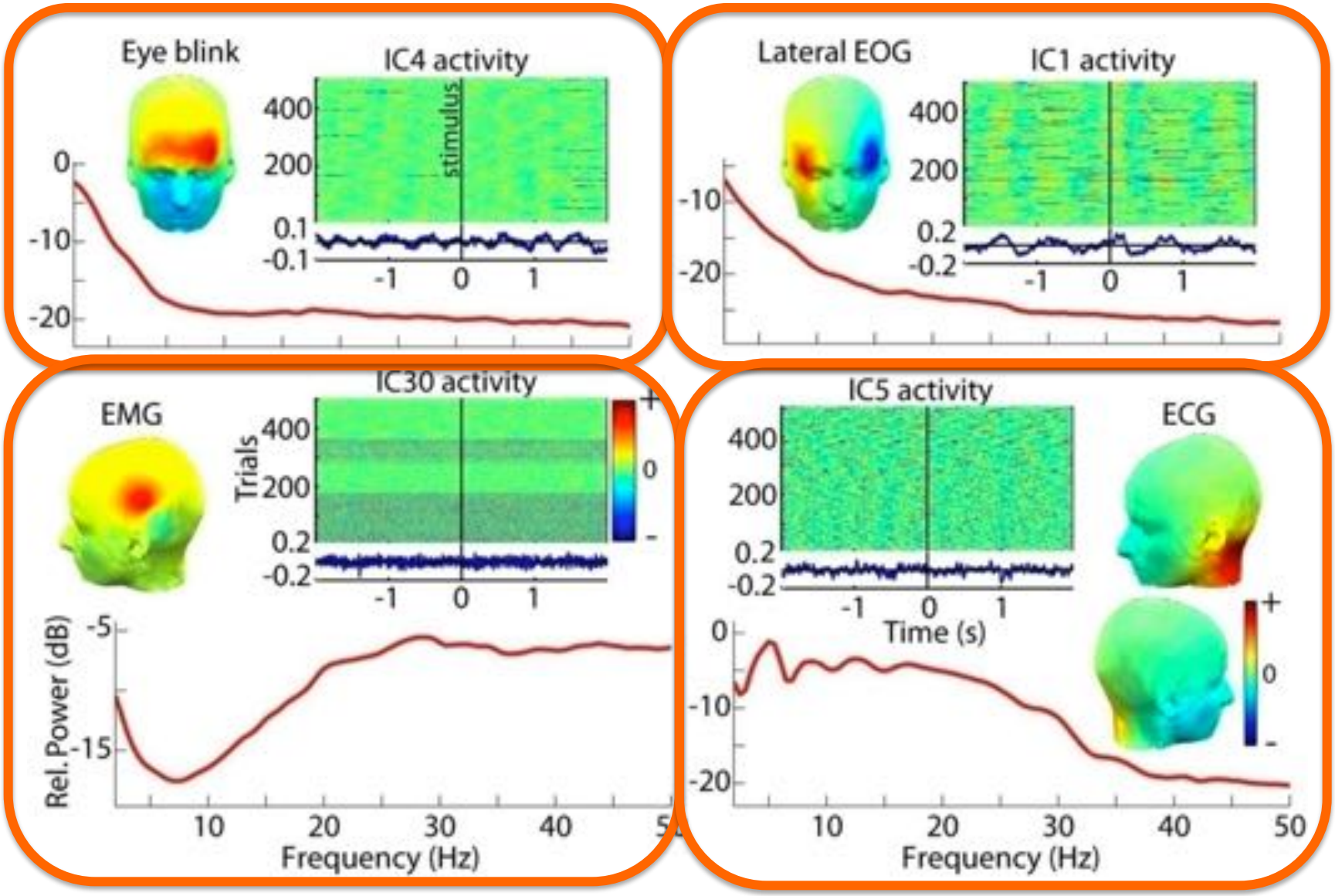
- ***What* are the effective sources? (identification)**

And it greatly helps answer the second question:

- ***Where* do these sources originate? (localization)**



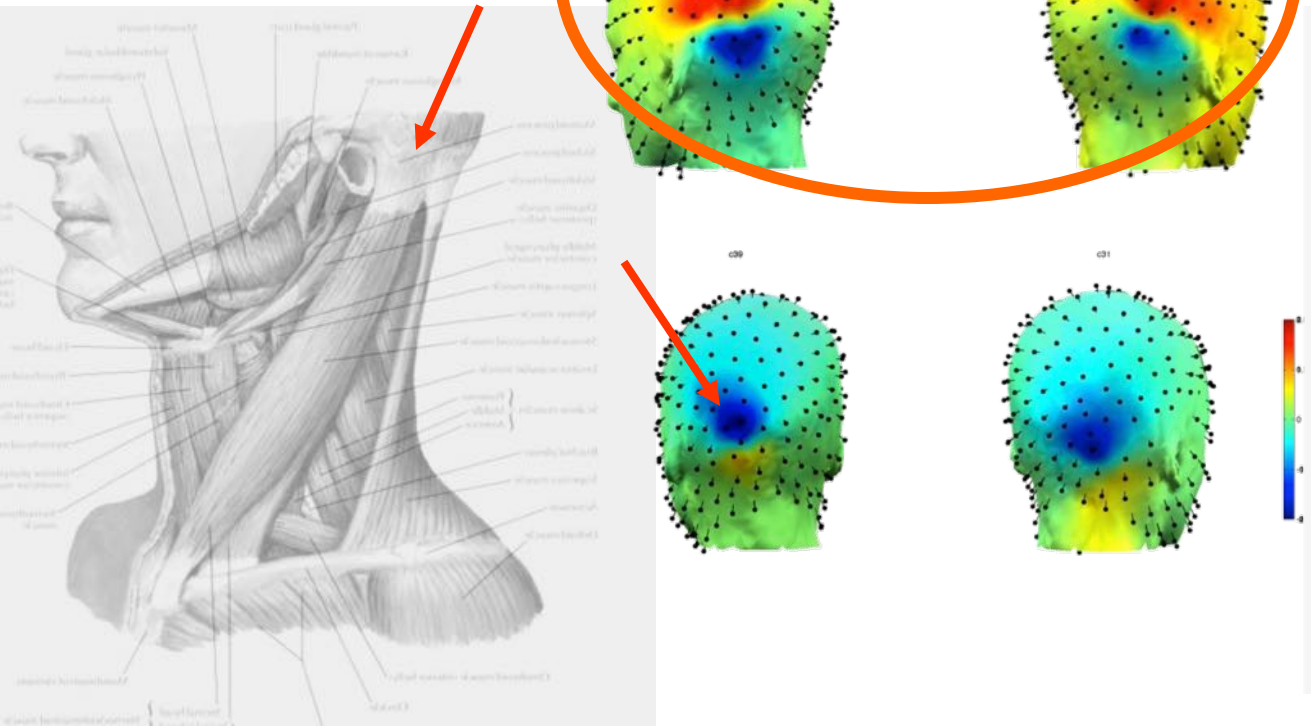
ICA finds non-brain independent component (IC) processes …

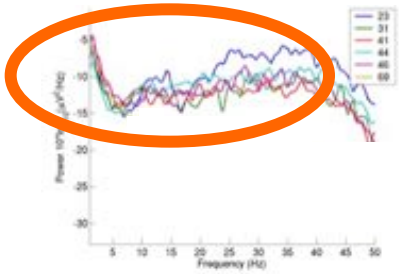


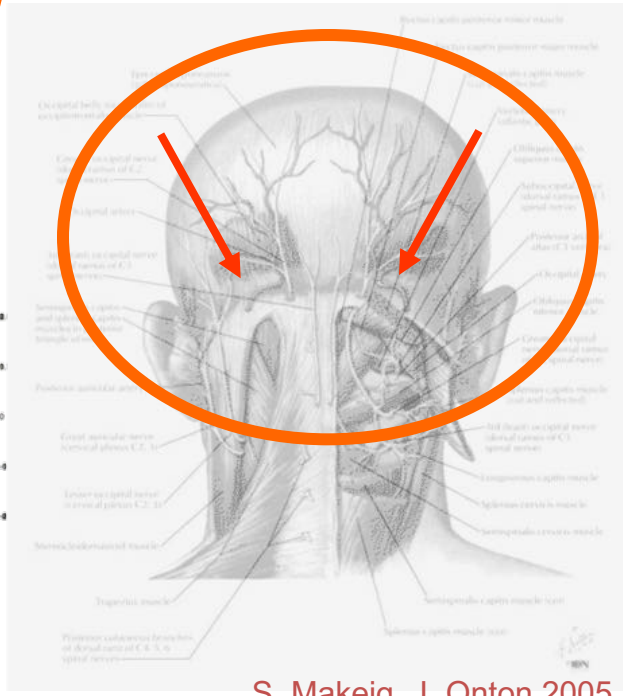
… separates them from the remainder of the data …

J. Onton & S. Makeig 2006

… including IC EMG sources

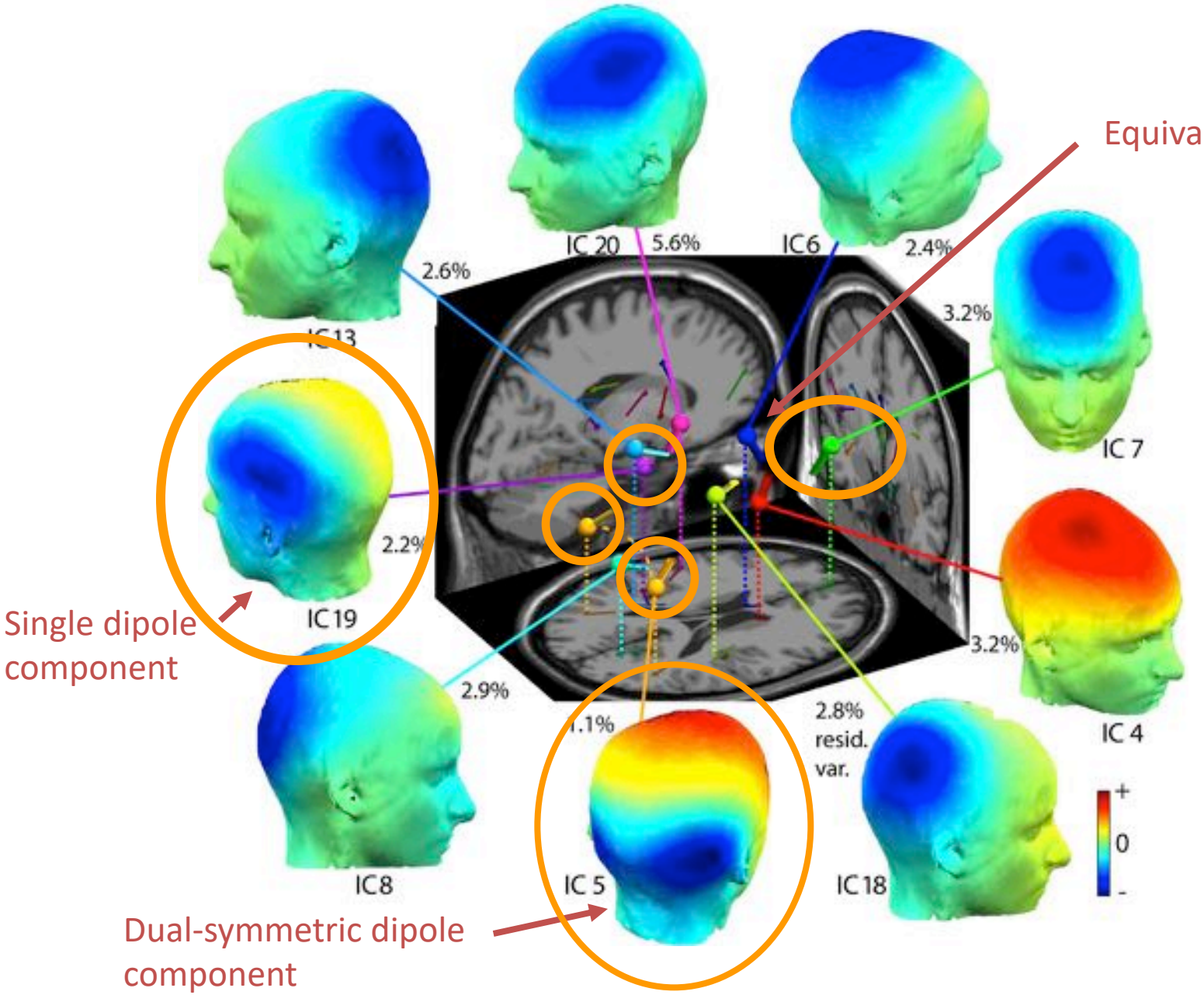






S. Makeig, J. Onton 2005

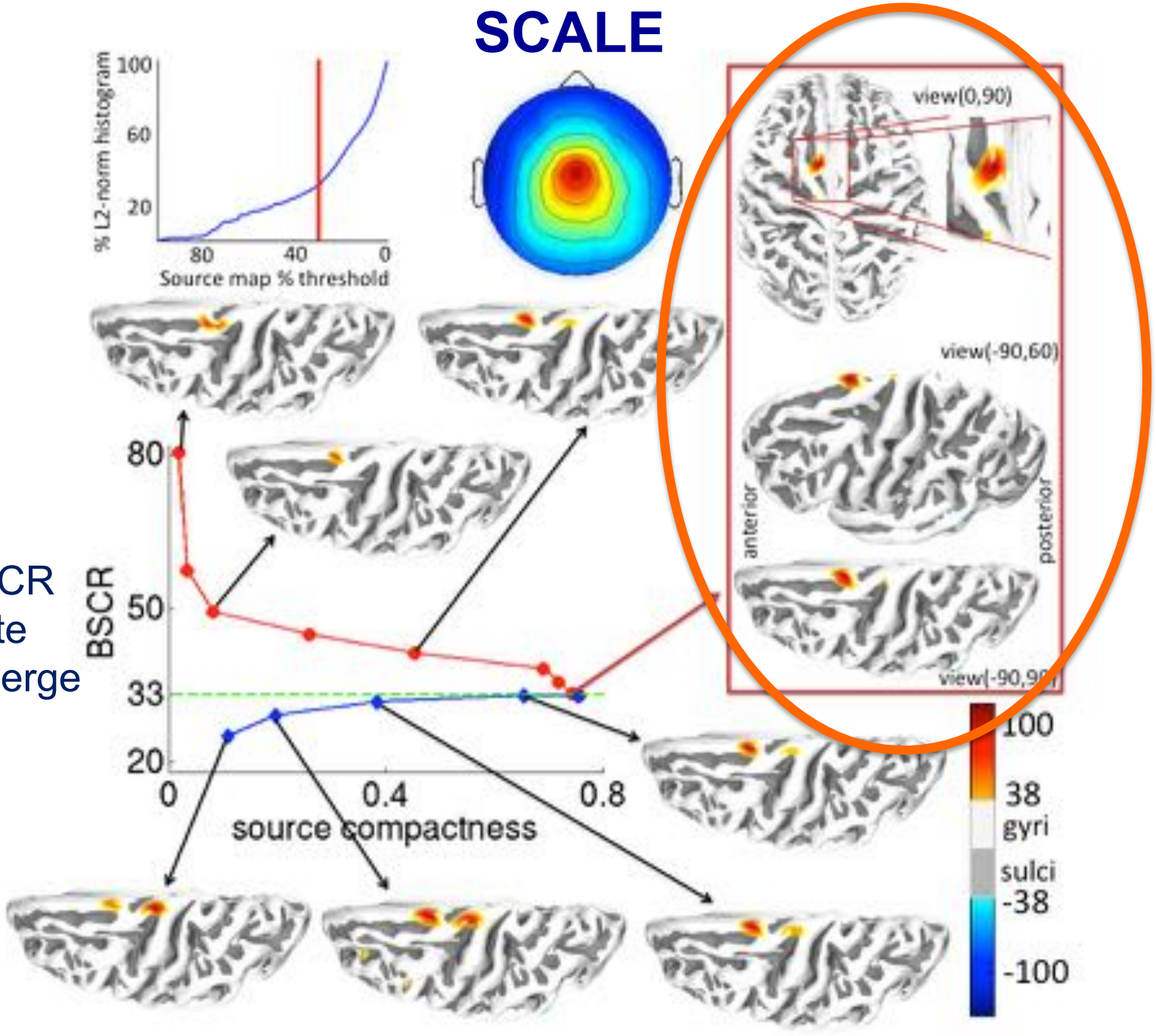
… and IC effective brain sources



Julie Onton & S. Makeig (2006)

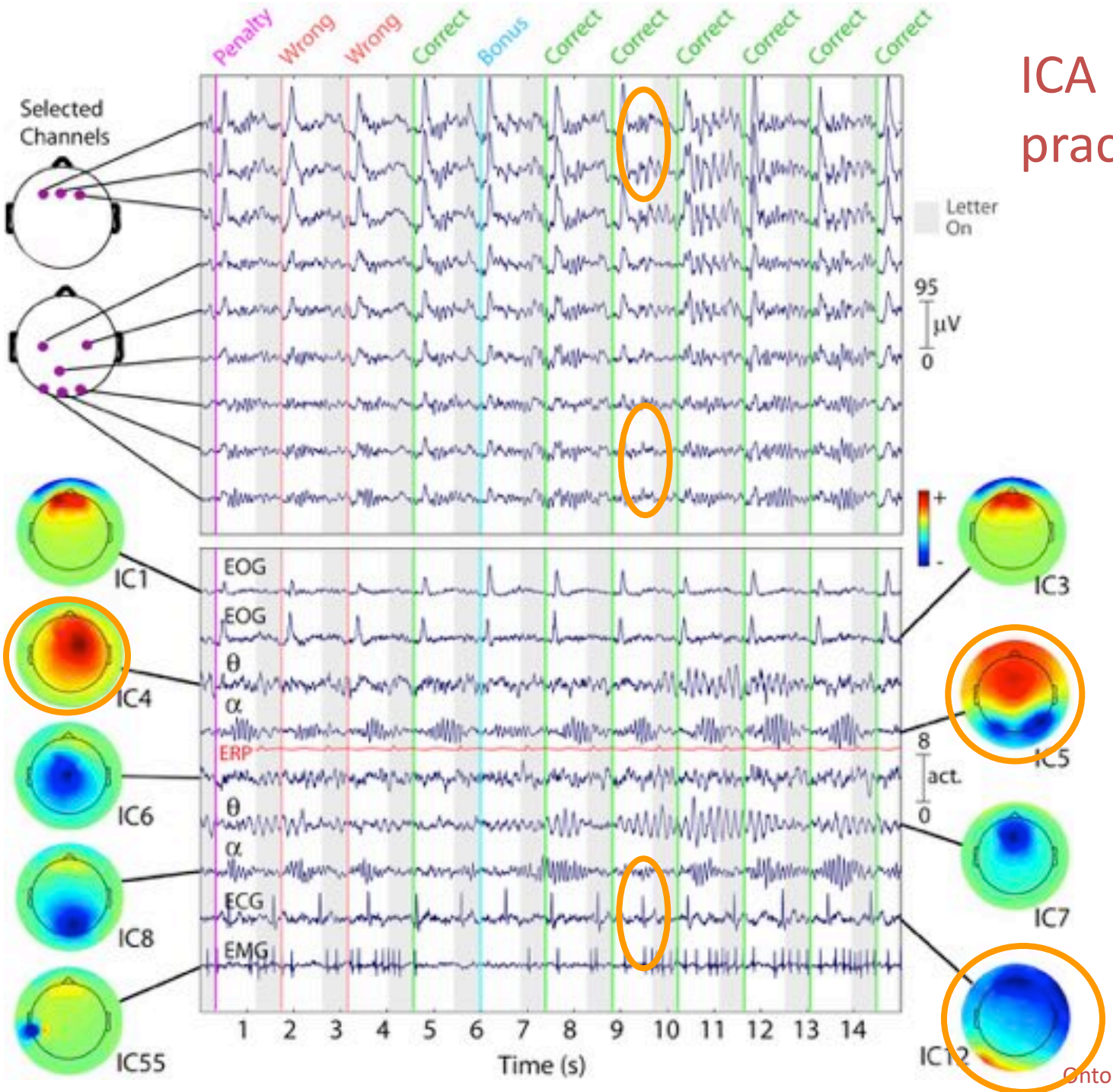
SCALE

SCALE
- NFT
- ICA
- SCS
- ΔBSCR
- iterate
- converge



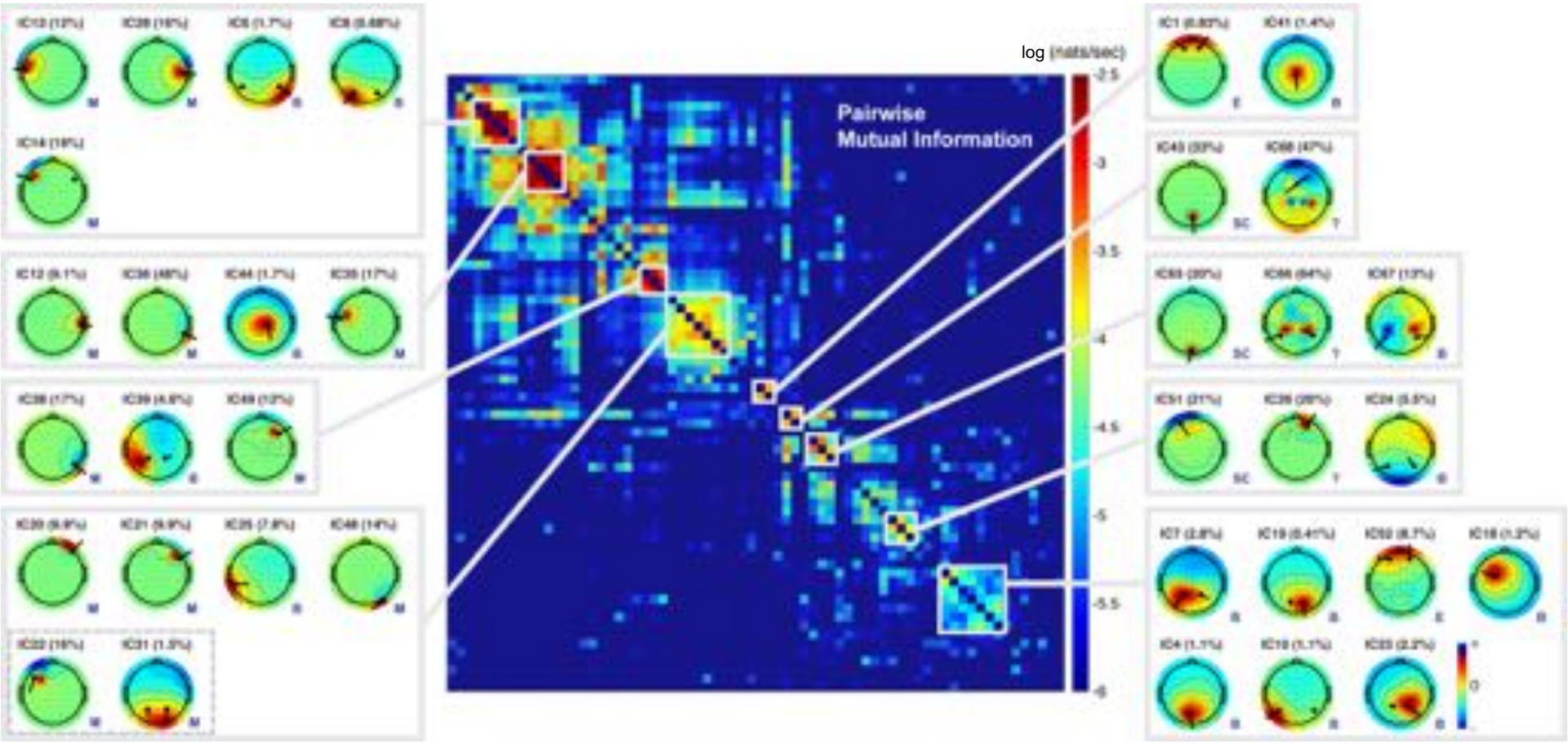
Z. Akalin Acar et al., 2016

ICA in practice



Onton & Makeig, 2006

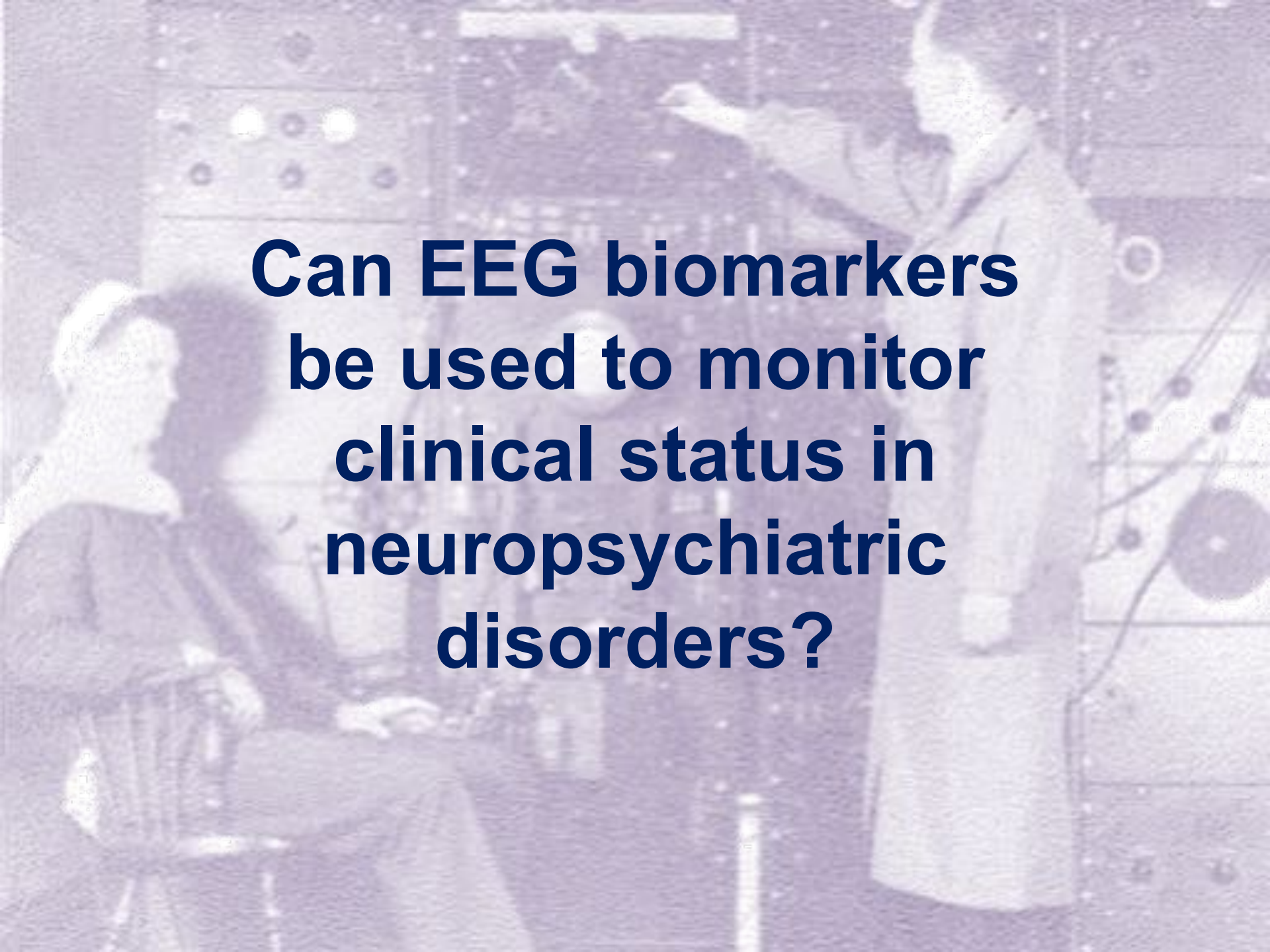
Residual mutual information following ICA decomposition – dependent subspaces



B = brain
M = muscle
E = eye
? = other
SC = channel

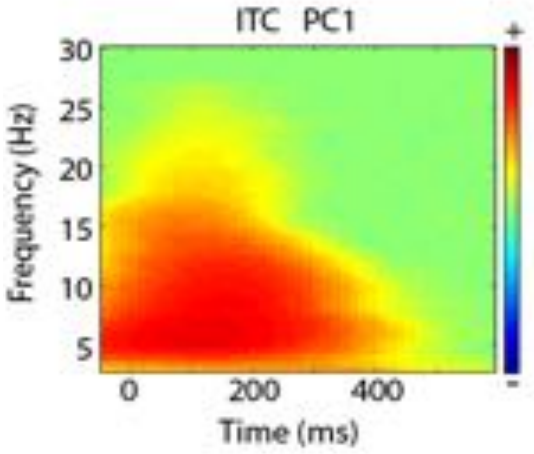
ICLabel component type labels

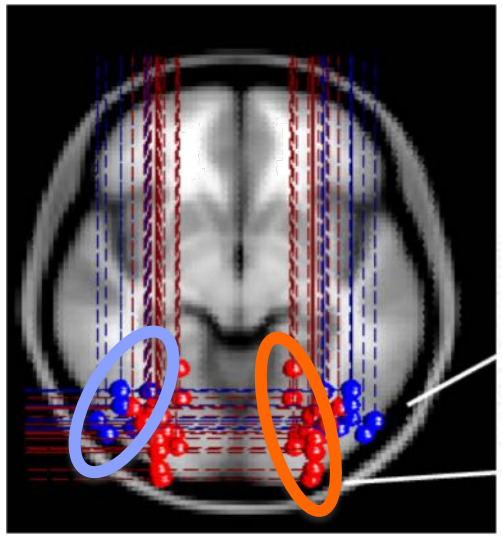
S. Makeig, R. Martinez-Cancillo, 2018

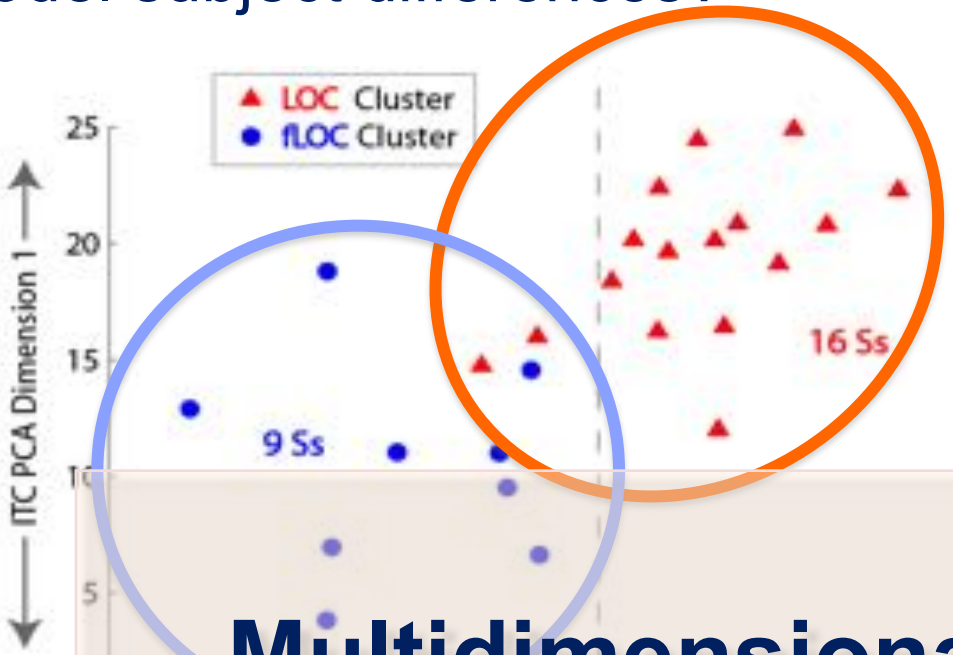


Can EEG biomarkers be used to monitor clinical status in neuropsychiatric disorders?

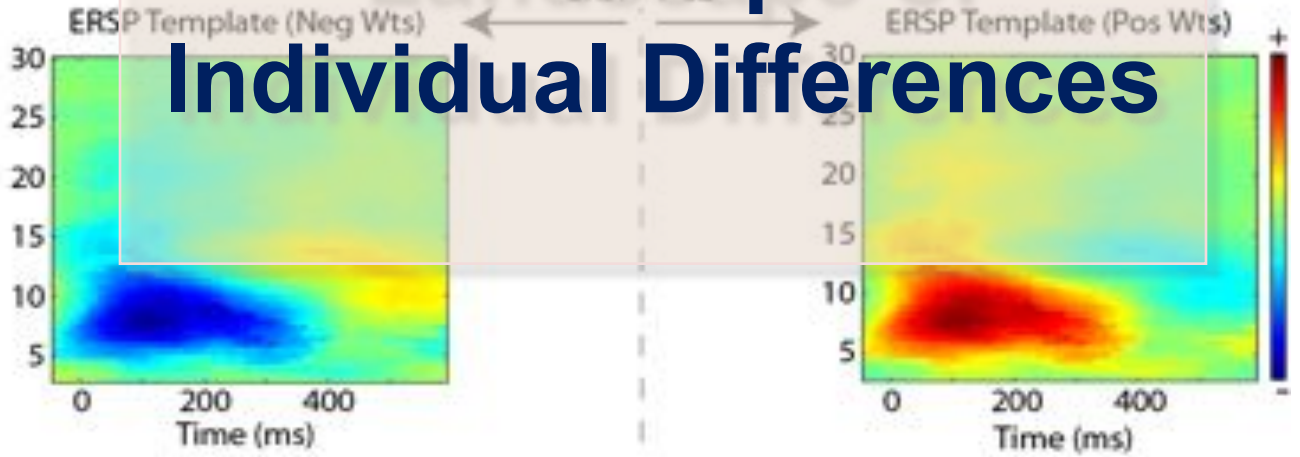
Can measures of source-resolved EEG dynamics model subject differences?





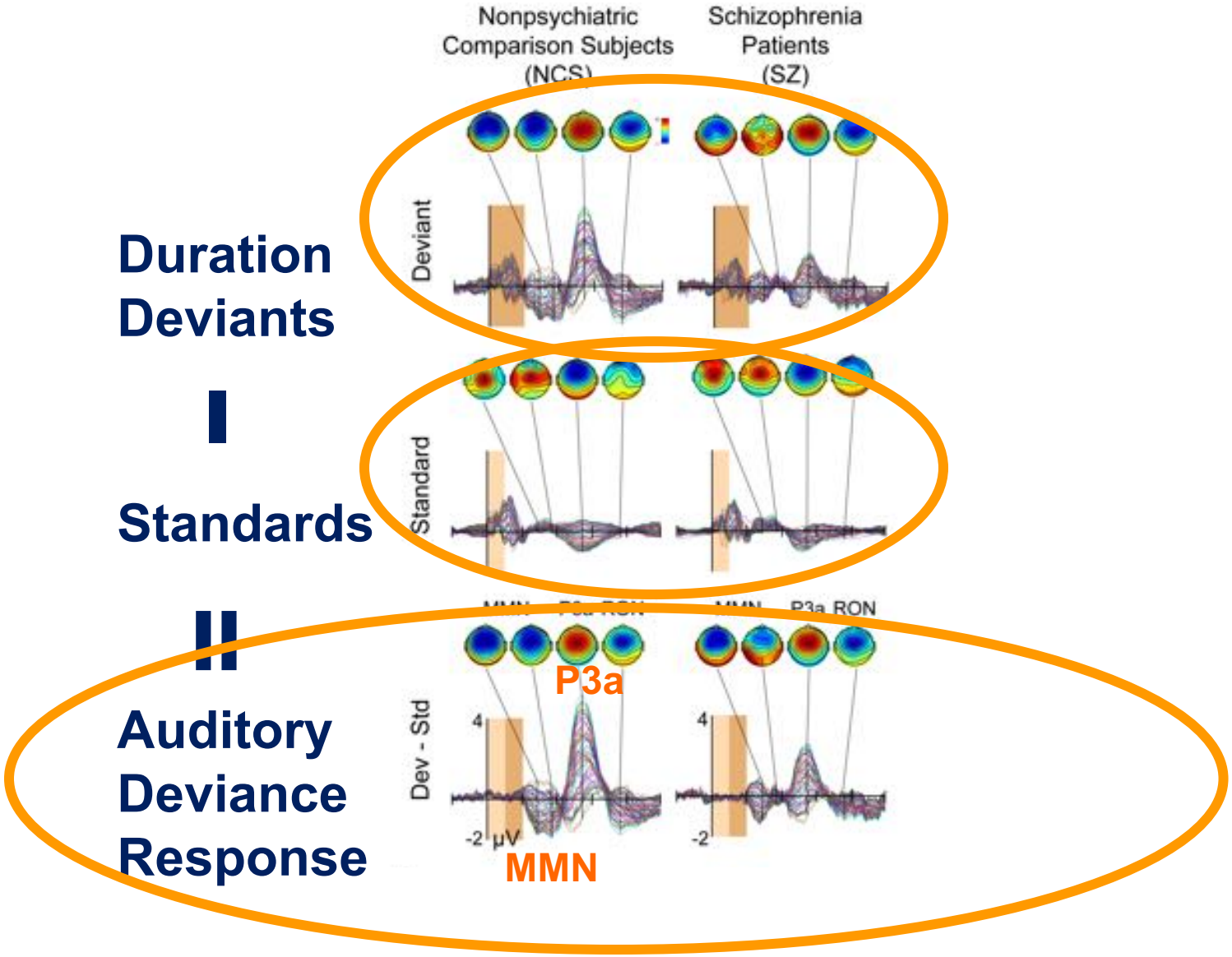


Multidimensional Landscape of Individual Differences



Schizophrenia

Auditory Passive Oddball Task (SZ, Cntrl)



Duration Deviants

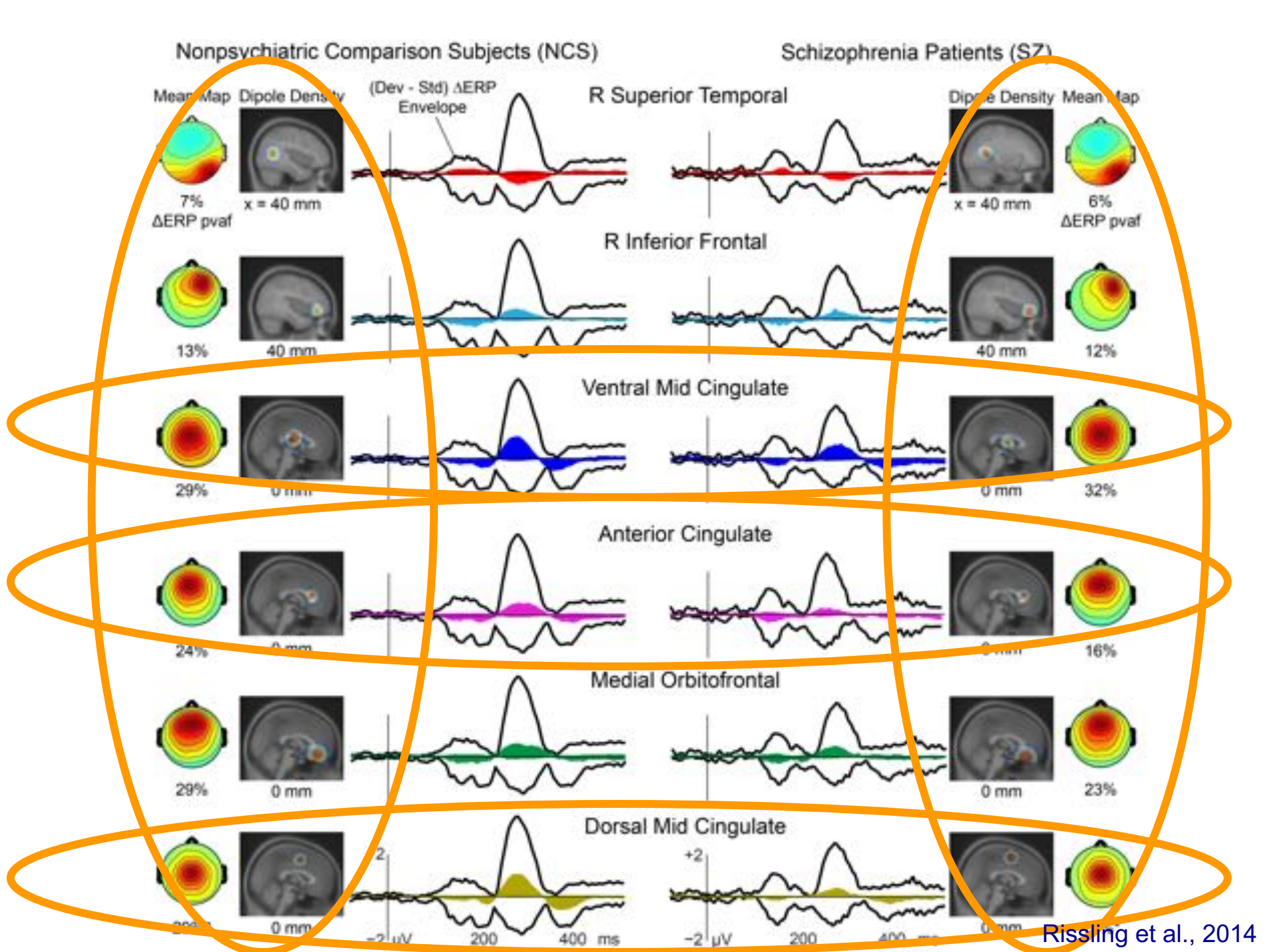
I

Standards

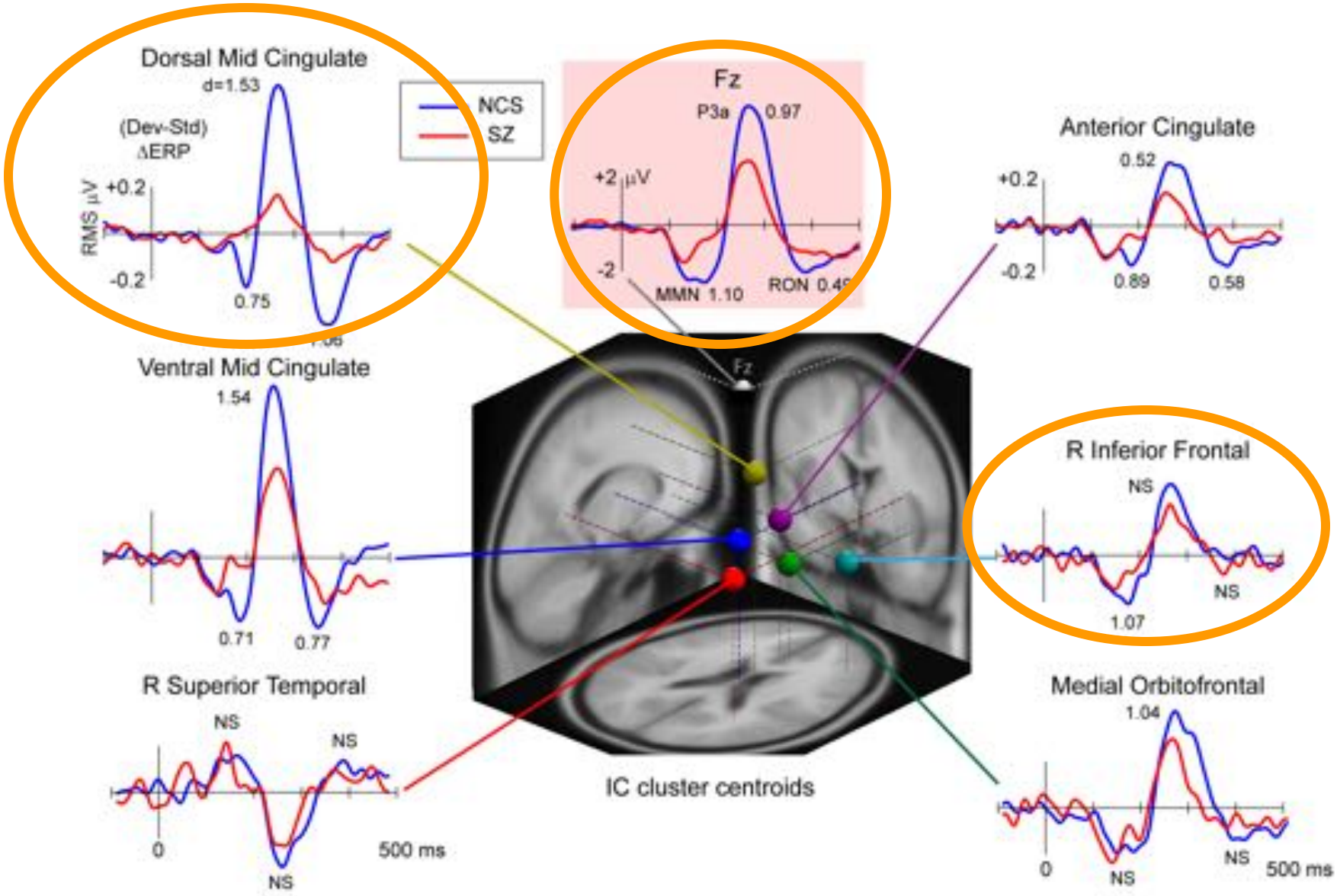
II

Auditory Deviance Response

Rissling et al., 2014

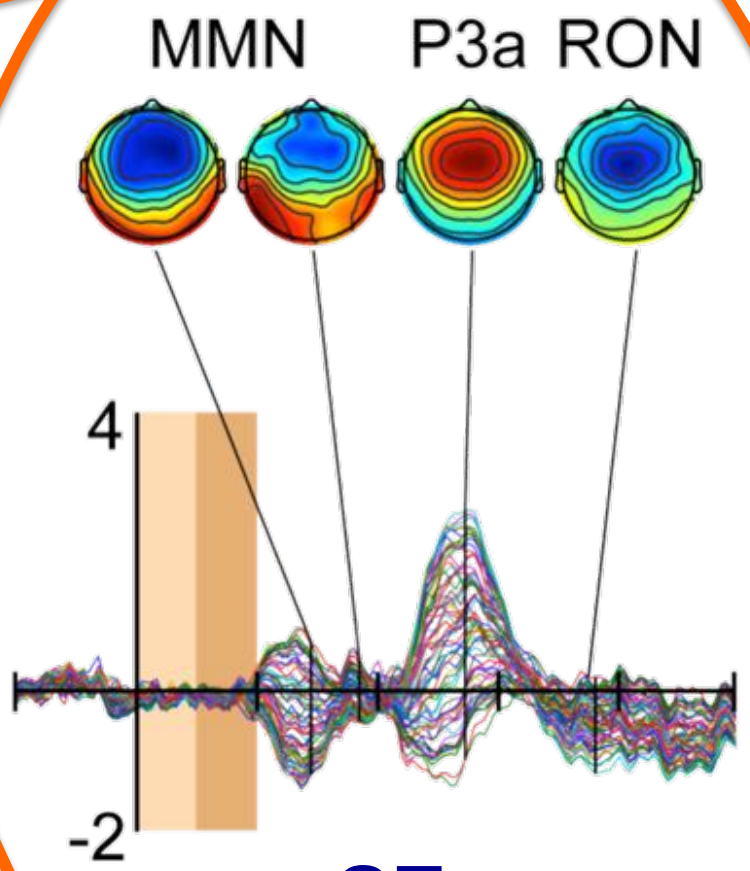


Rissling et al., 2014



Rissling et al., 2014

PEAK AMPLITUDES	ERP	r^2
Scalp Electrode (Fz)		
Verbal IQ (WRAT)	P3a	
Functional Capacity (UPSA)	RON	
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 Oribitofrontal		
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

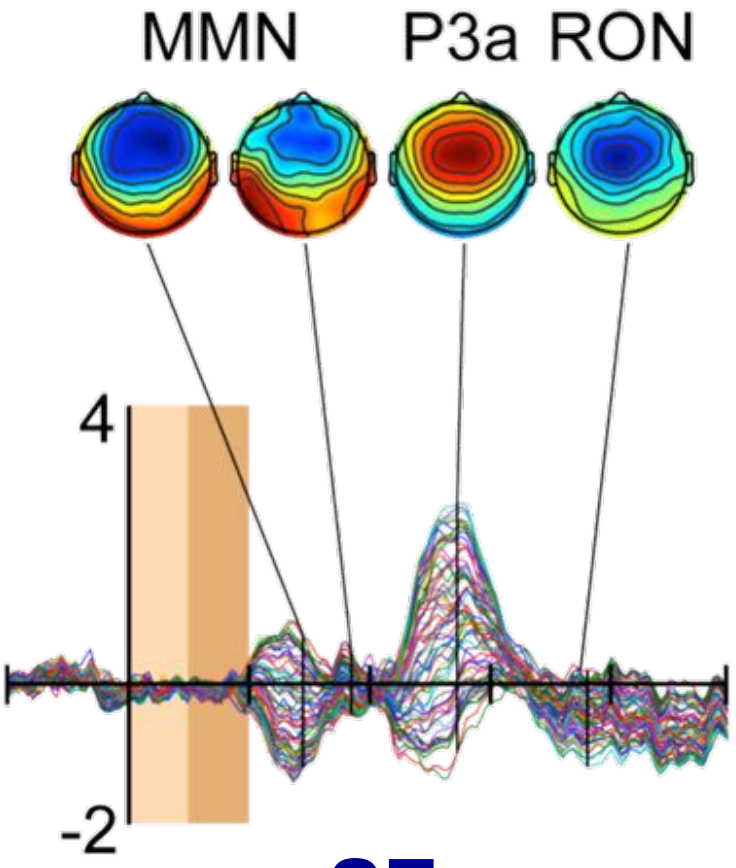


Rissling et al., 2014

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

X

ADR



SZ

Rissling et al., 2014

EEG & *feeling*

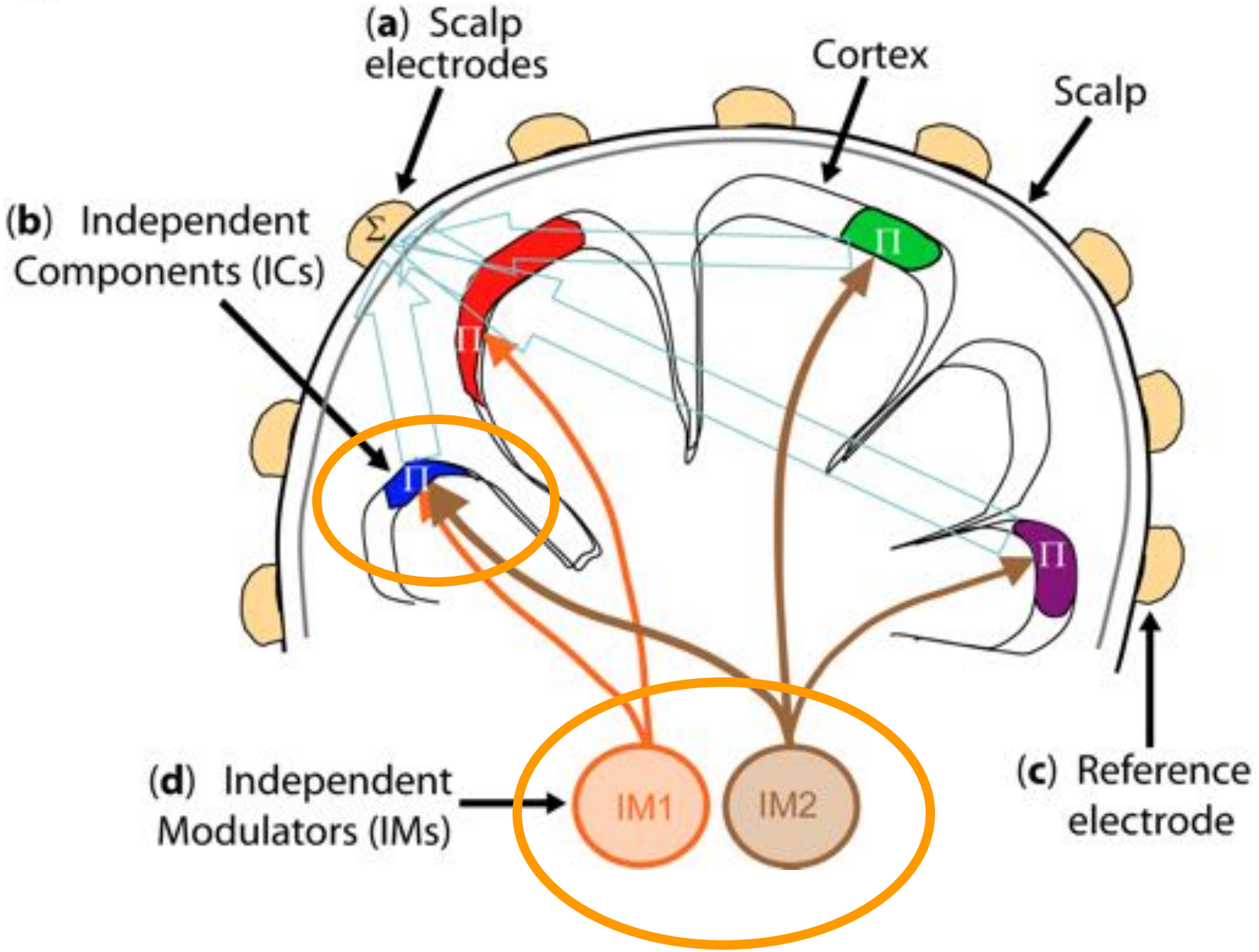
EEG Dynamics of Emotion Imagination

Suggest the imaginative experience of 15 emotions:

- after Helen Bonny
- initial relaxation instruction
- alternate suggestions to imagine scenes engendering positive and negative emotions
- relaxation instructions between emotion episodes
- **obtained 1-5 min periods of eyes-closed spontaneous EEG** for each emotion from 33 subjects.

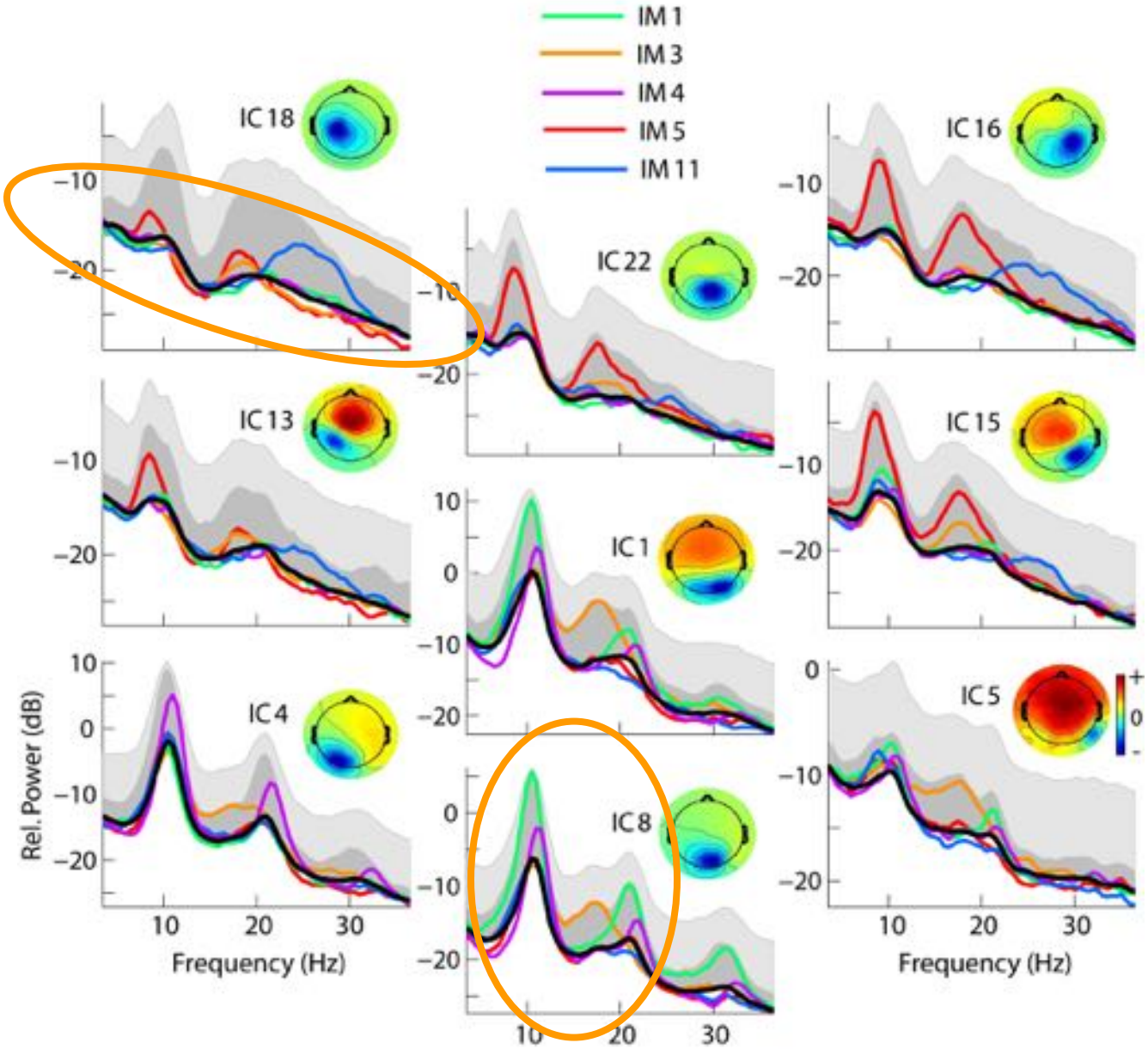
Onton & Makeig, *Frontiers in Human Neuroscience* '09

Independent Modulators

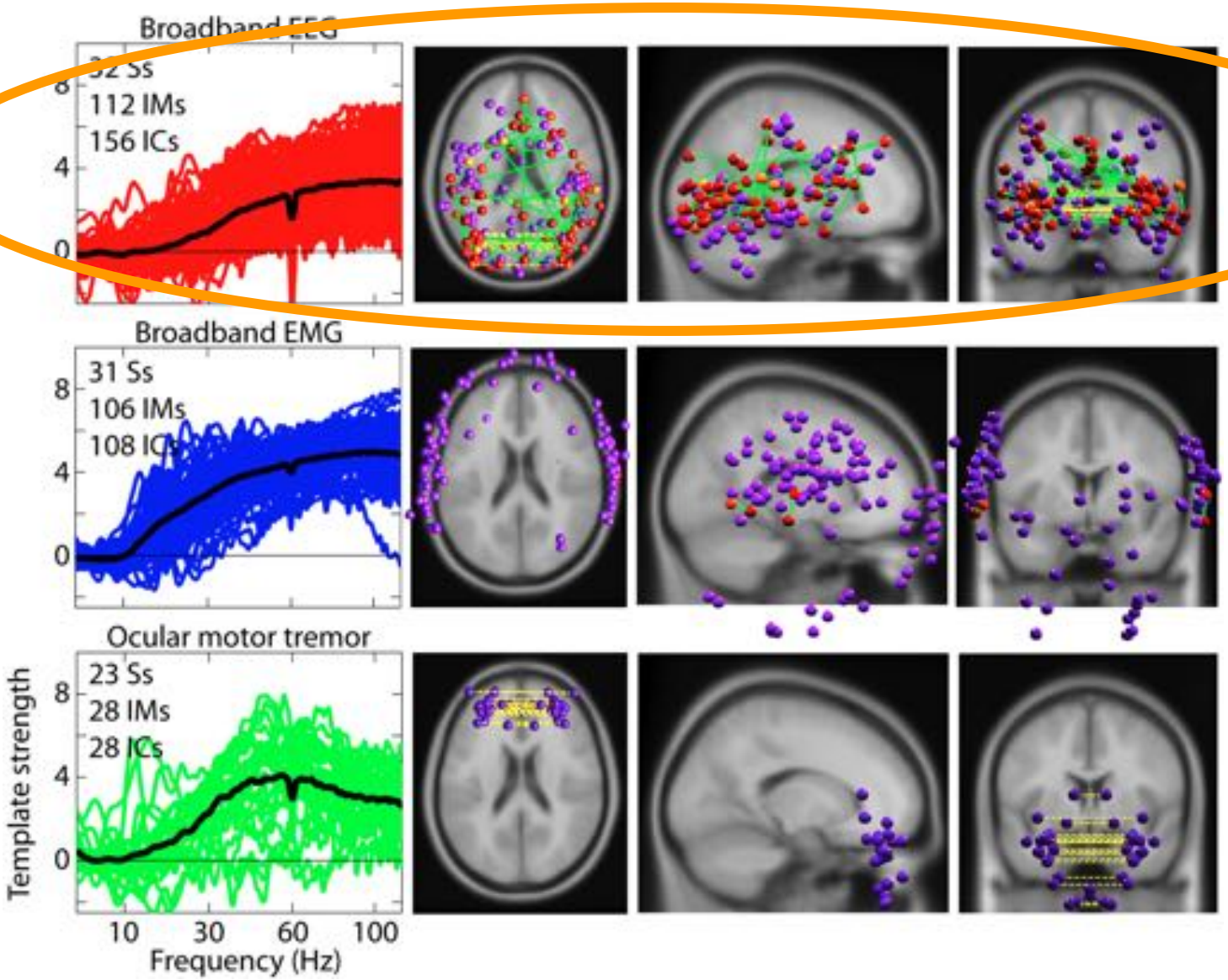


Onton & Makeig, *Frontiers in Human Neuroscience* '09

Independent Modulators

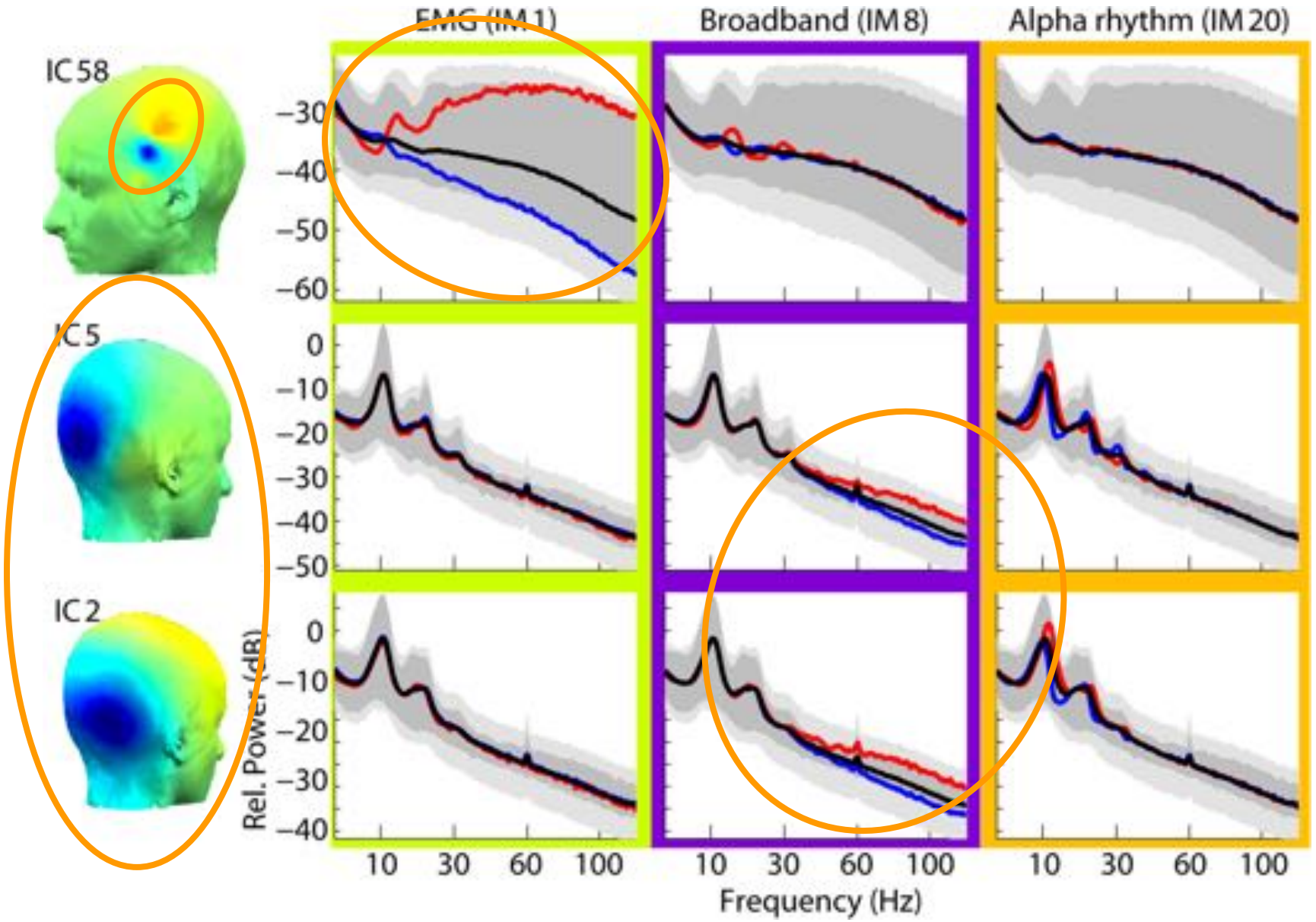


Onton & Makeig, *Frontiers in Human Neuroscience* '09



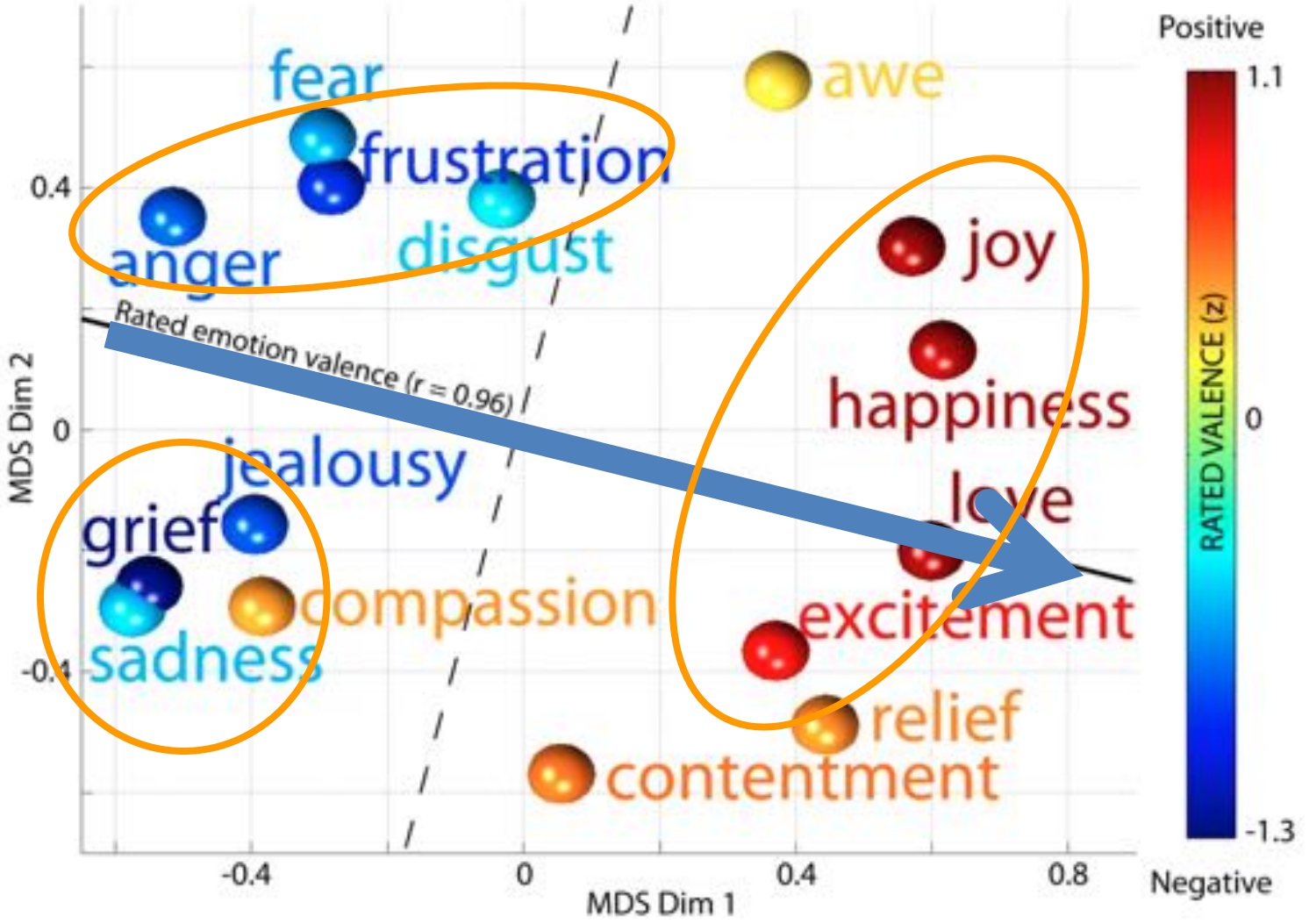
Onton & Makeig, *Frontiers in Human Neuroscience* '09

Independent Modulators

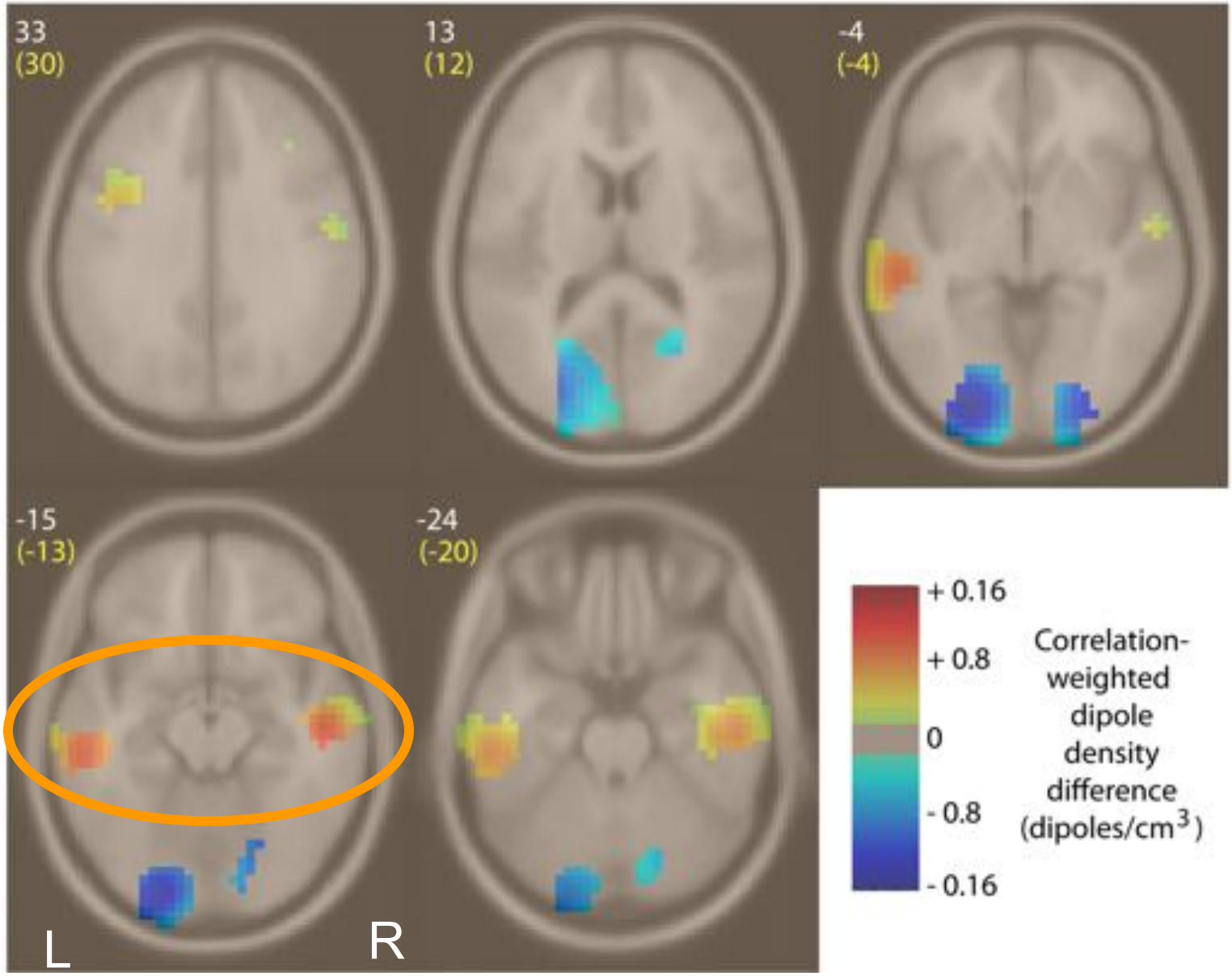


Onton & Makeig, *Frontiers in Human Neuroscience* '09

Changes in distribution of *broadband high-frequency* EEG power with imagined emotion

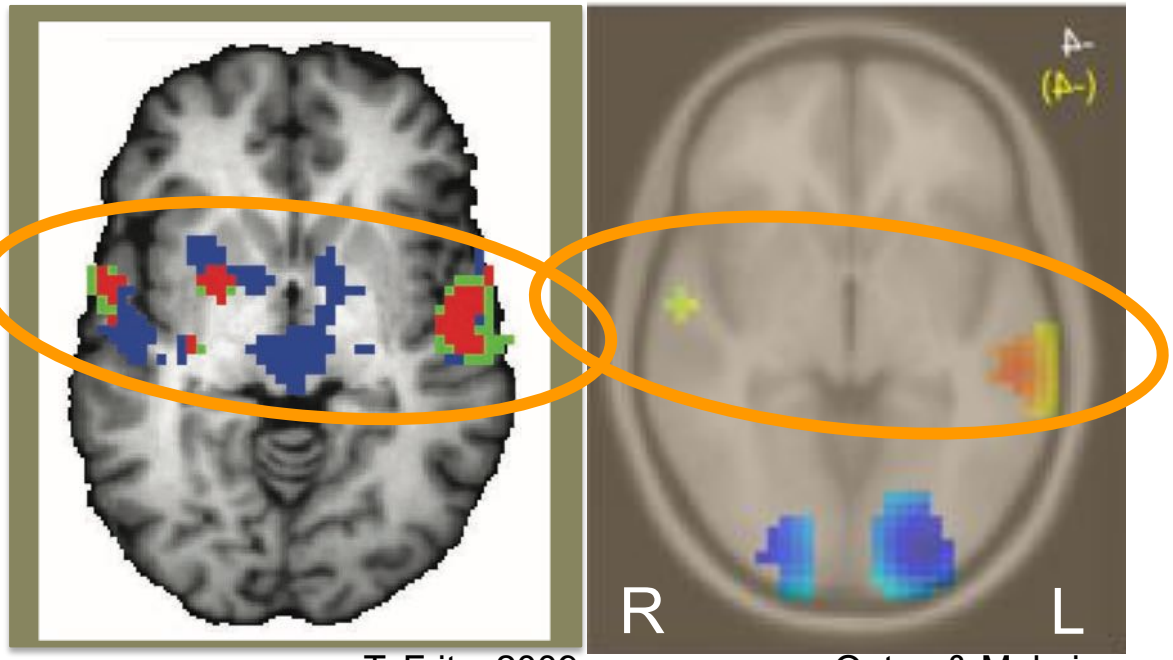


Julie Onton & Scott Makeig, *Frontiers in Human Neuroscience*, 2009



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

High-Frequency Broadband (HFB) activity level indicates feeling *valence*



T. Fritz, 2009

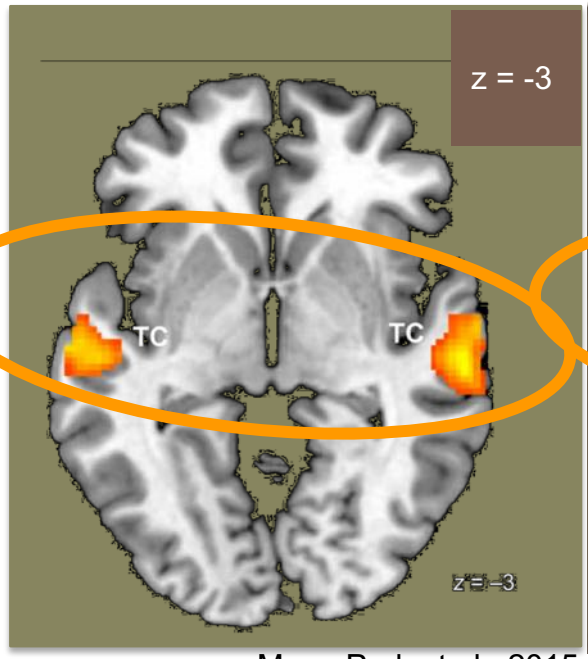
Onton & Makeig, 2009

fMRI BOLD

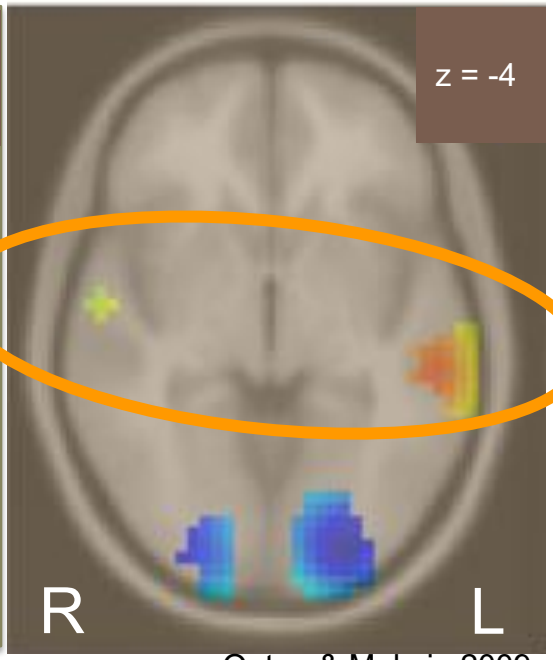
EEG HFB

Makeig, 2016

High-Frequency Broadband (HFB) activity level indicates feeling *valence*



Mona Park et al., 2015



Onton & Makeig 2009

fMRI BOLD

EEG HFB

Makeig, 2016

Expressive gesturing task

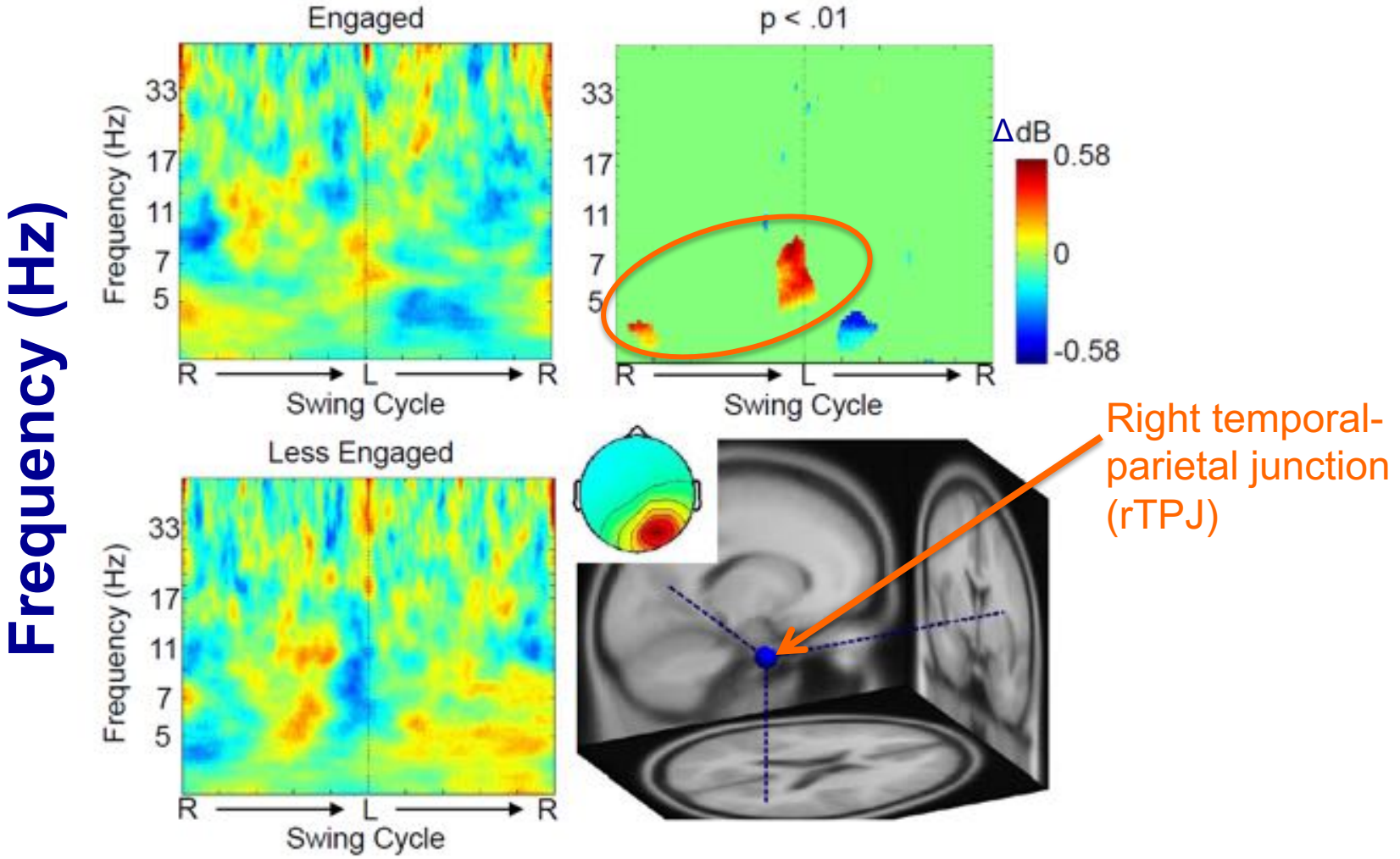
The Heart is a
Lonely Hunter (1968)

Two conditions:
- **Fully engaged**
- **Less engaged**

Conducting Experiment (2013)

Grace Leslie & S Makeig, 2013

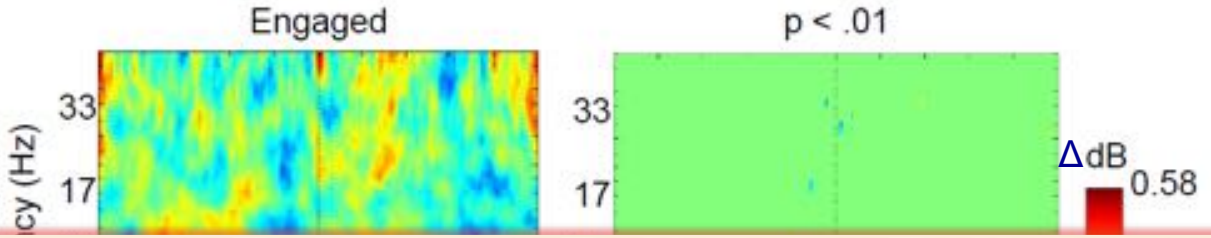
EEG Result: Full relative to Dual-task challenged affective engagement conditions



Spectral Perturbations Synced to the Arm Swing Cycle (%)

Grace Leslie & S Makeig, 2014

EEG Result: Full relative to Dual-task challenged affective engagement conditions



The TPJ controls **representations of the self or of another individual** across a variety of low-level and high-level and socio-cognitive processes (mentalizing, empathy, agency discrimination, visual perspective taking, imitation) …

The rTPJ is a key cortical structure for both motor and emotional control; **rTPJ volume predicts level of emotional awareness of others** in autistics; etc. …

Grace Leslie & S Makeig, 2014

Swartz Center for Computational Neuroscience

The Beginning

fEMI,

BMI,

MoBI …