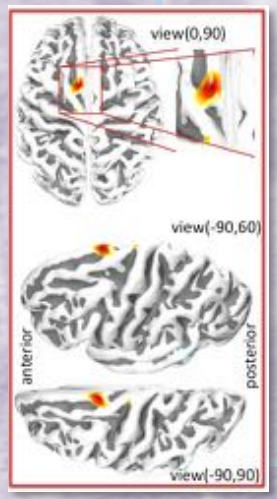
EEG Data Mining I: Toward High-Resolution EEG Source Imaging

Scott Makeig
Institute for Neural Computation
University of California San Diego

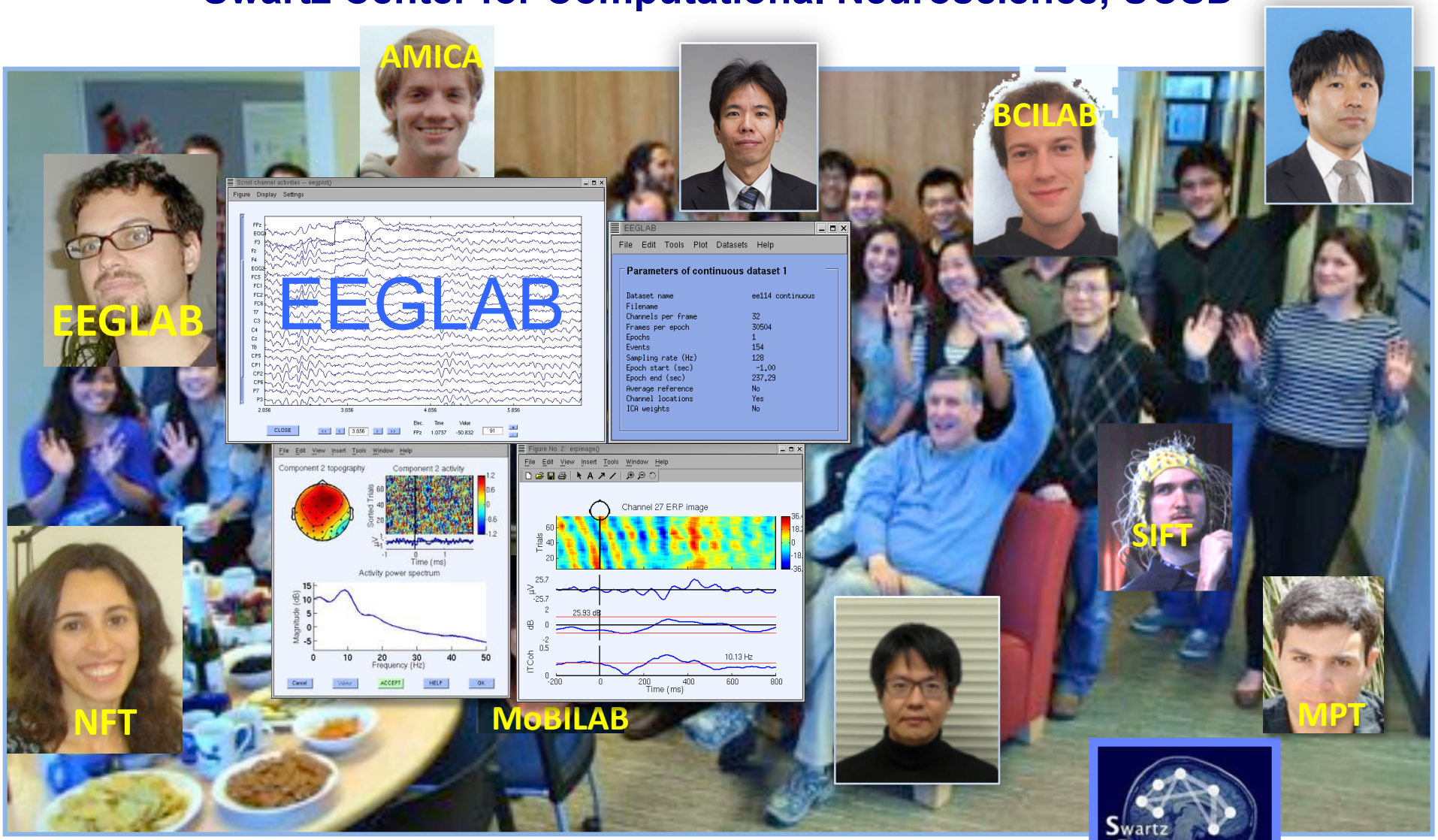
29th EEGLAB Workshop

Les Bois Perché, Aspet, France
June 17-21, 2019

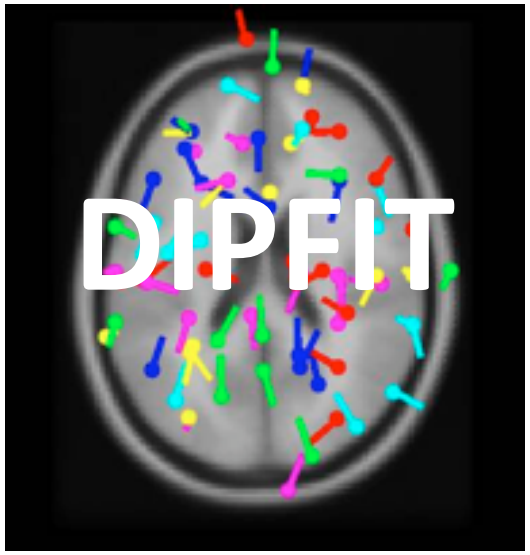


smakeig@ucsd.edu, 2018

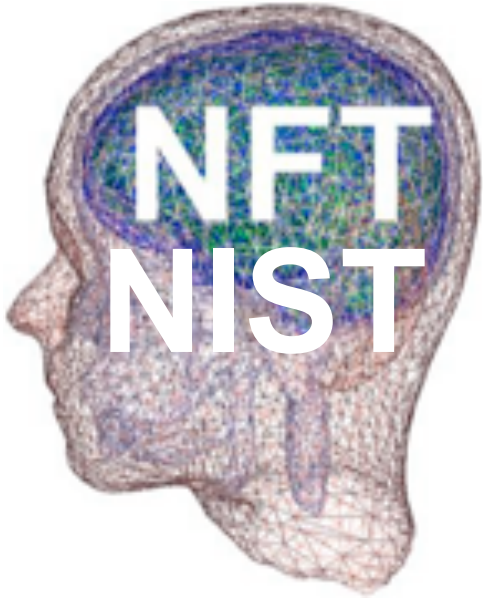
Swartz Center for Computational Neuroscience, UCSD

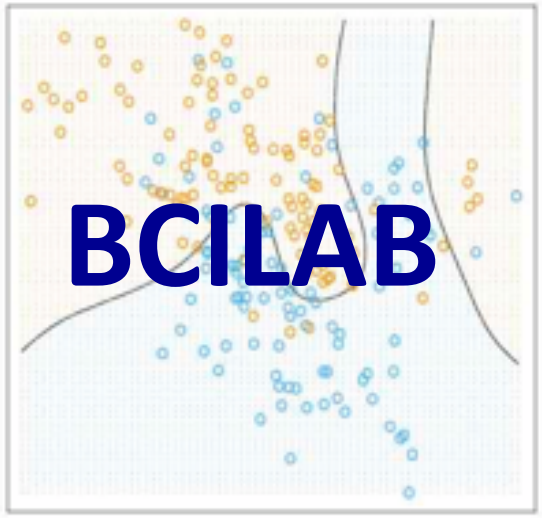


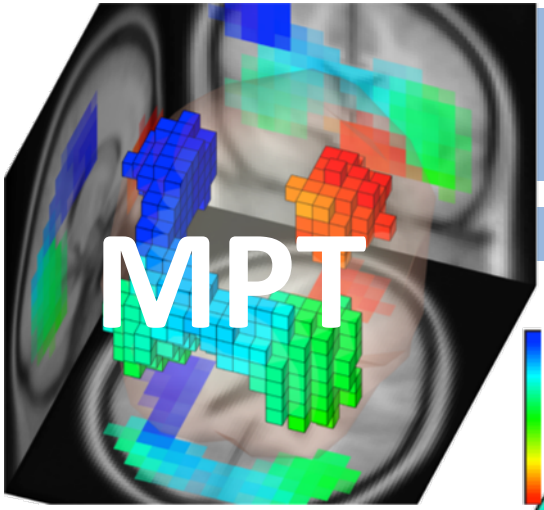
10th Anniversary SCCN Impromptu celebration 1/2/12

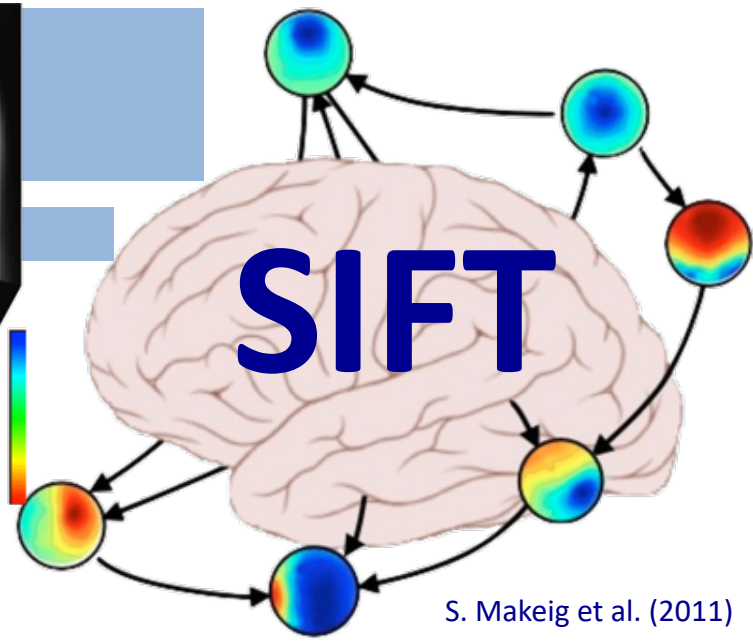


EEGLAB Plug-In Extensions







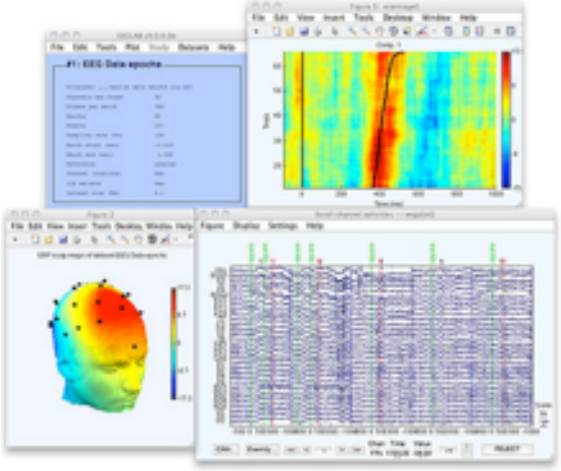


S. Makeig et al. (2011)

List of data import extensions

Plug-in name	Version	Short plug-in description	Link	Contact	Comments
MFFimport	1.00	Import MFF files from the EGI company	Download	S. Chennu	User comments
ANTeepimport	1.10	Import ANT .cnt data and trigger files	Download	M. van de Velde	User comments
BCI2000import	0.36	Import BCI2000 data files	Download	C. Boulay	User comments
BDFimport	1.10	Import BDF data files	Download	A. Delorme	User comments
biopac	1.00	Import BIOPAC data files	Download	A. Delorme	User comments
ctfimport	1.04	Import CTF (MEG) data files	Download	D. Weber	User comments
erpssimport	1.01	Import ERPSS data	Download	A. Delorme	User comments
INSTEPascimport	1.00	Import INSTEP ASCII data files	Download	A. Delorme	User comments
neuroimaging4d	1.00	Import Neuroimaging4d data files	Download	C. Wienbruch	User comments
ProcomInfinity	1.00	Import Procom Infinity data files	Download	A. Delorme	User comments
WearableSensing	1.09	Import Wearable Sensing files	Download	S. Hillen	User comments
NihonKoden	0.10	Import Nihon Koden M00 files (beta)	Download	M. Miyakoshi	User comments
xdfimport	1.12	Import files in XDF format	Download	C. Kothe	User comments
bva-io	1.5.12	Import Brain Vision Analyser data files	Download	A. Widmann	User comments
Fileio	Daily	Import multiple data files formats	Download	R. Oostenveld	User comments
Biosig	2.88	Import multiple data files formats	Download	A. Schloegl	User comments
Cogniscan	1.1	Import Cogniscan data files	Download	P. Sajda	User comments
NeurOne	1.0.3.2	Import NeurOne data files	Download	Support	User comments
loadhdf5	1.0	Load hdf5 files recorded with g.recorder	Download	Simon L. Kappel	User comments

EEGLAB History



- 1993 – ERSP (Makeig)
- 1995 – Infomax ICA for EEG (Makeig, Bell, Jung, Sejnowski)
- **1997 - EEG/ICA Toolbox (cnl.salk.edu), ITC & ERC**
- 1999 - ERP-image plotting (Jung & Makeig)
- 2000 – **EEGLAB GUI design (Delorme)**
- **2002 – 1st EEGLAB (sccn.ucsd.edu)**
- **2004 - 1st EEGLAB support from U.S. NIH and reference paper (Delorme & Makeig, 2004)**
- **2006 - 1st EEGLAB plug-ins, STUDY structure, and component clustering tools**
- **2009+ – New toolboxes: NFT, SIFT, BCILAB, MPT, … (Akalin Acar, Mullen, Kothe, …)**
- **2011 – EEGLAB, the most widely used EEG research environment (Henke & Halchenko)**
- **2013 – Lab Streaming Layer (LSL) (Kothe) for Mobile Brain/Body Imaging (MoBI) (Makeig)**
- **2013 – *HeadIT.org* online, HED/ESS neuroinformatic tools (Bigdely-Shamlo)**
- **2017 – LIMO / GLM integrated (Pernet) -- and 24rd- 26th EEGLAB Workshops …**
- **2018 – The Open EEGLAB Portal via the Neuroscience Gateway (nsgportal.org).**
- **2019 – EEGLAB 2019, BIDS integration, ICLabel, get_chanlocs, etc.**

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 –

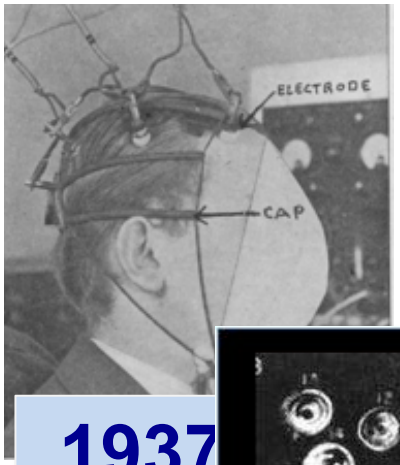
local spatial field coherence..

1926 -

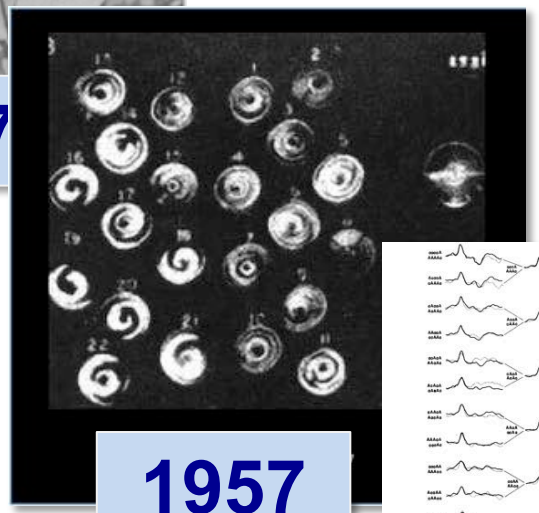
Functional Brain Imaging using EEG

- 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

Development of EEG brain Imaging …

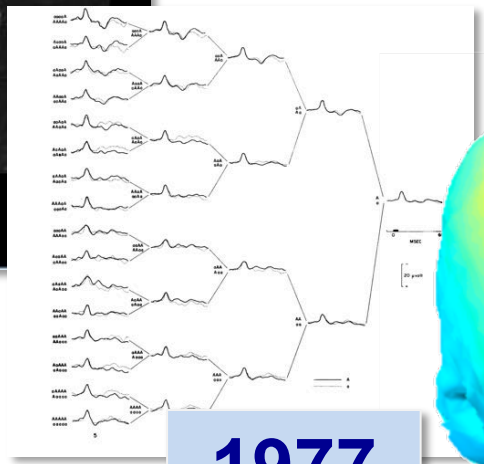


1937



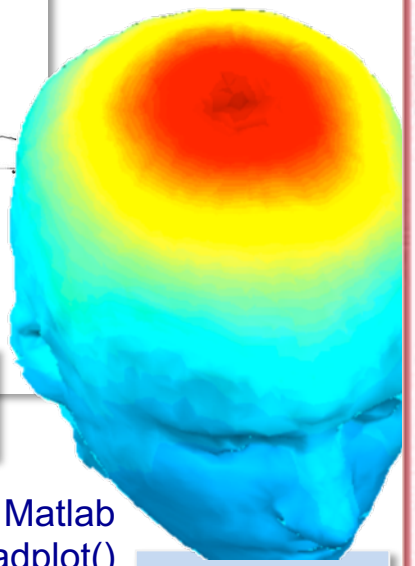
1957

Toposcope
Grey Walter



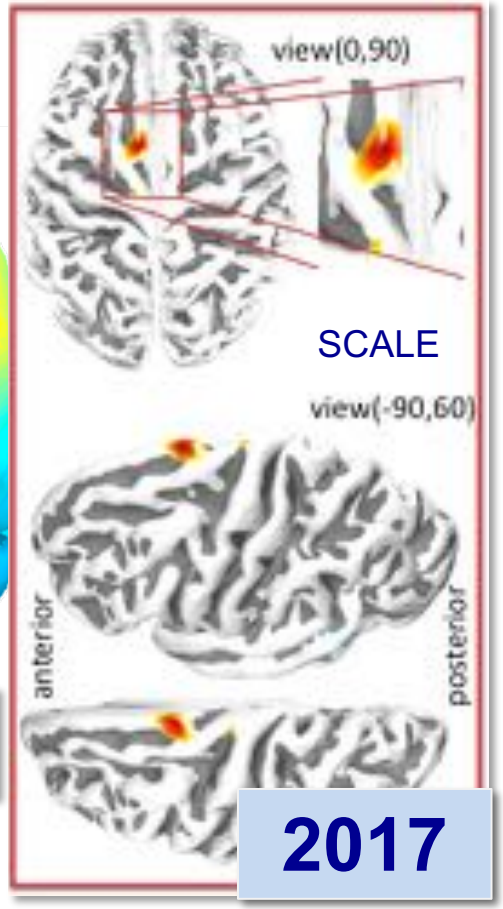
Oddball ERPs
K. Squires et al.

1977



Matlab
headplot()
→ EEGLAB

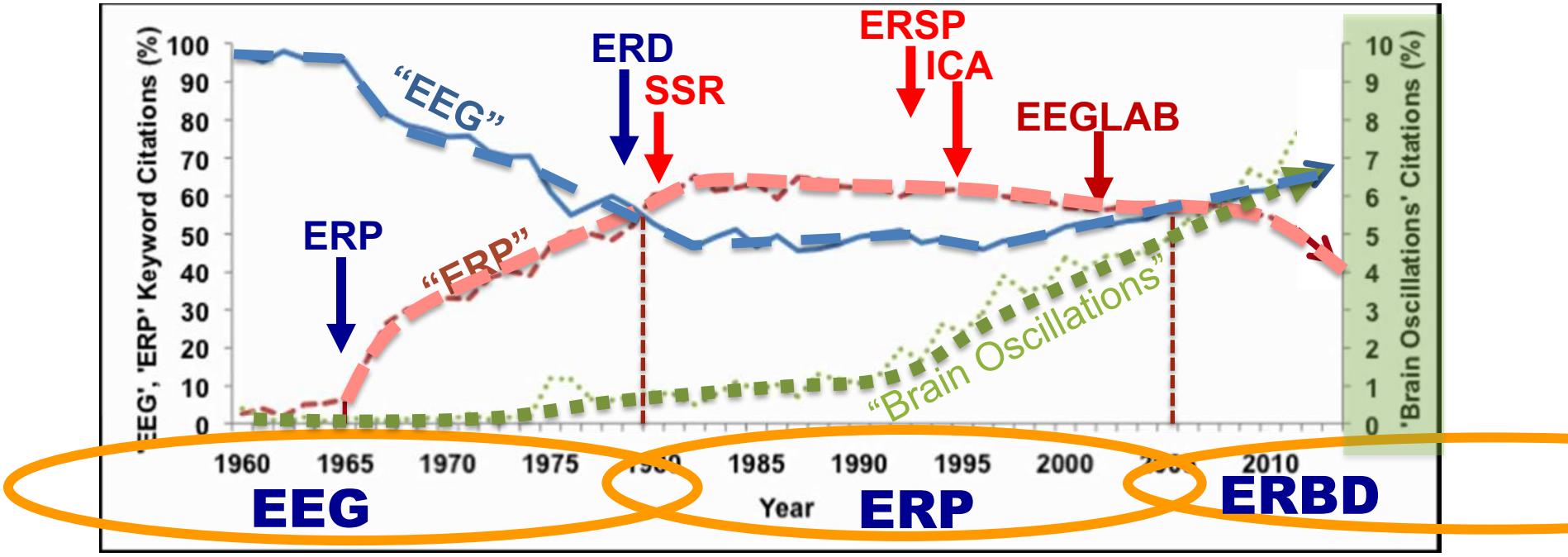
1997



2017

Z. Akalin Acar et al.

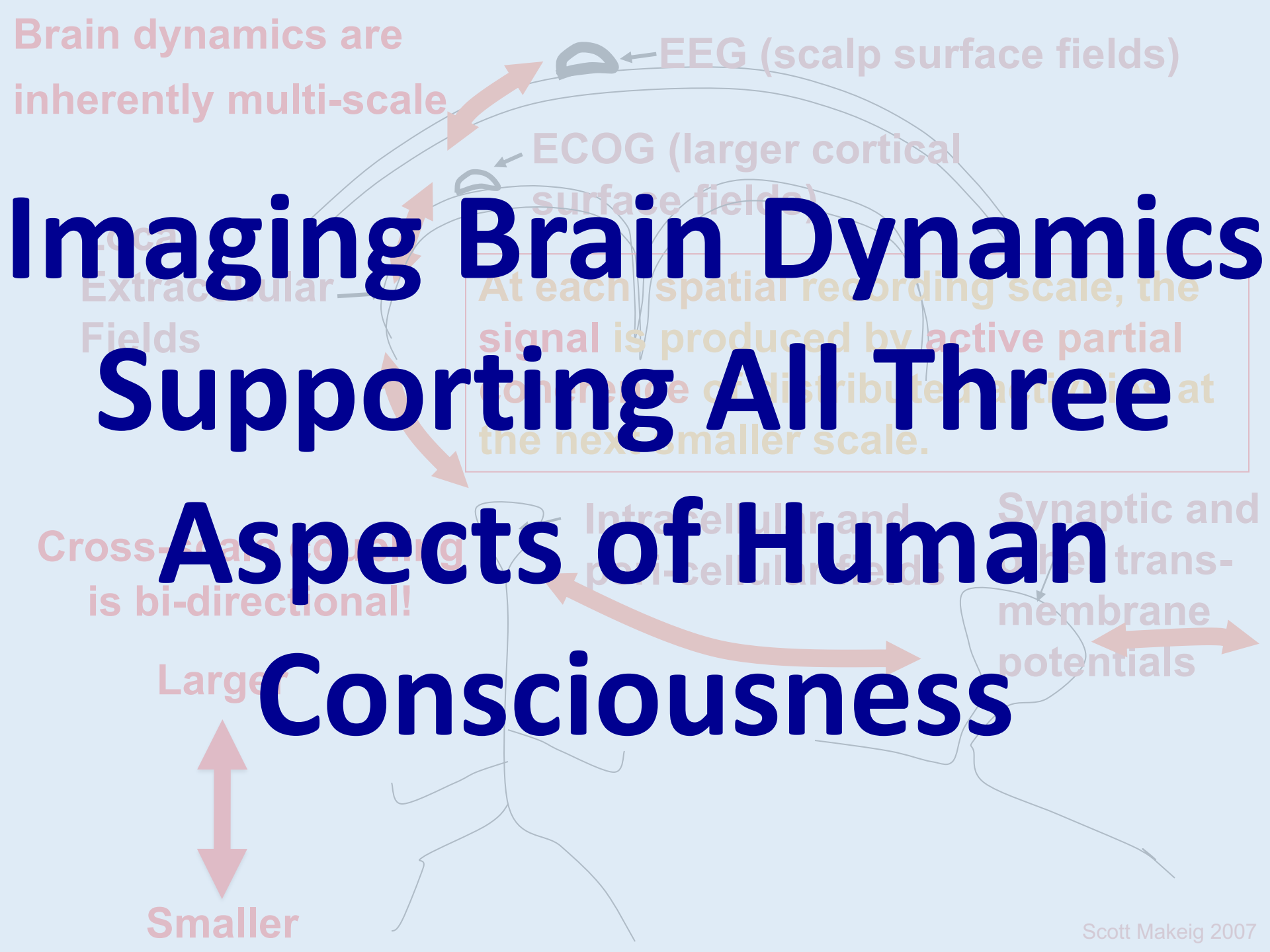
Three Modern Eras of EEG Research



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



Imaging Brain Dynamics Supporting All Three Aspects of Human Consciousness

Embodied Agency

Brain processes

have evolved and function

to optimize the ***outcomes***

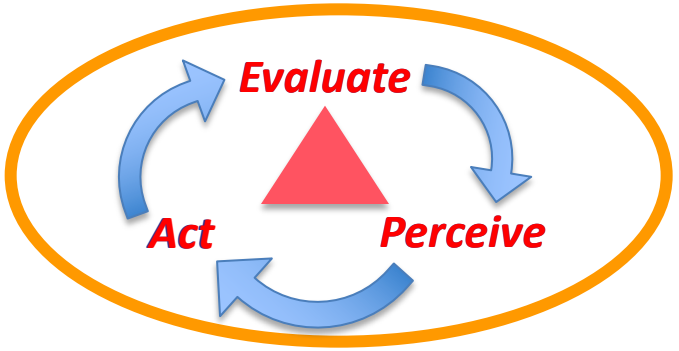
of the ***behavior***

the brain organizes

in response to

perceived challenges

and opportunities.



Brains meet the challenge
of the moment
– *every* moment!

S Makeig 2010

Embodied Agency

Brain processes

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*of the **willed** behavior*

the brain organizes

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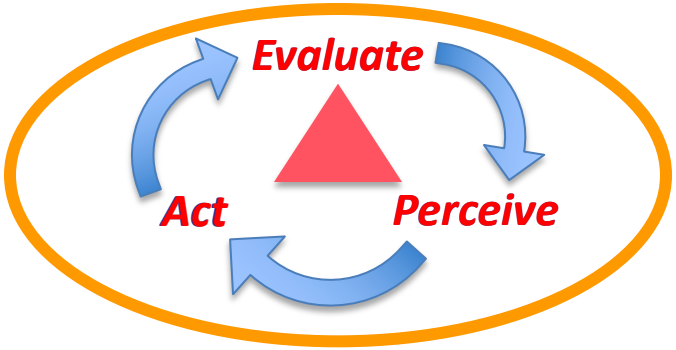


Brains meet the challenge
of the moment
– *every* moment!

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

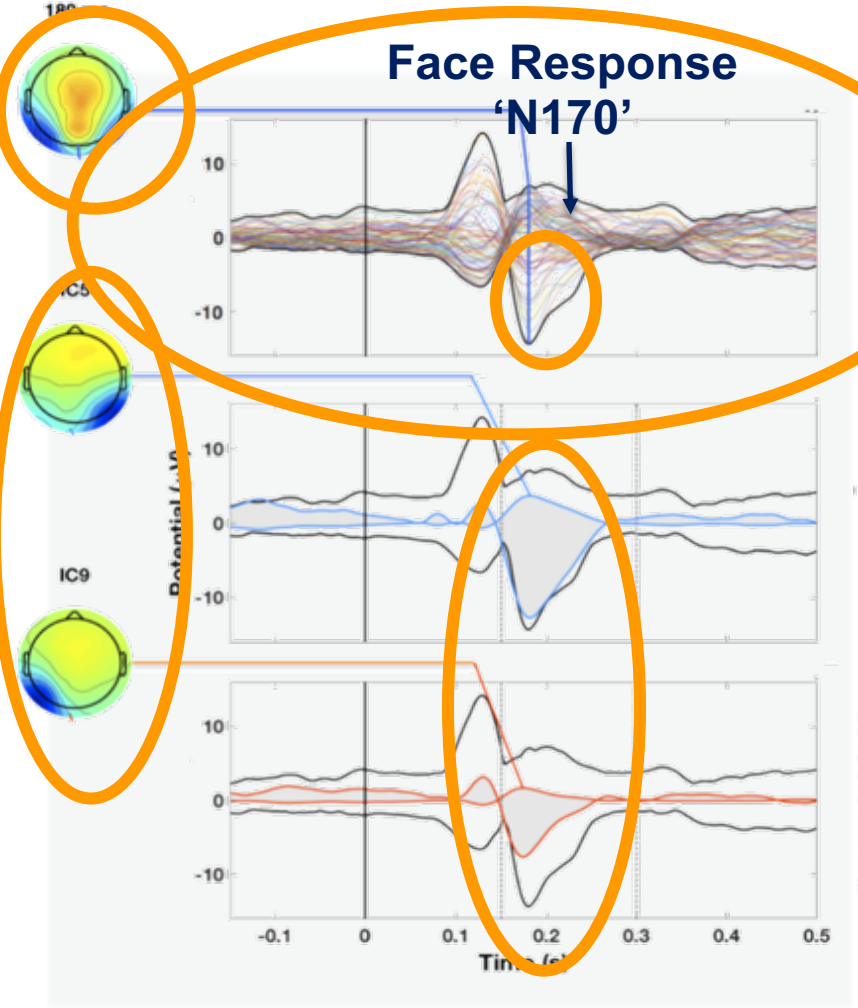
Feeling

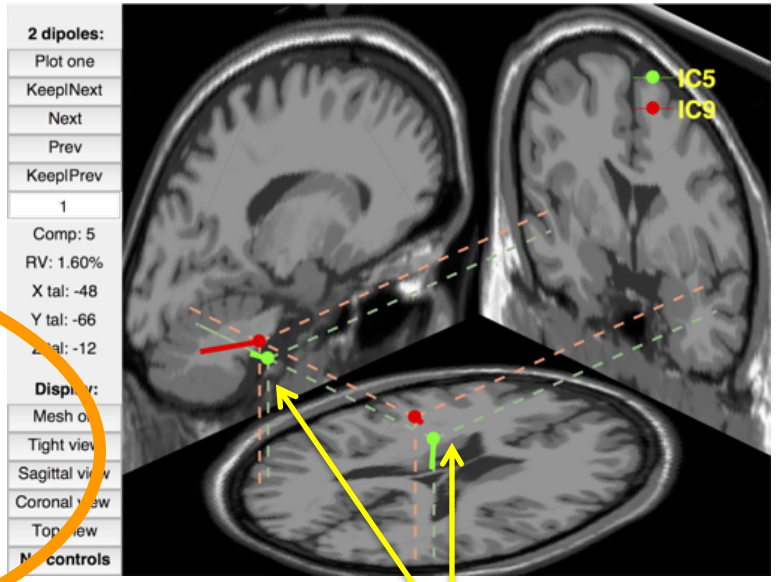
Willing

S. Makeig (2017)

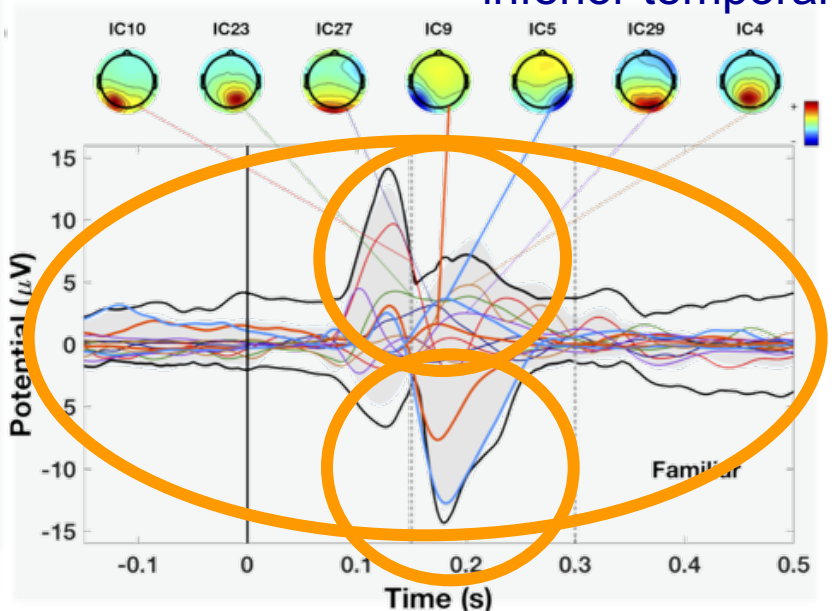
Knowing

- "I see a face photo."
- "I see a house photo."





Face area in bilateral inferior temporal cortex



S. Makeig (2017)

Feeling

Emotion Imagination Experiment

Suggested the eyes-closed experience of 15 different emotions *via guided imagery*.

Collected 1-5 min of continuous high-density EEG data in each emotion state.

28 subjects

Onton & Makeig, 2009

Willing

Imaging Human Agency

S . Makeig, 2007

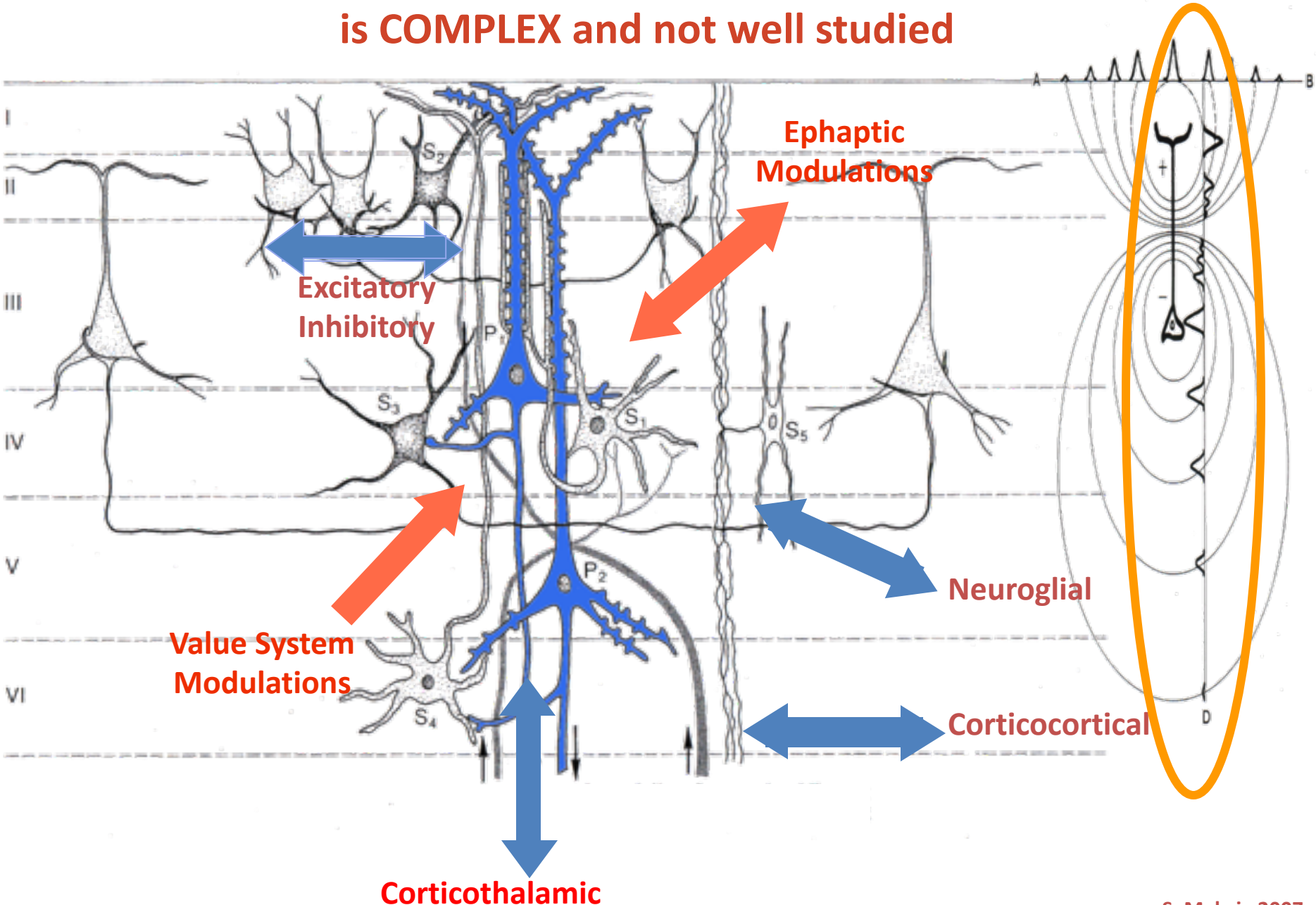
What is scalp EEG?

- 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?**

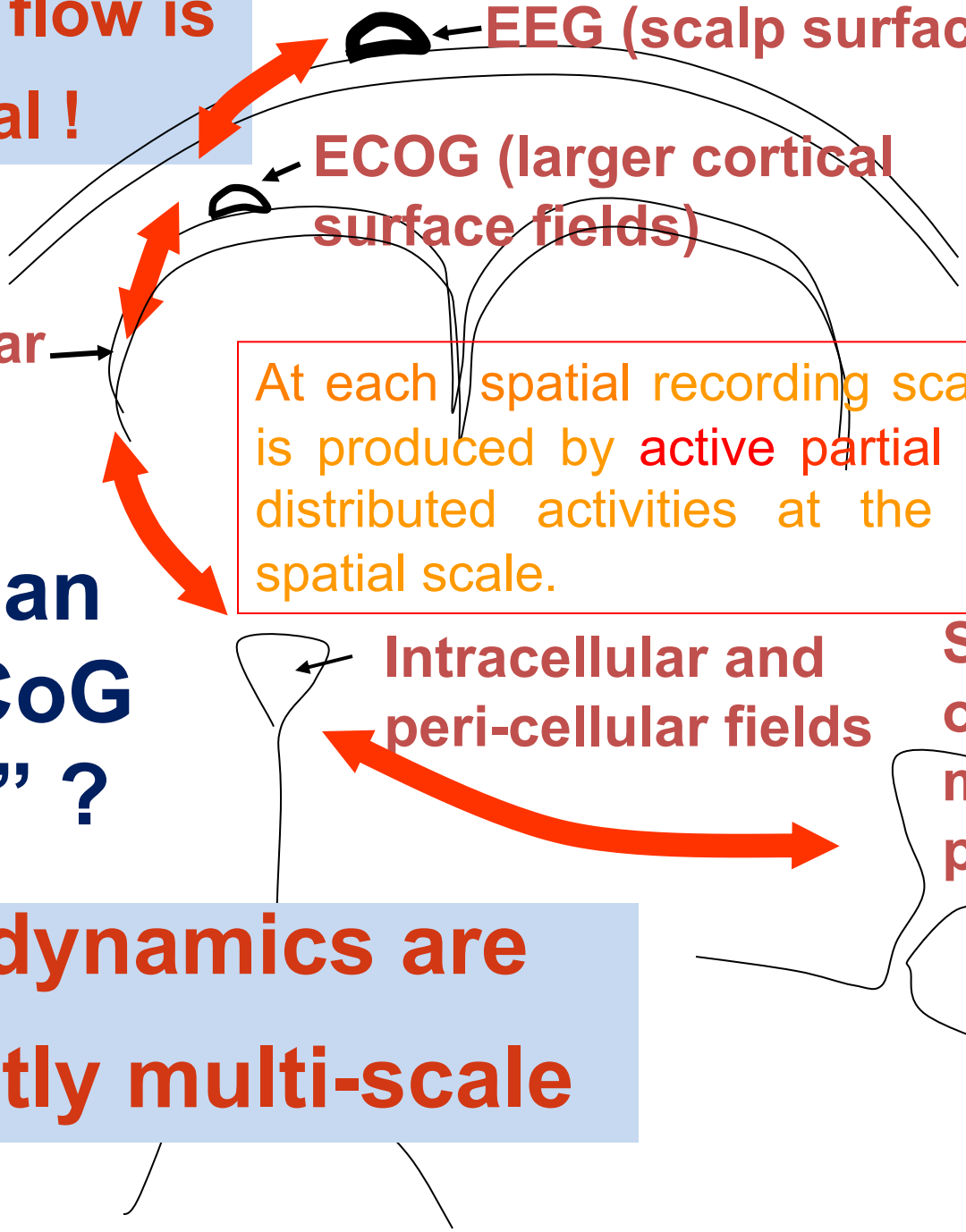
Cloud art: Berndnaut Smilde

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.

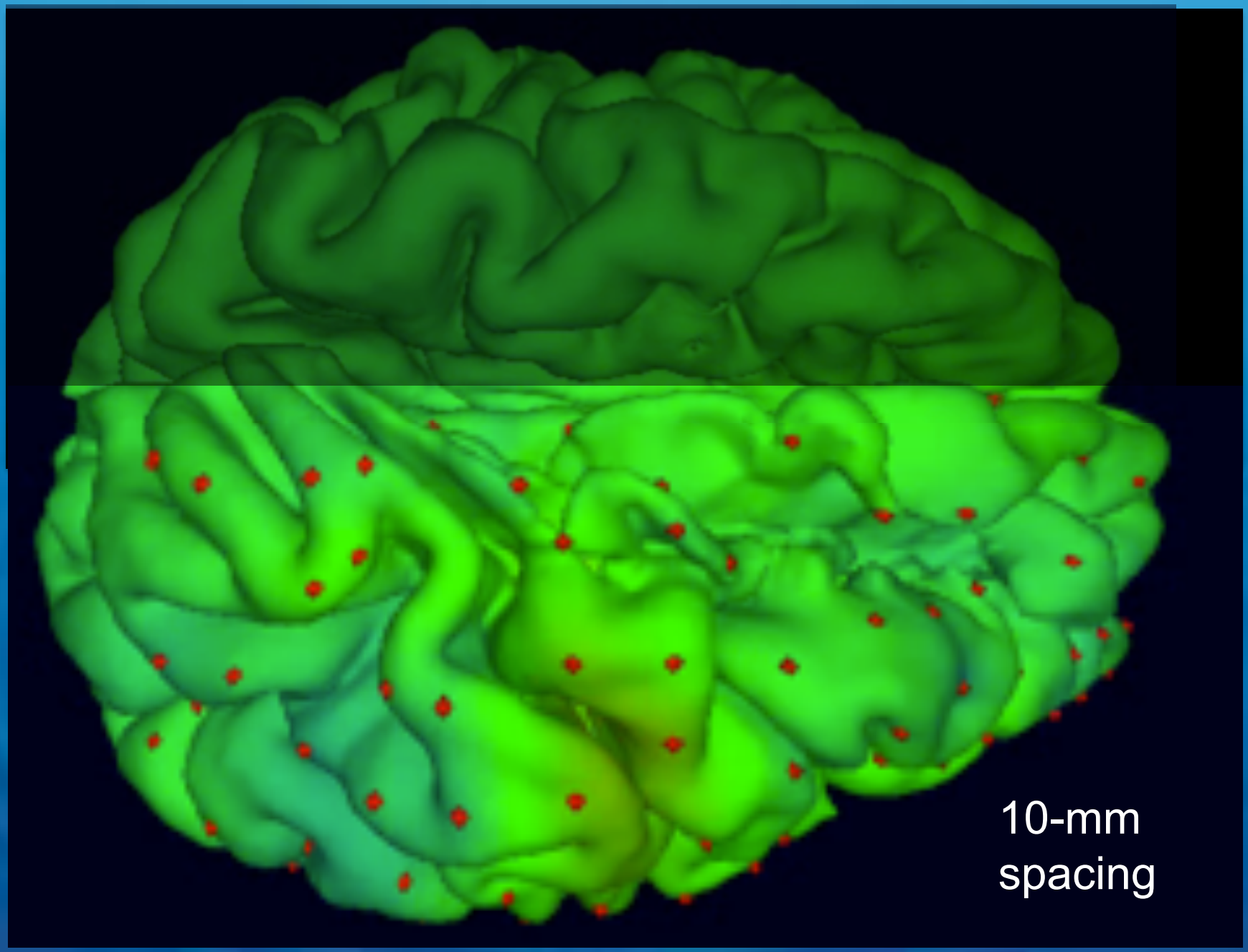
What is an EEG / ECoG "source" ?

Brain dynamics are inherently multi-scale

Scott Makeig 2007

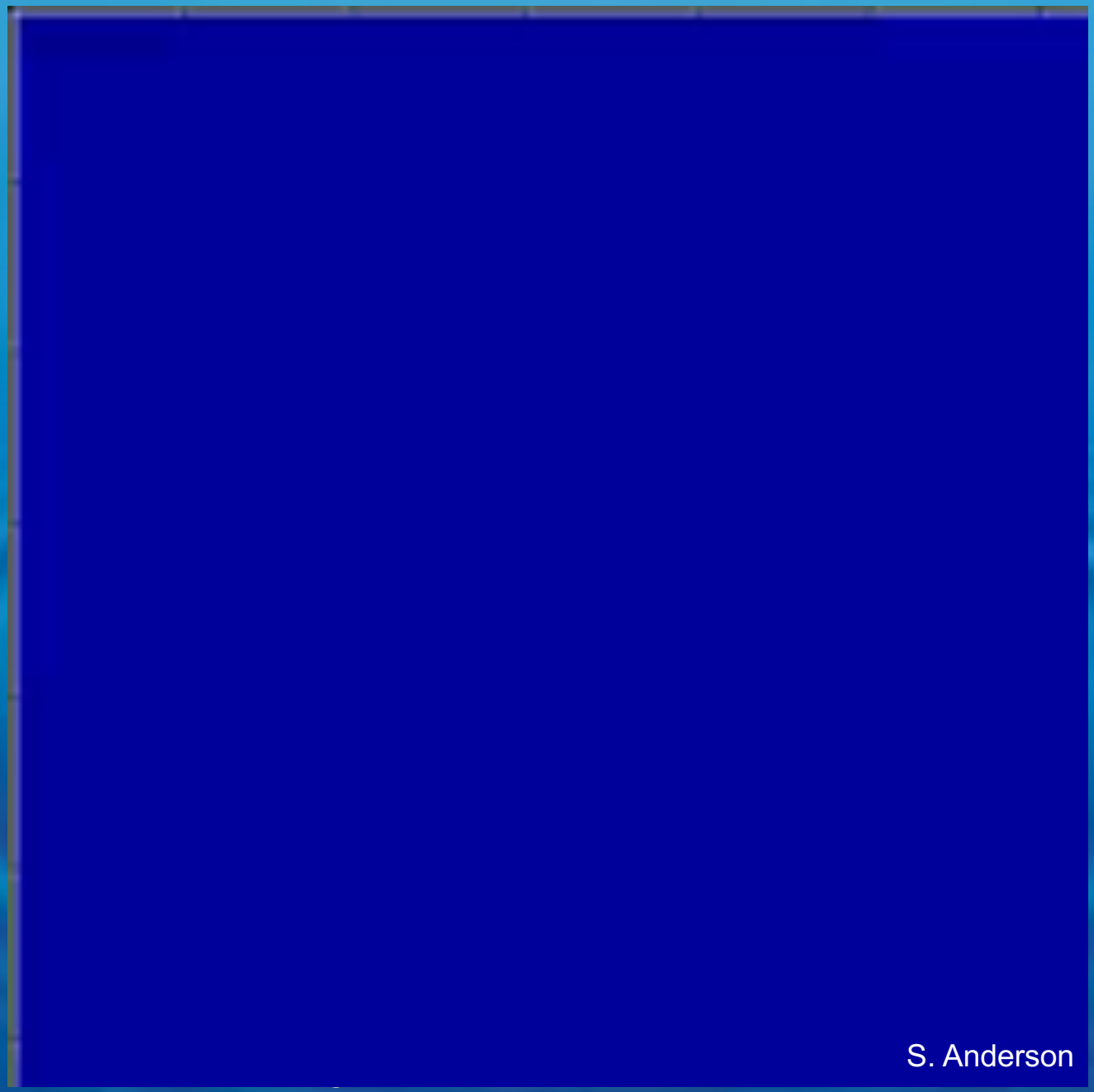
The spatiotemporal dynamics of cortex & brain have not yet been imaged on multiple spatial scales!

Alan Friedman



Z Akalin Acar, 2017

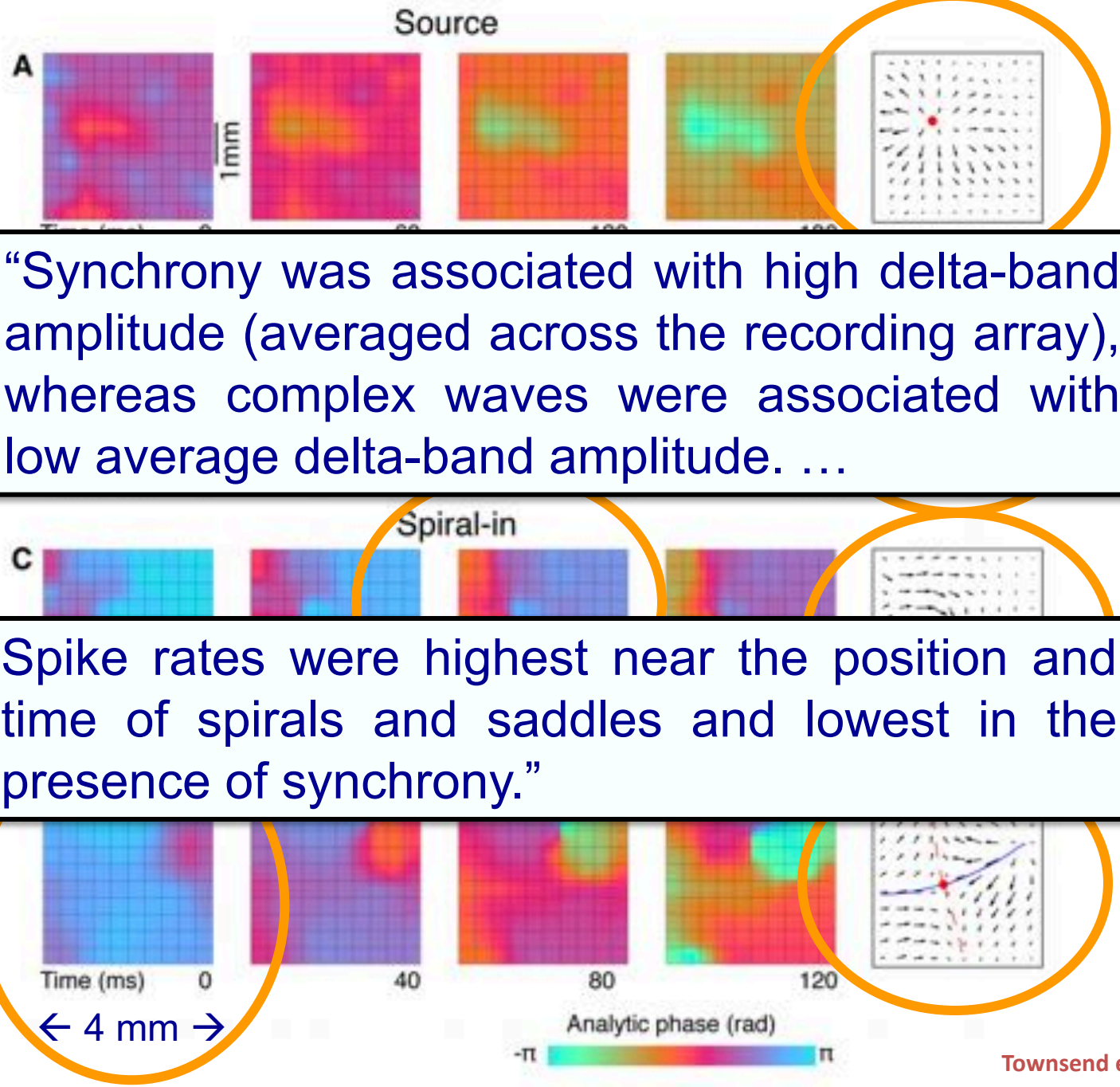
Phase cones (Freeman)



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."

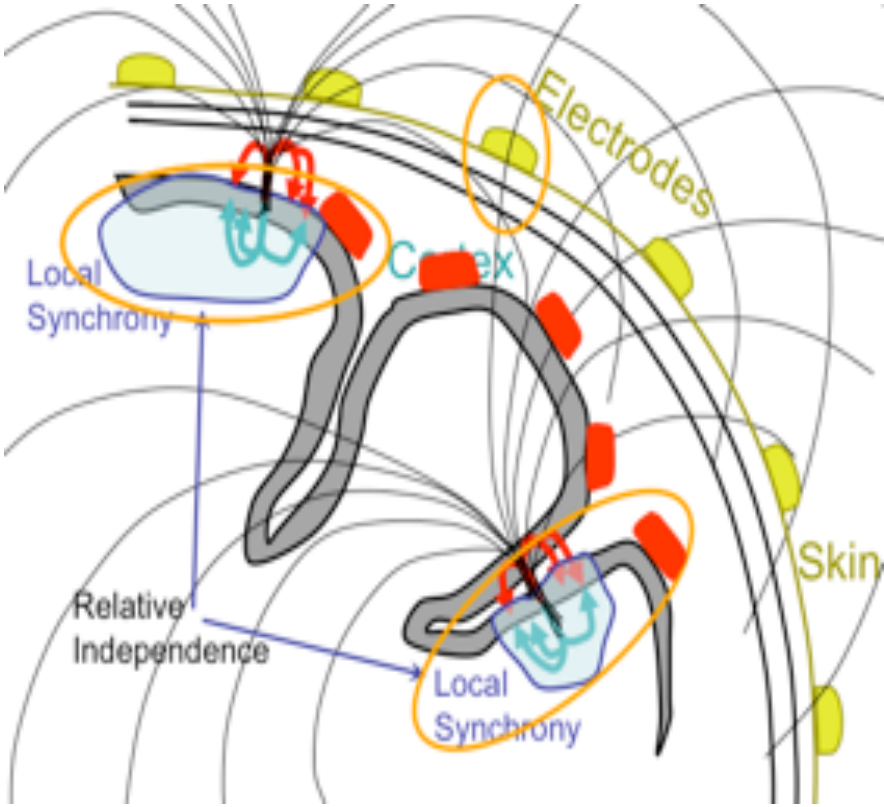
Simple patterns

Complex patterns

Townsend et al., 2015

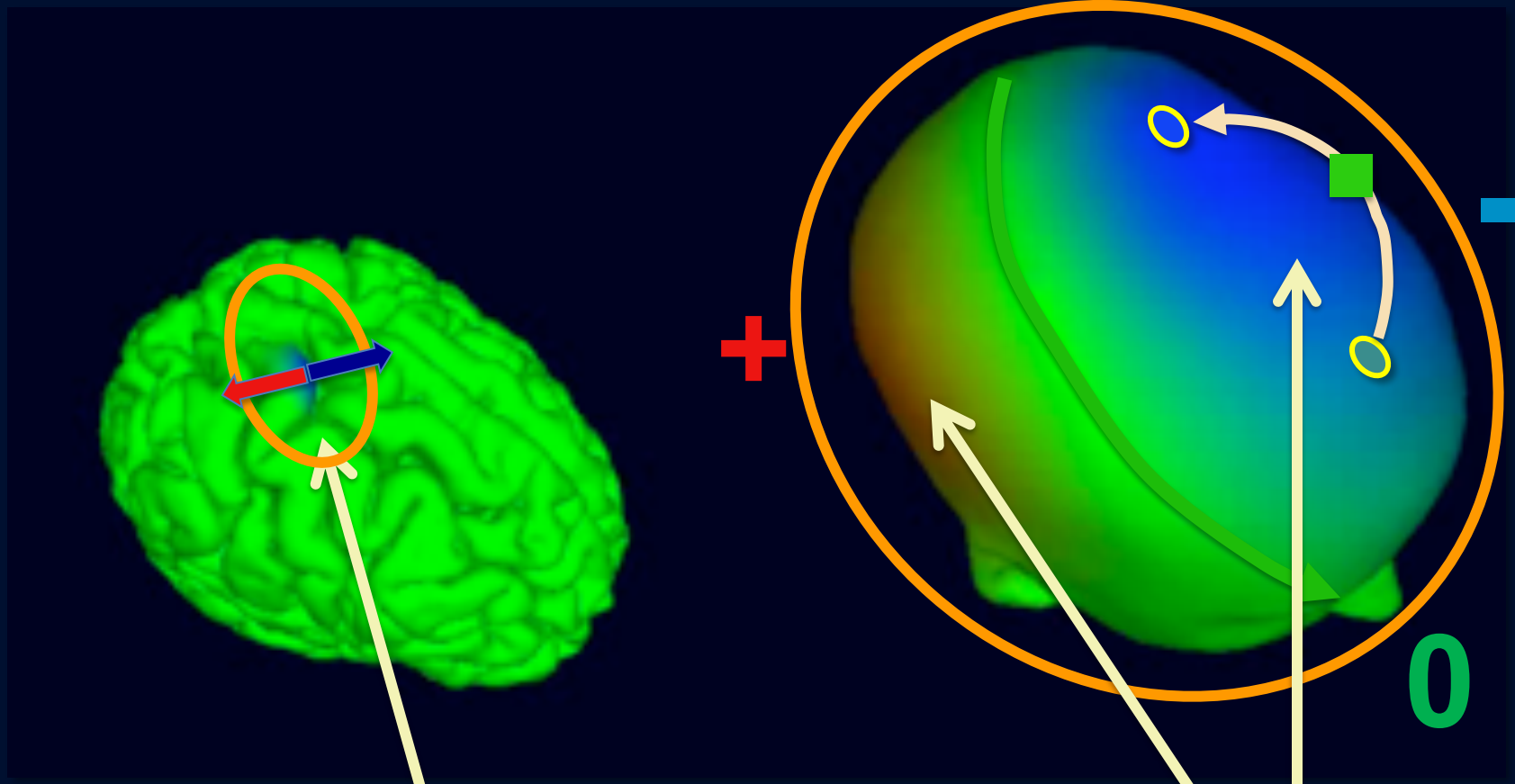
Naïve 2-D interpretation of EEG signals?

Cortical EEG signal projection patterns as point processes



Cortical source current volume conduction patterns

The very broad EEG point-spread function

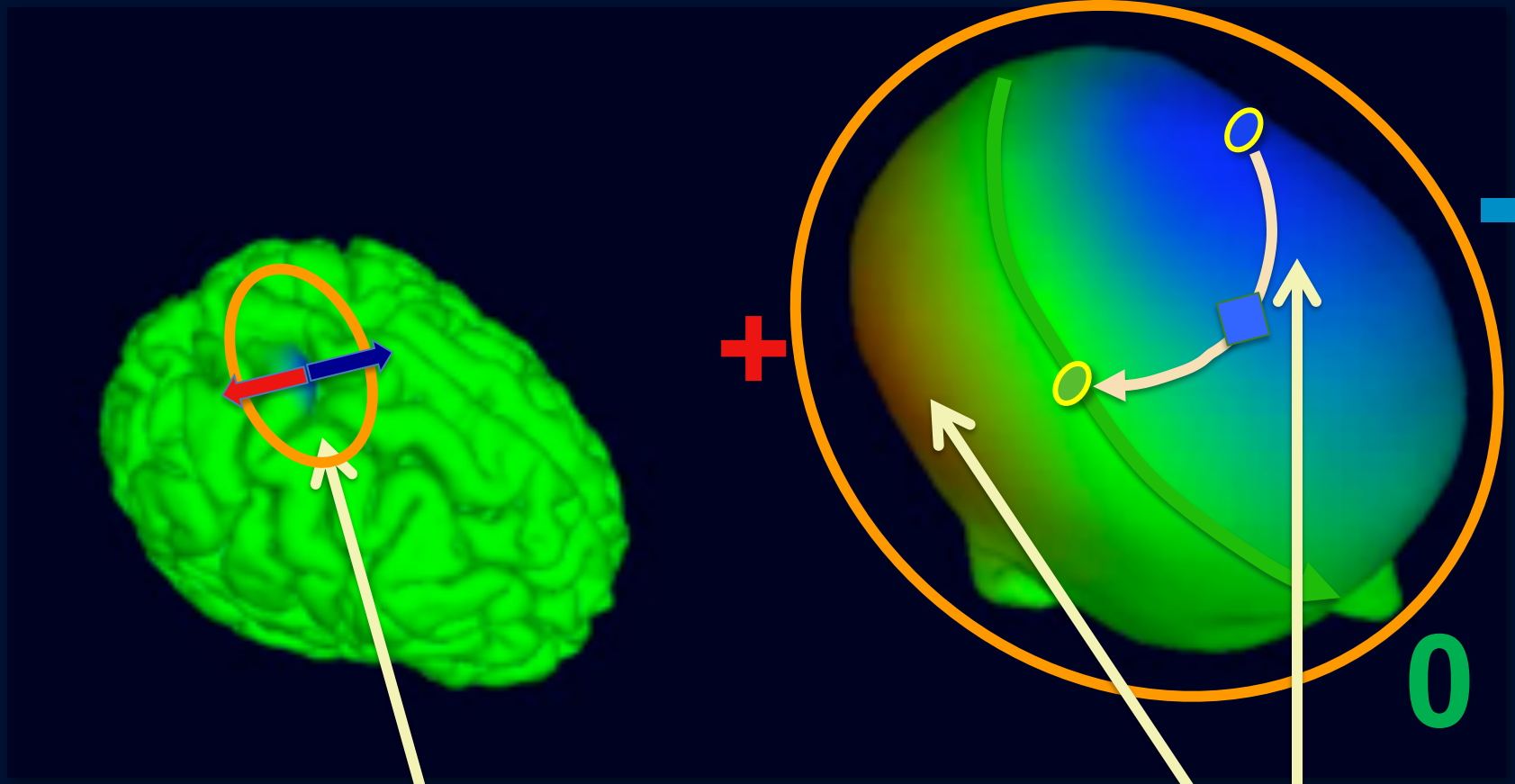


Single simulated parietal source →

Very broad projected scalp potentials

Akalin Acar & Makeig 2010

The very broad EEG point-spread function



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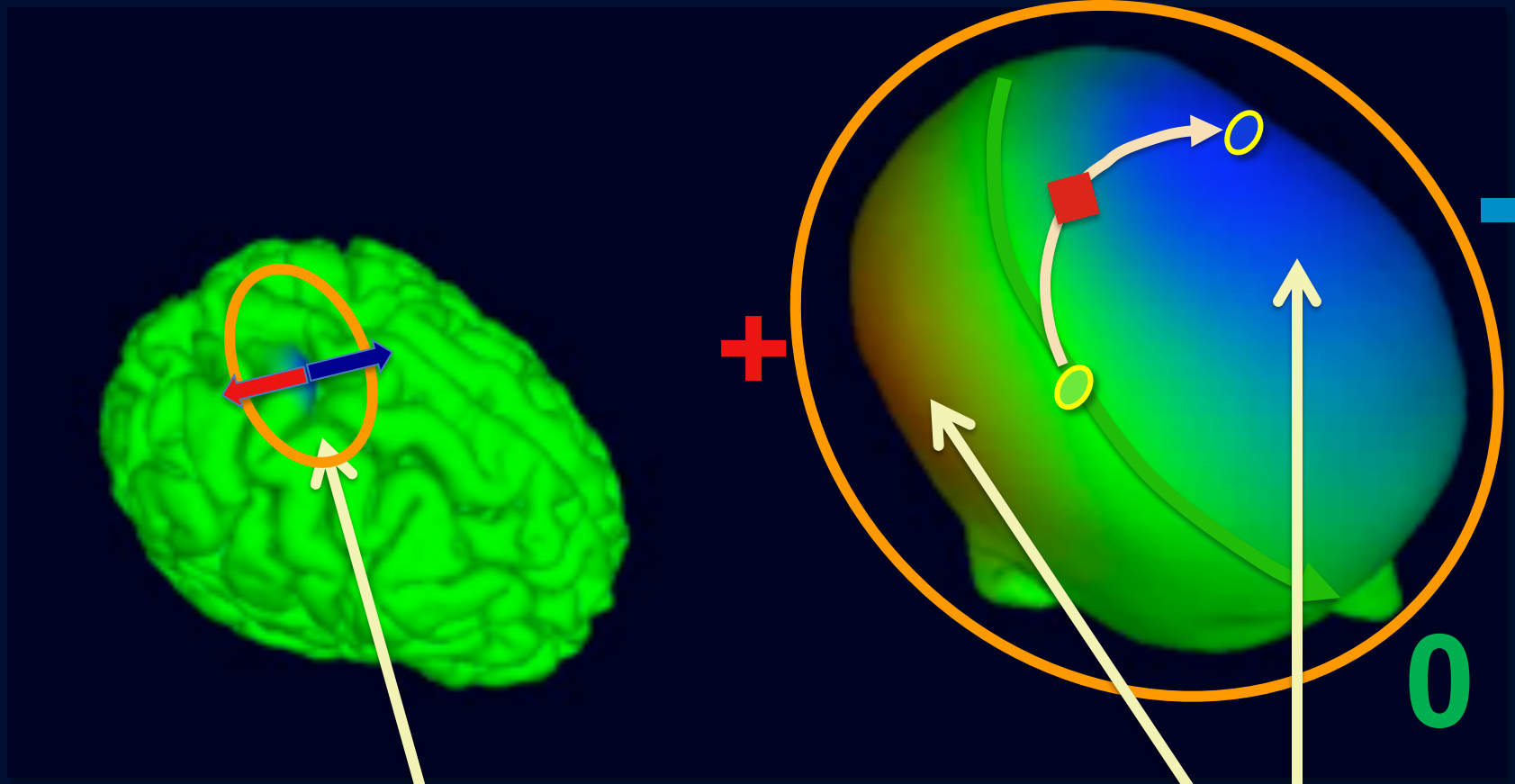

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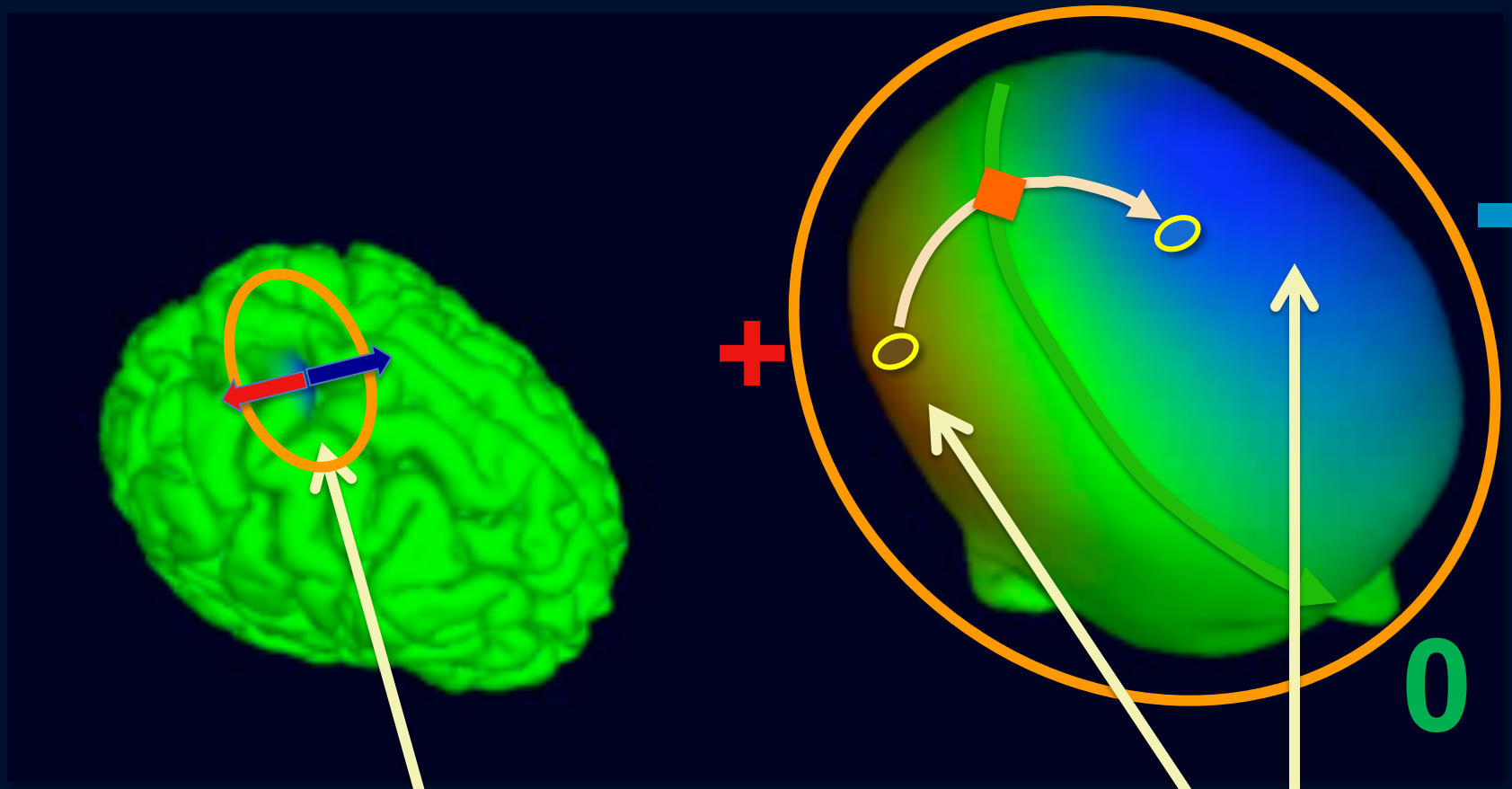

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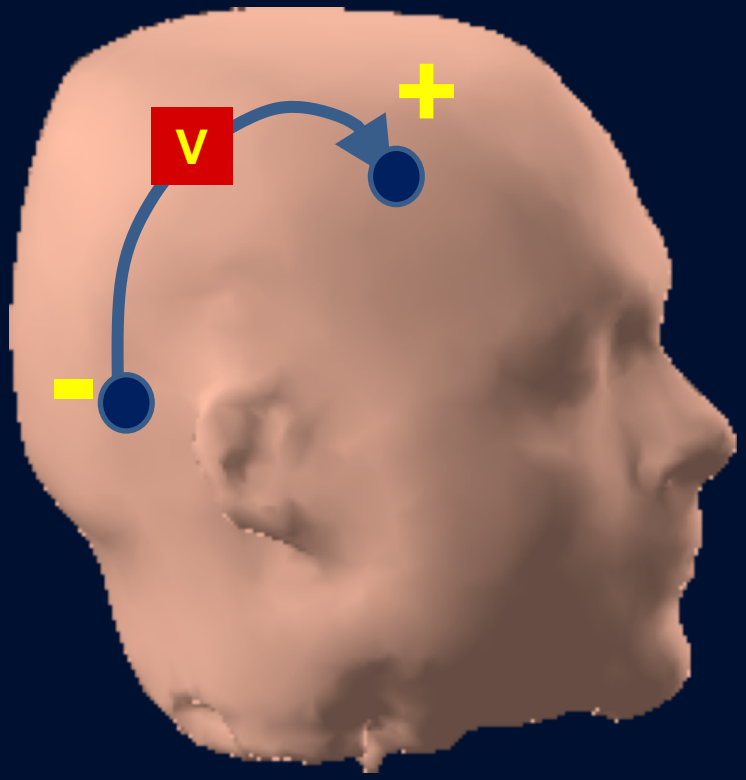
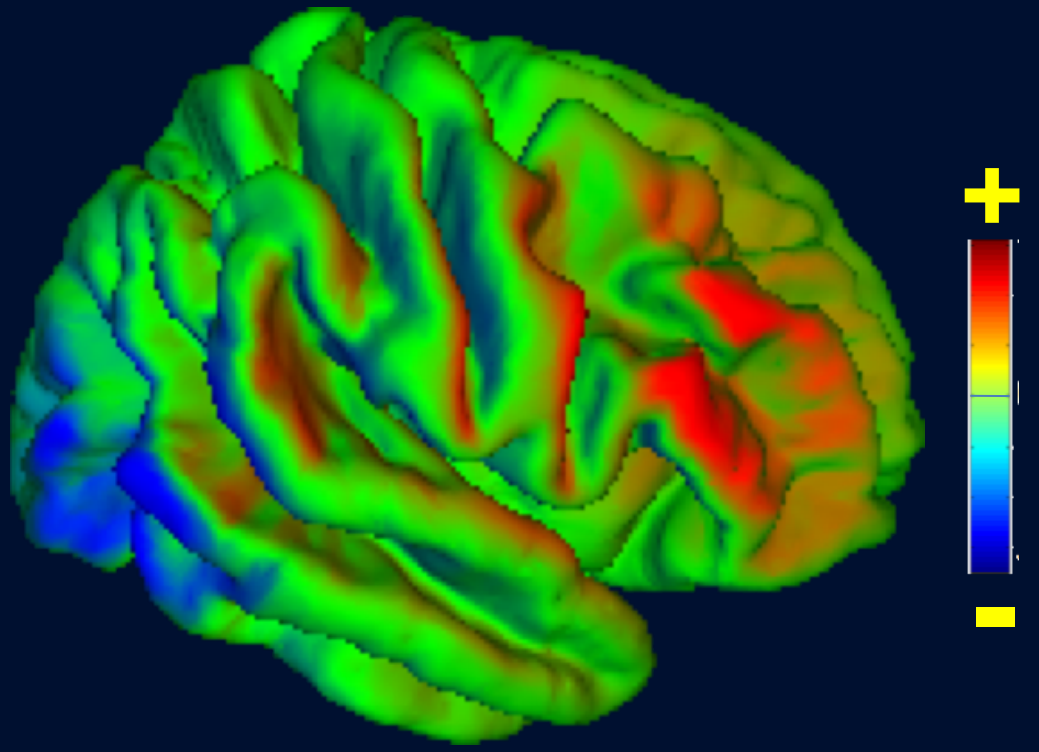
Akalin Acar & Makeig 2010

The ‘receptive field’ of a bipolar EEG channel



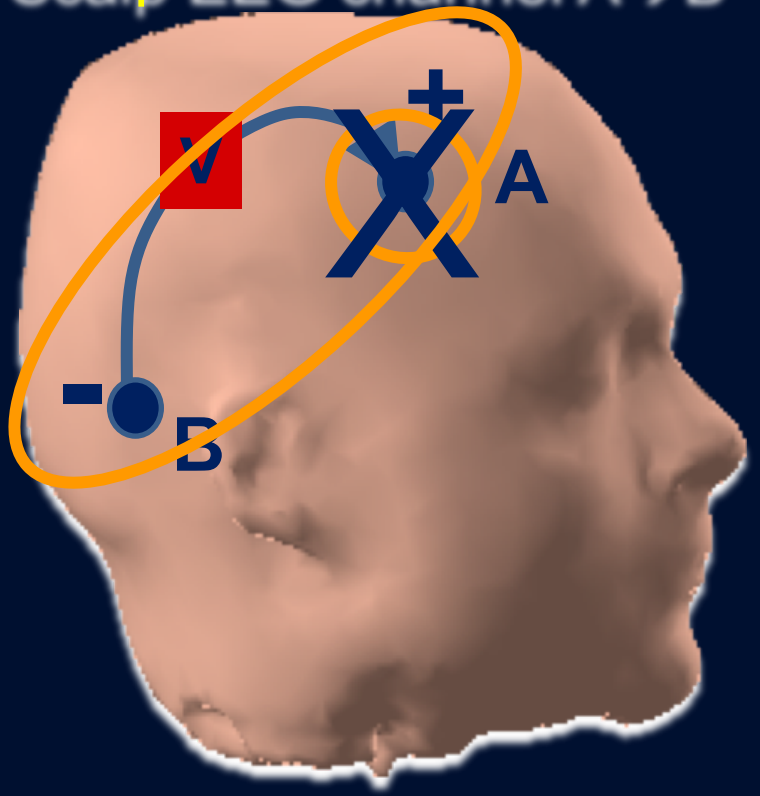
Scalp EEG channel

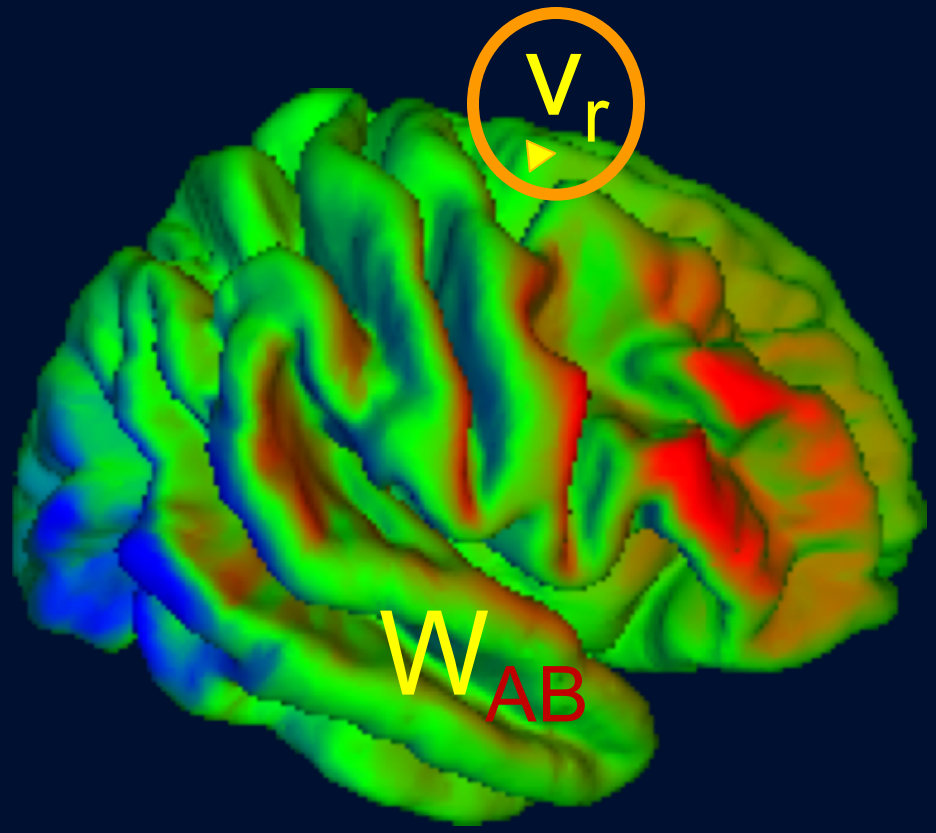


Its cortical ‘receptive field’

The ‘receptive field’ of a bipolar EEG channel!

Scalp EEG channel A→B





Its cortical ‘receptive field’

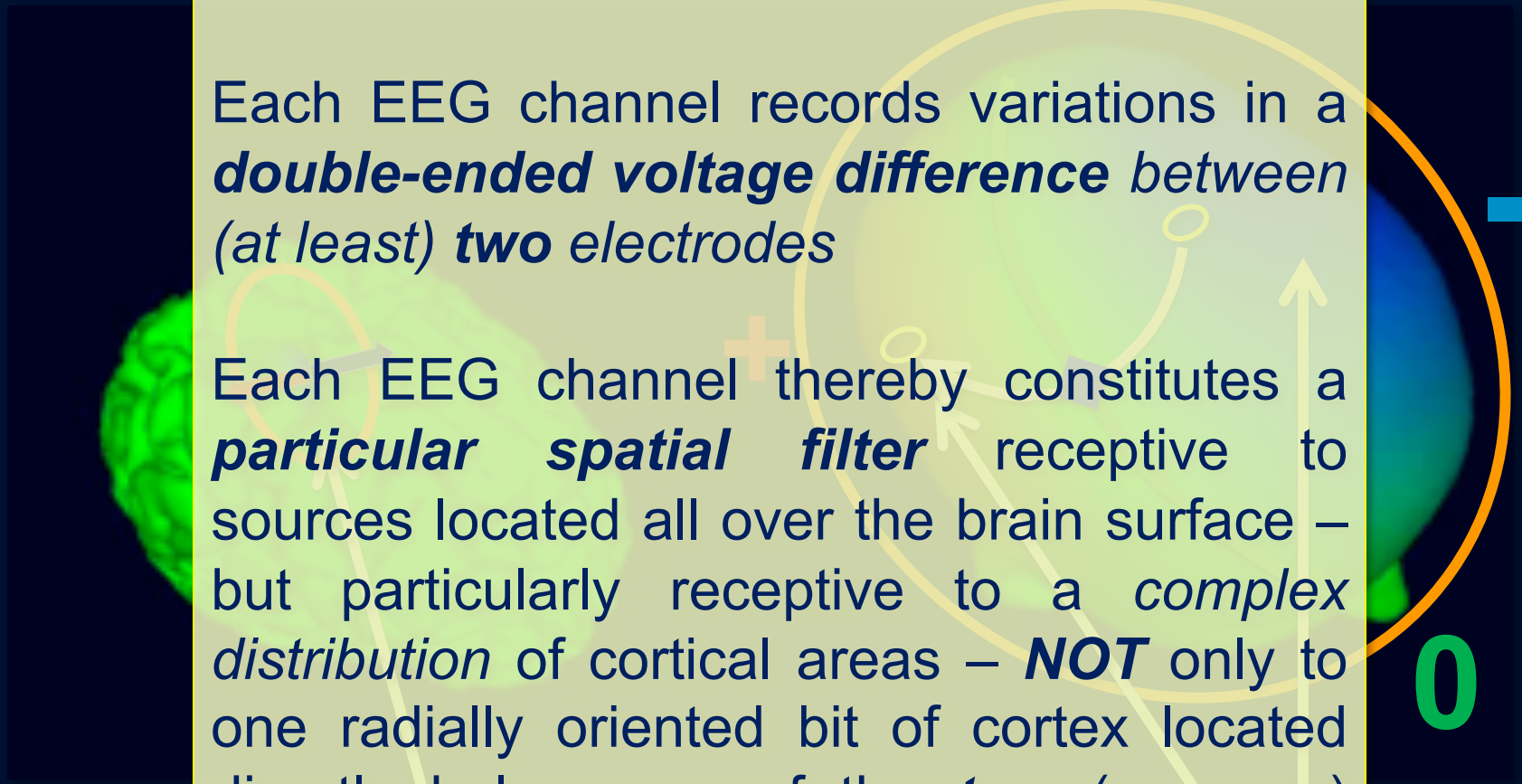
At time t,

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

The very broad EEG point-spread function

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

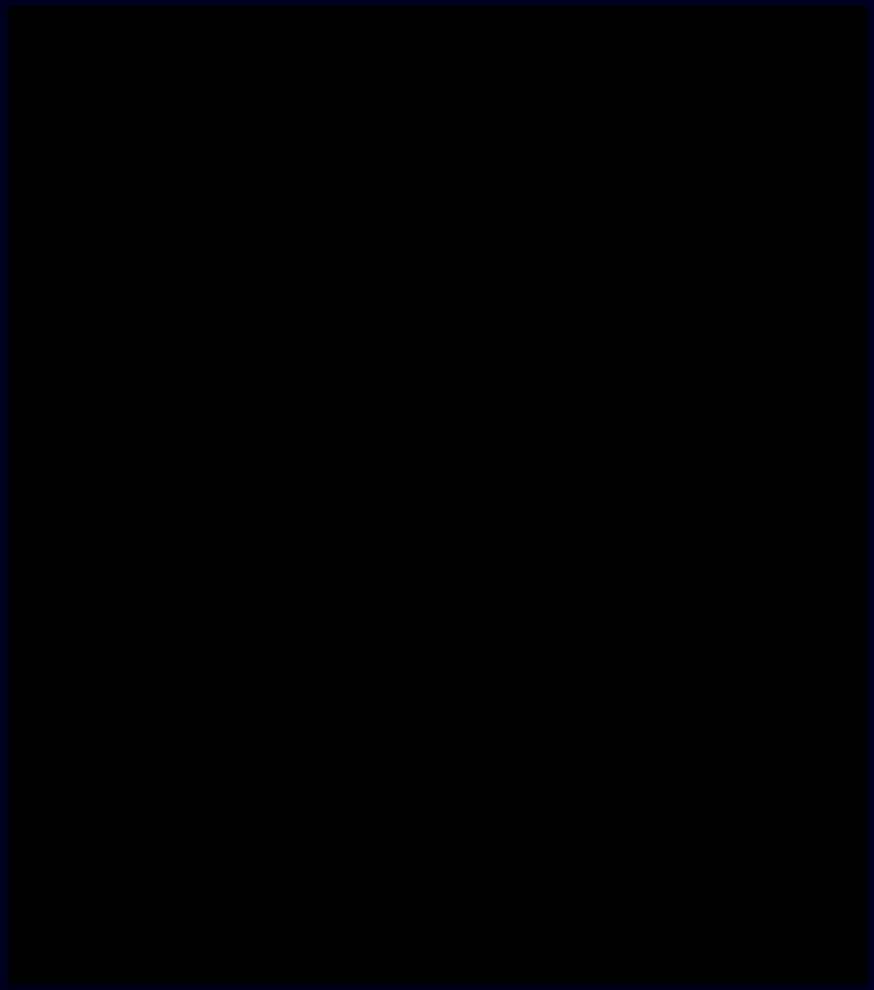
Each EEG channel thereby constitutes a ***particular spatial filter*** receptive to sources located all over the brain surface – but particularly receptive to a *complex distribution* of cortical areas – ***NOT*** only to one radially oriented bit of cortex located directly below ***one*** of the ***two***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

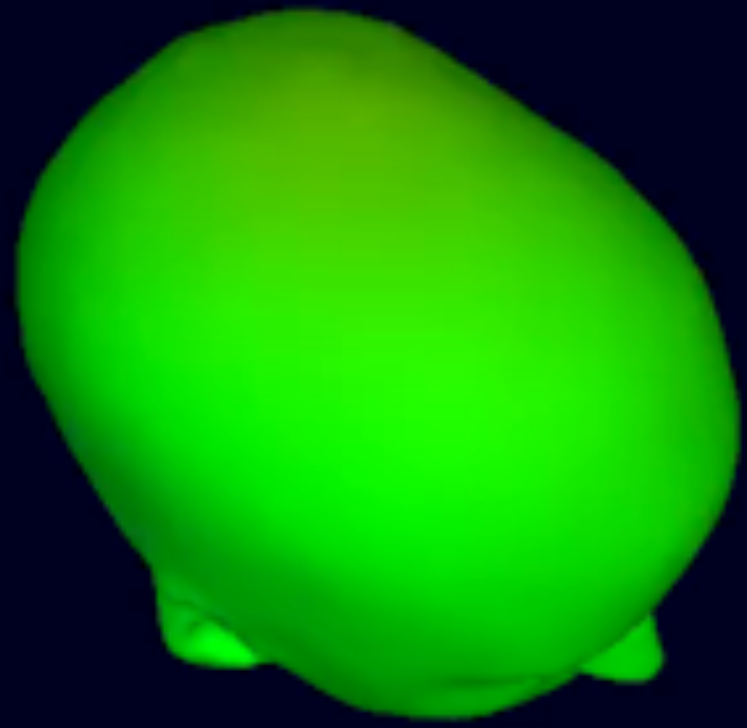


Single simulated parietal source → Very broad projected scalp potentials

Akalin Acar & Makeig 2010

What are the cortical ‘sources’?



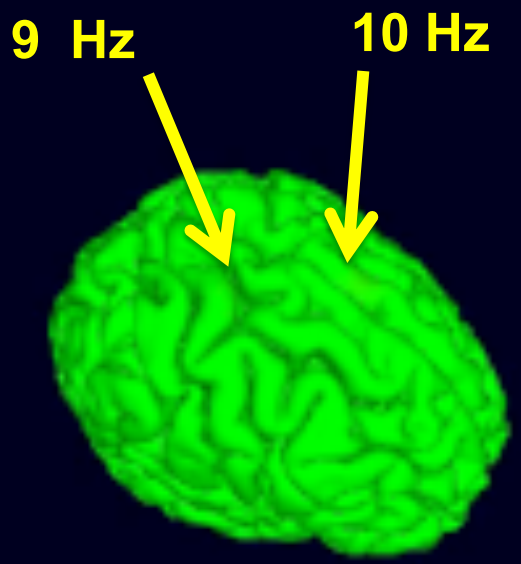


Scalp projection

Z. Akalin Acar & S. Makeig (2012)

Scalp epiphenomena !

Phenomena



Two spatially stationary cortical effective sources

Epiphenomenal

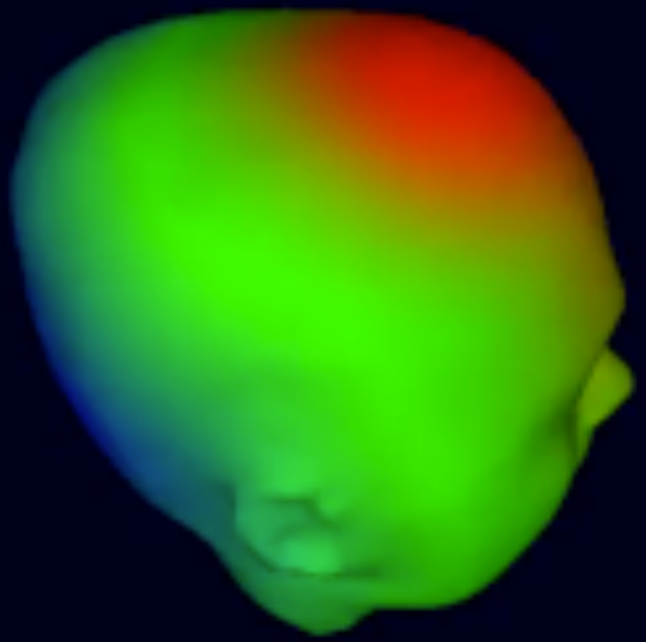
epiphenomena --

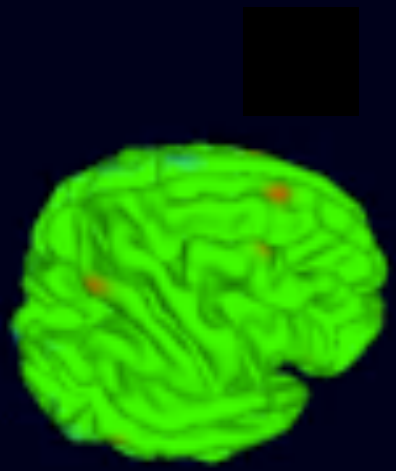
secondary effects or byproducts that arise from but do not causally influence a process.

Summed scalp projection

Z. Akalin Acar & S. Makeig (2012)

Summed scalp projections of 13 effective brain sources

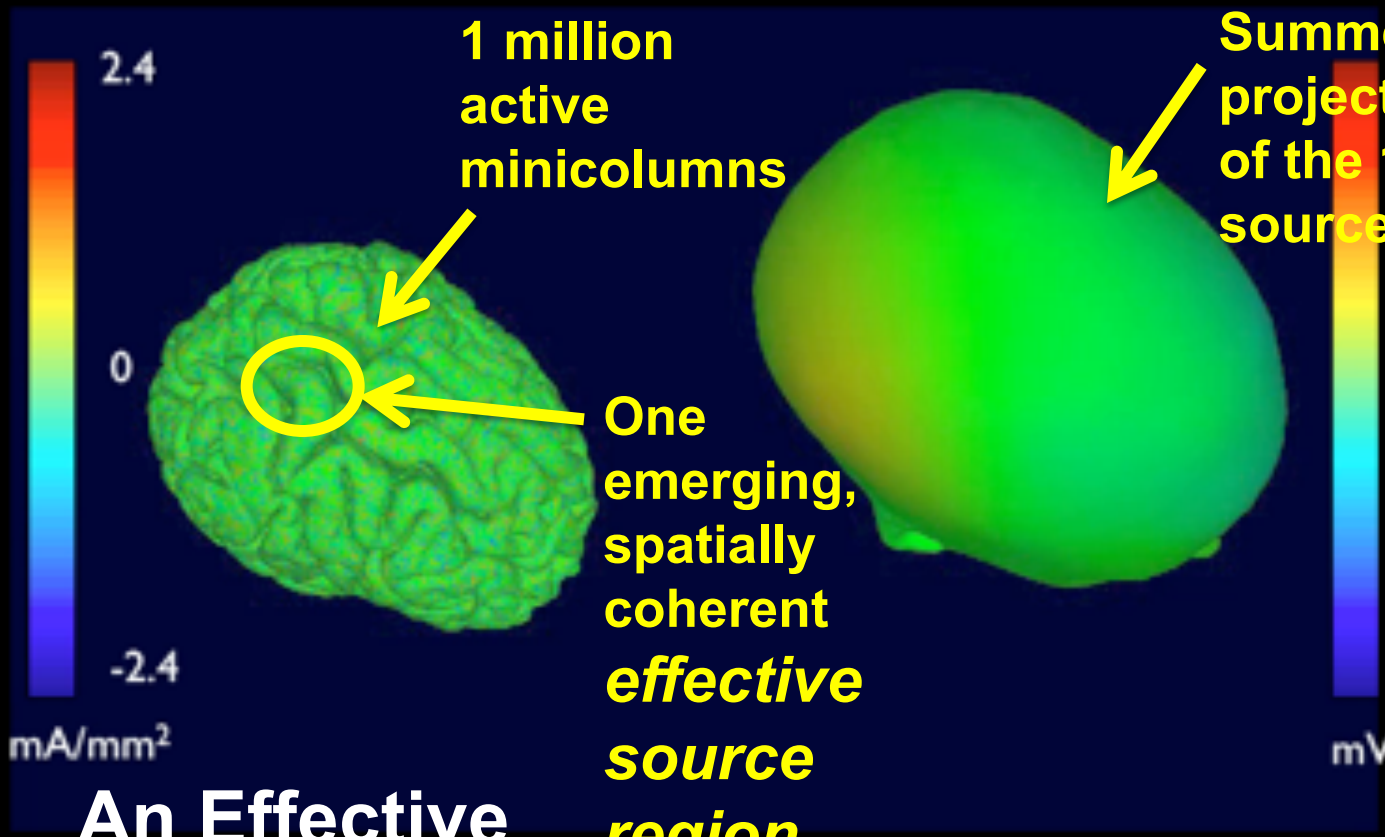




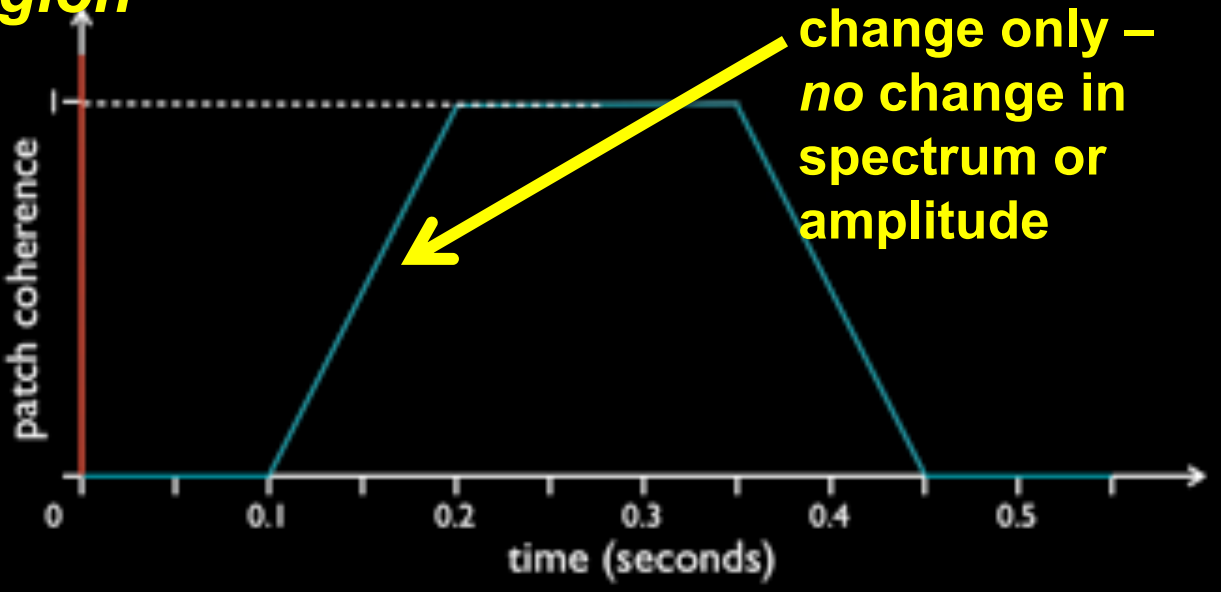
Epiphenomenal Impressions

Causal Phenomena

Z. Akalin Acar & S. Makeig (2016)

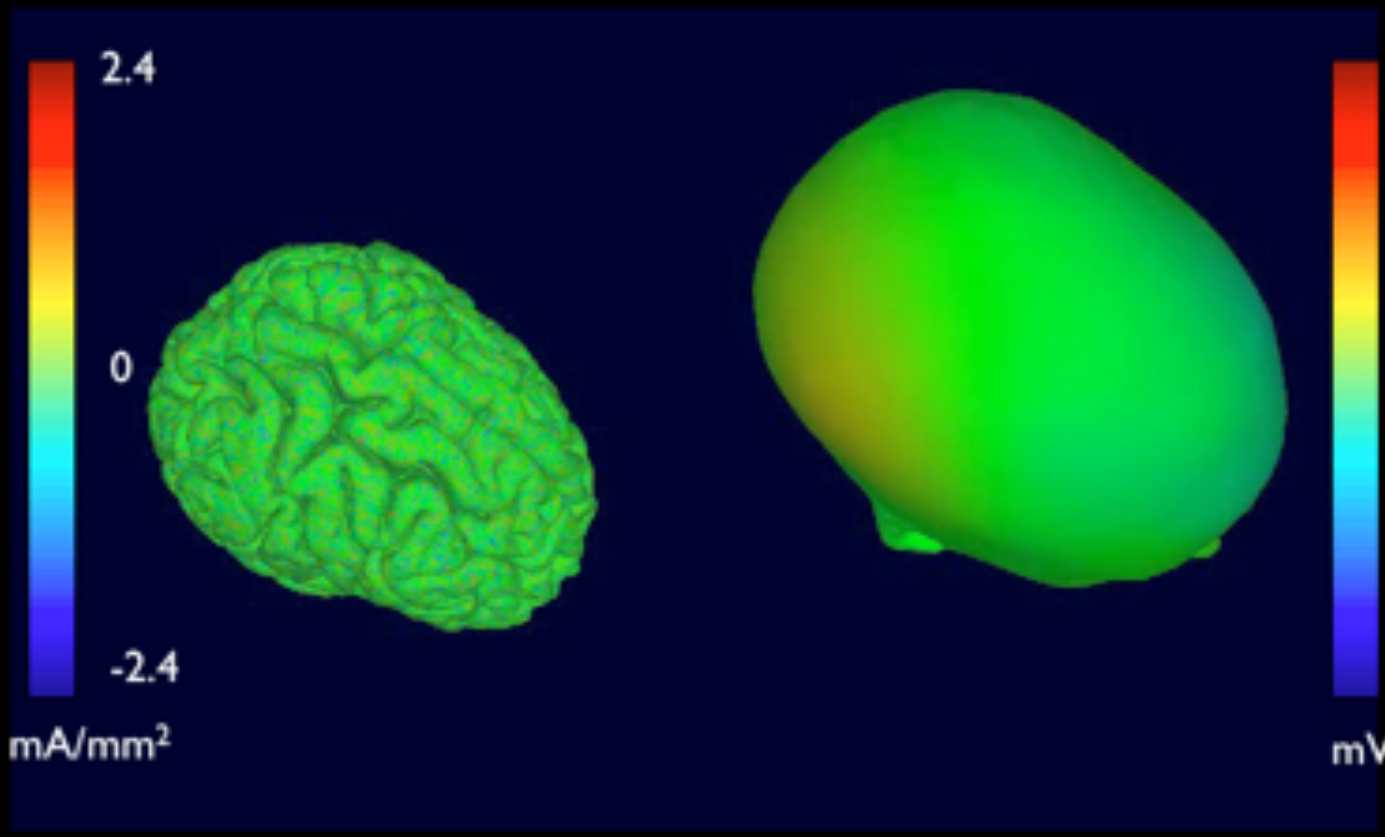


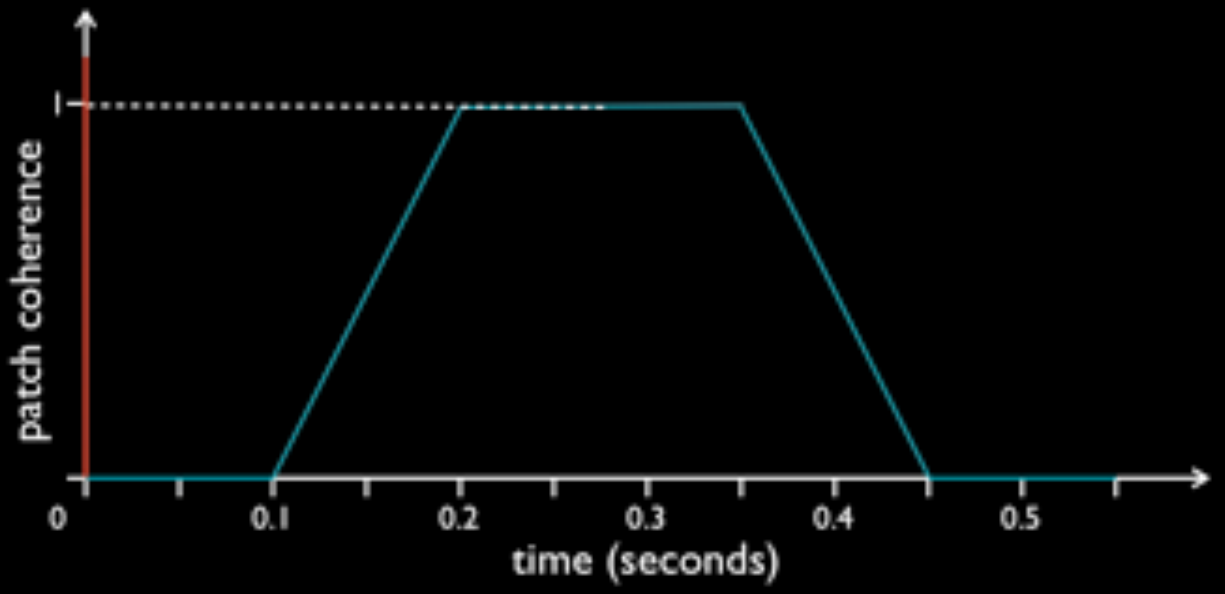
An Effective EEG Source



Local coherence change only – *no* change in spectrum or amplitude

Z. Akalin Acar & S. Makeig (2015)





Z. Akalin Acar & S. Makeig (2015)

1 million active minicolumns

Summed scalp projection

2.4

0

-2.4

mA/mm²

0.13

-0.13

mV

Cortical brain dynamics comprise spatiotemporal dynamics at all spatial and frequency scales at once.

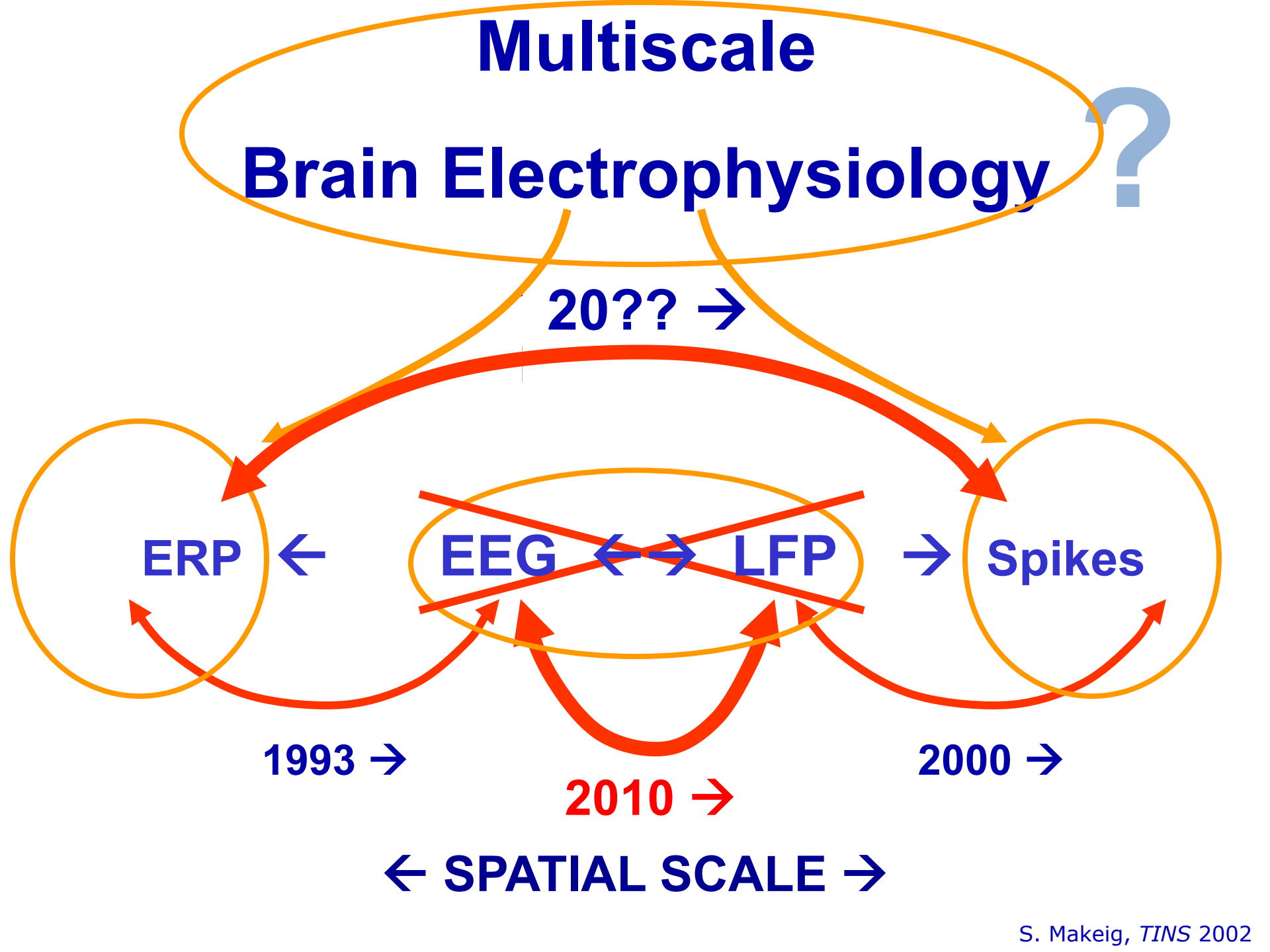
One spatially coherent *effective source*

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

0 0.1 0.2 0.3 0.4 0.5

time (seconds)

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

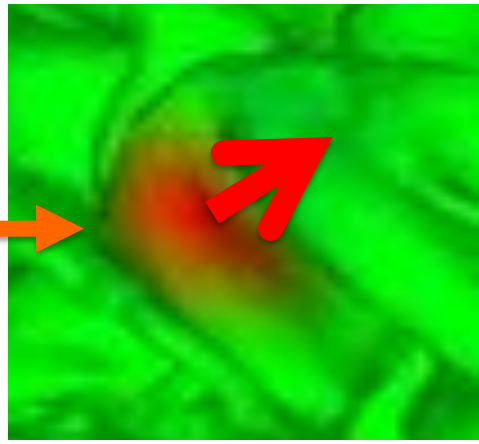
MRI

Proto

Segmentation

Simple Map

Signal Processing



Source Estimate

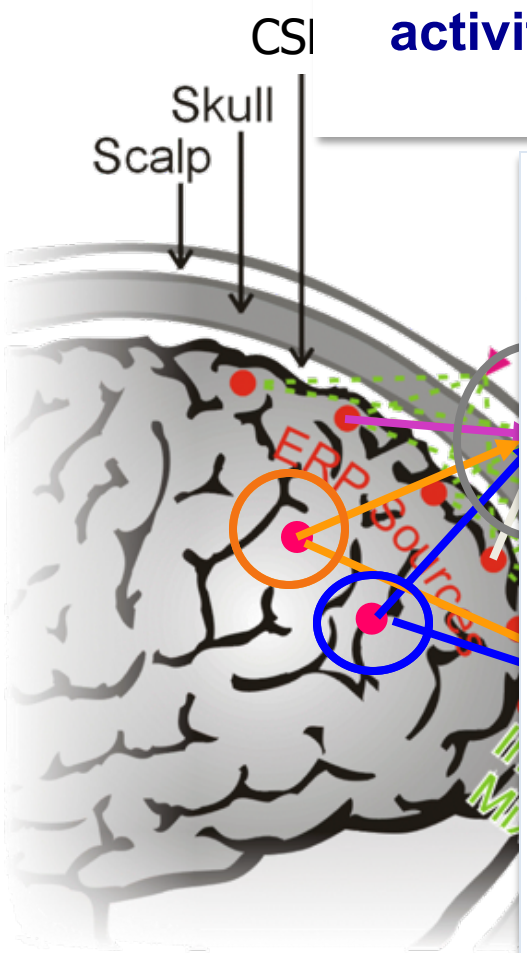
EEG/MEG

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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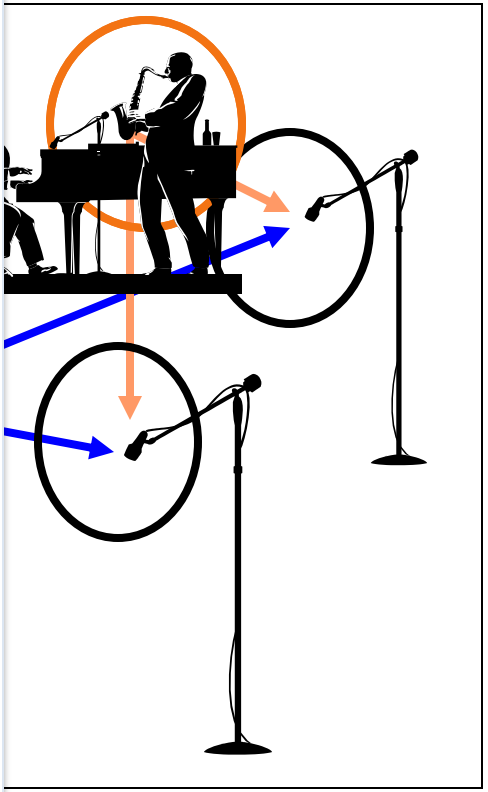
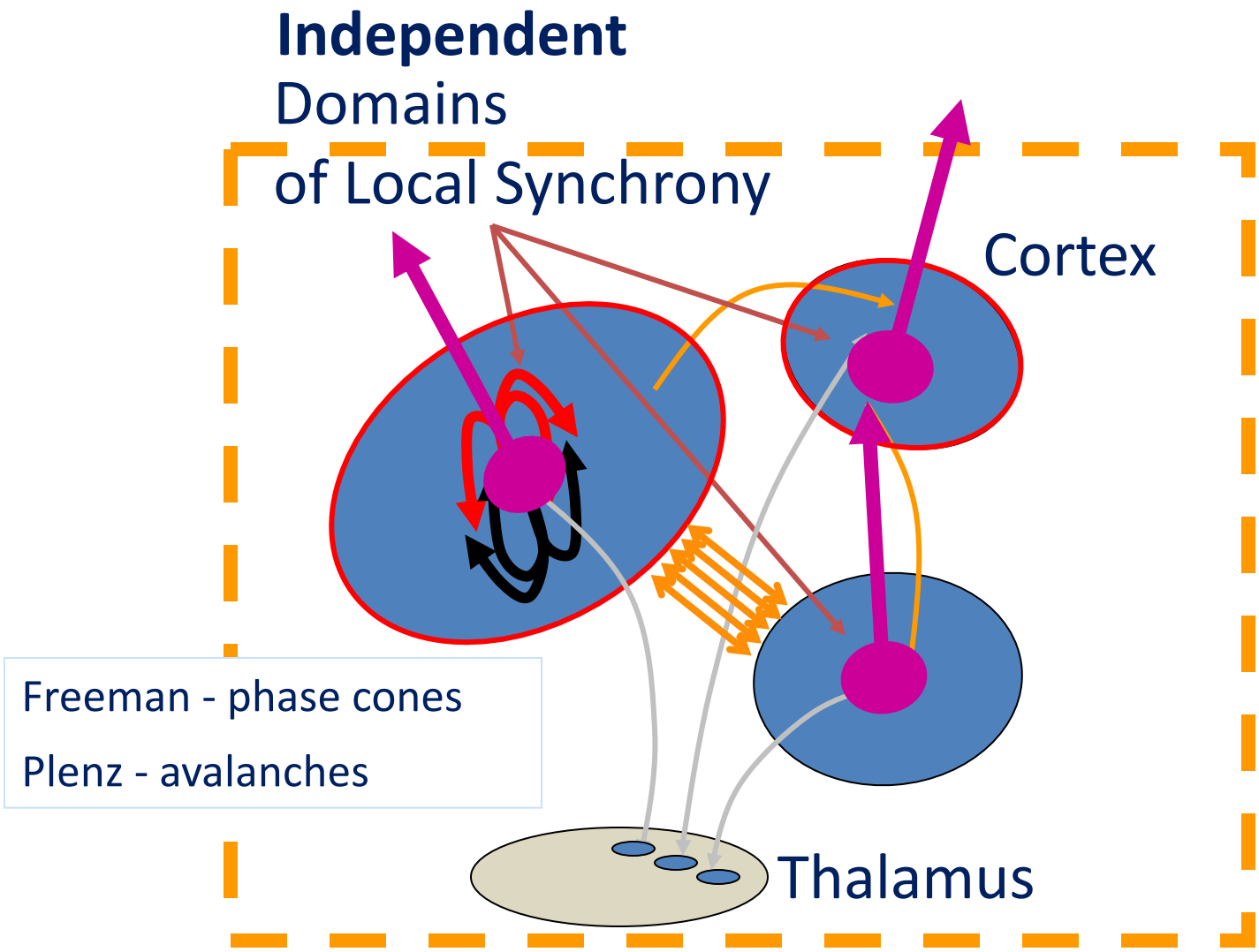
Abstract

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

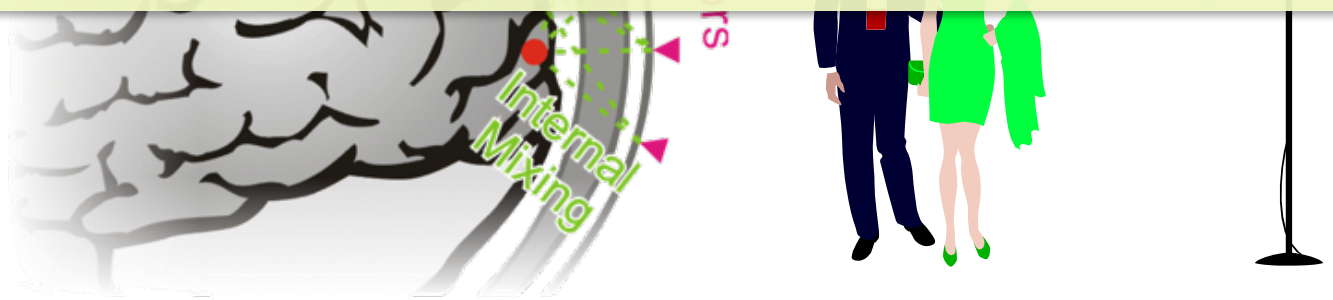
Effective source
Identification → Localization

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

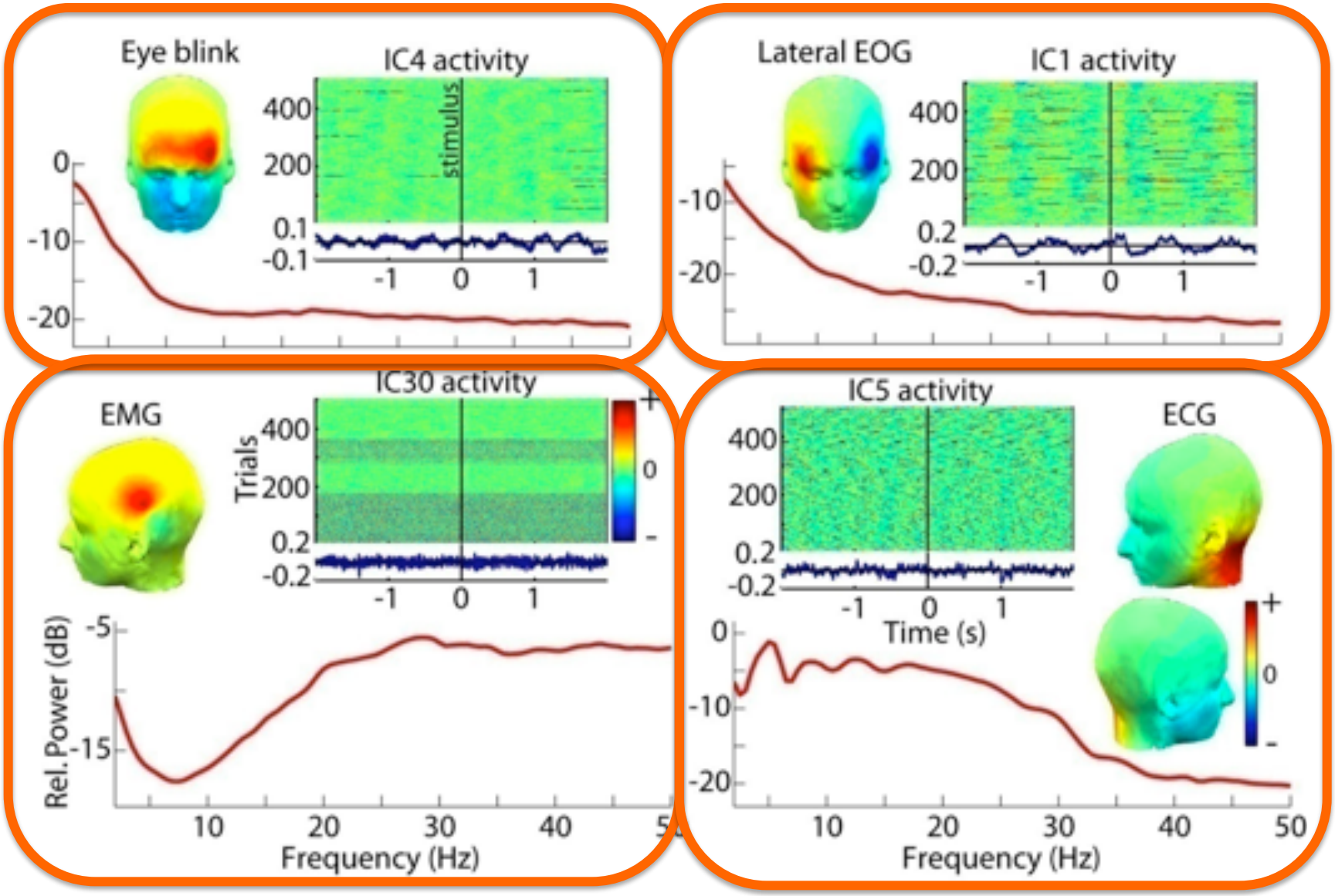
- ***What* are the effective sources? (identification)**

And it greatly helps answer the second question:

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



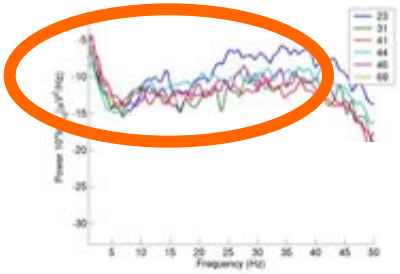
ICA finds non-brain independent component (IC) processes …

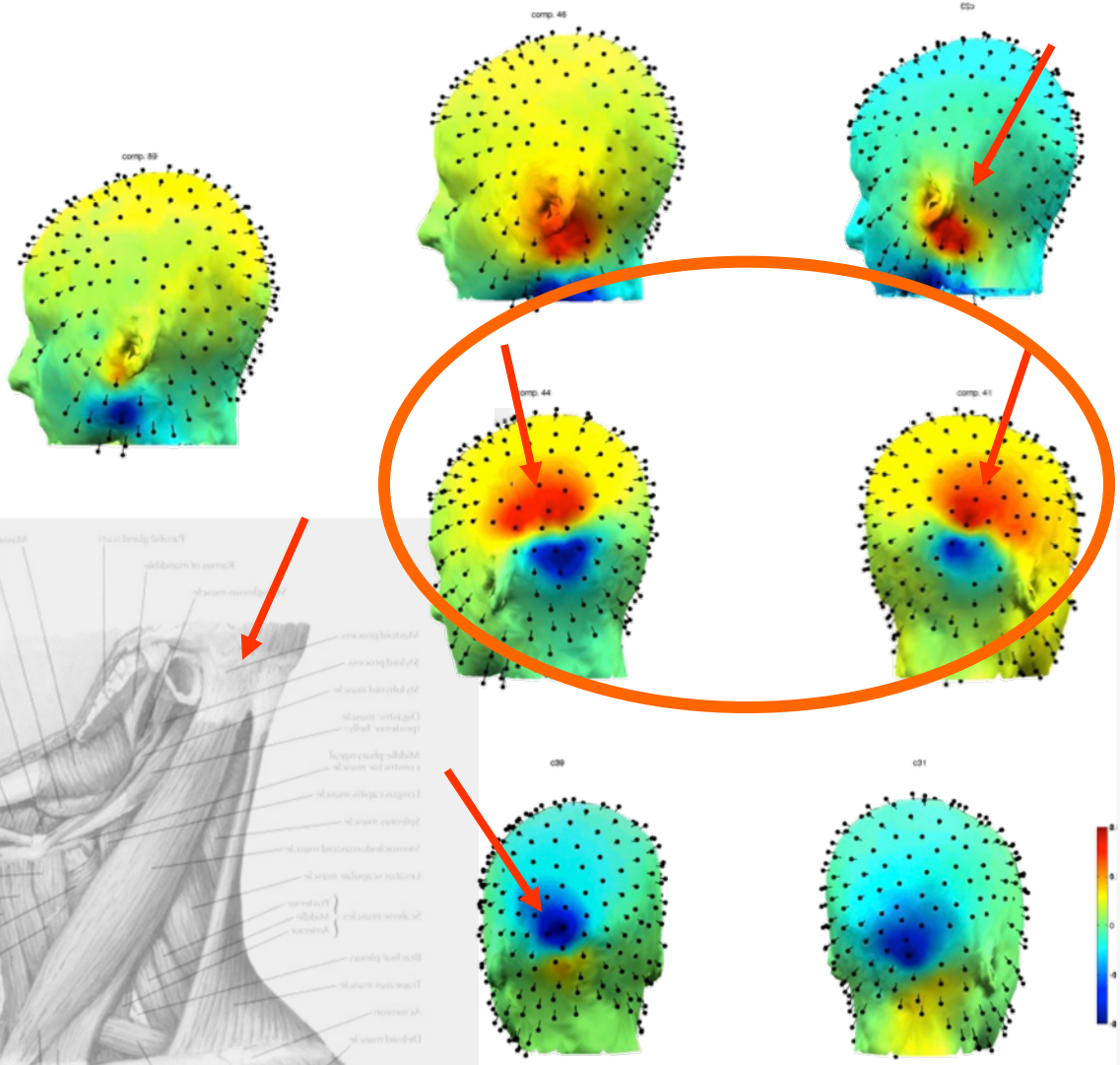


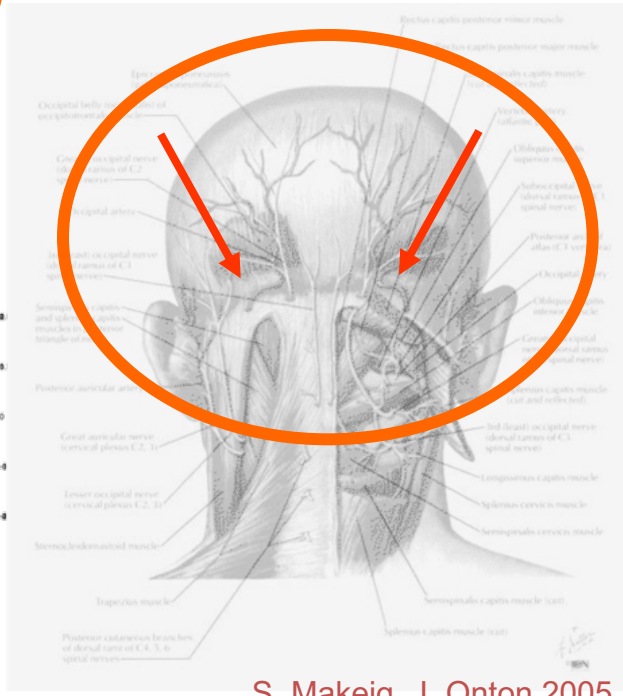
… separates them from the remainder of the data …

J. Onton & S. Makeig 2006

… including IC EMG sources

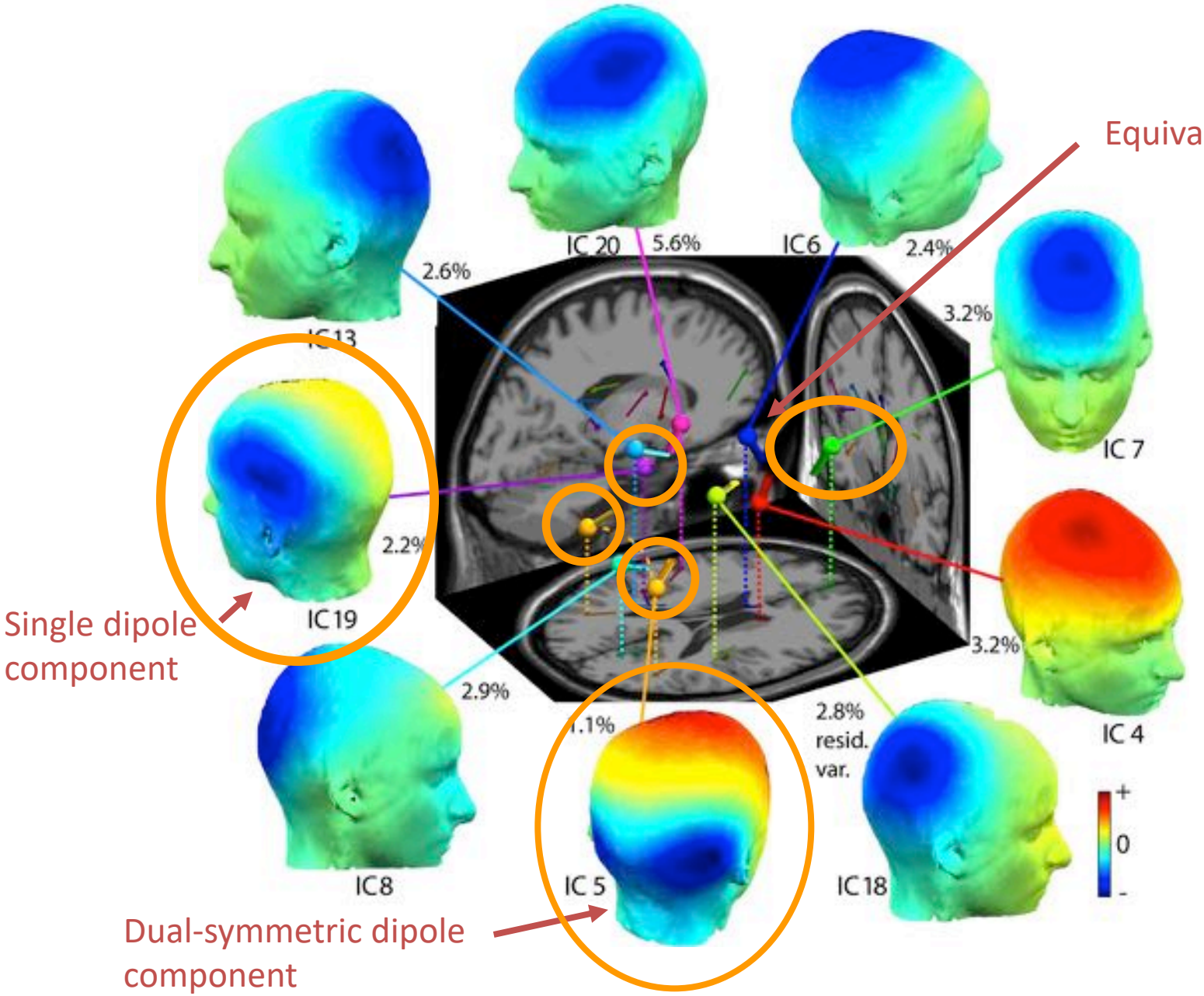






S. Makeig, J. Onton 2005

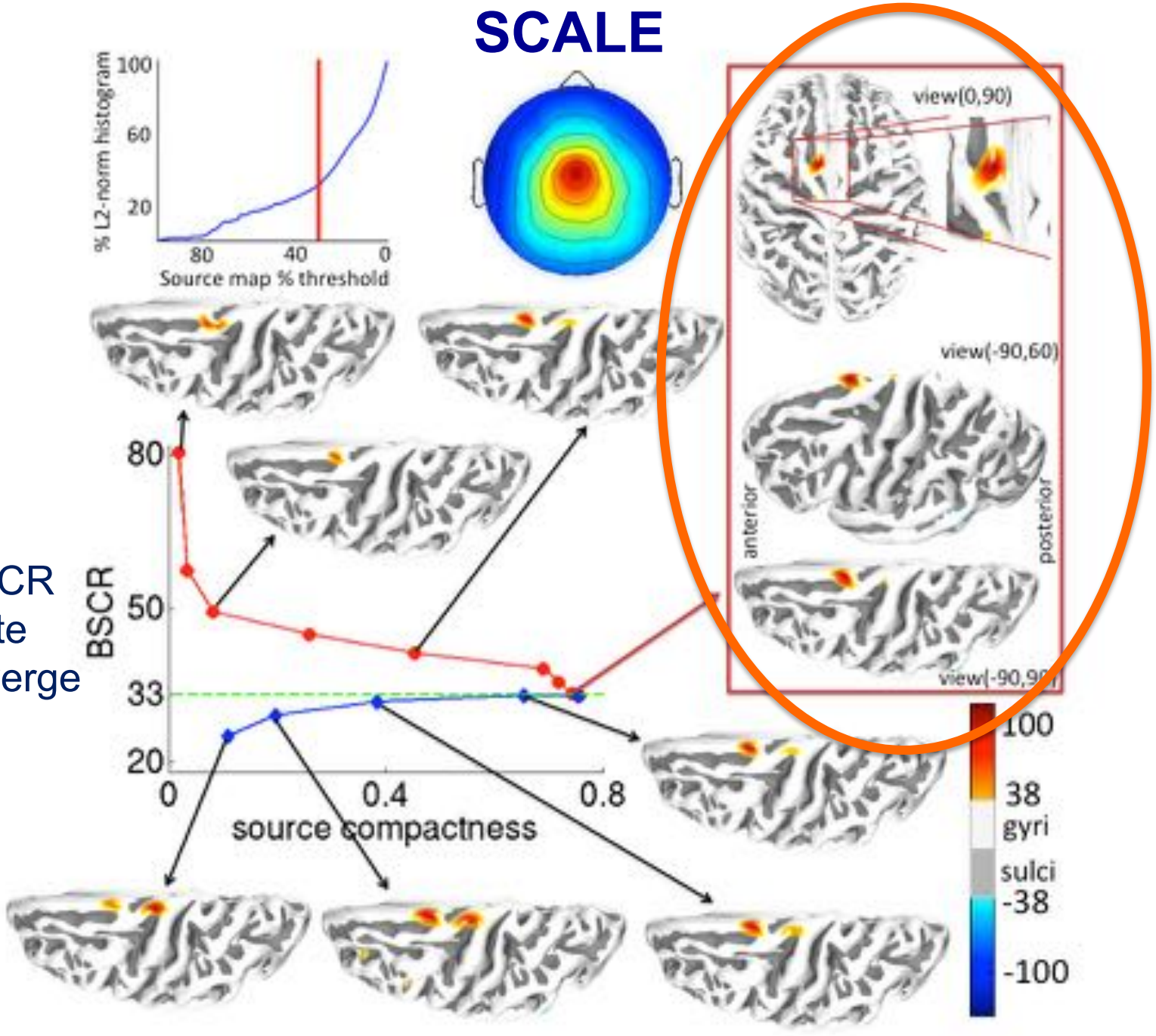
… and IC effective brain sources



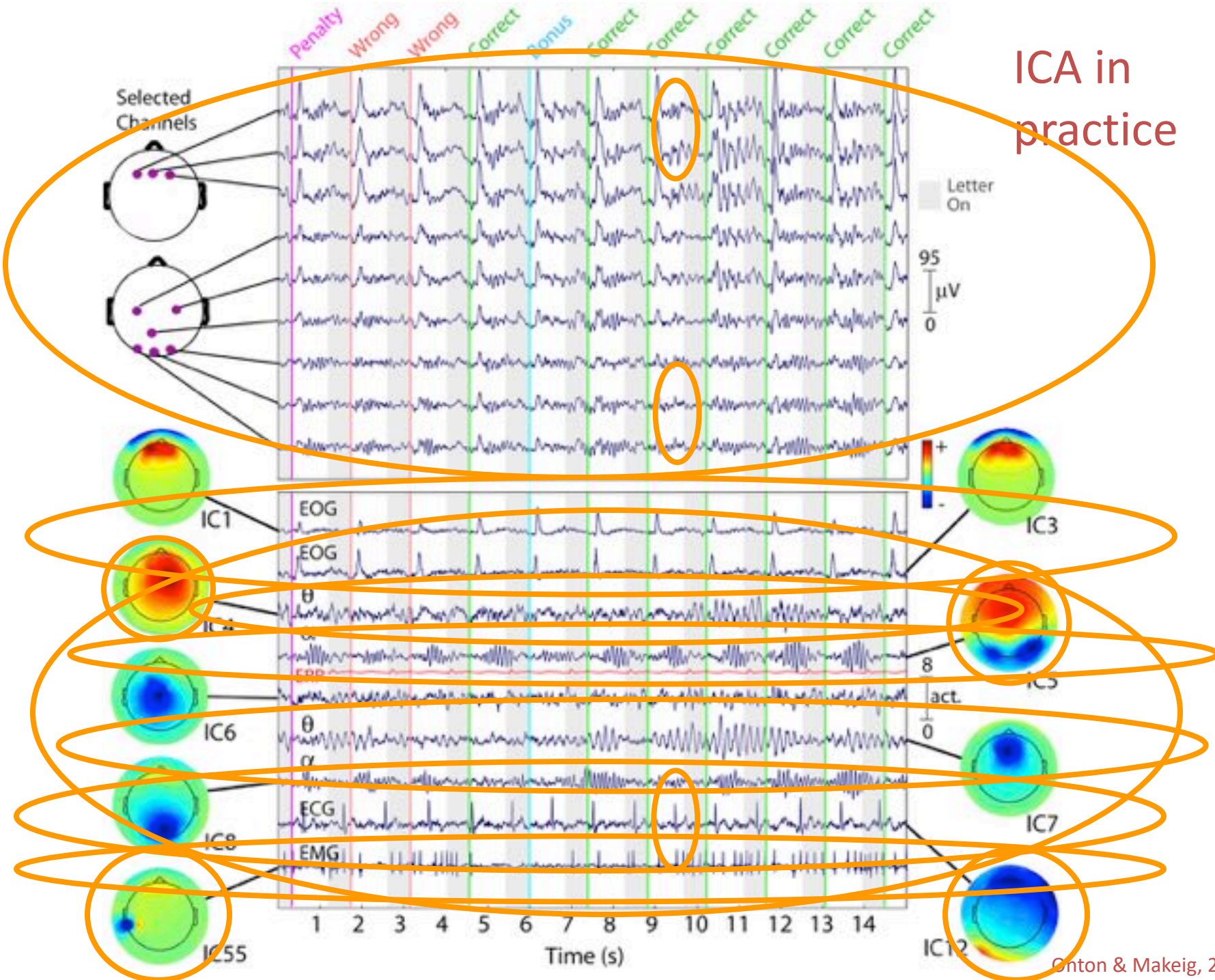
Julie Onton & S. Makeig (2006)

SCALE

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

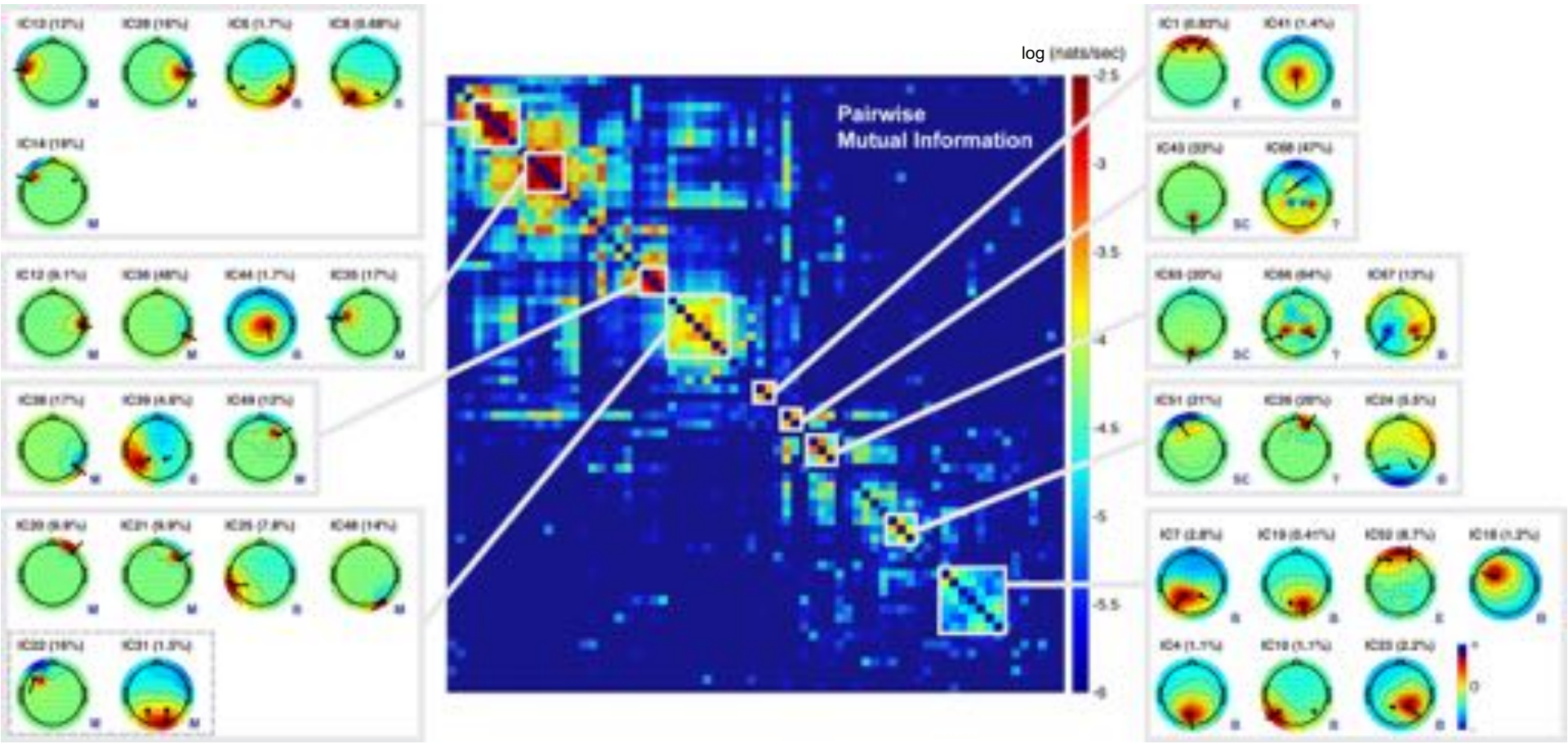


Z. Akalin Acar et al., 2016



Onton & Makeig, 2006

Residual mutual information following ICA decomposition – dependent subspaces



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

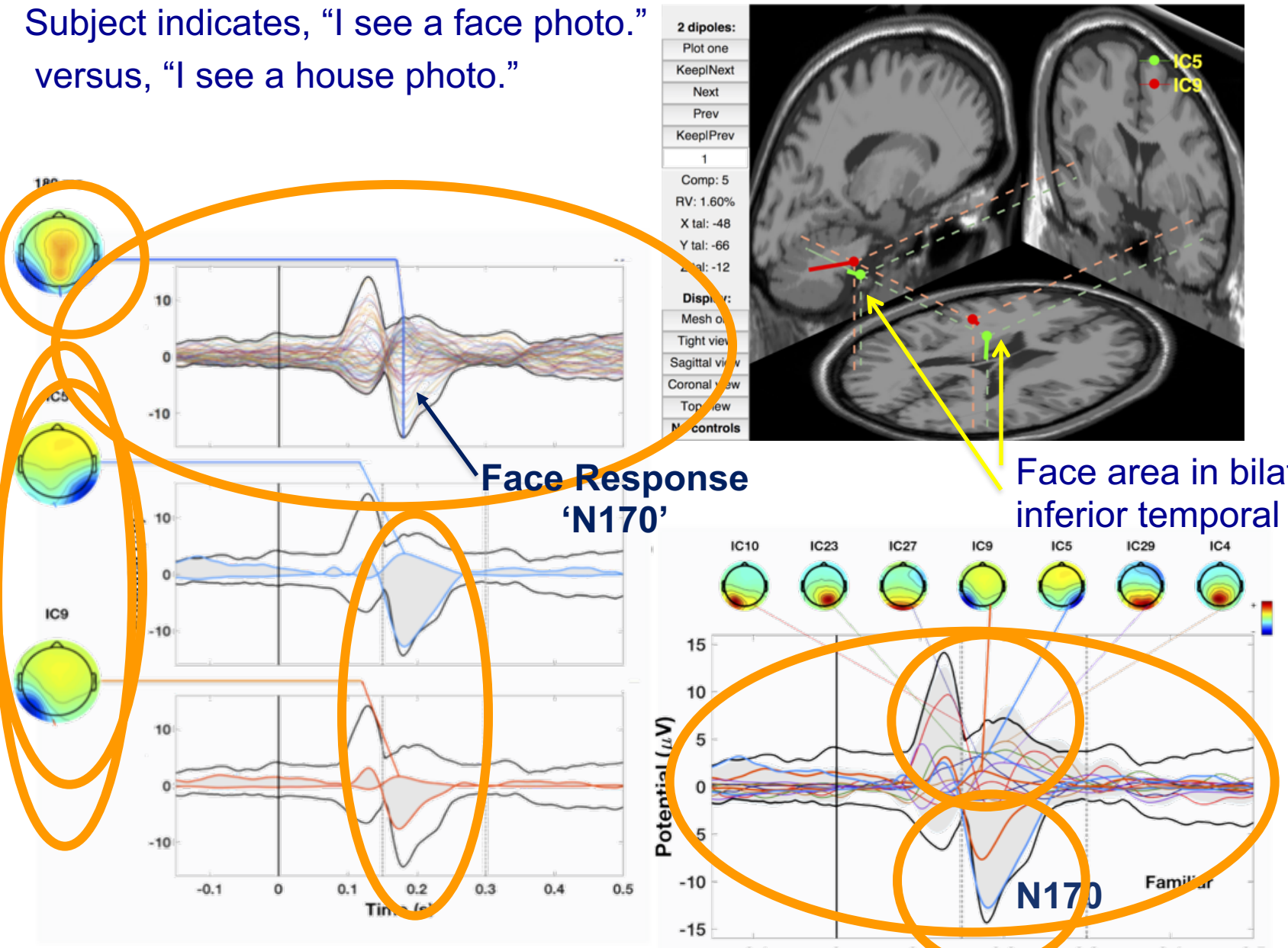
S. Makeig, R. Martinez-Cancillo, 2018

EEG & *knowing*

Knowing

Face Perception

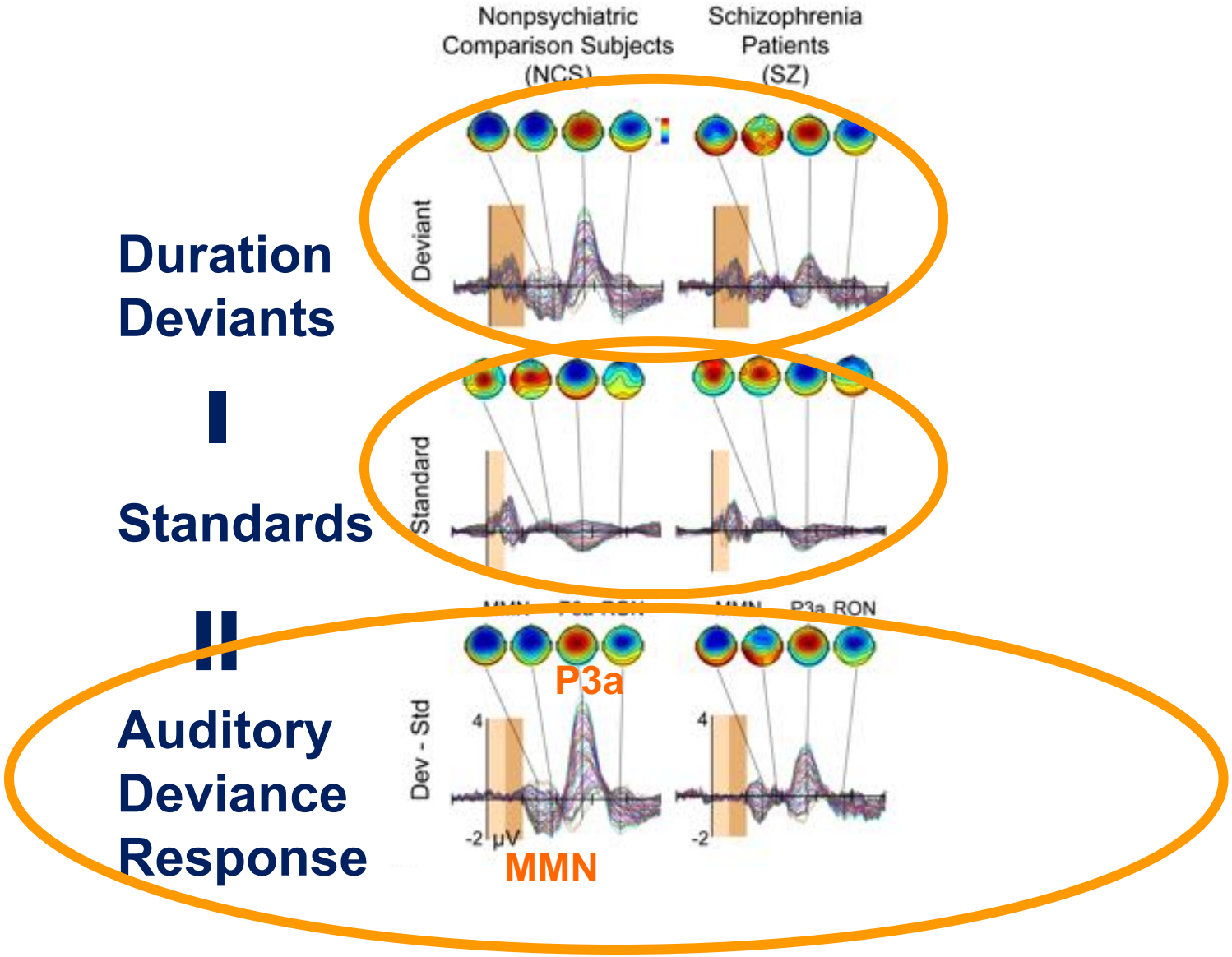
Subject indicates, “I see a face photo.”
versus, “I see a house photo.”



S Makeig, 2017

Schizophrenia

Auditory Passive Oddball Task (SZ, Cntrl)



Duration Deviants

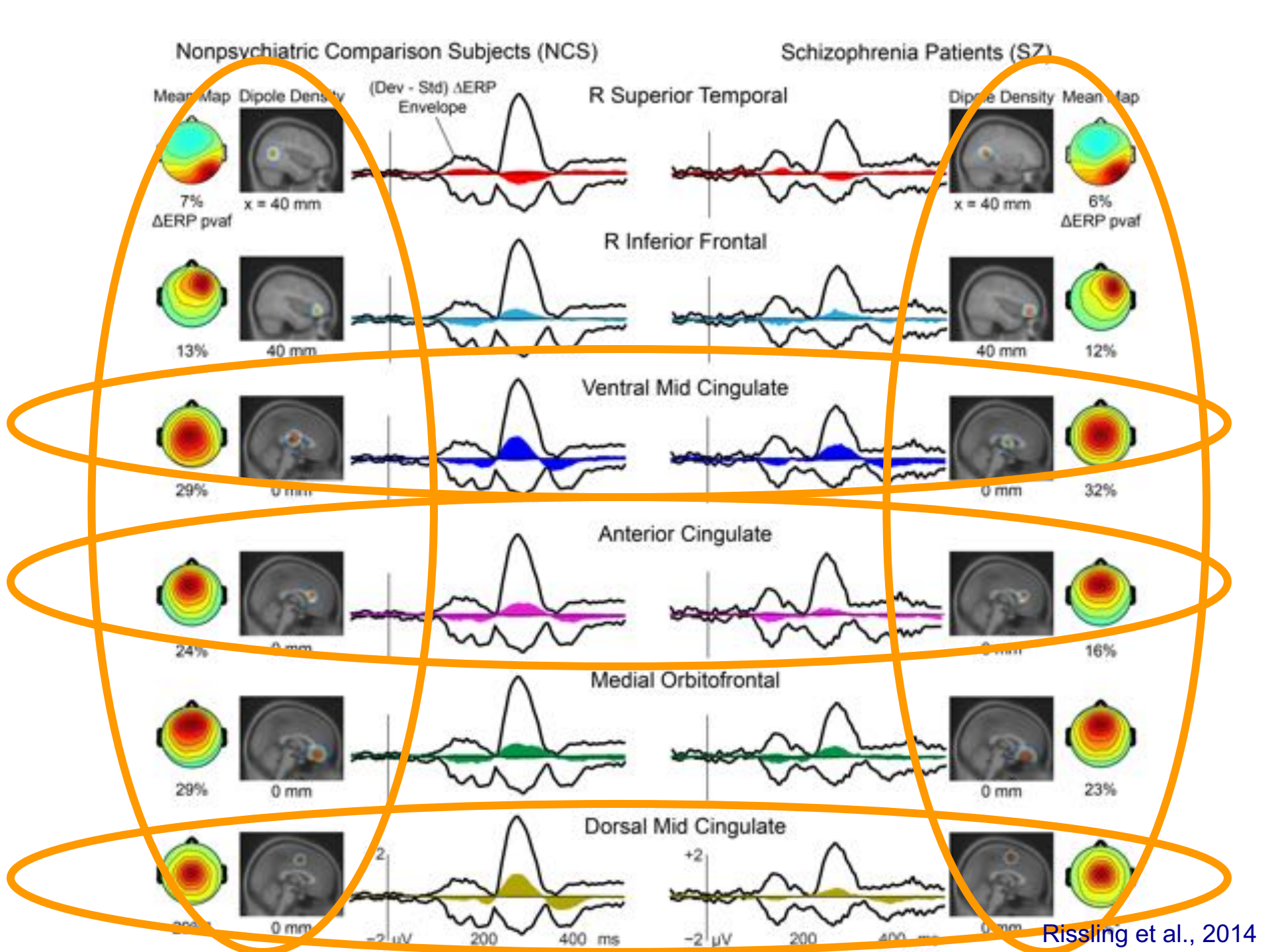
I

Standards

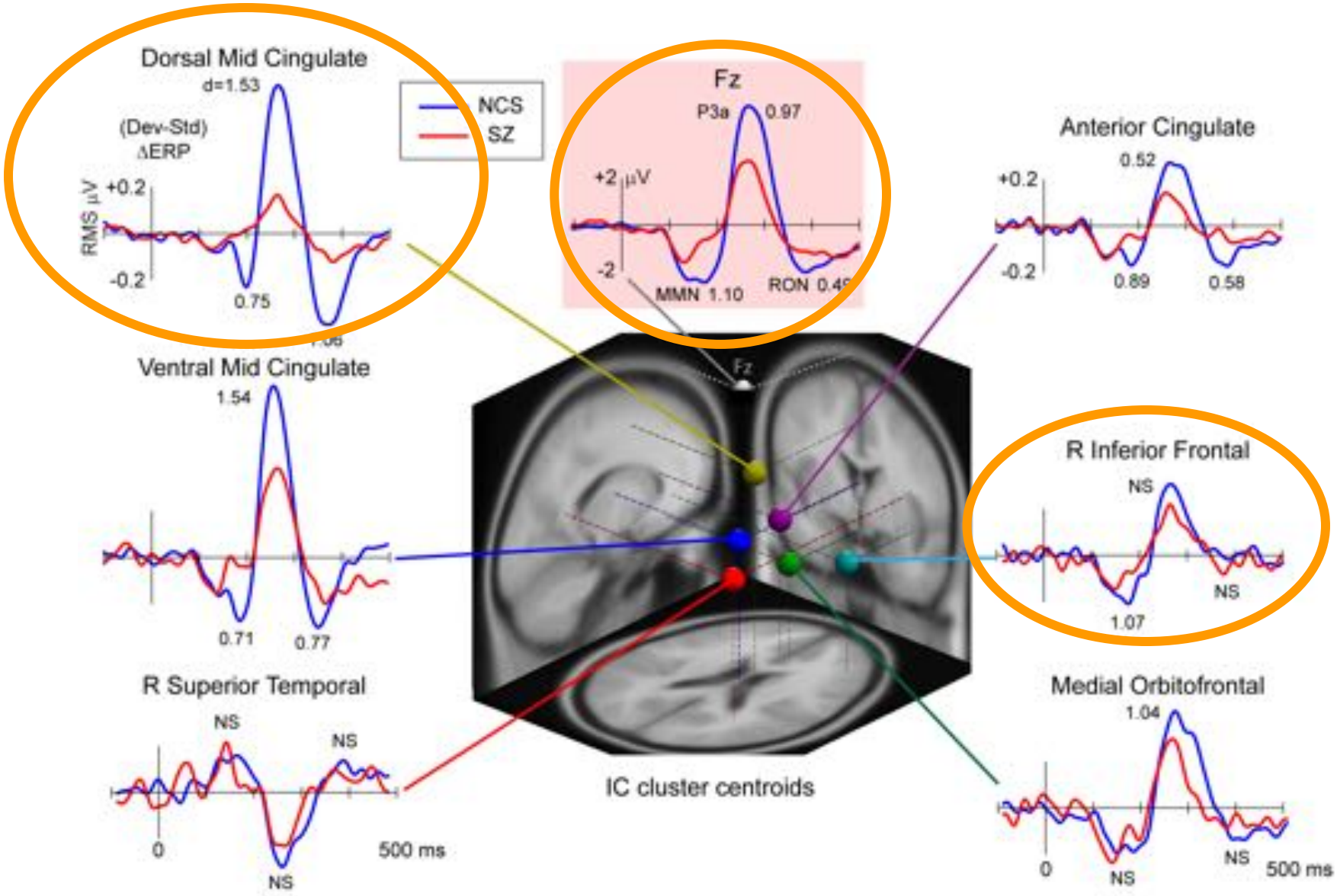
II

Auditory Deviance Response

Rissling et al., 2014

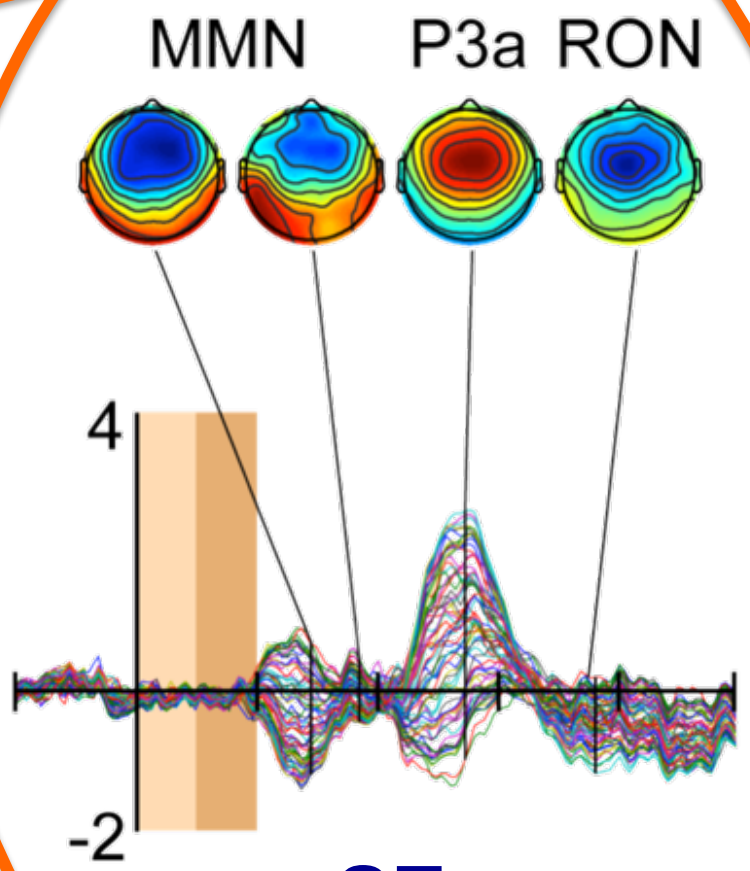


Rissling et al., 2014



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

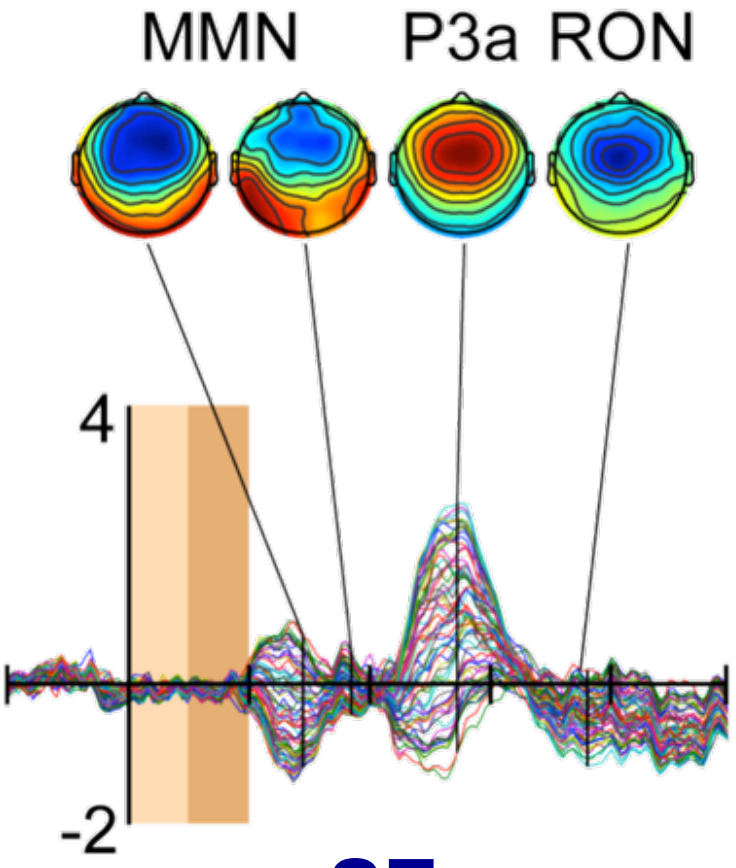


Rissling et al., 2014

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

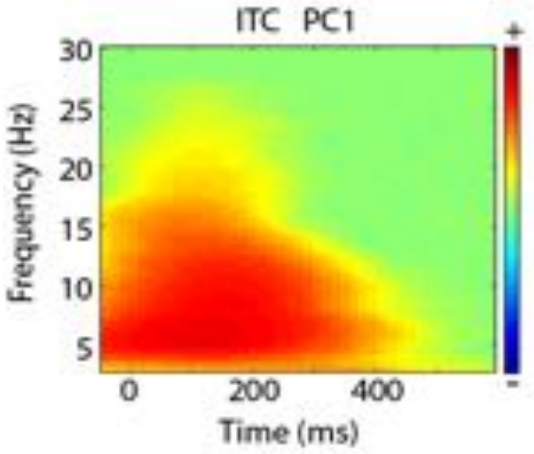
ADR

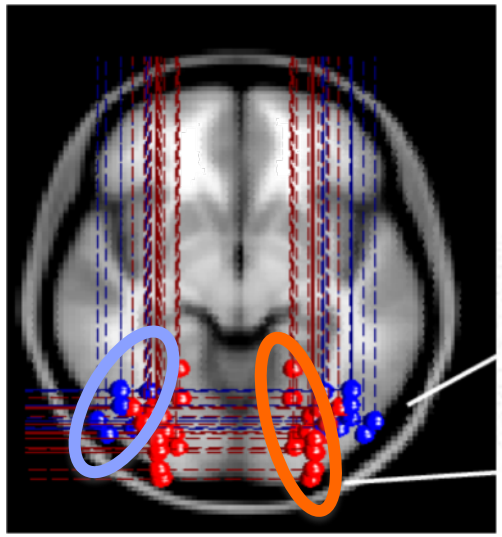


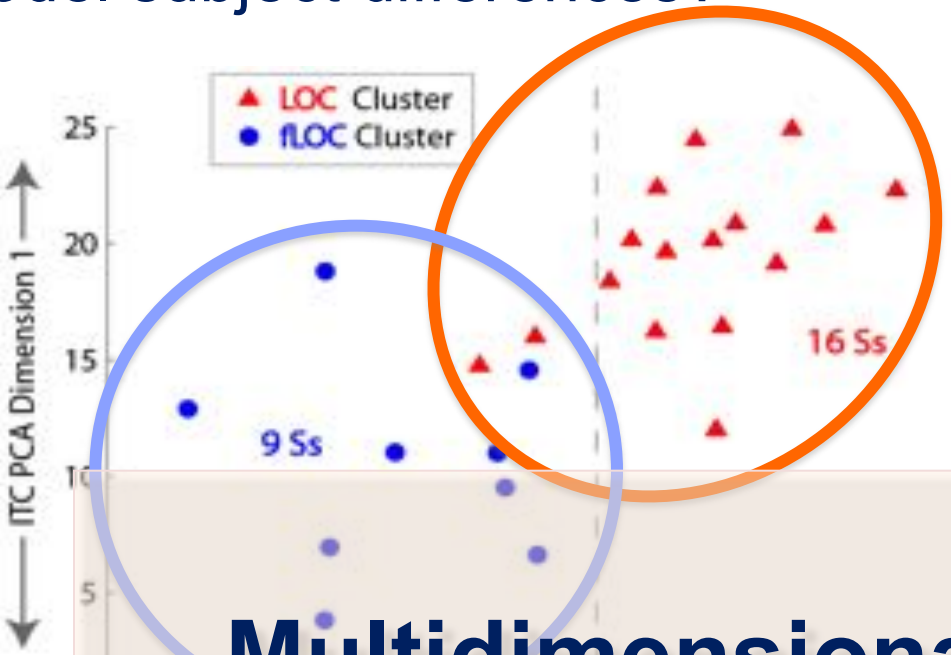
SZ

Rissling et al., 2014

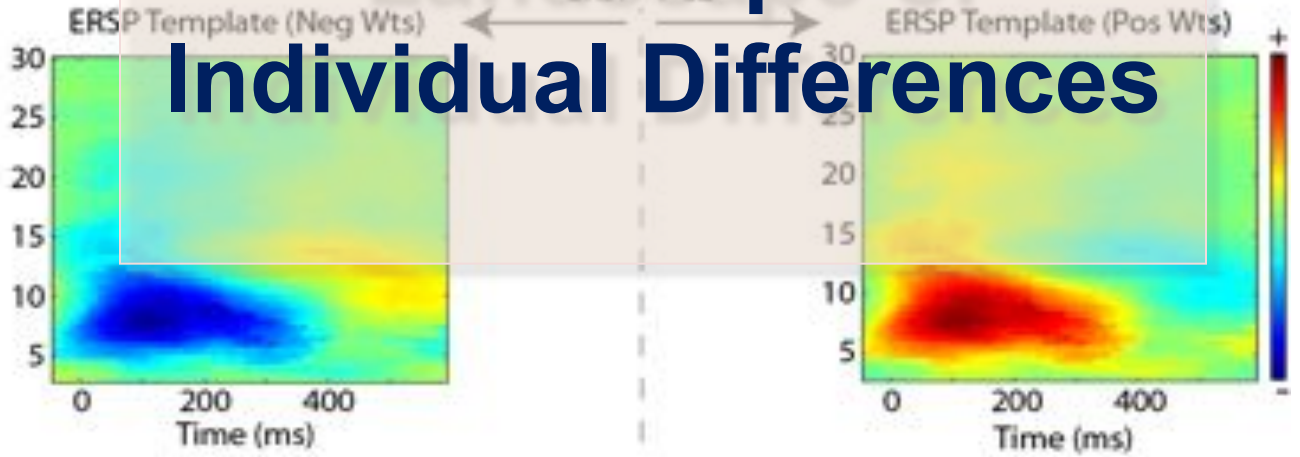
Can measures of source-resolved EEG dynamics model subject differences?







Multidimensional Landscape of Individual Differences



Swartz Center for Computational Neuroscience

The Beginning

fEMI,

BMI,

MoBI …