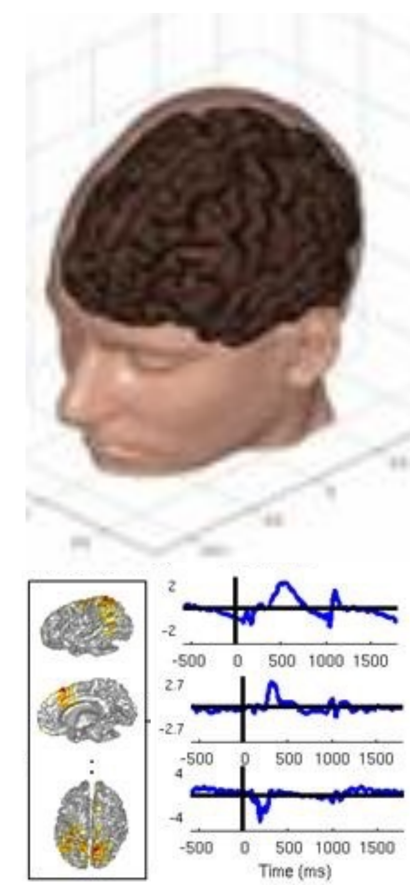
Computational EEG Analysis for Characterizing Cognitive Activity: Methods and Applications



Arthur C. Tsai

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2020 WASEDA UNIVERSITY - ACADEMIA SINICA
DATA SCIENCE WORKSHOP

2020-12-12 12:05 Session I

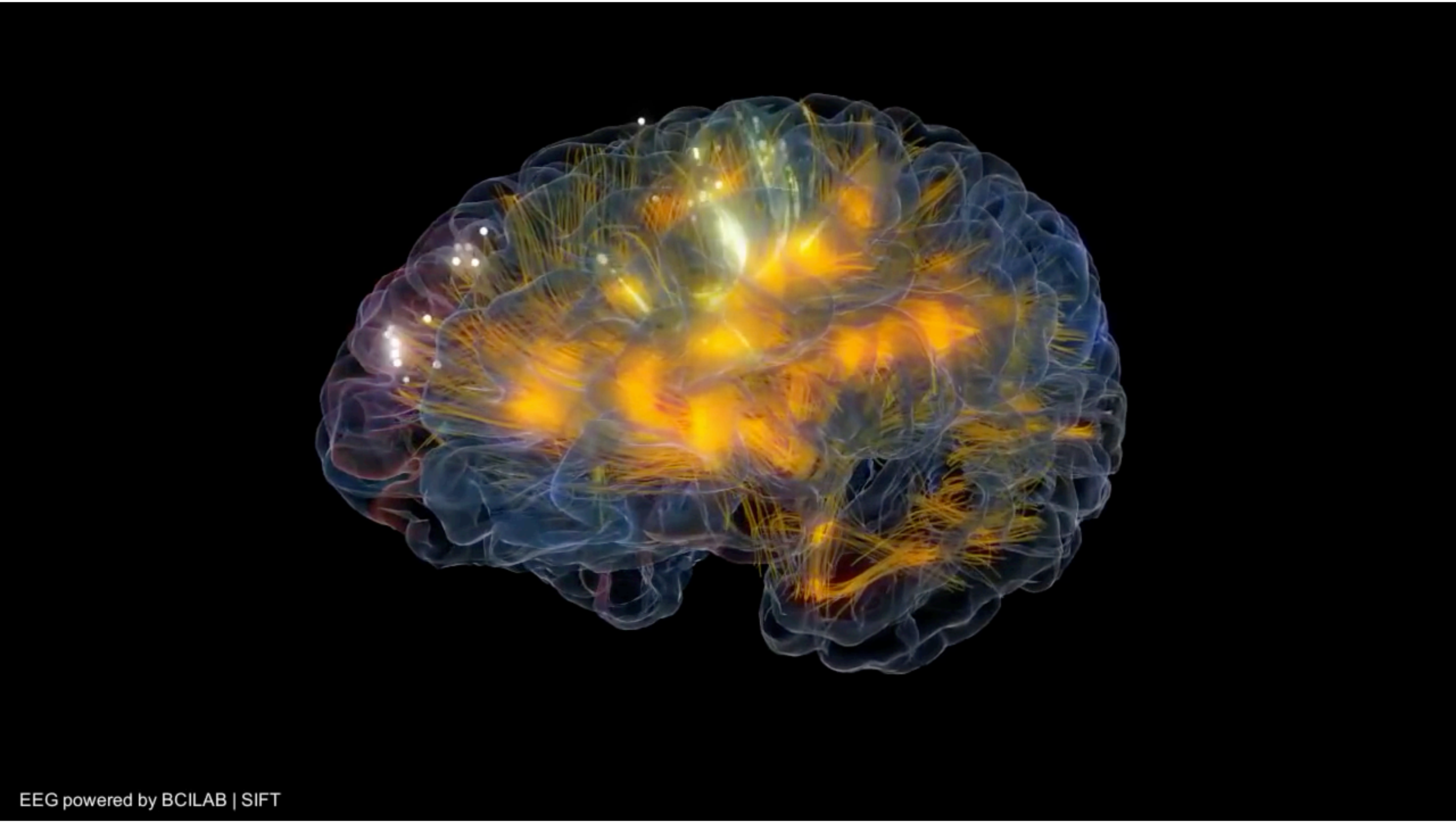
(Academia Sinica)

Computational EEG Analysis for Characterizing Cognitive Activity: Methods and Applications

Outline

1. **Introduction to the first functional brain imaging modality - EEG**
2. History of EEG analysis
    I. ERP, Power spectral analysis
    II. Source localization
    III. Separation of EEG signals by Independent Component Analysis
3. Electromagnetic Spatiotemporal Independent Component Analysis (EMSICA)
4. Multi-subject spatiotemporal independent source imaging

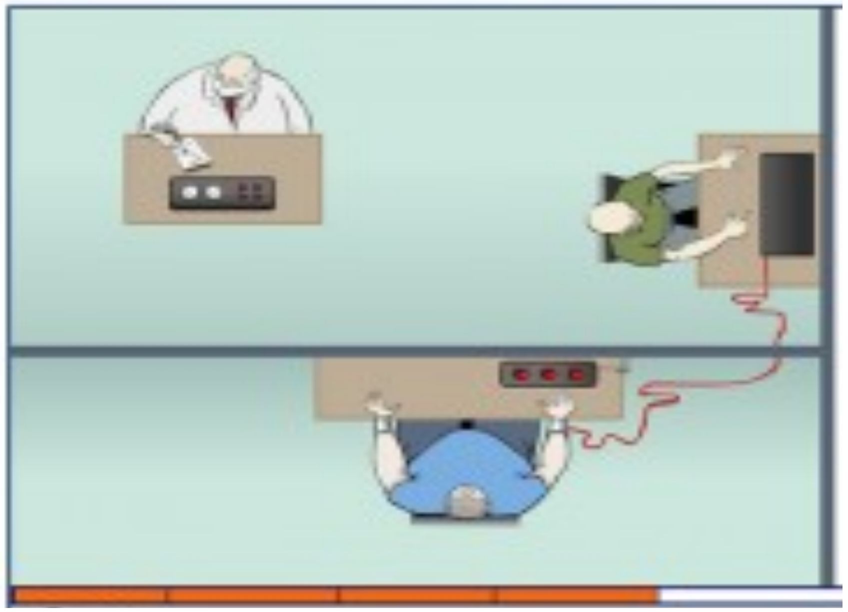
Introduction



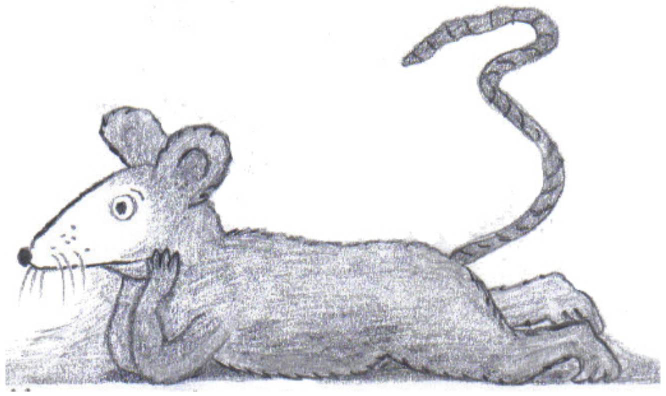
Introduction

Until about 20 years ago

Psychologist

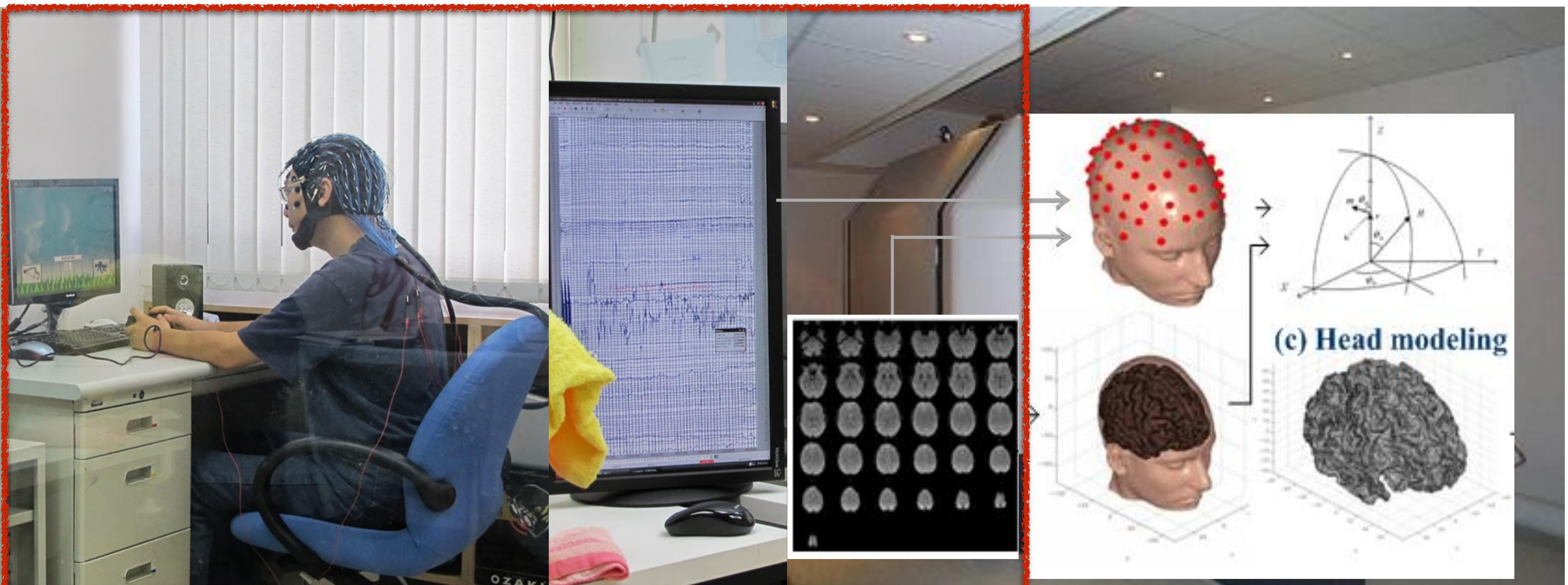


Brain Biologists



- **To look the working structure and function of living human brain**

- **High-density 128 channels EEG + structure MRI**



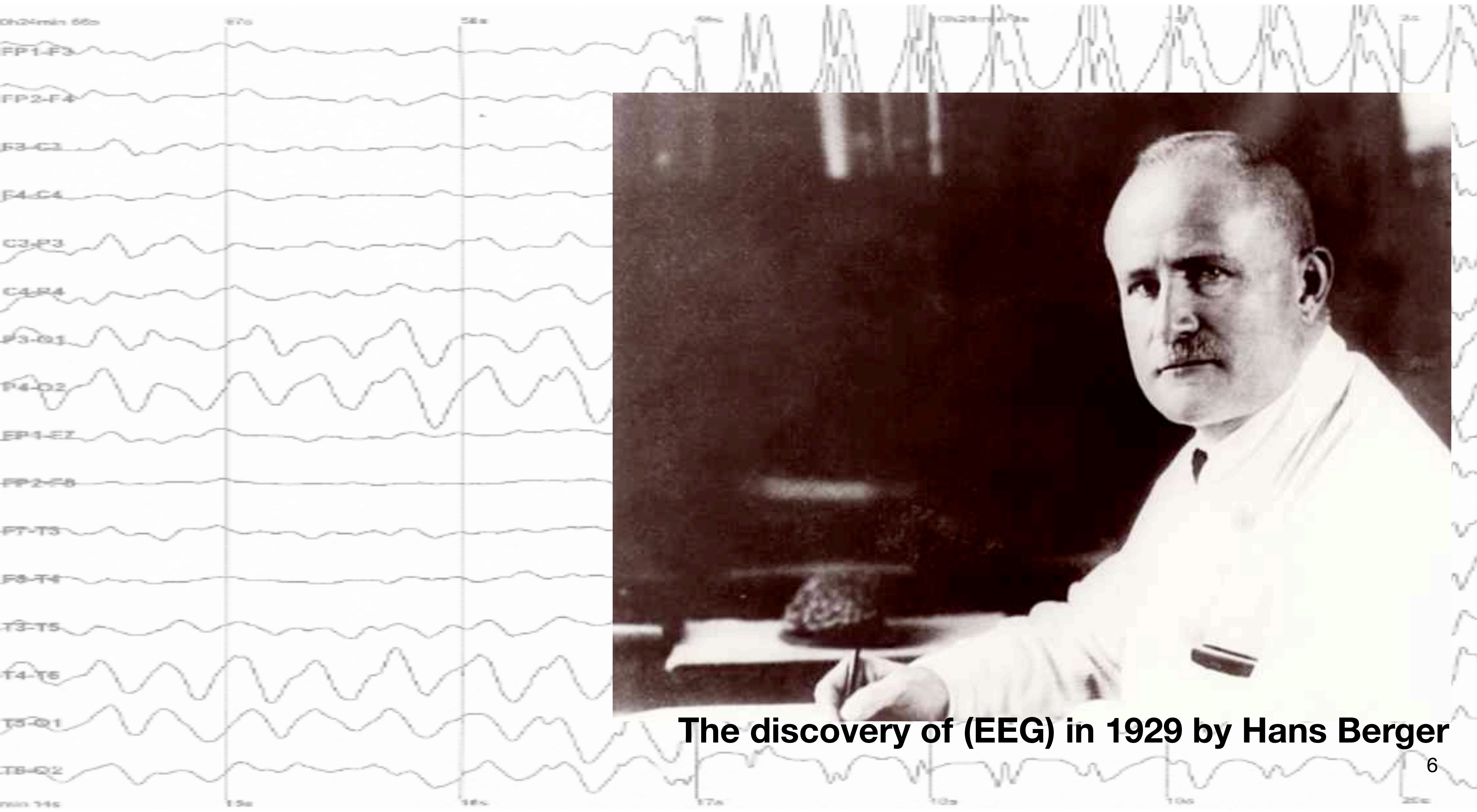
EEG Lab, Institute of Statistical Science, Academia Sinica

Anatomical structure from MRI

- what changes are happening in real time in the brain

Electroencephalography (EEG)

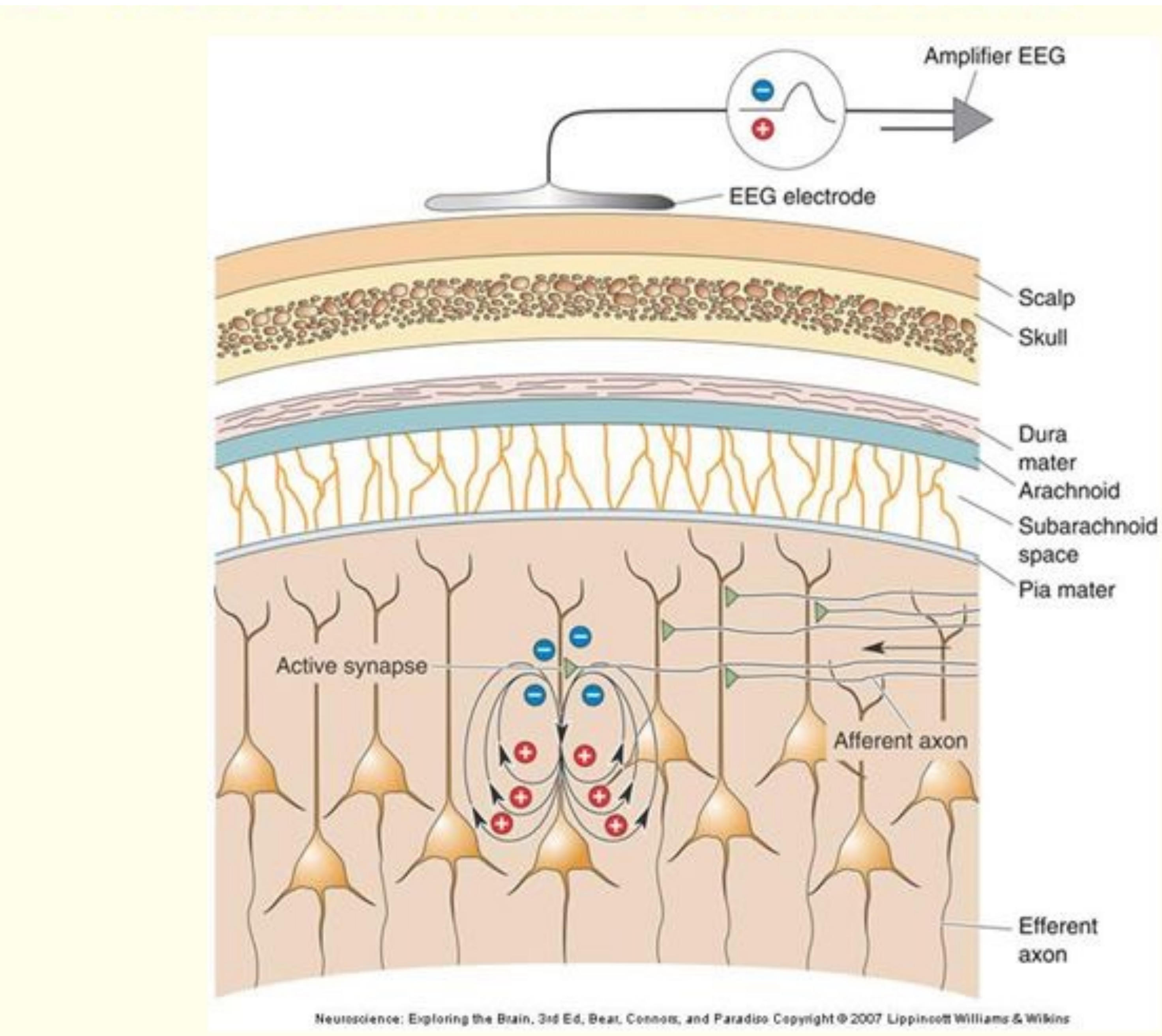
- the first functional brain imaging modality

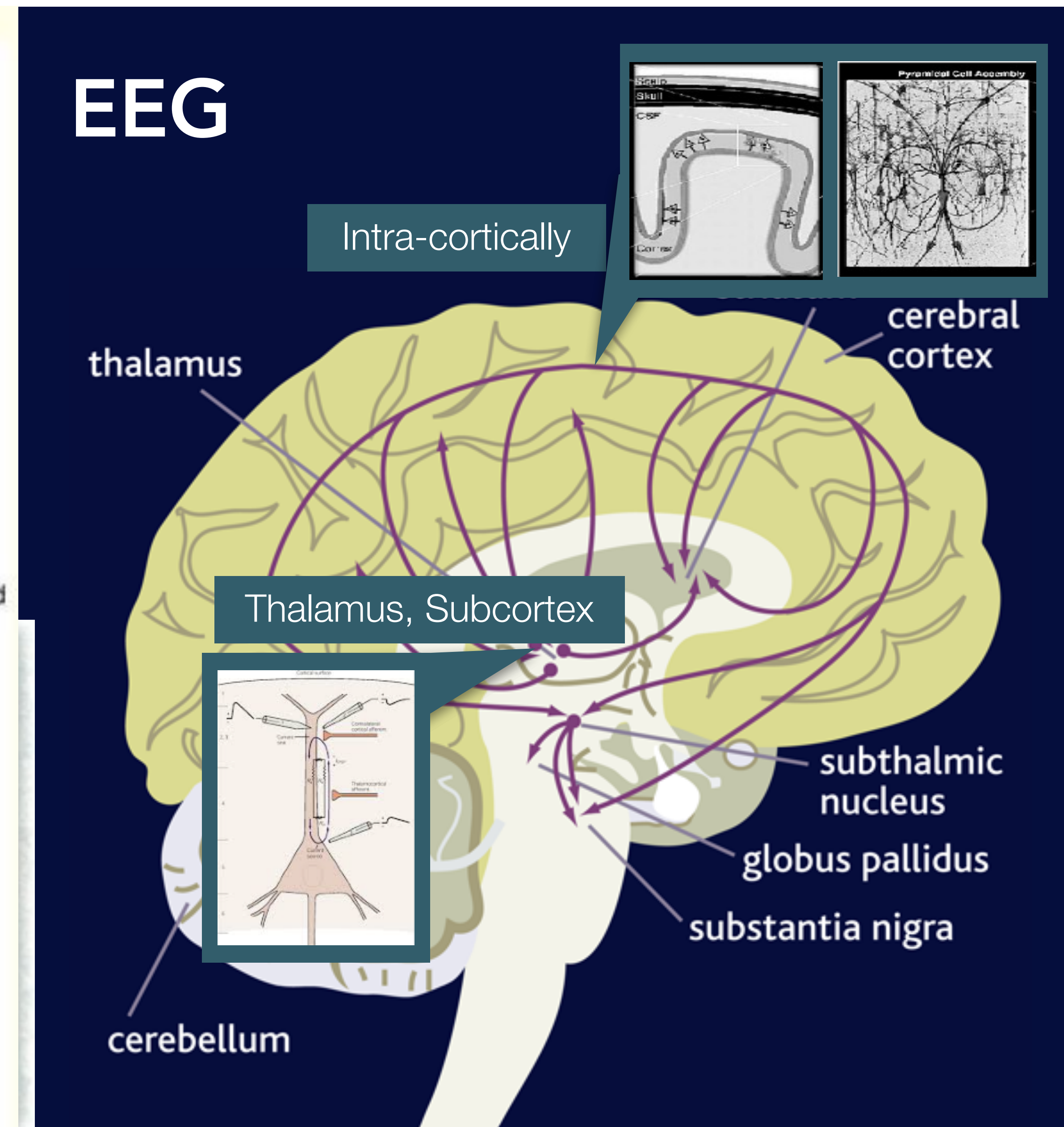


The discovery of (EEG) in 1929 by Hans Berger

Introduction - Electroencephalography (EEG)

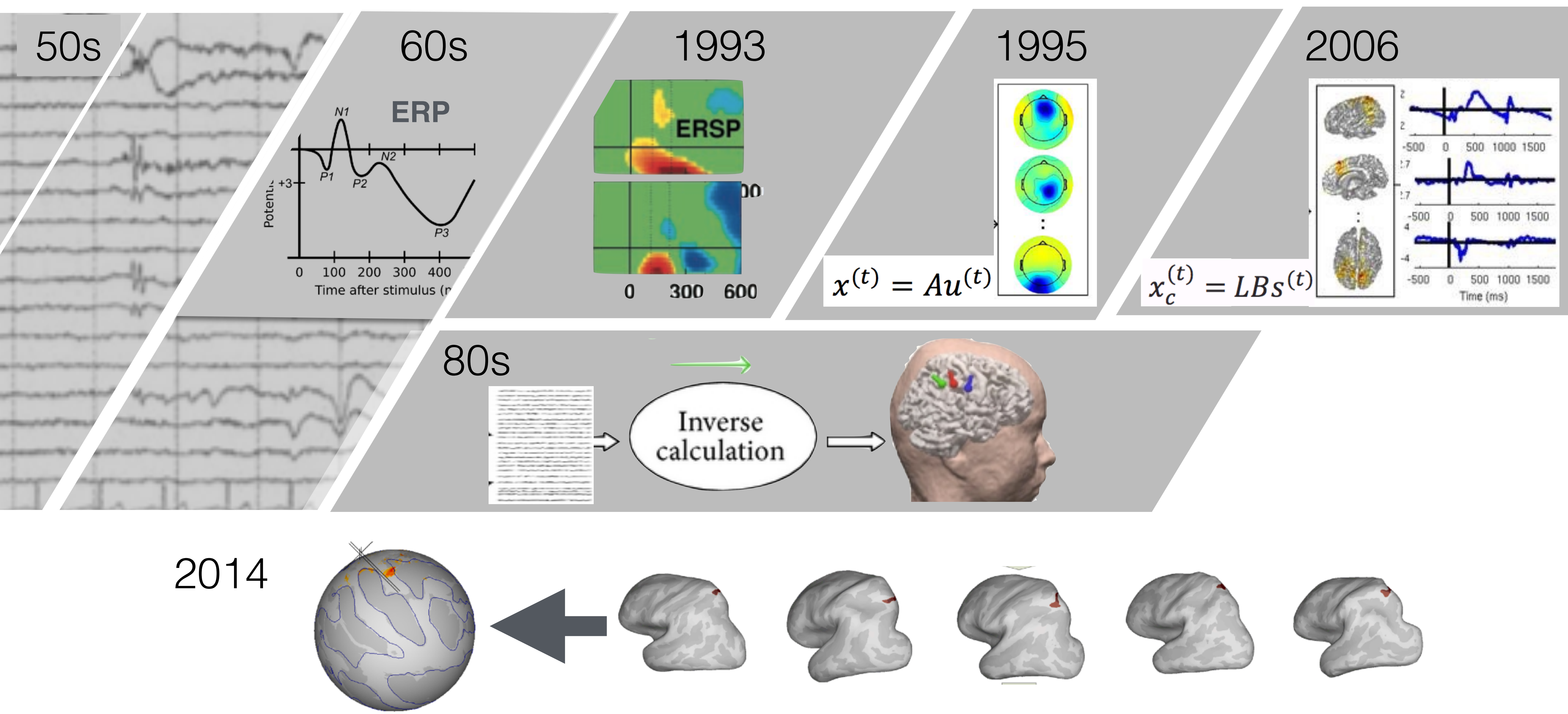
- Electroencephalogram (EEG). Glutmate is the major excitatory neurotransmitter in the brain.





Neuroscience: Exploring the Brain Fourth, North Americ Edition by Bear, Mark F., Connors, Barry W., Paradiso, Mich (2015)

Computational EEG Analysis



→ Machine learning

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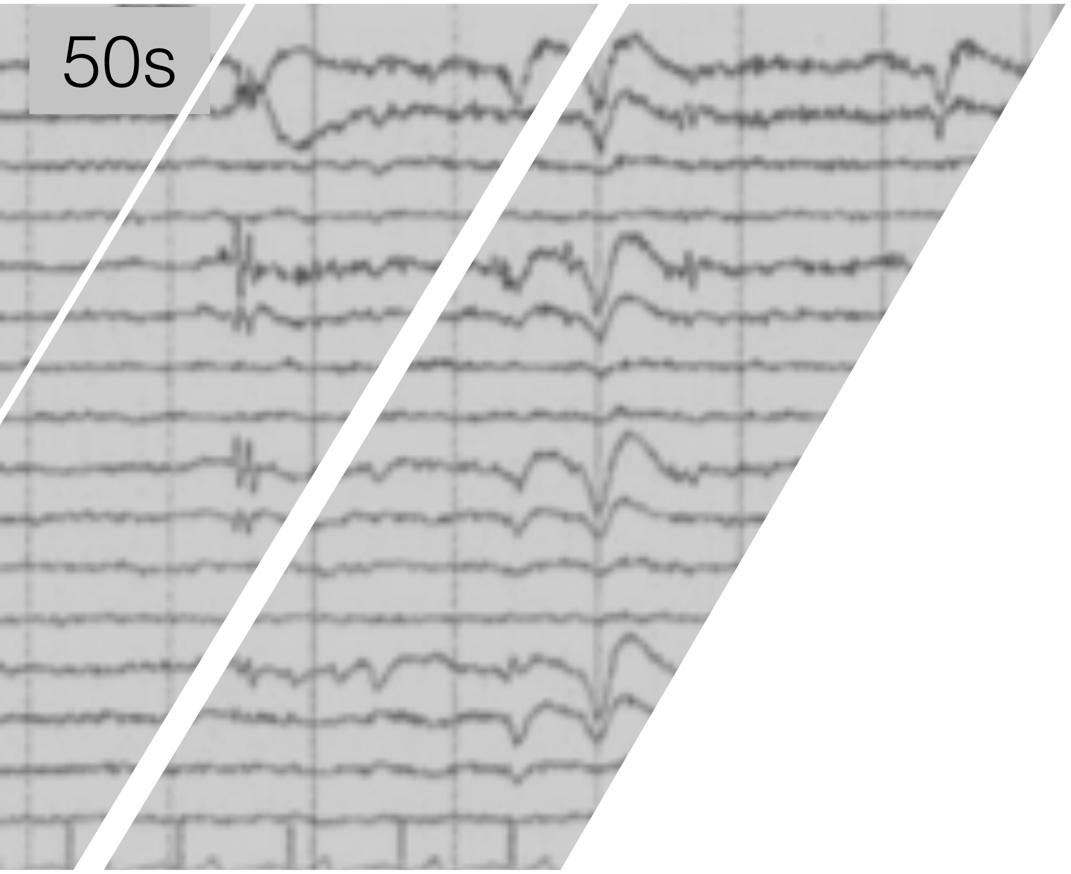
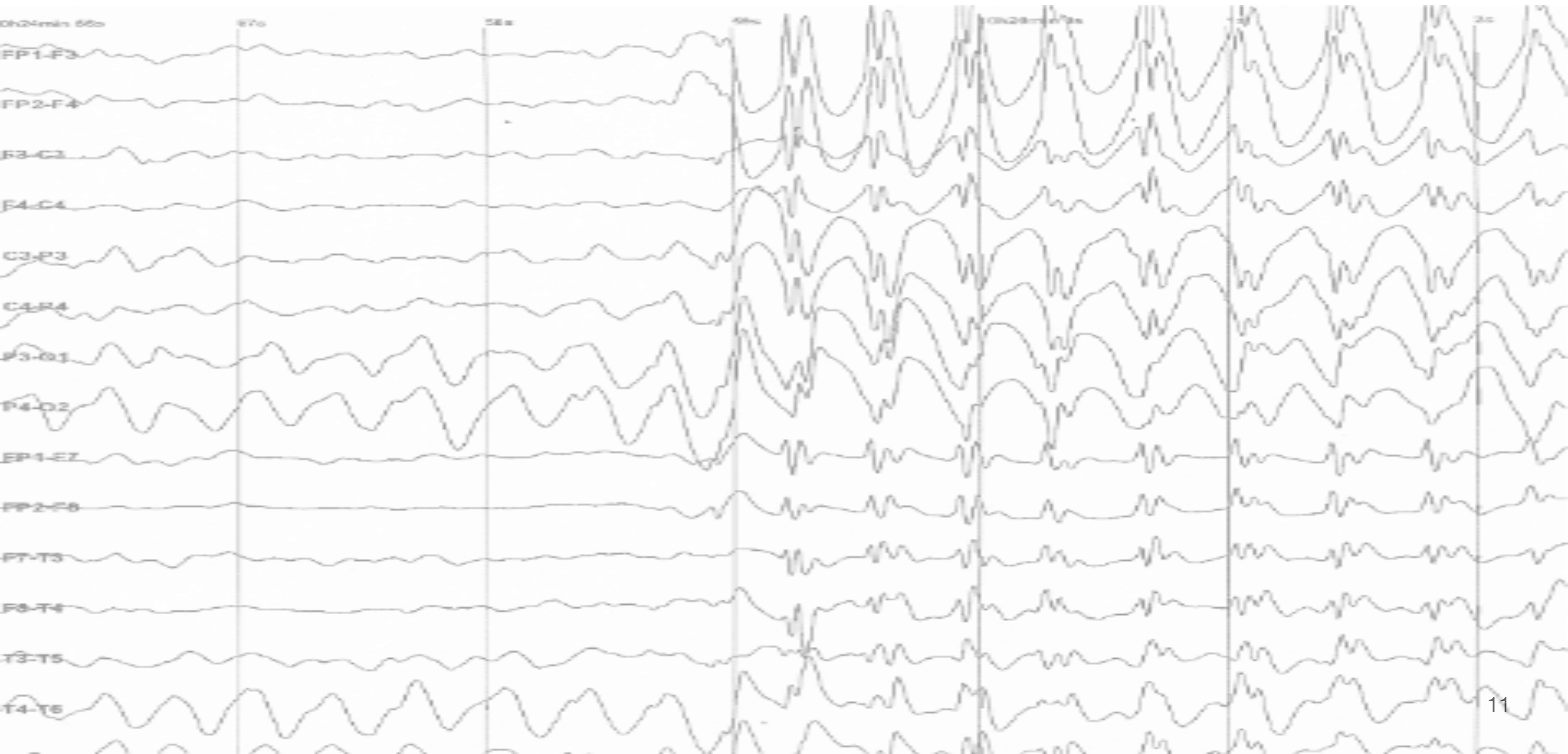
History of EEG analysis



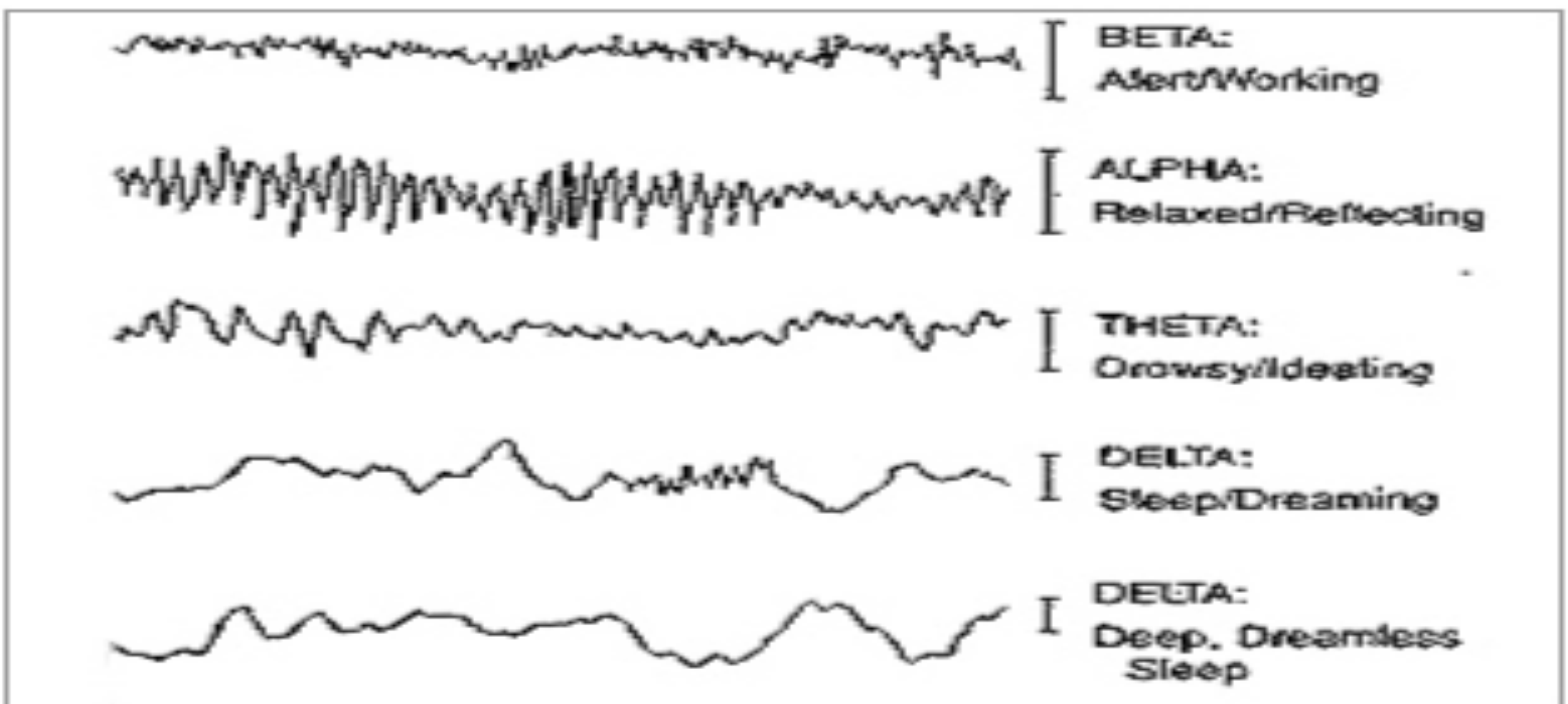
The history of EEG analysis

- Era 1. 50s - looking at ripples on the paper

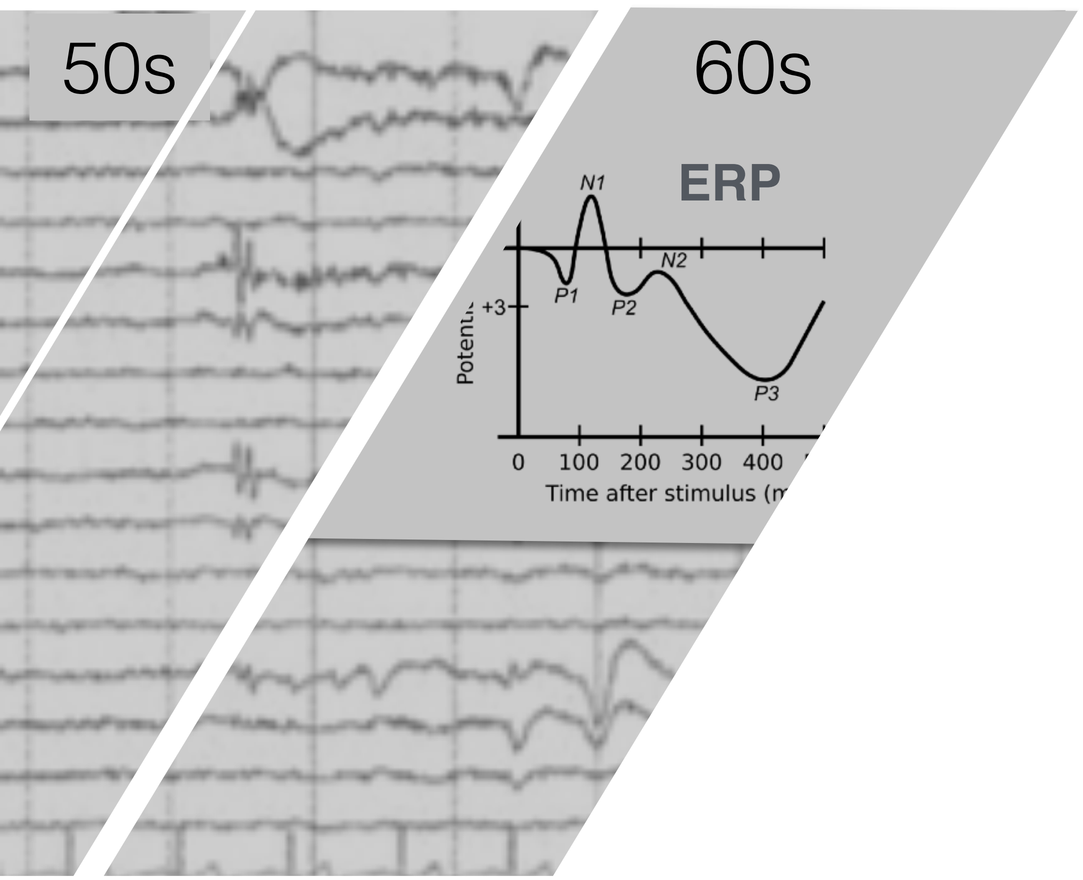


The history of EEG analysis

- Era 1. 50s - looking at ripples on the paper
  - How could you identify EEG by looking at the ripple?
  - Inhibitory <-- --> excitatory function



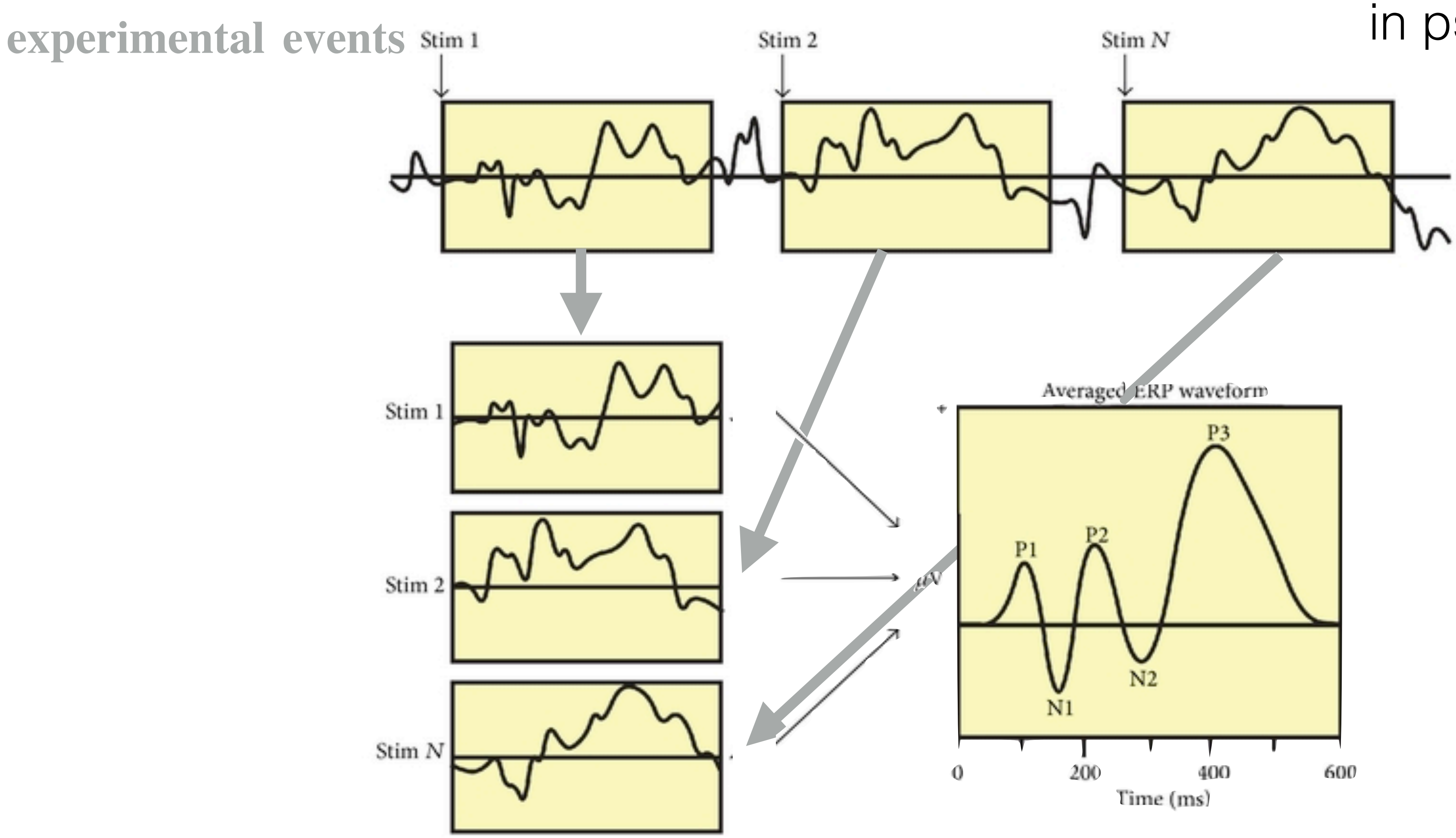
History of EEG analysis



The history of EEG analysis

- Era 2. 60s - Event Related Potential (ERP) analysis

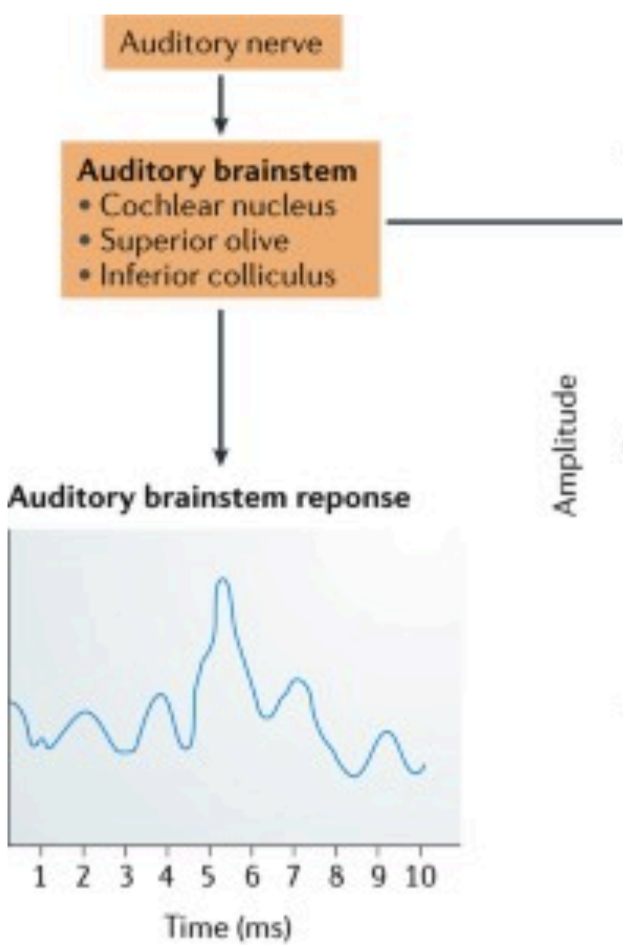
in psychological parameters

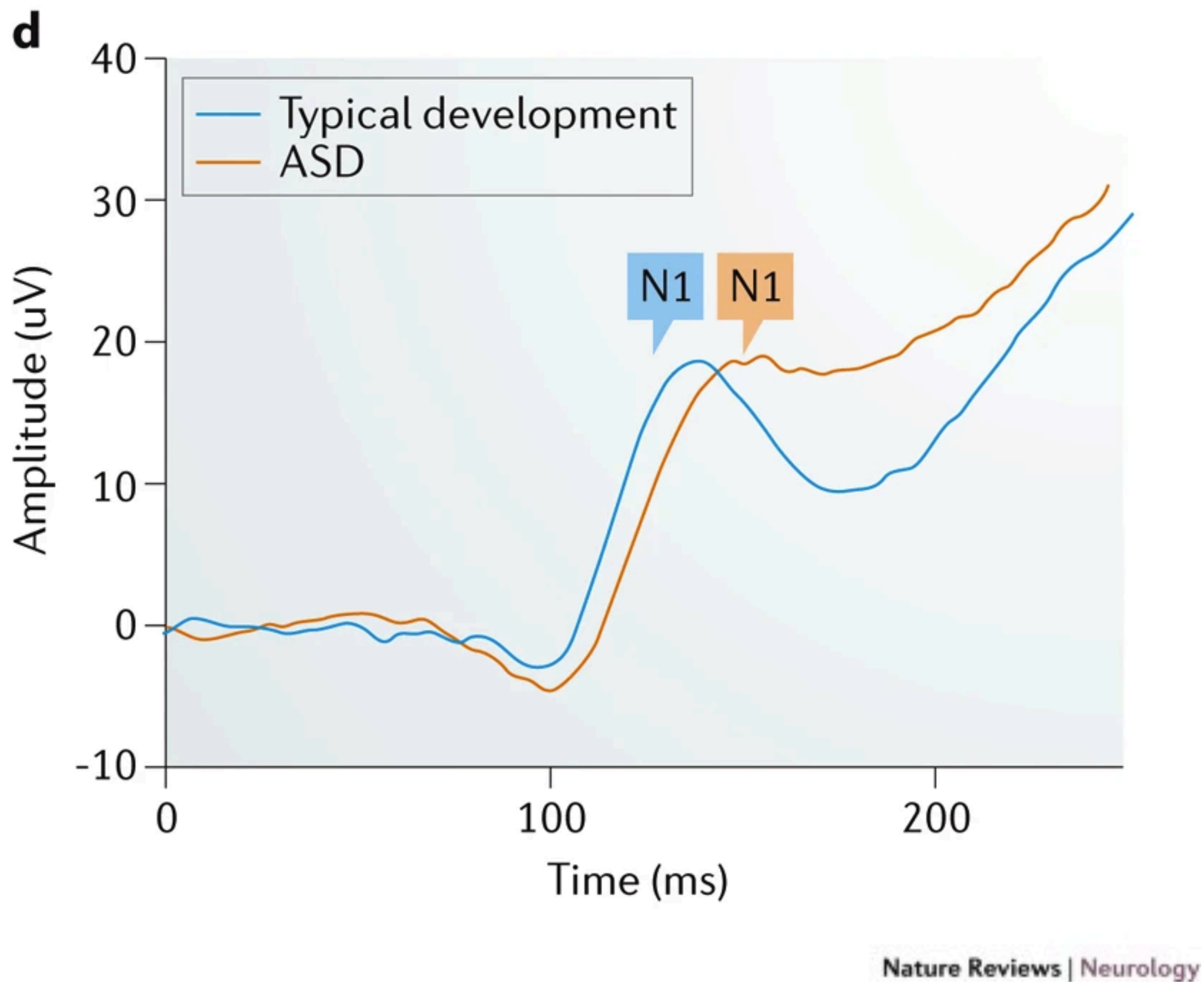


- functional recording of brain activity ◄ events, participant's experiences

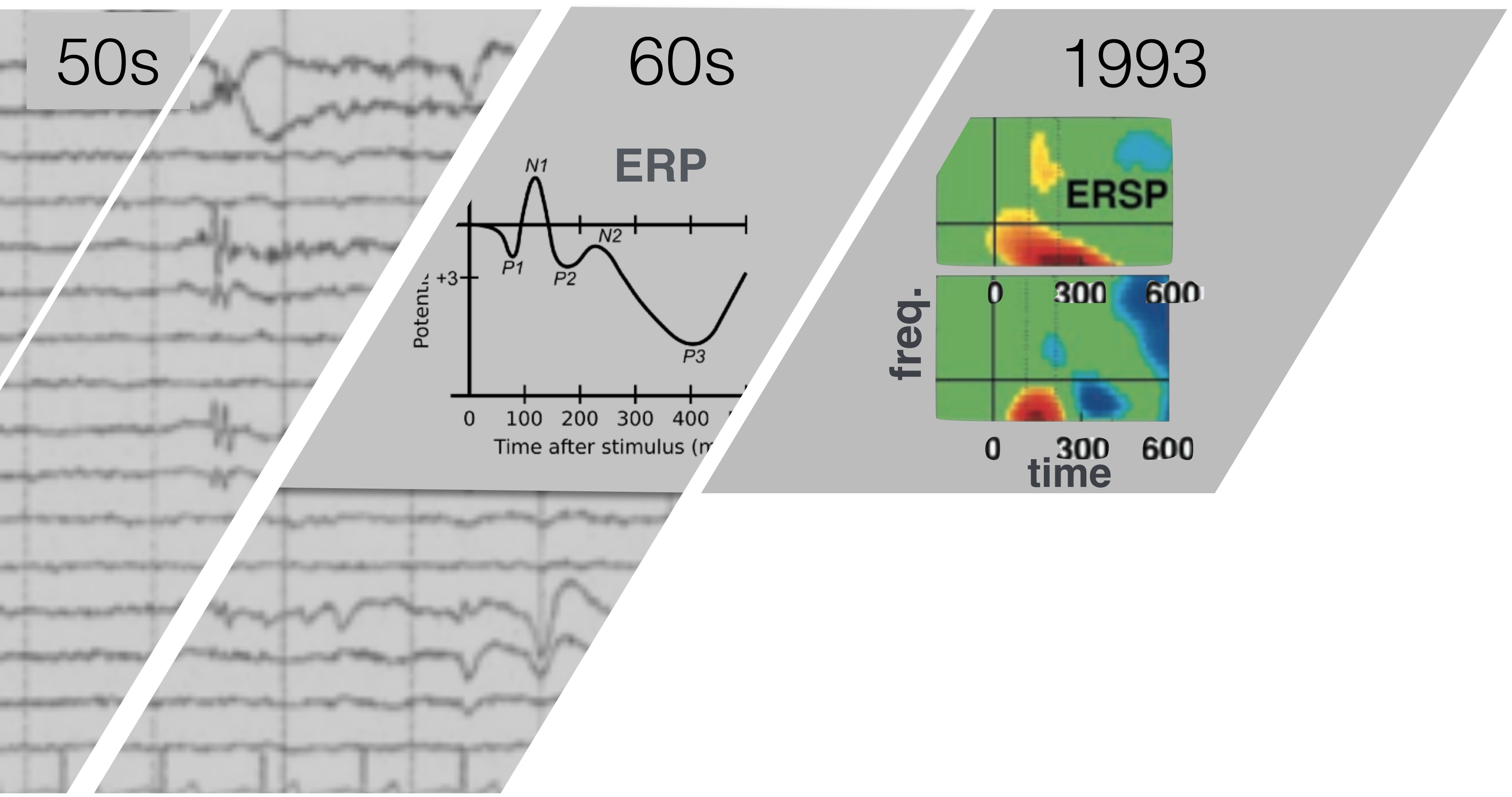
The history of EEG analysis

- Era 2. 60s - Event Related Potential (ERP) analysis



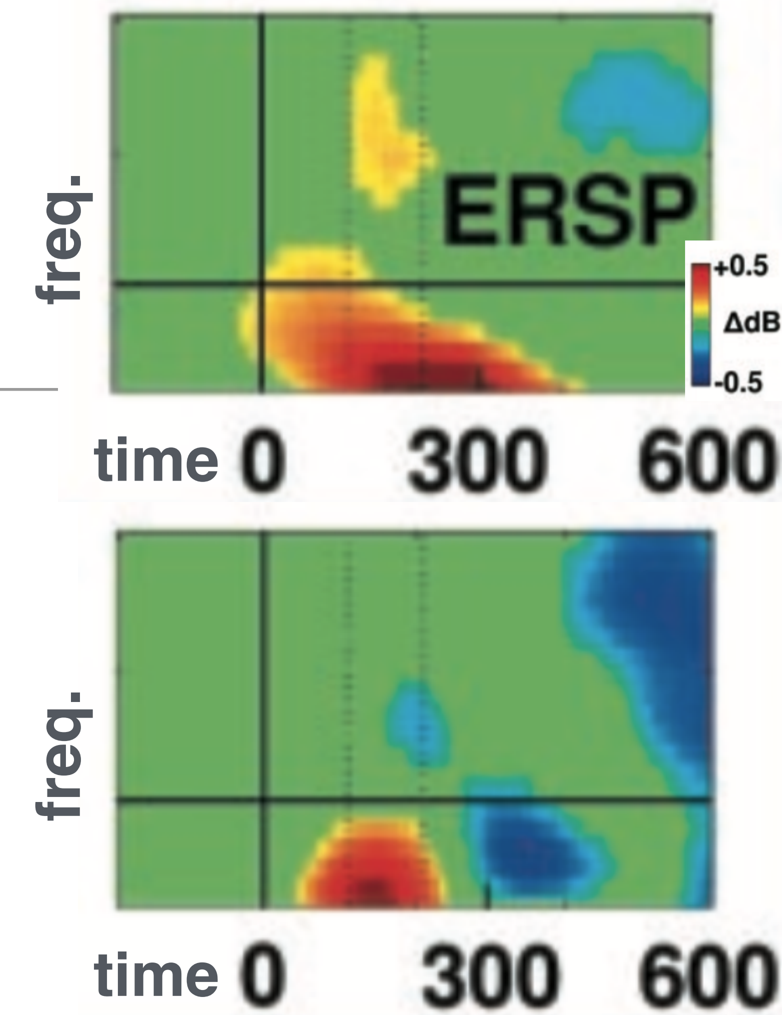


History of EEG analysis - ERSP

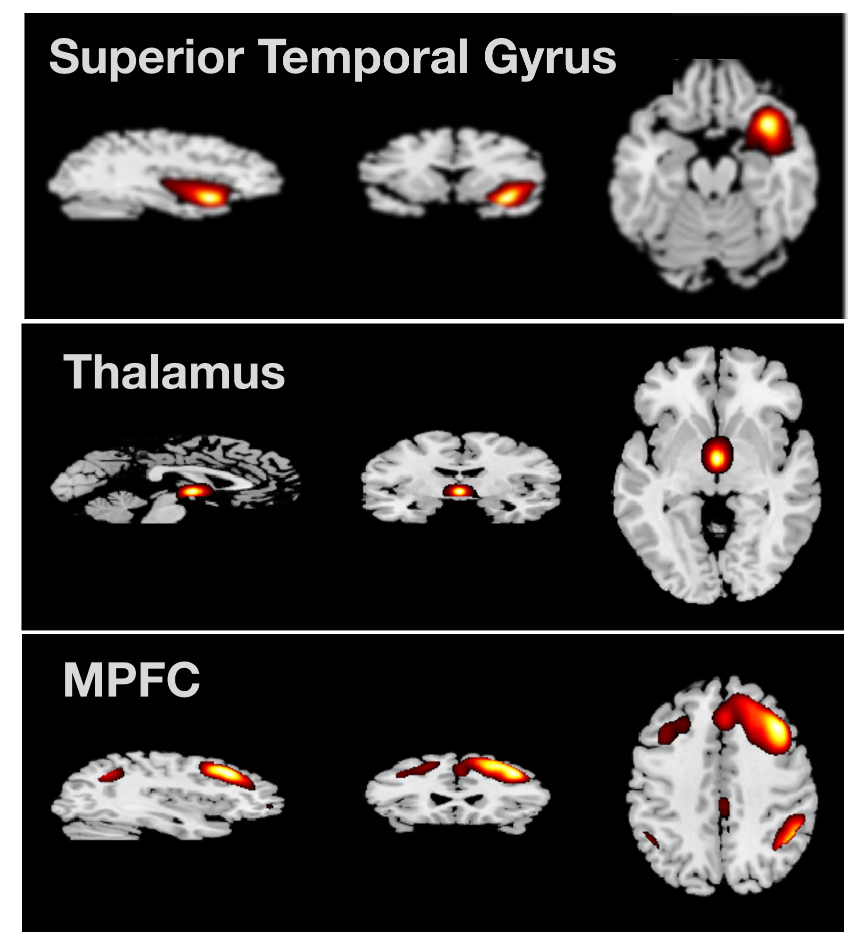


The history of EEG analysis

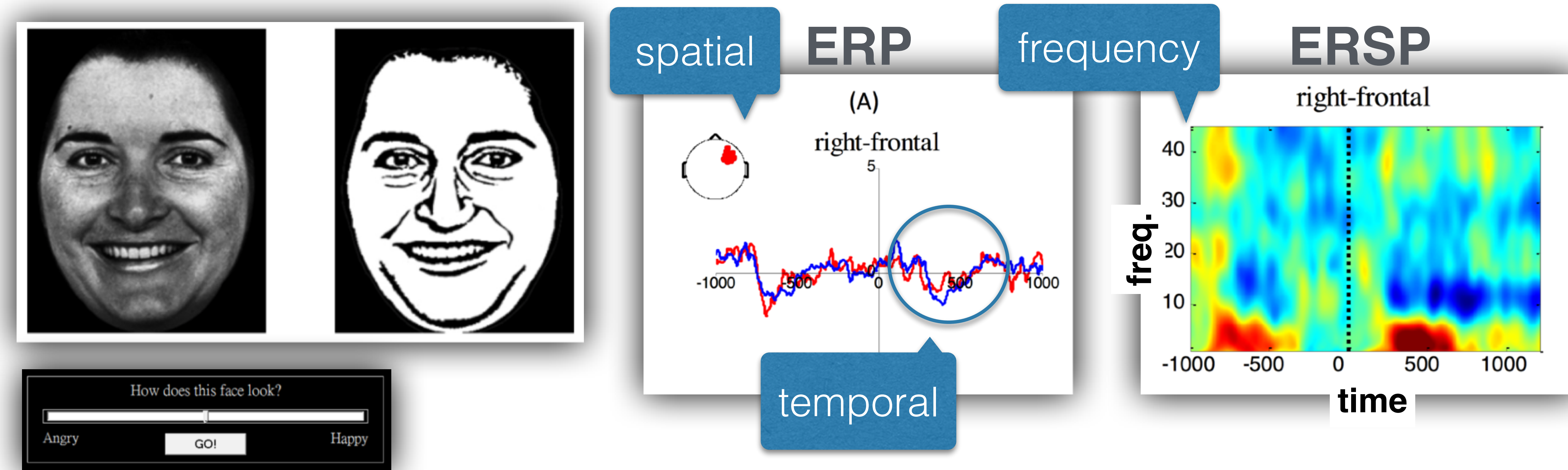
- Era 3. Spectral perturbation analysis
  - 1993. Scott Makeig defined broadband event-related spectral perturbation (ERSP) measure
  - 1993. fMRI research - blood oxygenation level-dependent (BOLD) recording (Ogawa, et. al 1992, Bandettini, et. al. 1993)



(Makeig, 2002. Science)



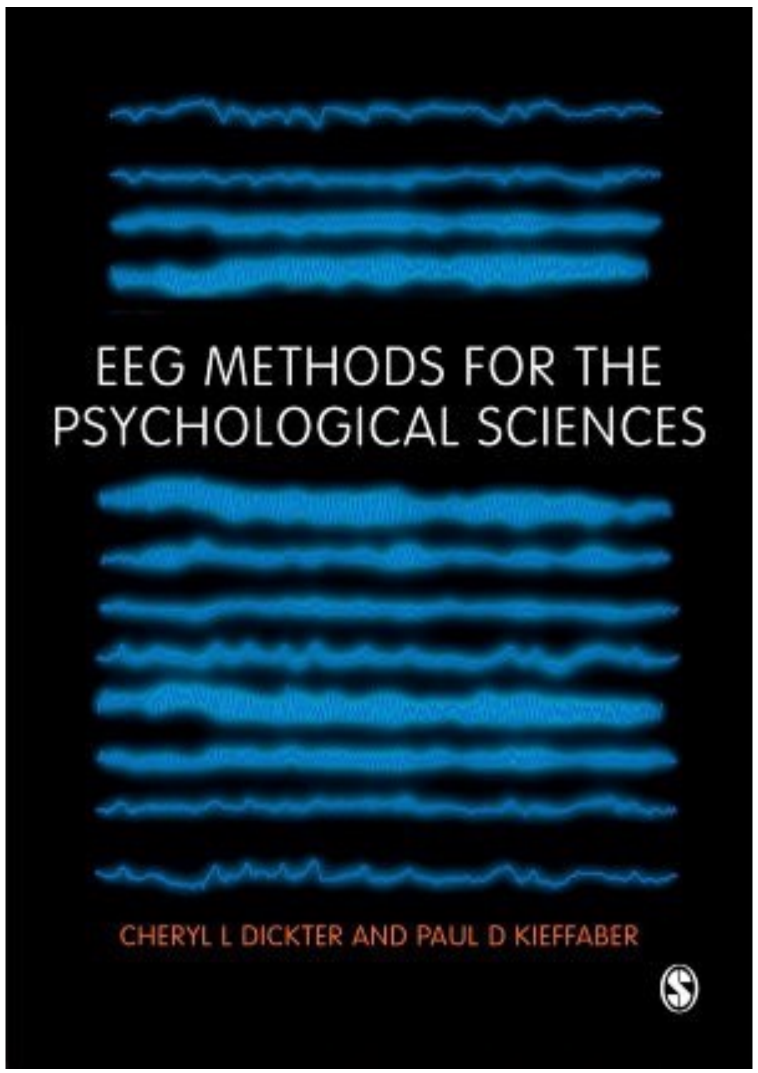
EEG form young adults with Asperger's Syndrome



- **significant difference in the N400 component**
- **differentiate the affective and cognitive functions**

(Tsai & Liou, *et al.*, 2013. Chien, Liou, & Tsai, *et al.*, 2016)

Conventional EEG Analysis



EEG Methods for the Psychological Sciences

Cheryl L Dickter Paul D Kieffaber
December 20, 2013

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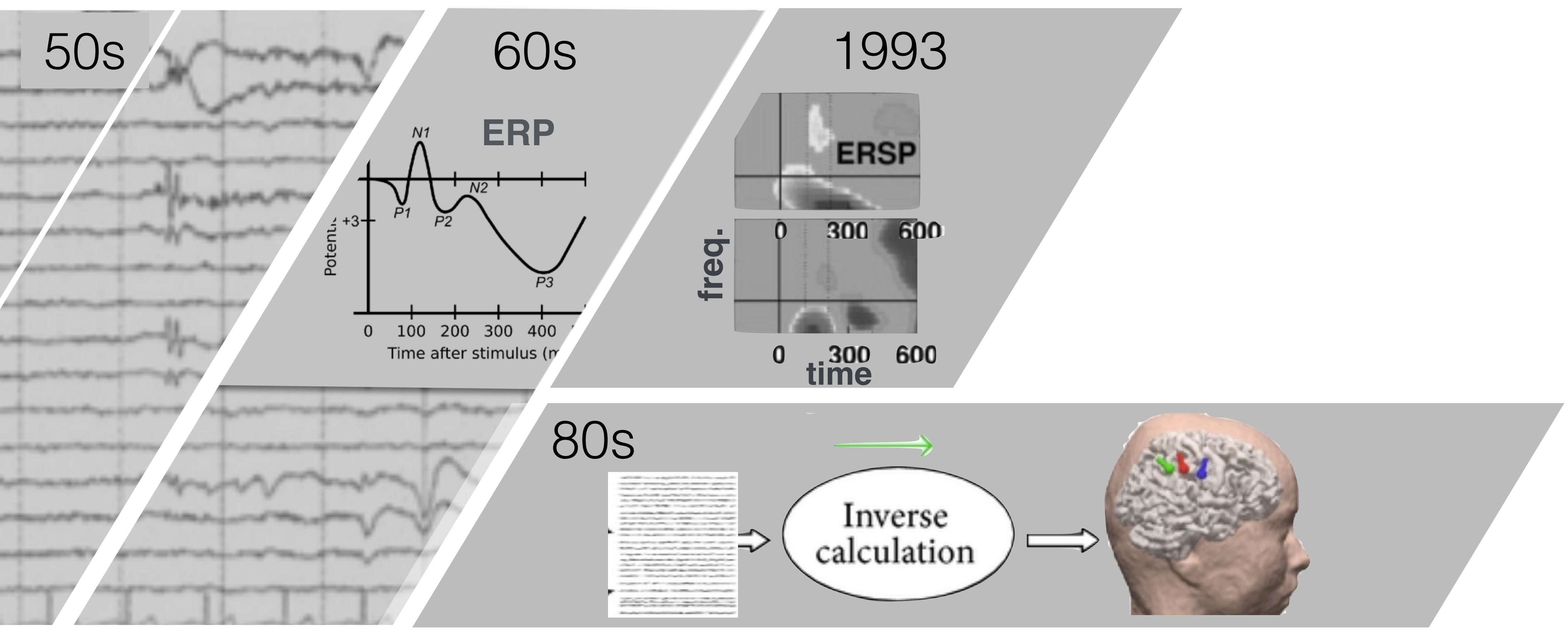
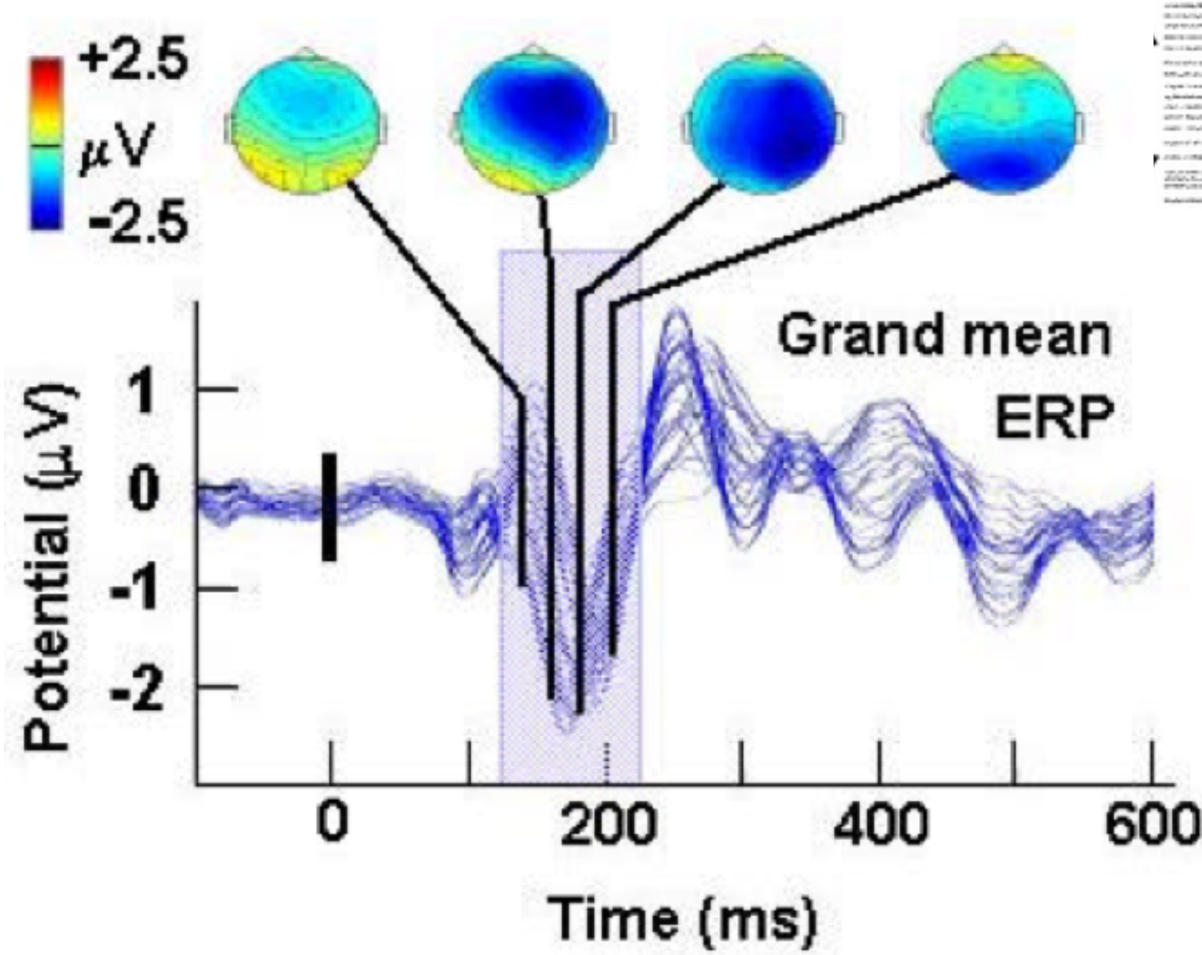
History of EEG analysis

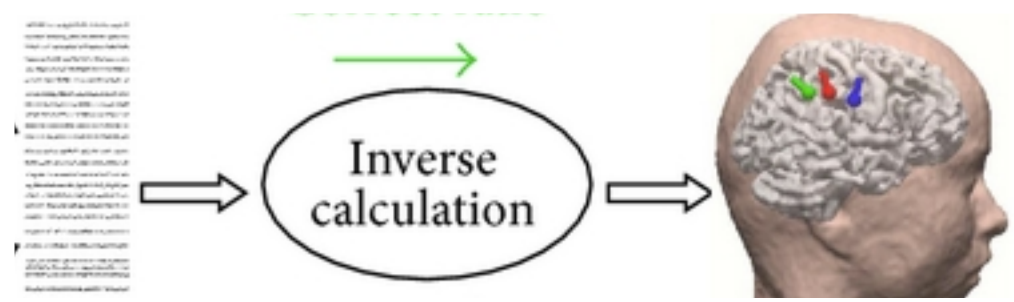


Source imaging in EEG

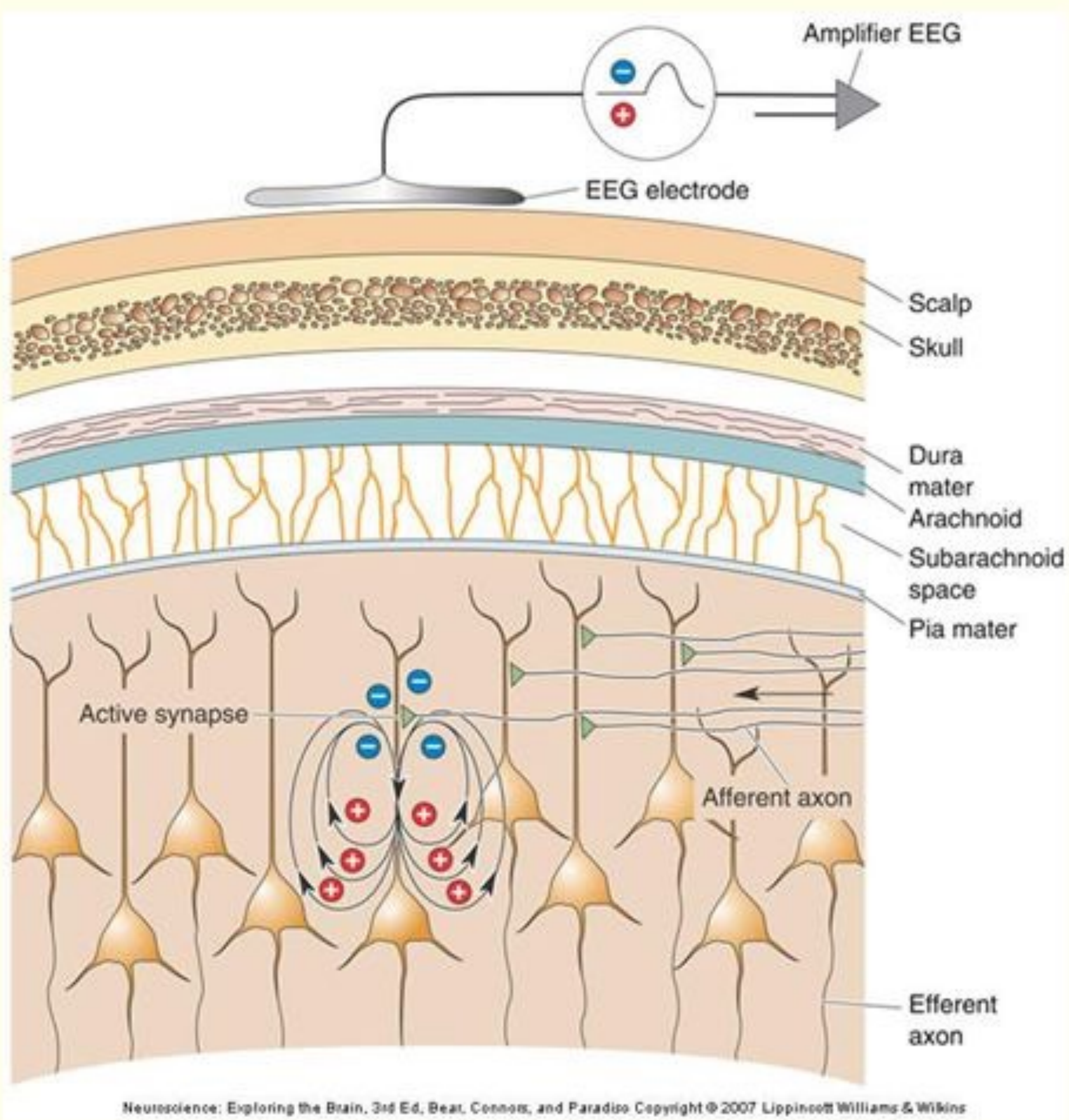
- Perform inverse solutions in an event-related latency interval relevant to average event-related potential (ERP) measures (e.g., the latency range including the **P1, N1, P2, N2, P300, N400 ERP peaks**).

Conventional approach:





Schematic presentation of **dipole** sources.



If you have many of these neurons, the electric field can be summed up and seen on the scalp.

Dipole source localization:

solves $A_B = G(\{\gamma_k, \theta_k\})$

Distributed source imaging:

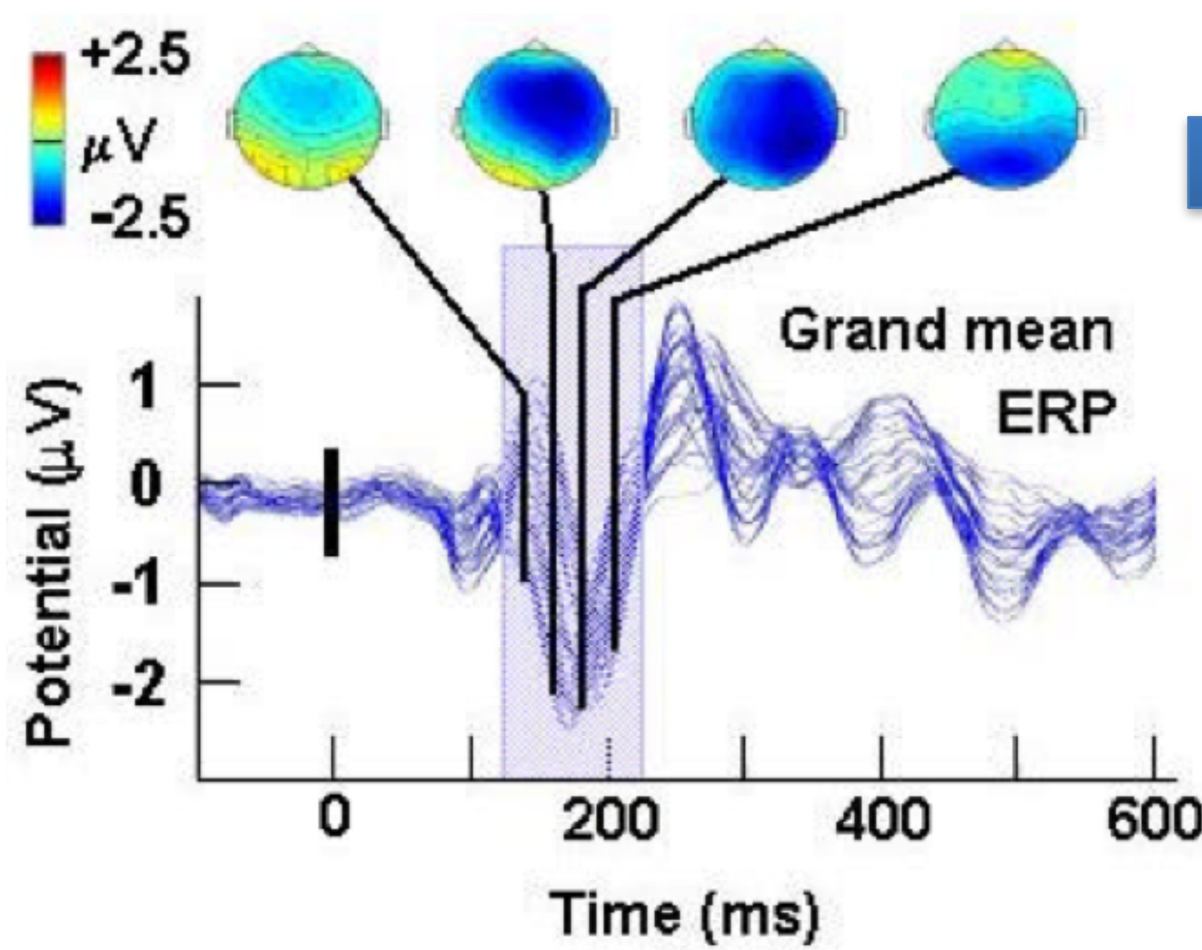
solves $A_B = LB$

Neuroscience: Exploring the Brain Fourth, North Americ Edition by Bear, Mark F., Connors, Barry W., Paradiso, Mich (2015)

EEG --- mixture of underlying cortical sources

Average ERPs 🡐 multiple distributed sources

– Studies applying ICA (Independent Component Analysis) to individual subject data have found that time courses of average ERPs in cognitive tasks are generated by multiple distributed sources with overlapping scalp topographies.



(Makeig *et al.*, 2002, 2004; Moores *et al.*, 2003).

➡ Take single-trial and source separation into account.

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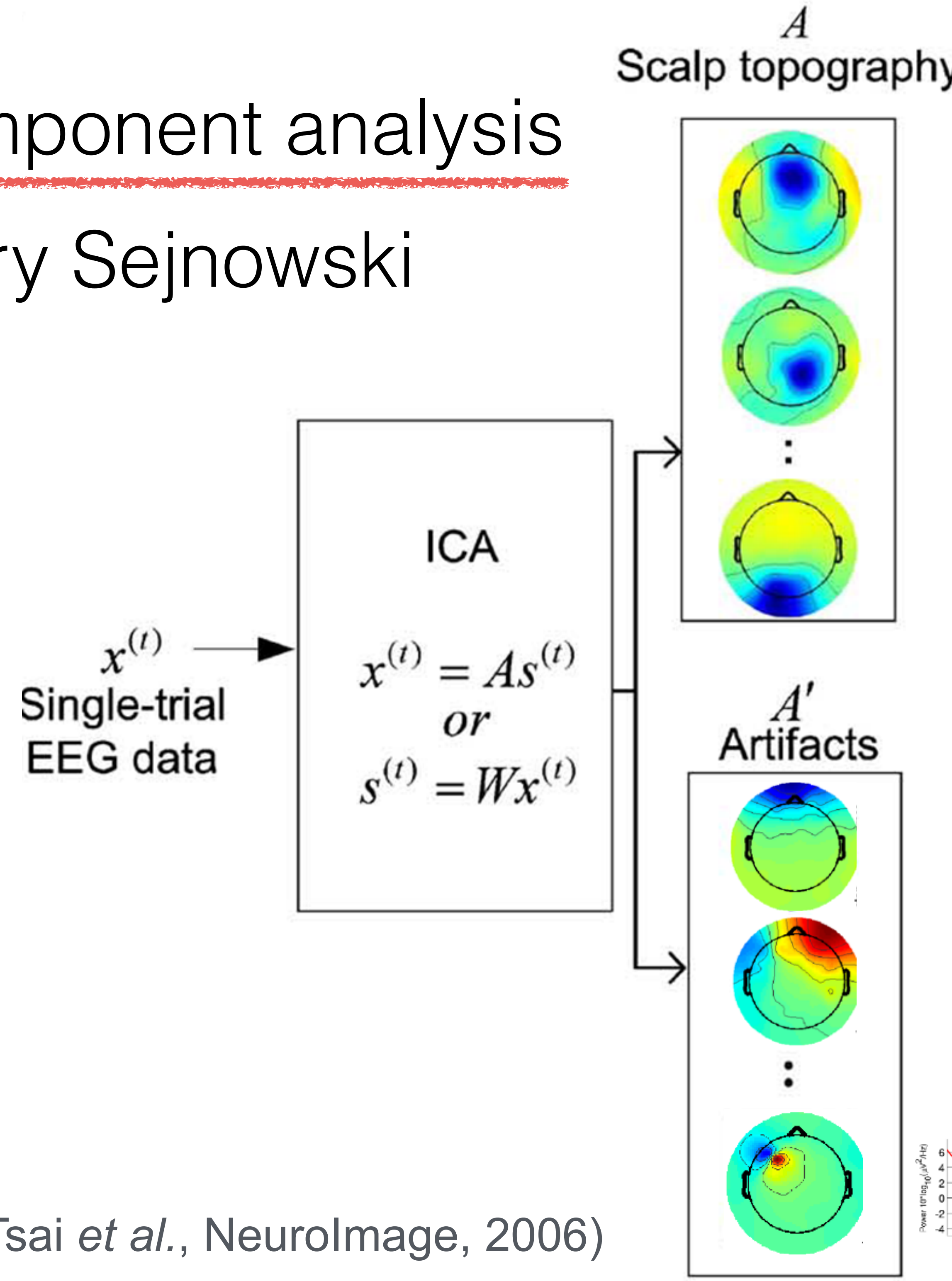
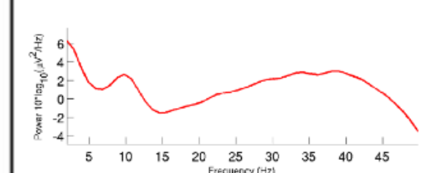
The history of EEG analysis $x^{(t)} = Au^{(t)}$

- Era 4. Independent component analysis
  - 1995. Tony Bell & Terry Sejnowski
  - applied to EEG:

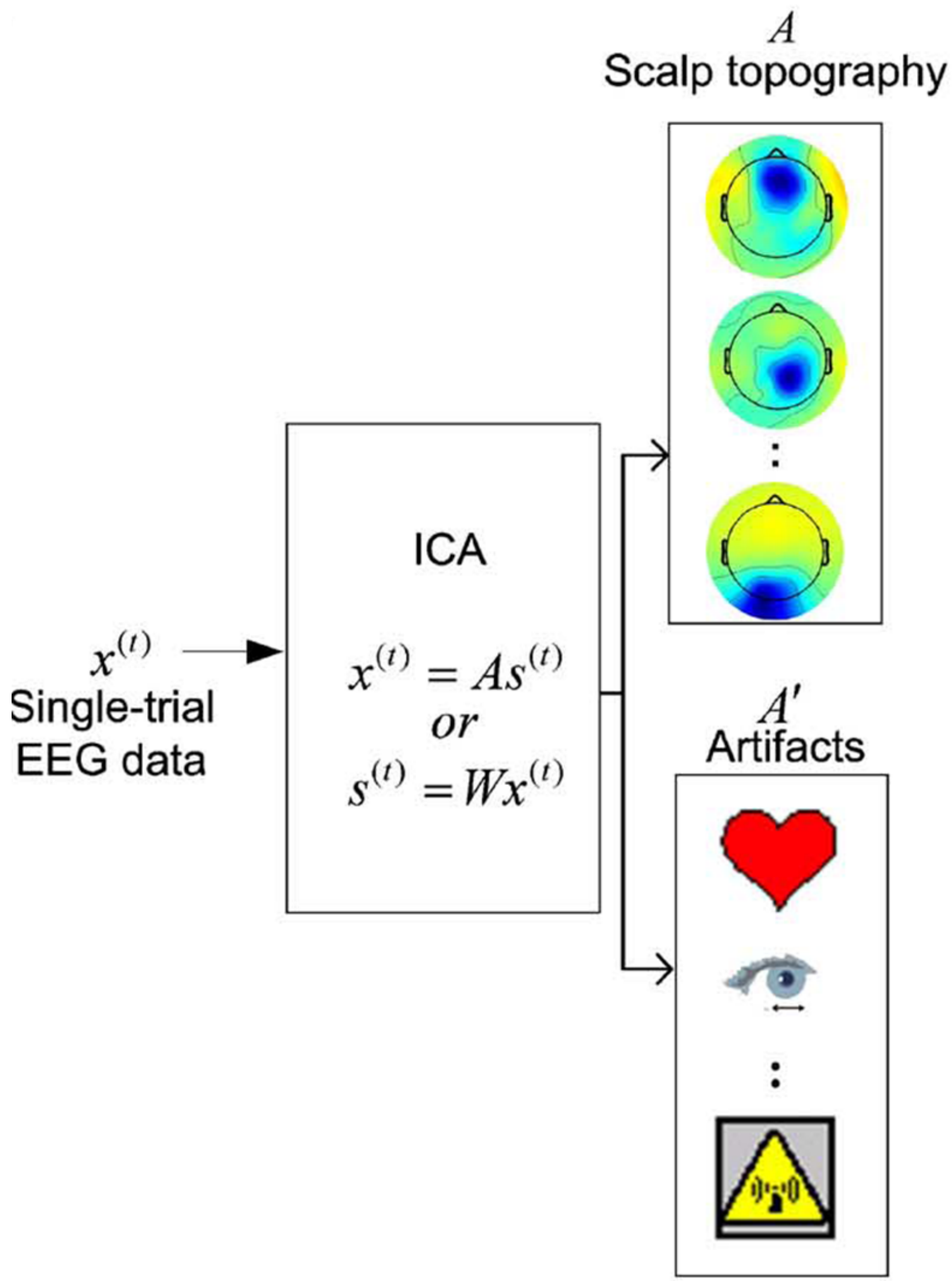




- ICA explains **what** (independent) processes are involved in the cognitive tasks
- Source analysis method models **where** the possible sources of these processes occur.

(Tsai *et al.*, NeuroImage, 2006)

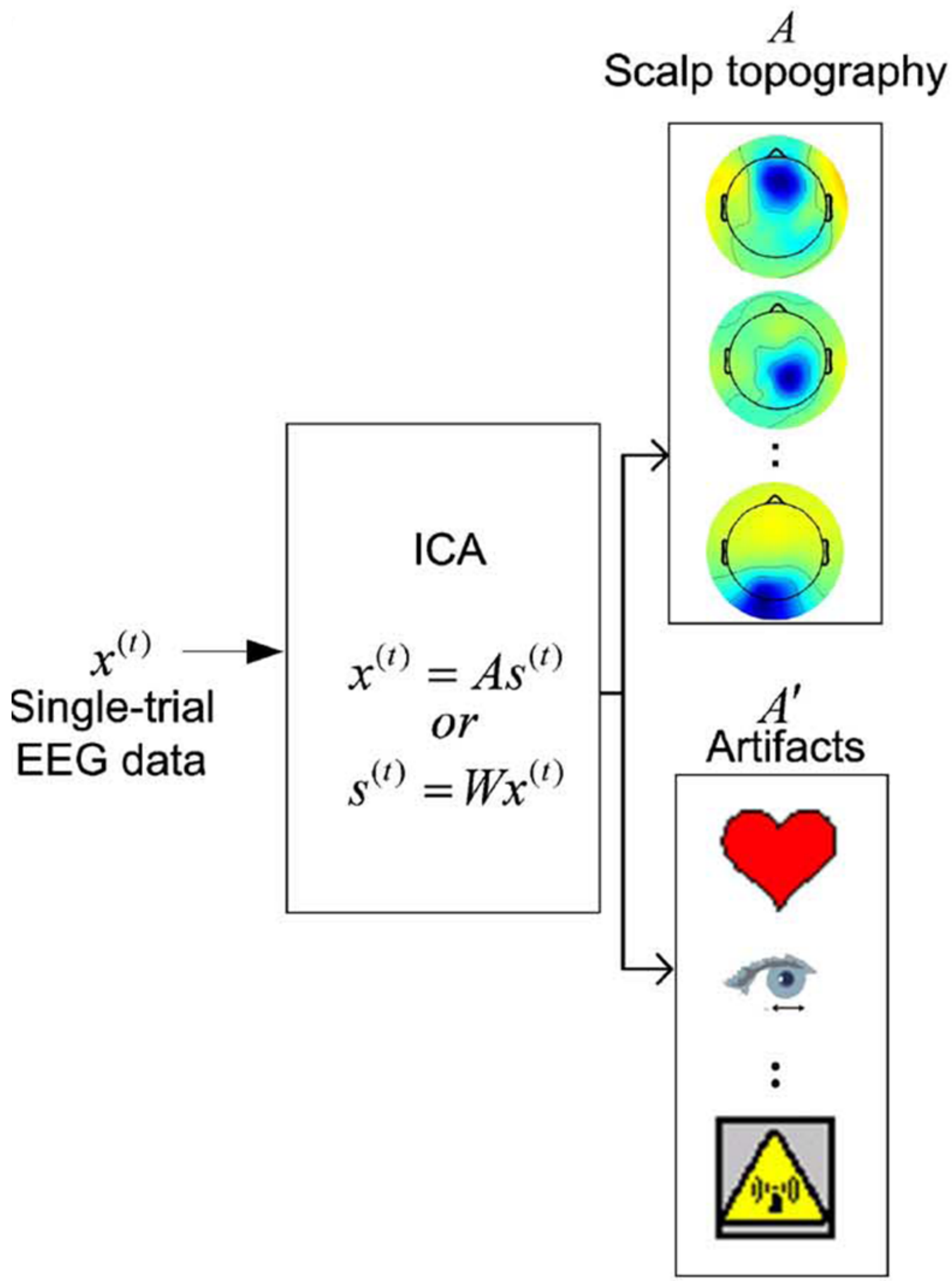
Source decomposition → localization:



- The equivalent dipole sources (Onton NI2005, Makeig-Autism2009, Cogn2007, Russian's 2010) or source current density (e.g., Congedo et al., 2010; De Lucia et al., 2010; Ponomarev et al., 2010) can be localized to represent the generators of these components.

Two-stage ICA

The Issues of Two-stage ICA



ICA model:

$$x^{(t)} = Au^{(t)}$$

where A denoting the mixing matrix whose columns can be partitioned into

$$A = [A_A, A_B]$$

$$x_c^{(t)} = A_B \, u_B^{(t)}$$

64xT IxK KxT

Issues on Two-stage ICA

$$x_c^{(t)} = A_B u_B^{(t)}$$

128x600,000 128x20 20x600,000

Parametric source localization:

Two-stage method- solves $A_B = G(\{\gamma_k, \theta_k\})$

128x20 solve 2x3xKx20. K is unknown

Distributed source imaging:

Two-stage method- solves $A_B = LB$

128x20 solve 12,000x20

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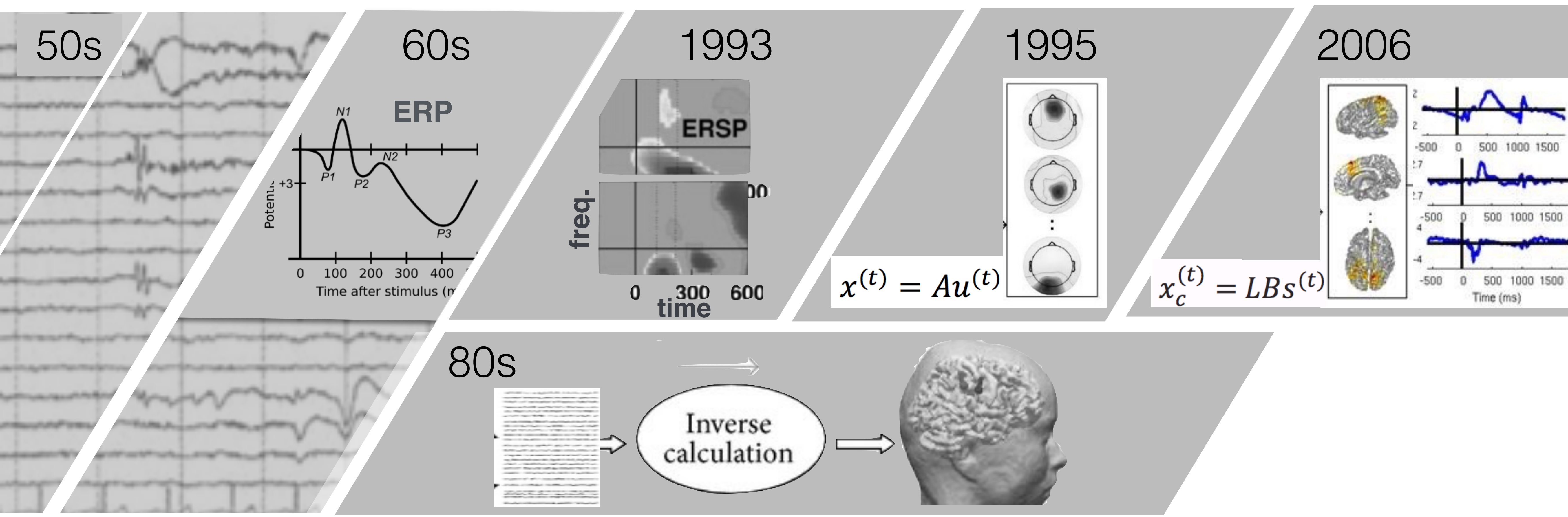
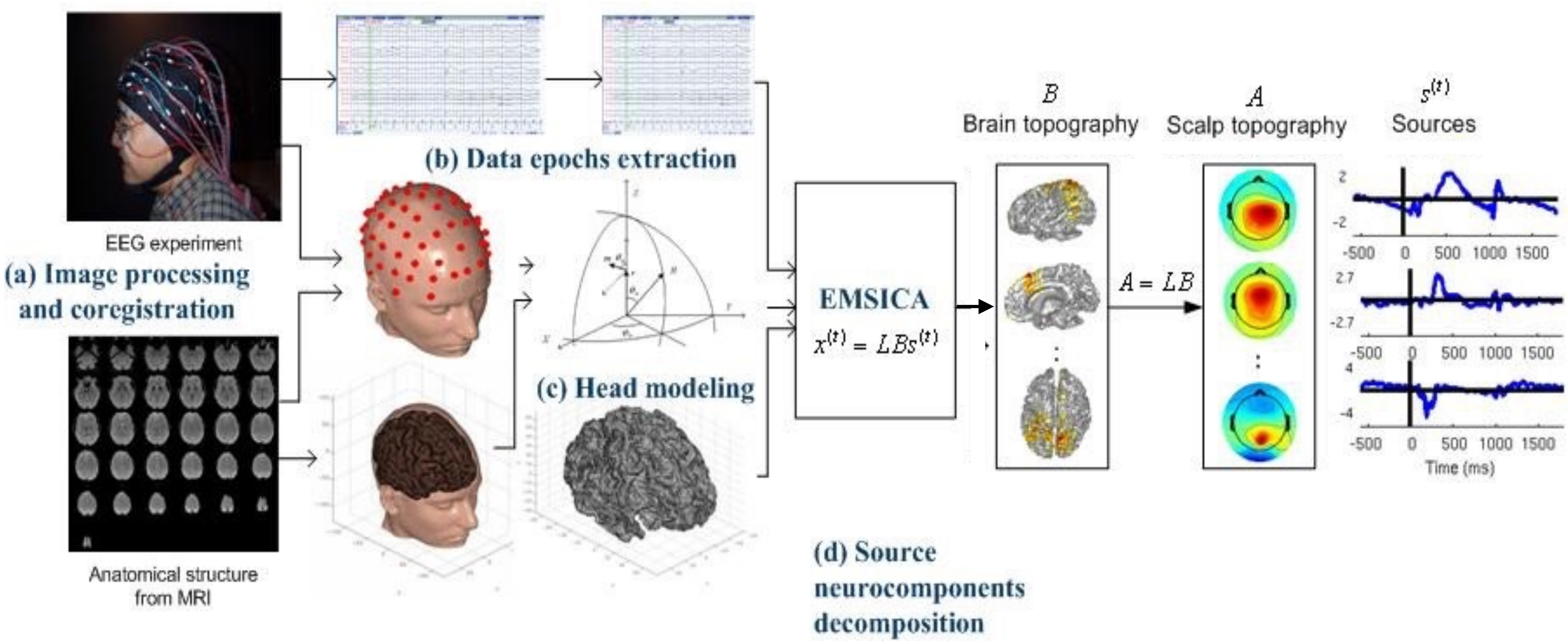
History of EEG analysis



Electromagnetic Spatiotemporal Independent Component Analysis (EMSICA)



Electromagnetal Spatiotemporal Independent Component Analysis (EMSICA)

EMSICA model:

$$x_c^{(t)} = LBs^{(t)}$$

128x600,000 solve 12,000x20

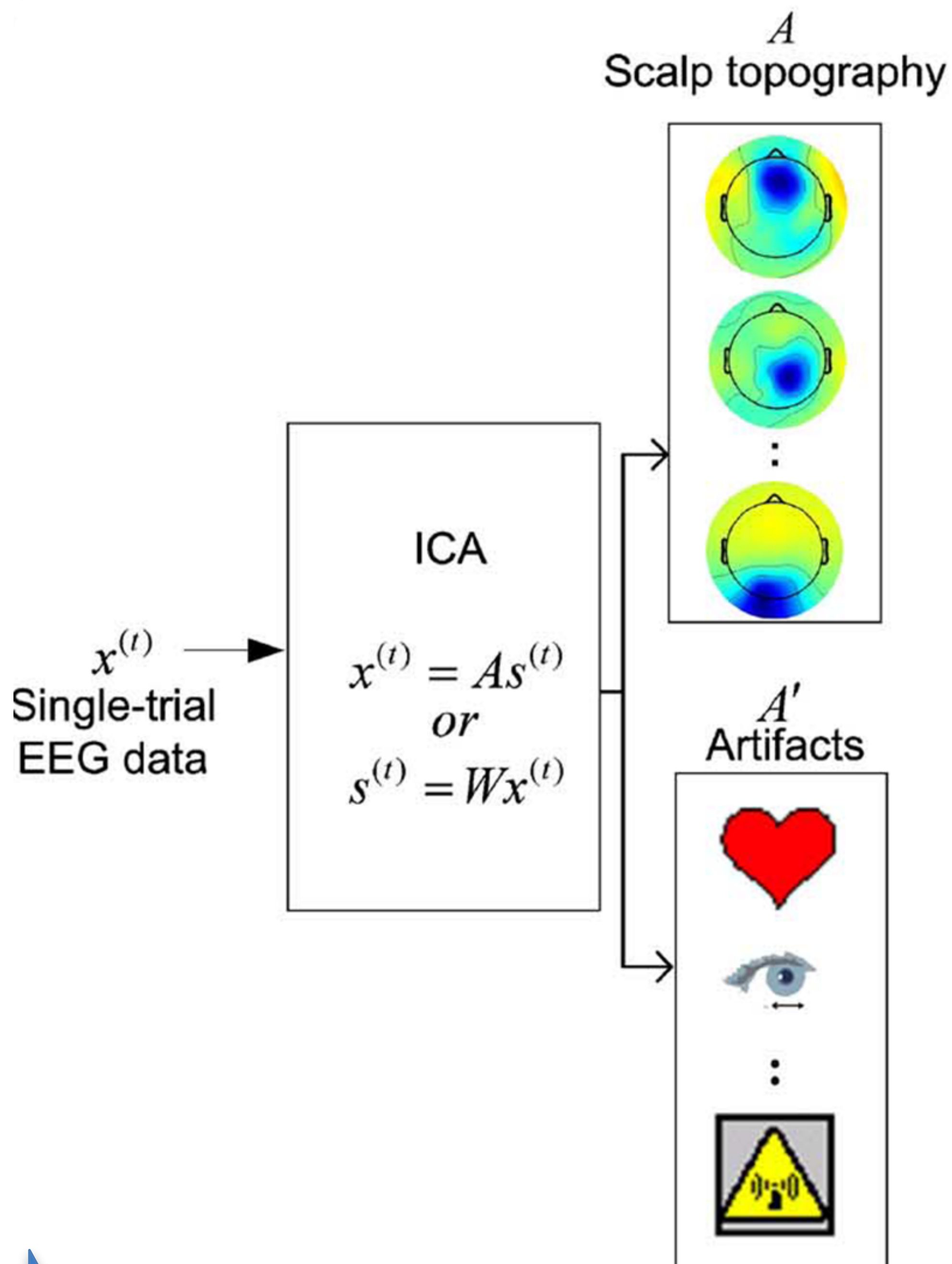
Single-trial, single-stage independent source imaging.

cf. Two-stage ICA:

$$x_c^{(t)} = A_B \, u_B^{(t)}$$

Two-stage method- solves $A_B = LB$

128x20 solve 12,000x20



source analysis from
IC scalp map $\underset{\text{IxK}}{A_B} = LB$

The two-stage ICA/PCA approach, dramatically reduces training data information for source analysis from $x_c^{(t)}$, for $t = 1, \ldots, T$, to A_B, where the number of data points are I-by-T (e.g.. 128x600,000) and I-by-K (e.g. 128x60), respectively, **while $T \gg K$**.

Single-stage ICA

$$\underset{\text{IxT}}{x_c^{(t)}} = LBs^{(t)}$$

IxJ JxK KxT

EMSICA algorithm

To Maximize:

$$p\left(B|x^{(t)},L\right) \propto p(B)\int ds^{(t)} p\left(x^{(t)}|L,B,s^{(t)}\right)p\left(s^{(t)}\right)$$

Assume spatial independence +
Markov Random Field as prior

Assume temporal independence

- $B \in R^{J \times K}$: b_{jk} the contribution of the *k*th source component to the *j*th tessellation element on the cortex
- *s*(*t*): the source signal
- *x*(*t*): Single-trial EEG recordings
- L : Leadfield obtained from realistic head model

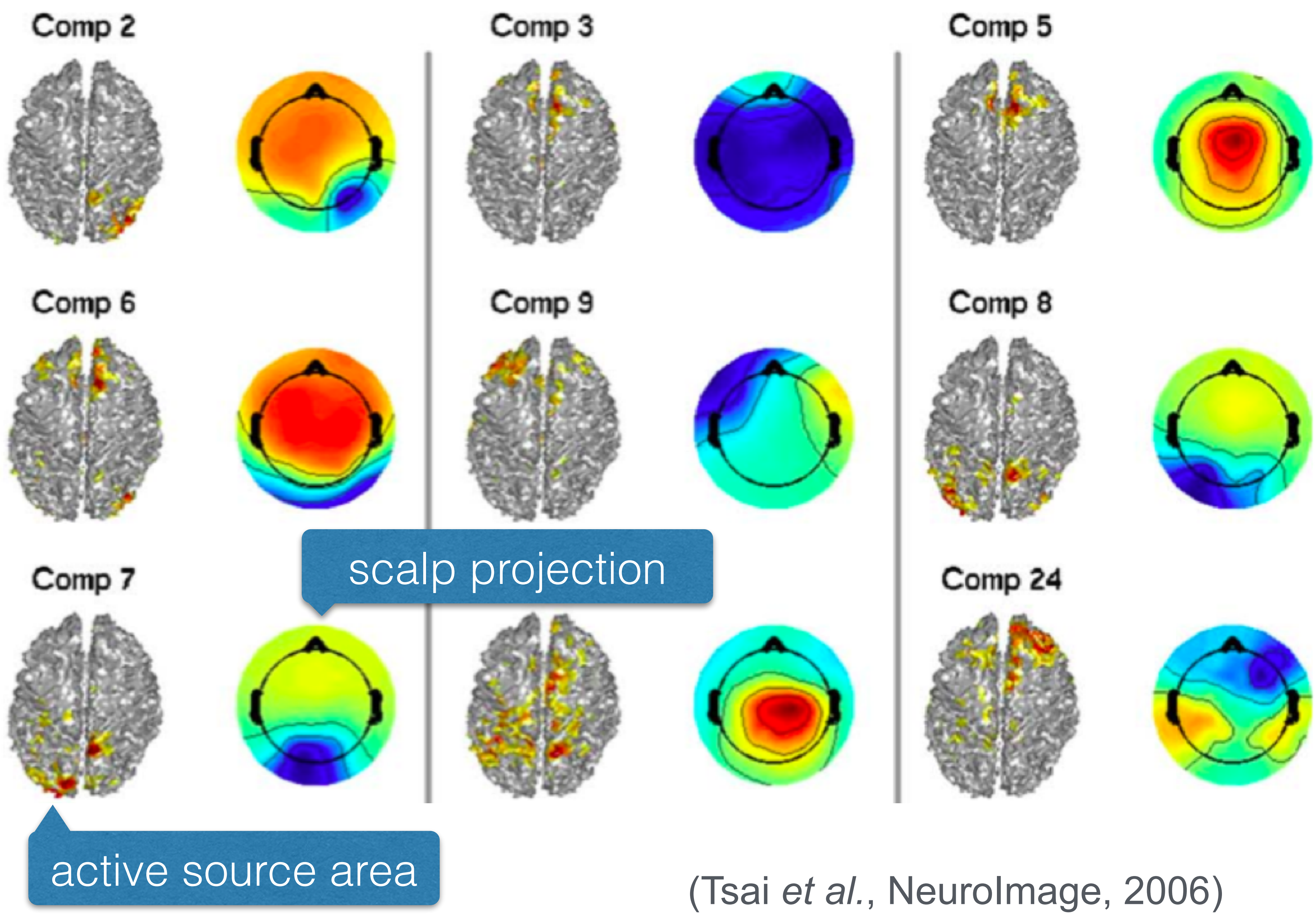
The learning rule:

$$\Delta B = B\left[B^T \phi(B) - I - (1/\tau)\varphi(U)U^T\right]$$

(Tsai *et al.*, NeuroImage, 2006)

☑ Single-trial, single-stage spatiotemporal independent component analysis

EMSICA components

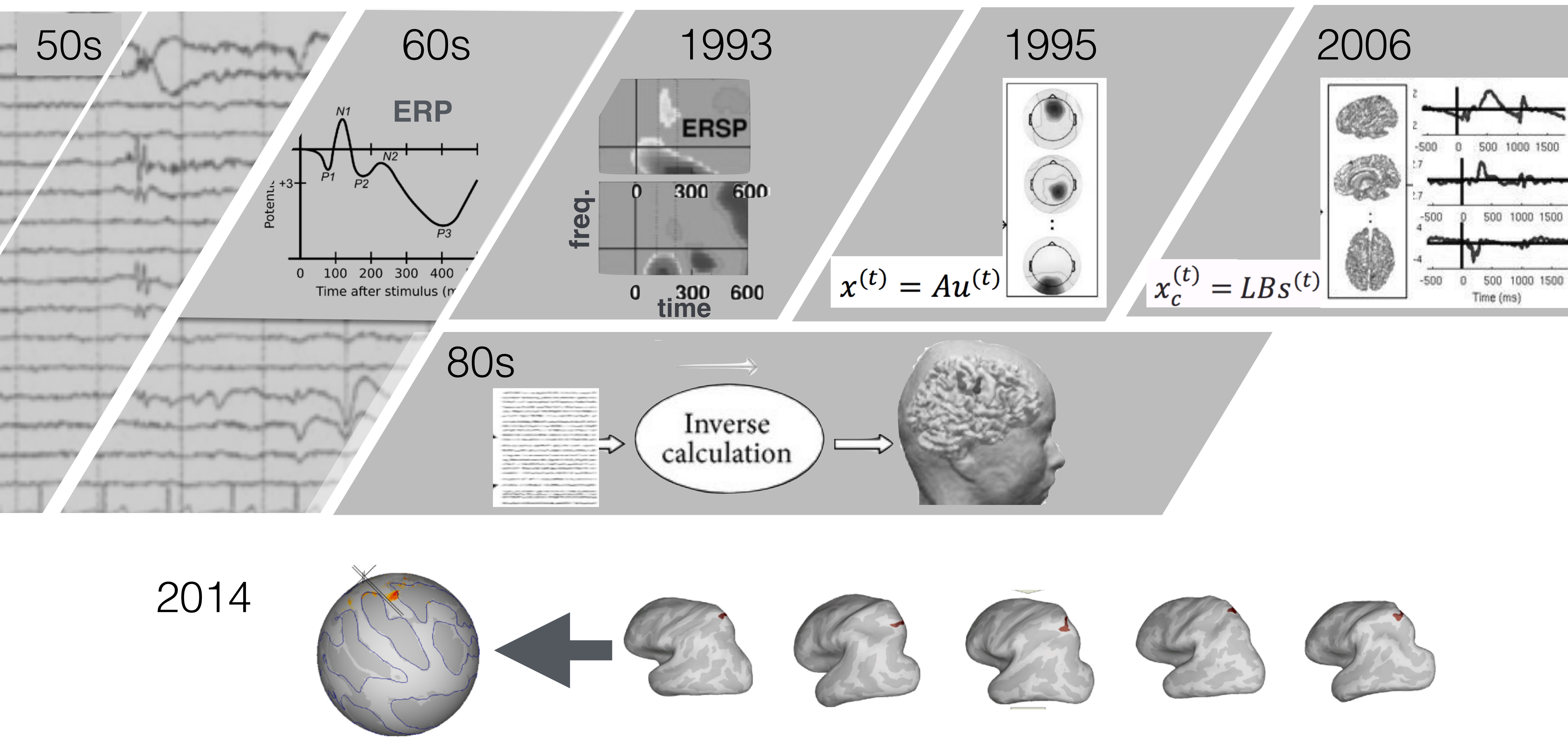


(Tsai *et al.*, NeuroImage, 2006)

~~Identical~~, what are they equivalent now?

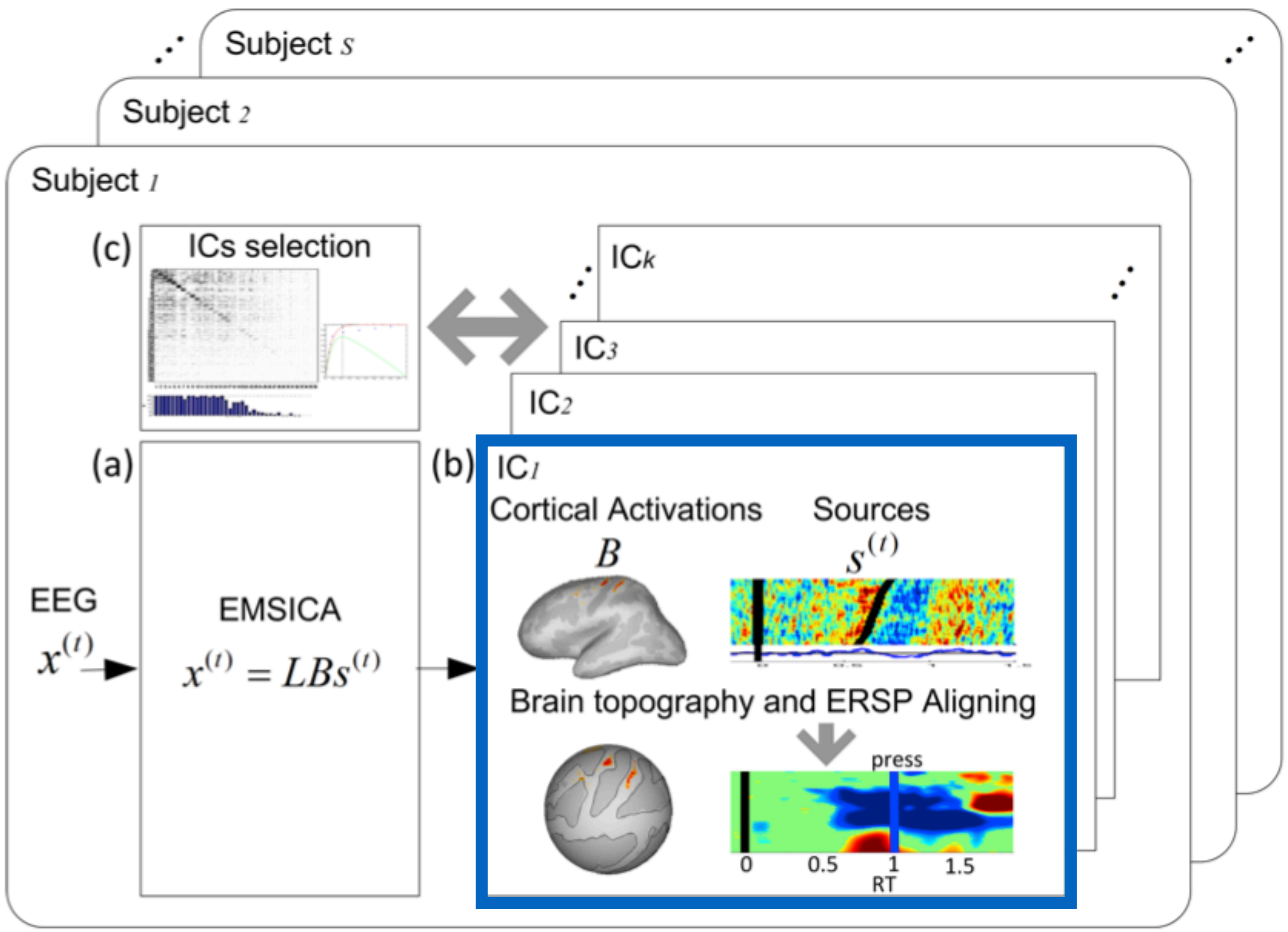
How to cluster the components?

History of EEG analysis



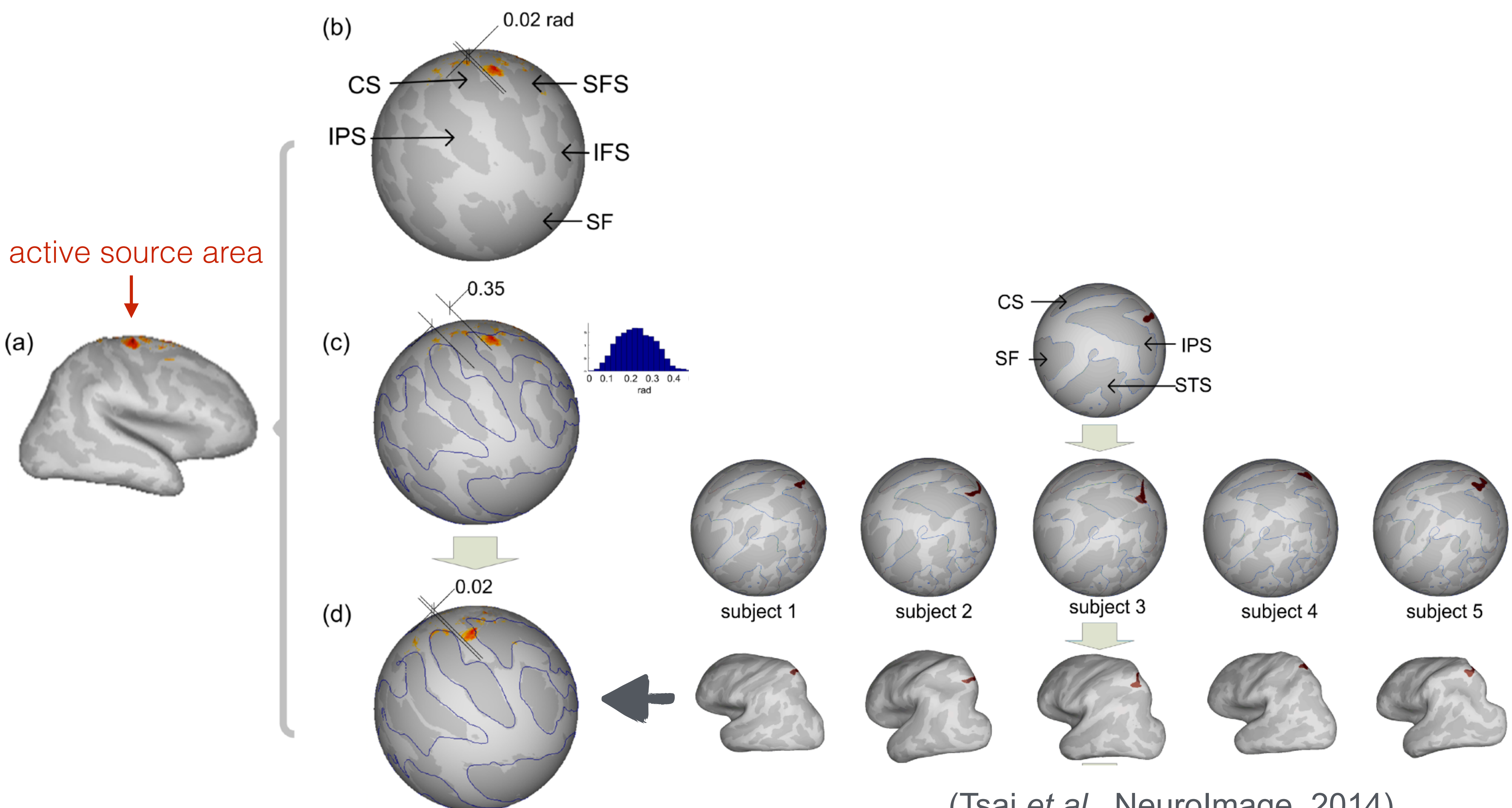
Multi-subject group analysis workflow

Cortical surface alignment in multi-subject spatiotemporal independent source imaging



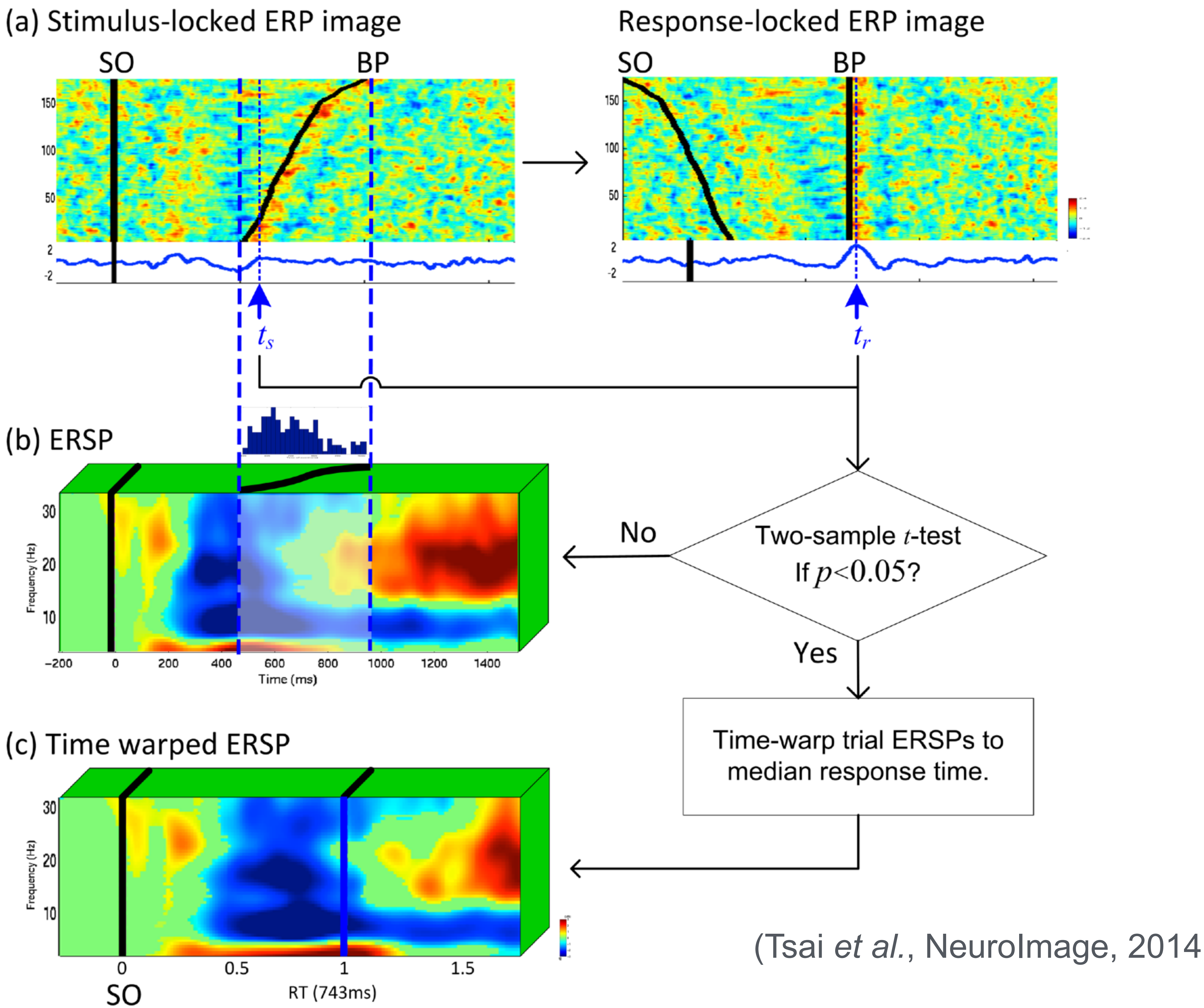
(Tsai *et al.*, NeuroImage, 2014)

Multi-subject Cortical surface alignment



(Tsai *et al.*, NeuroImage, 2014)

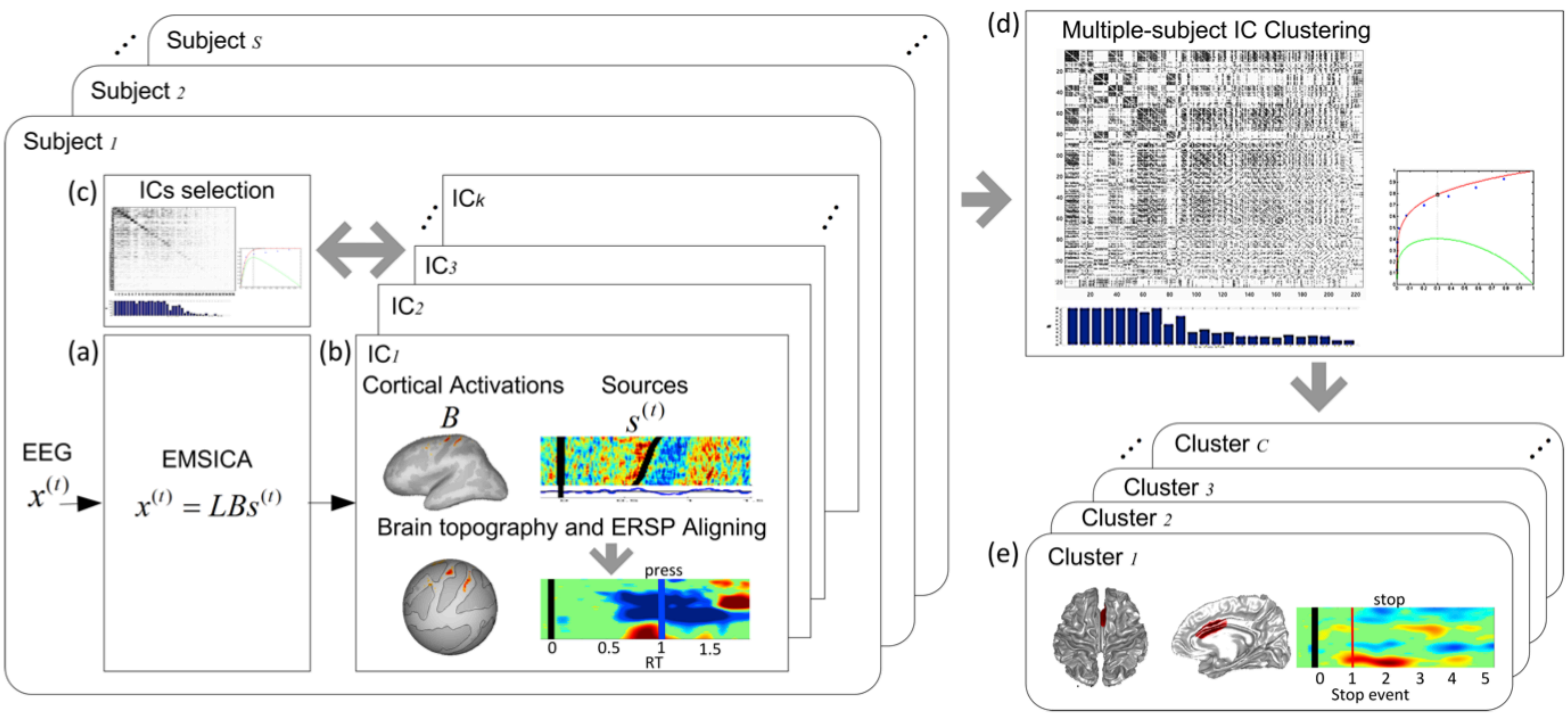
Latency-frequency Image Aligning



(Tsai *et al.*, NeuroImage, 2014)

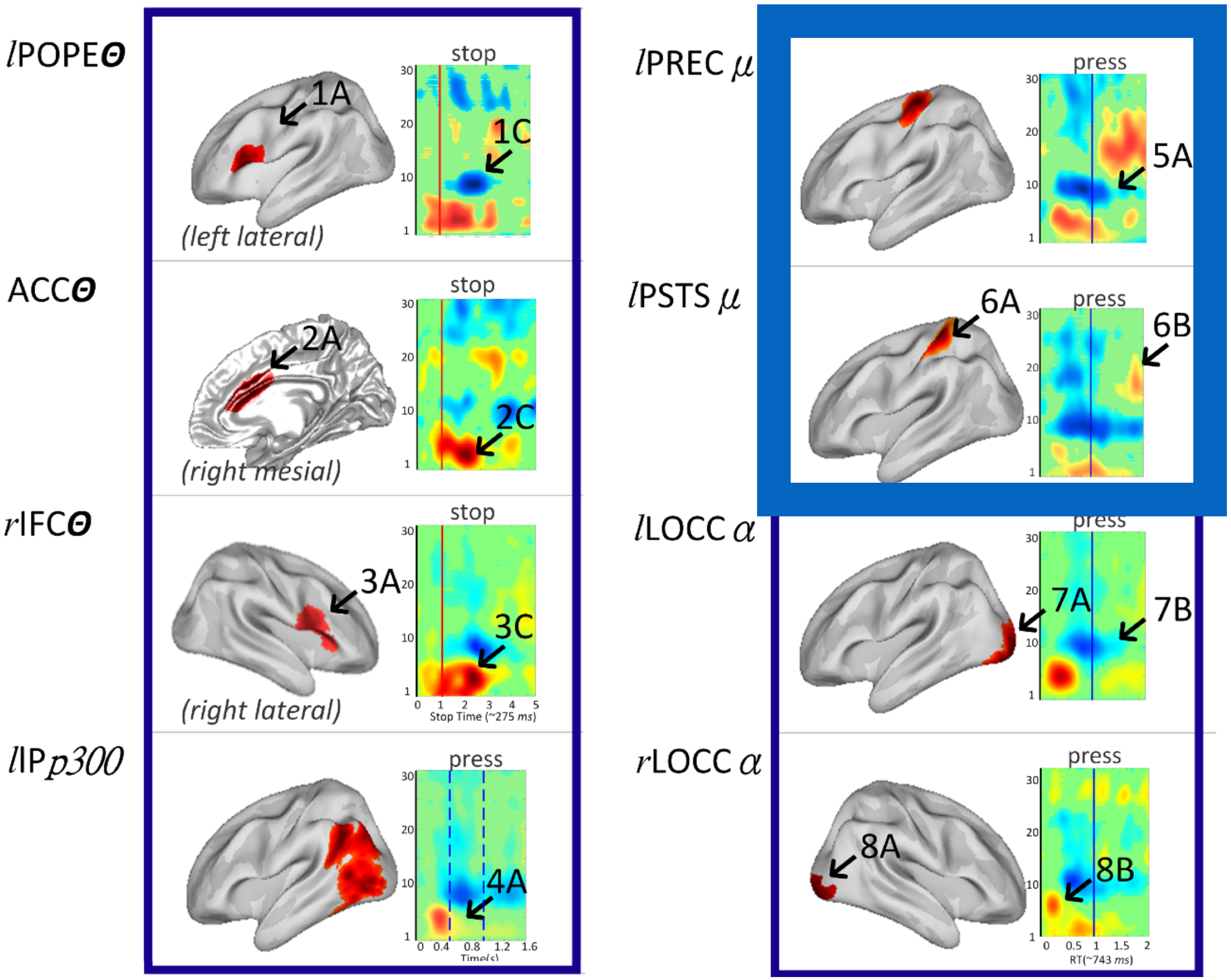
Multi-subject group analysis workflow

Cortical surface alignment in multi-subject spatiotemporal independent EEG source imaging

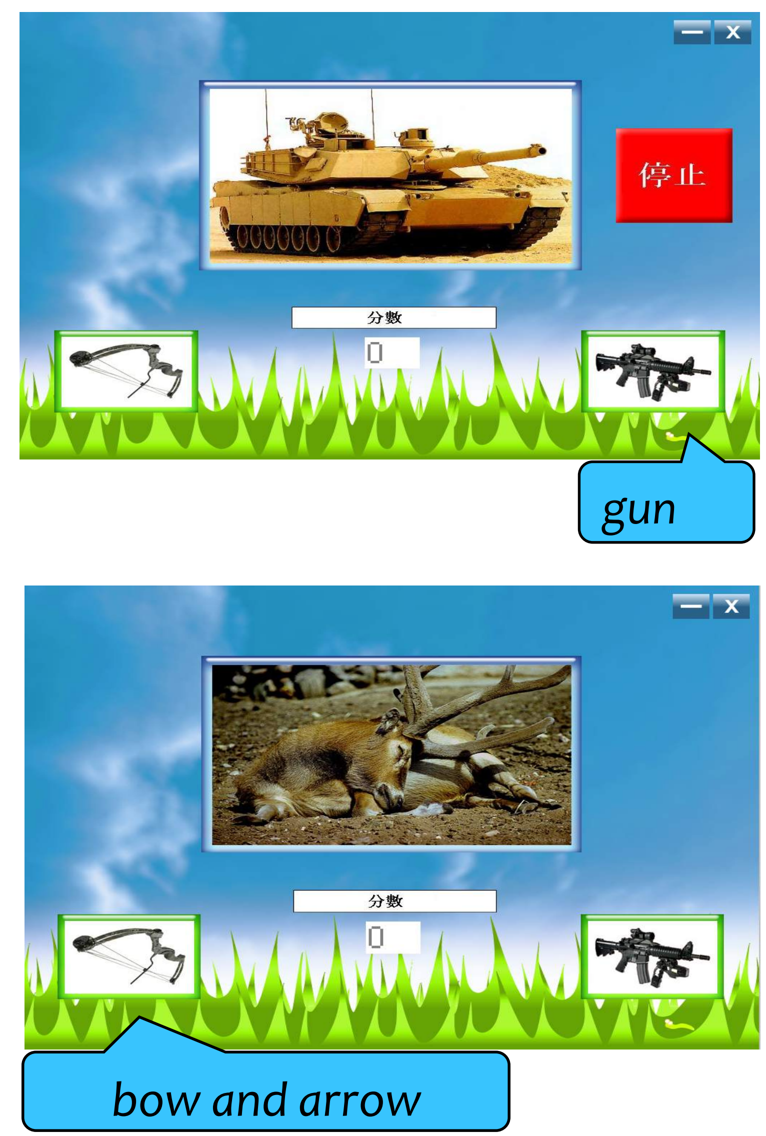


(Tsai *et al.*, NeuroImage, 2014)

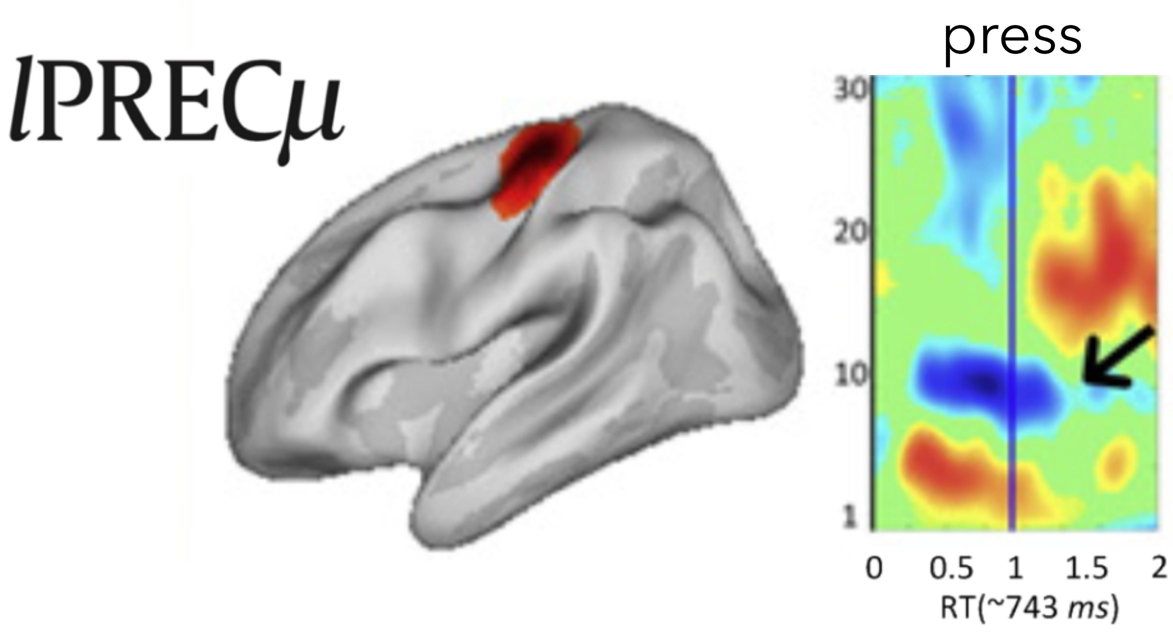
Results of component clusters

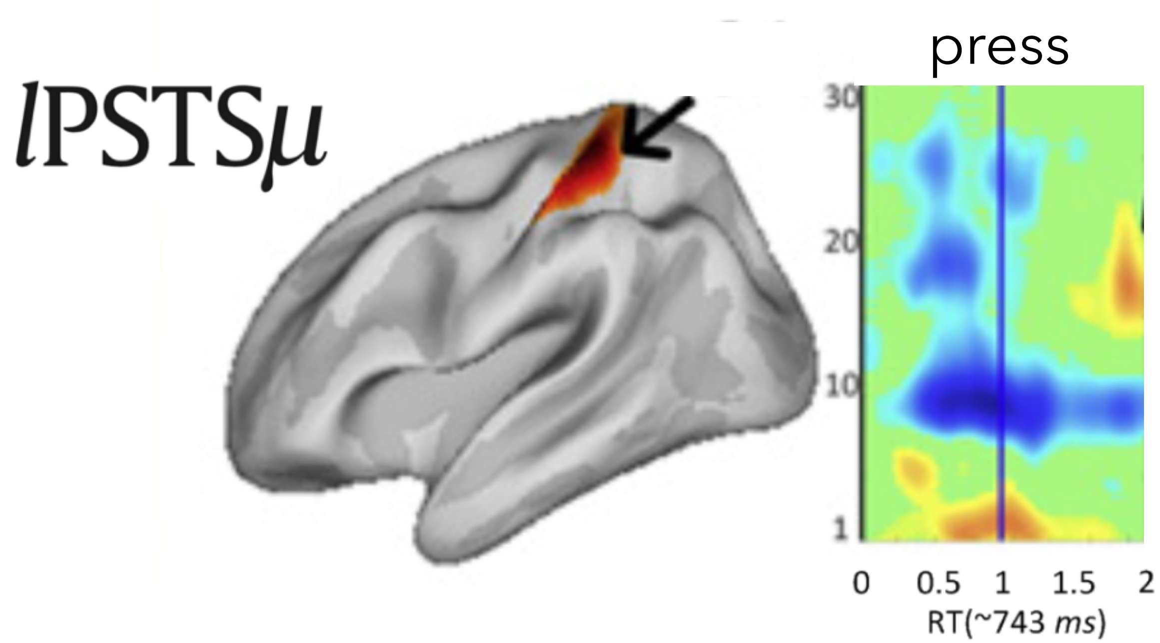


stop signal paradigm

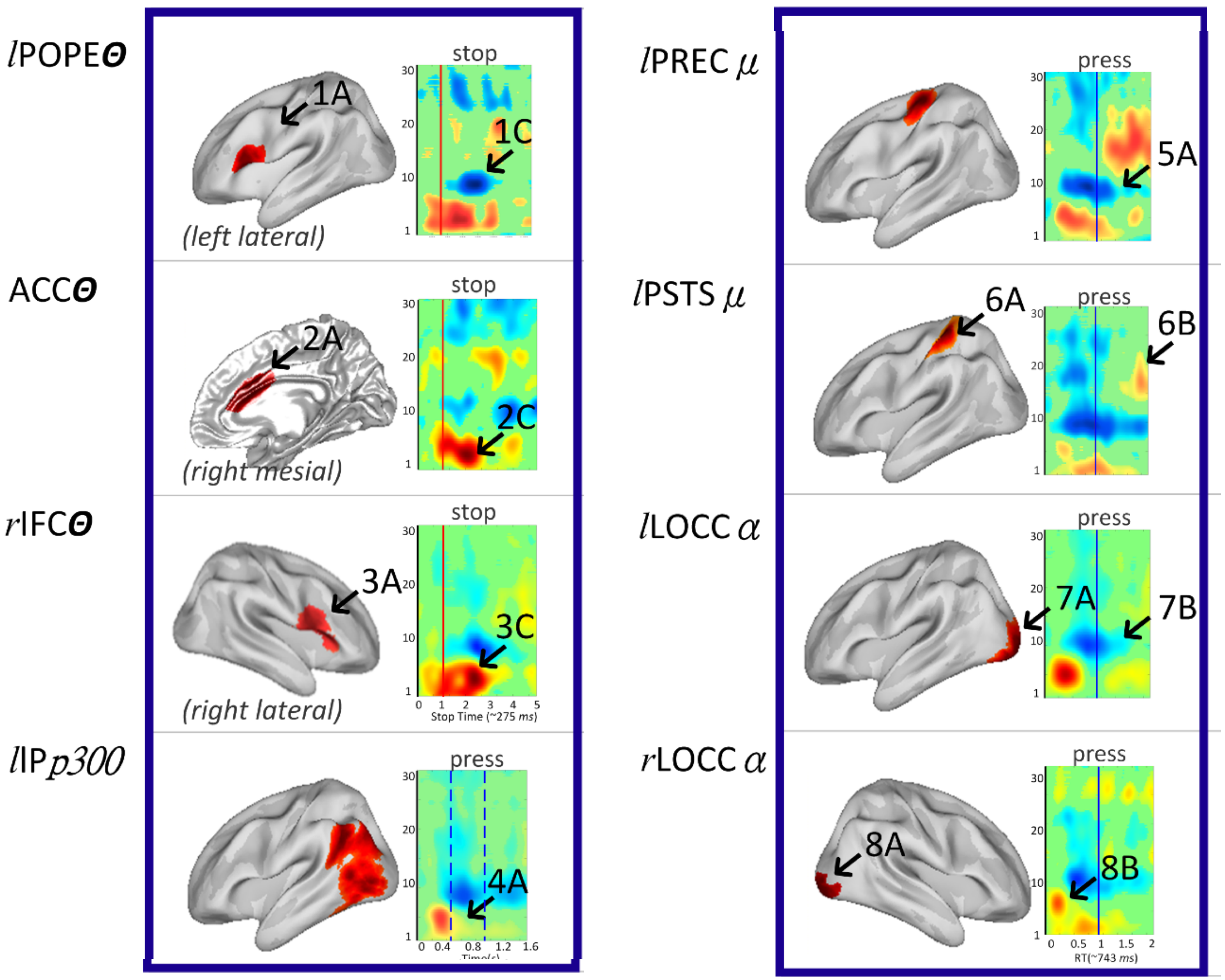


Results of component clusters (cont')





Results of component clusters (cont')



Neuroimaging studies have demonstrated that the anterior cingulate cortex (ACC) is engaged **in detecting or dealing with conflict** between a stop signal and an intended action [Gehring and Knight, 2000], and that, subsequently, **right inferior frontal cortex** (*r*IFC) is involved in **suppressing** the intended response [Aron *et al.*, 2004], supporting the findings of the involvement of ACCθ and *r*IFC*θ* in this study.

Summary and discussion

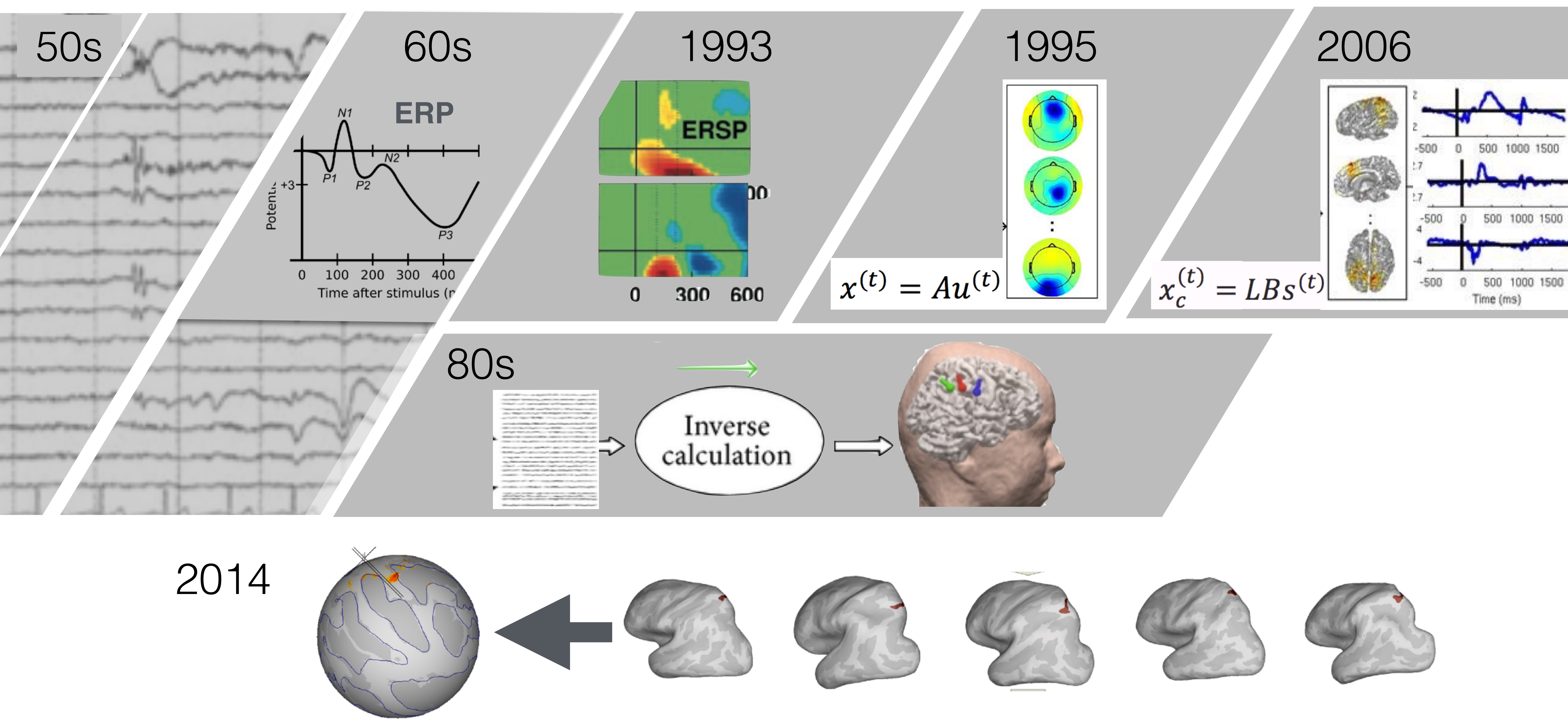
- **Direct comparison of the scalp maps of ICs** or **even the location of the equivalent dipole** calculated by scalp maps of ICs **across subjects** may not be scientifically meaningful, because
  - the signal recorded from a scalp electrode is actually **a mixture of underlying cortical sources** instead of single dipole(s) and
  - the **brain geometry can differ between subjects**, thus, yields different corresponding leadfields.

- The study presents the **cortically evidence-based aligned clustering strategy** and validates its effectiveness by applying to investigate the mechanism of activation and inhibition in the stop-signal paradigm.

- To assess the consistency of independent components across subjects, a group analysis method has been proposed by **directly compares spatiotemporal independent components** in **aligned activation brain topography** and **power spectral patterns over short time intervals** in an oscillatory fashion.


THANK YOU

Summary: History of EEG analysis



→ Machine learning