Multi-modal imaging: simultaneous EEG-fMRI

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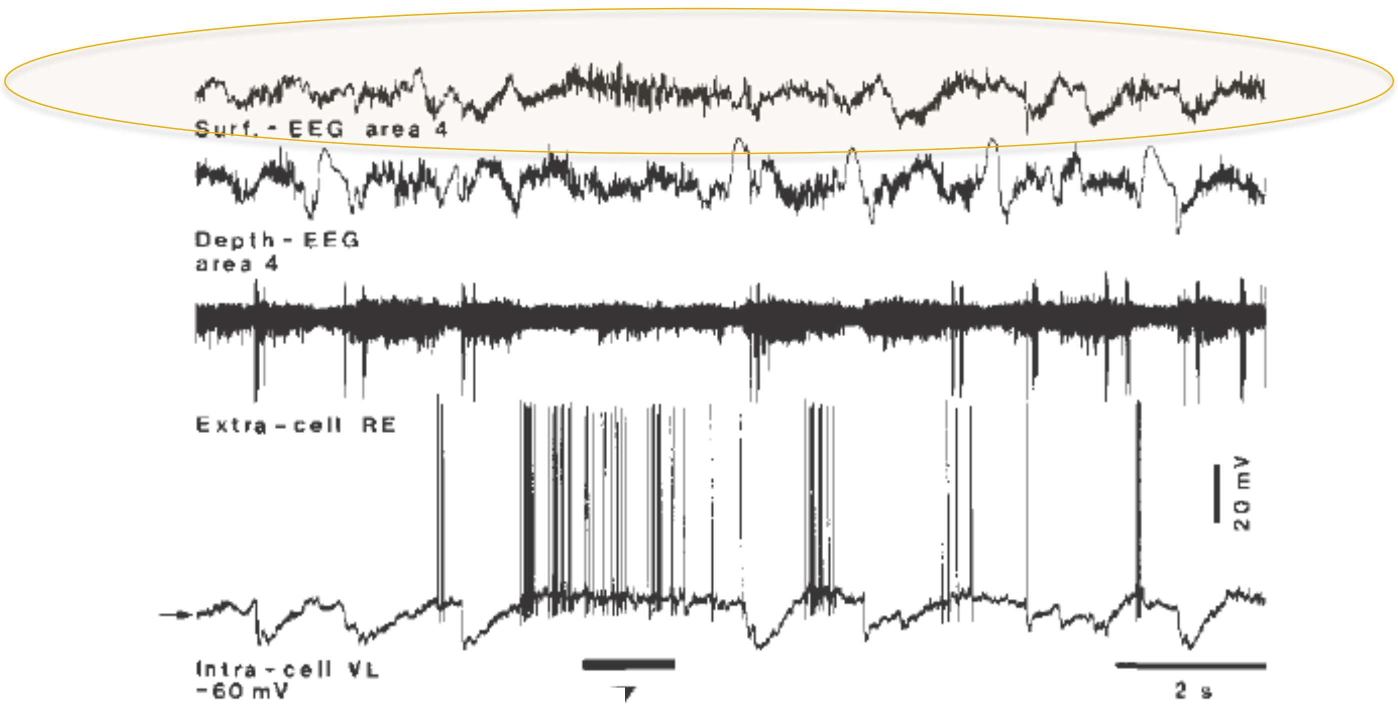
Outline

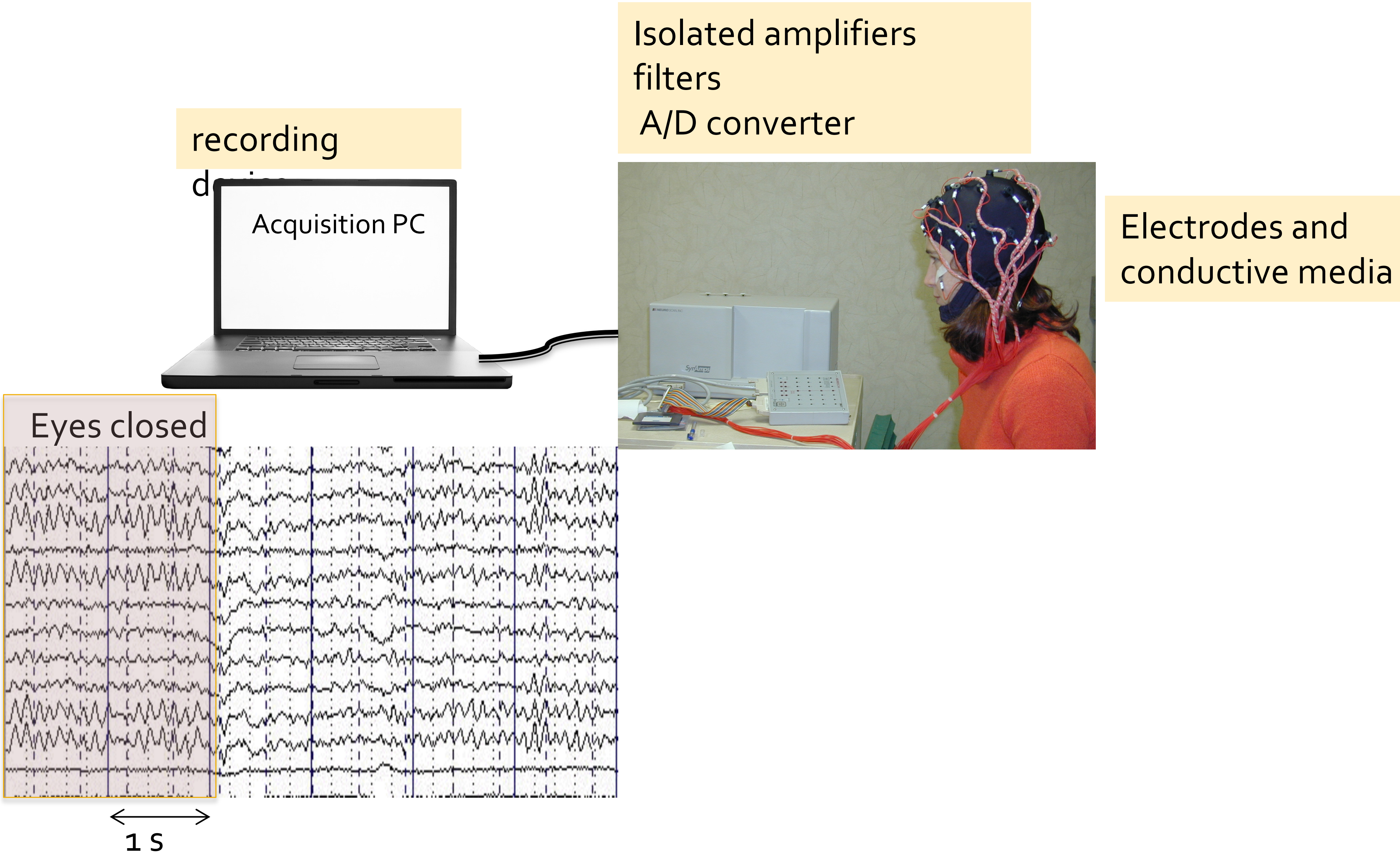
- EEG overview
- Why simultaneous EEG-fMRI?
- How? Technical considerations
- When? Examples

EEG (electroencephalography)

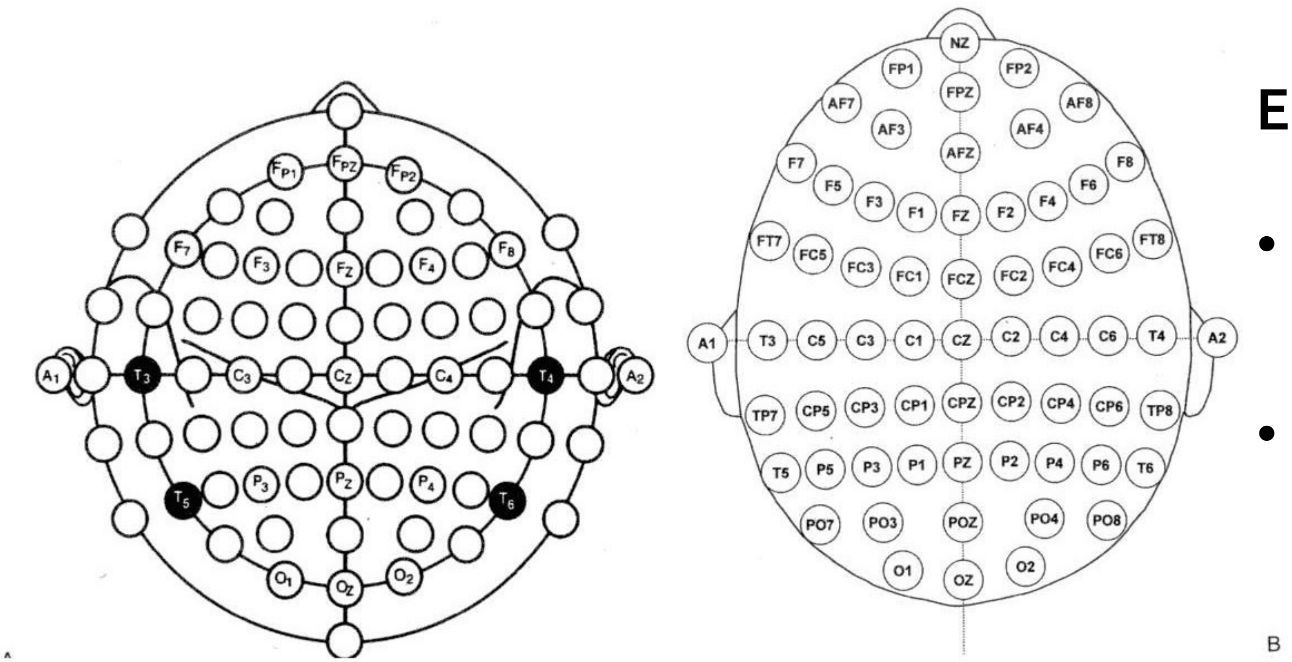
measure of synchronous activity of population of neurons, primarily reflects postsynaptic potentials.



EEG measures



montage



Electrode configuration

- Referential
  - (S_i vs. Ref; S_k vs. Ref)
- Bipolar
  - (S_i vs.. S_k)

International 10-20 System of Electrode Placement

F - Frontal lobe   T - Temporal lobe

C - Central lobe   P - Parietal lobe

O - Occipital lobe

"Z" refers to an electrode placed on the mid-line.

Odd: left

Even: right

Data processing

- Time domain
  - Event Related Potentials (ERPs)

    pre-processing:

    detrend - filtering

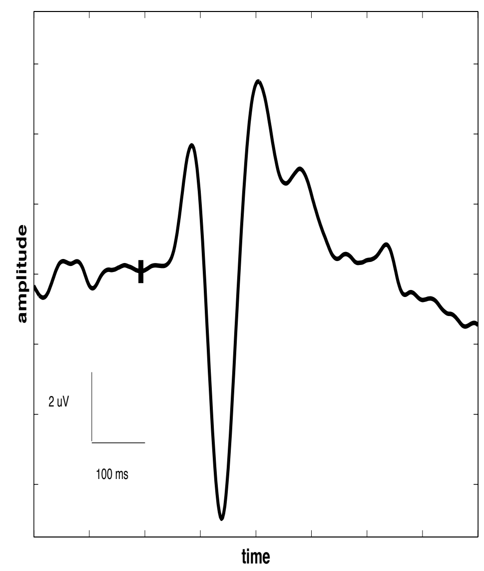
    epoch

    baseline correction

    ocular artifact reduction

    (common grounded, artifact rejection)

    time-locked averaging

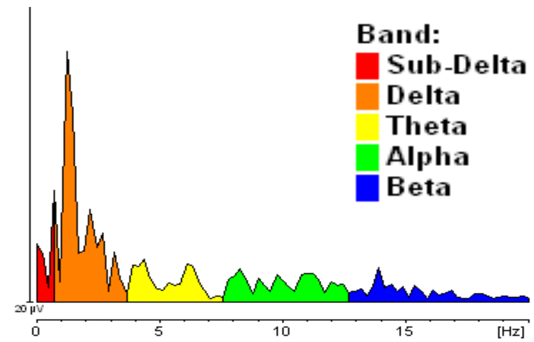


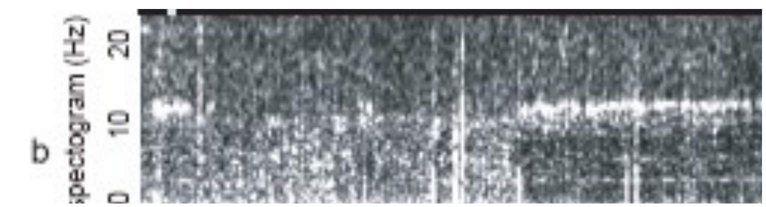
Data processing

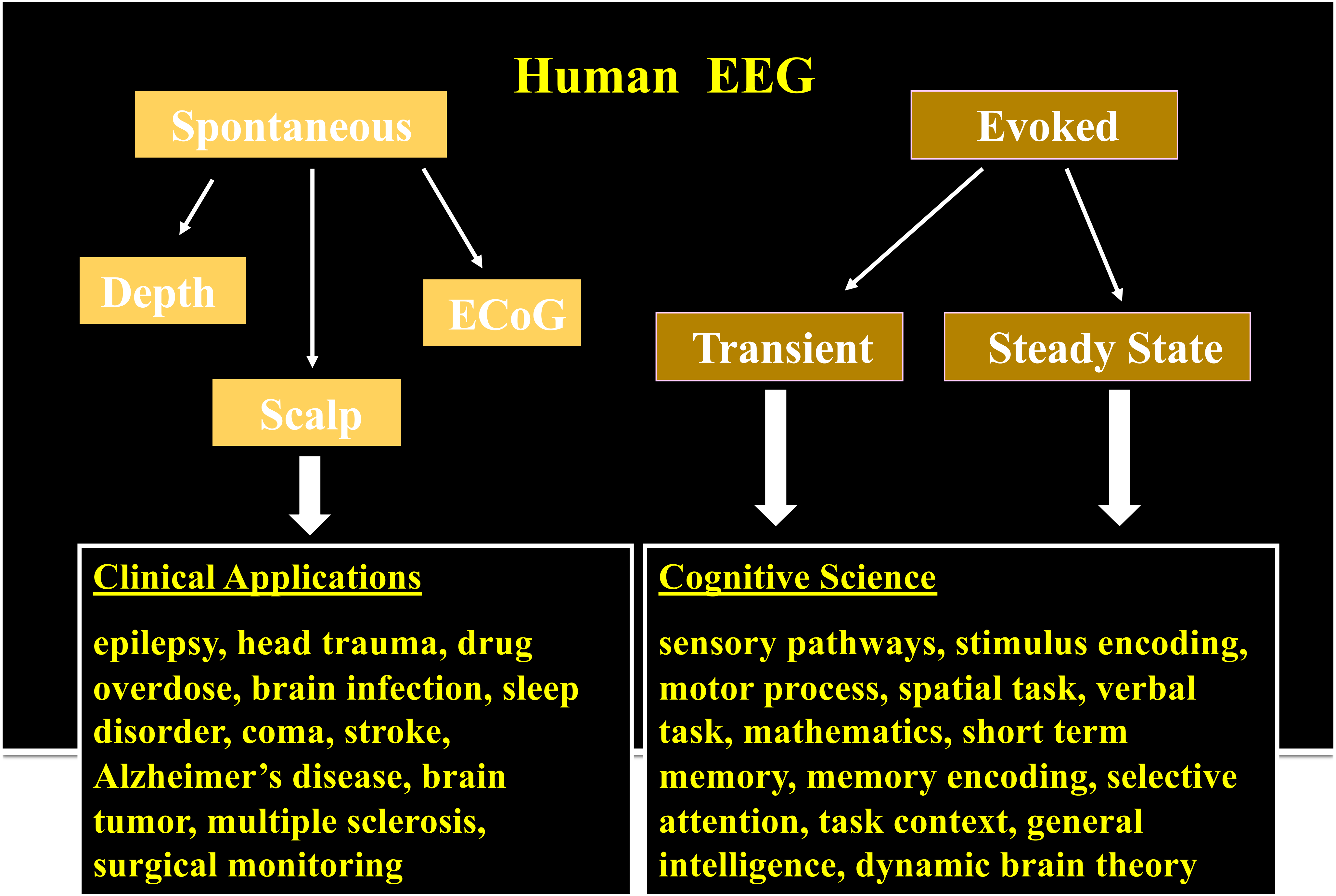
- Frequency domain
  - Power at different bands
  - Power spectra density (FFT)
  - Cross-spectra

    (correlation among different electrodes)
  - Coherence

    (measure of stability of the phase shift between electrodes)
  - Event related desynchronization







PL Nunez, EEG, *Encyclopedia of the Brain*, 2003

Why do we want to measure EEG and fMRI simultaneously?

Neuroimaging

BRAIN ACTIVITY
f(x,t)

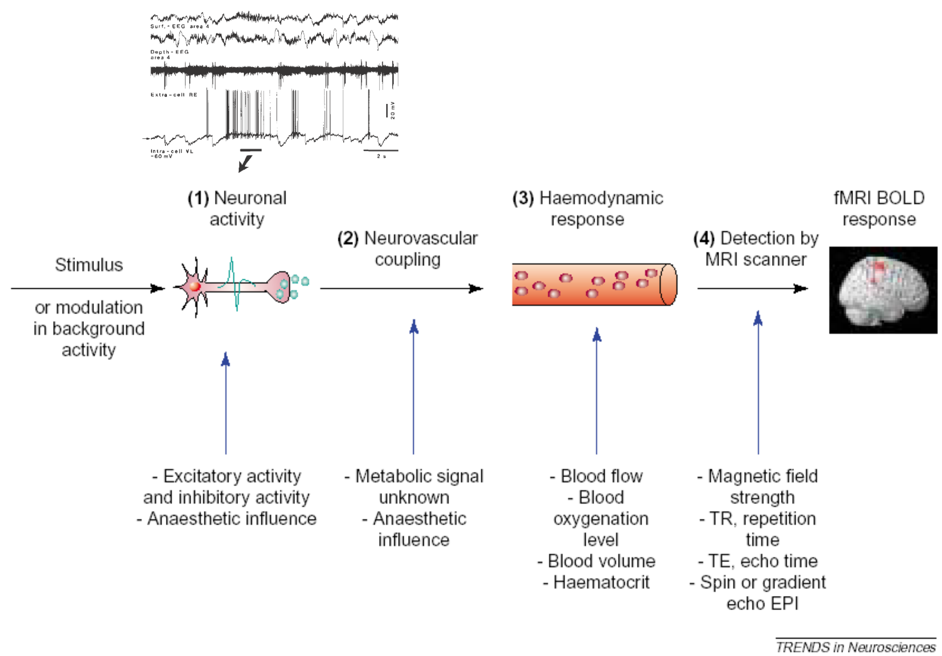
Metabolic/ vascular responses
g[f(x,t)]

fMRI
k{g[f(x,t)]}

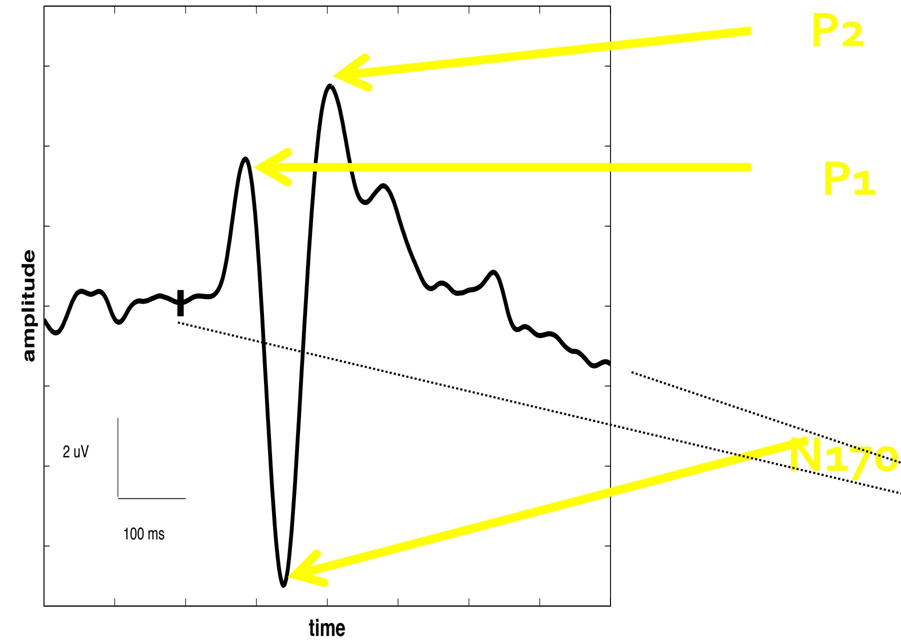
Poor time resolution (s)
Good spatial resolution (mm)

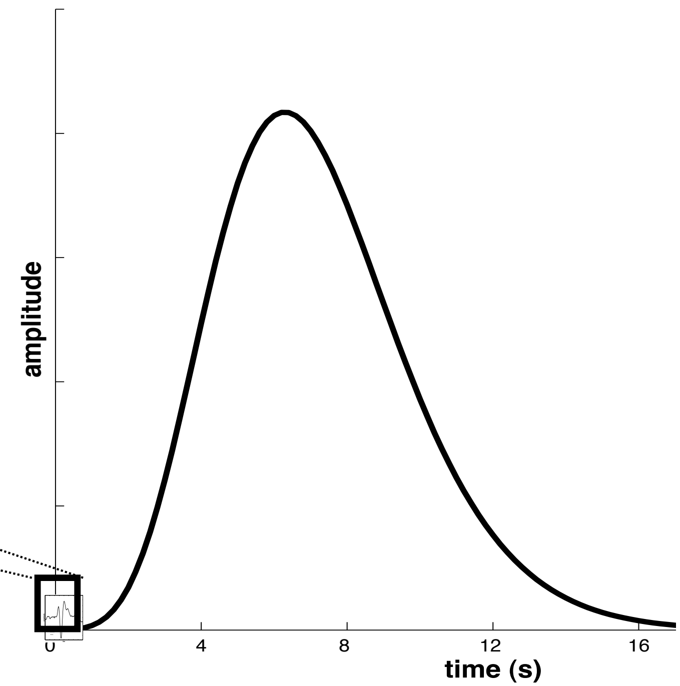
electrical EEG, MEG
m[f(x,t)]

Good time resolution (ms)
Poor spatial resolution



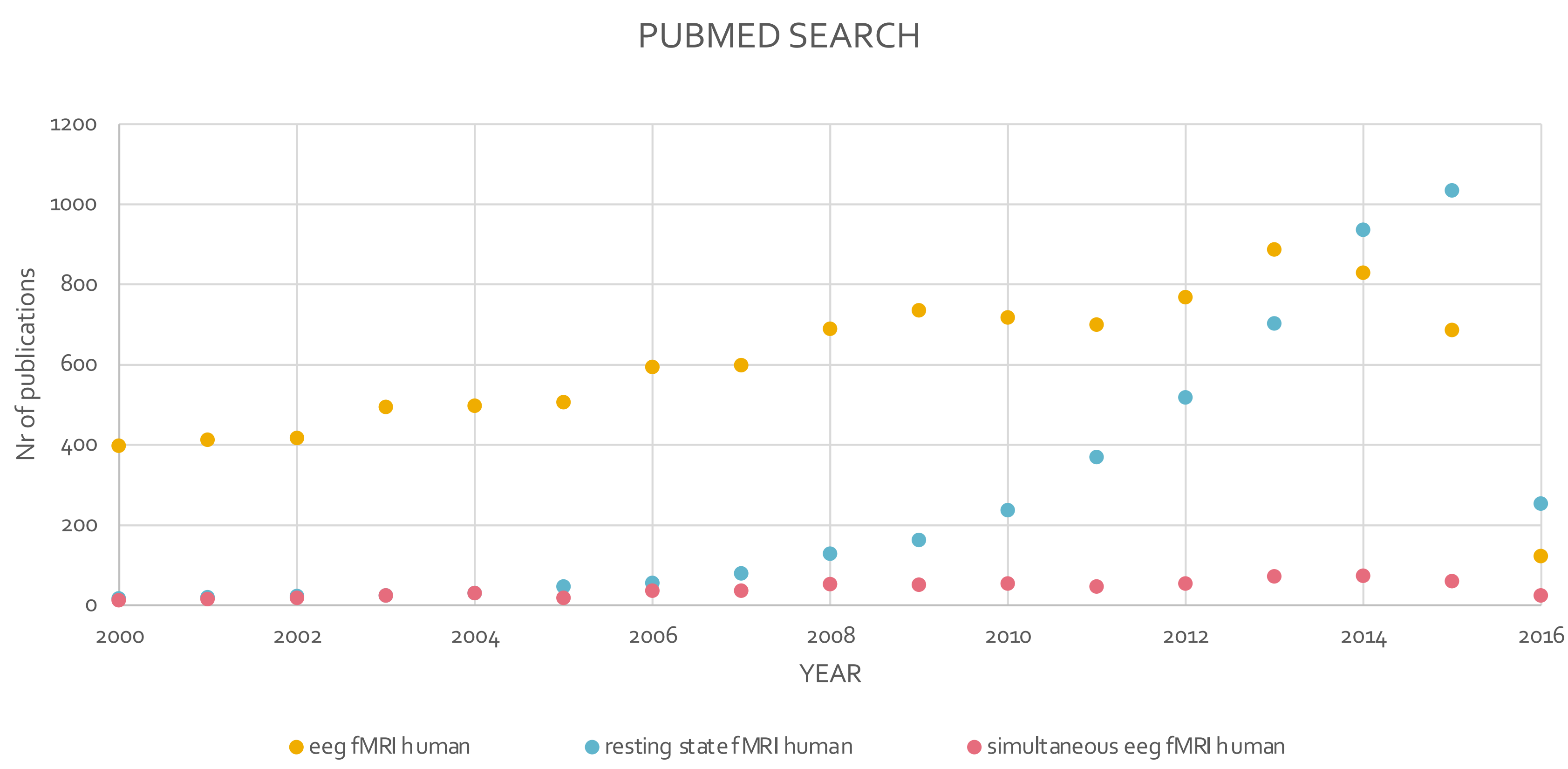
EEG fMRI





EEG is the *gold standard* for sleep studies, epilepsy, some cognitive tasks, etc

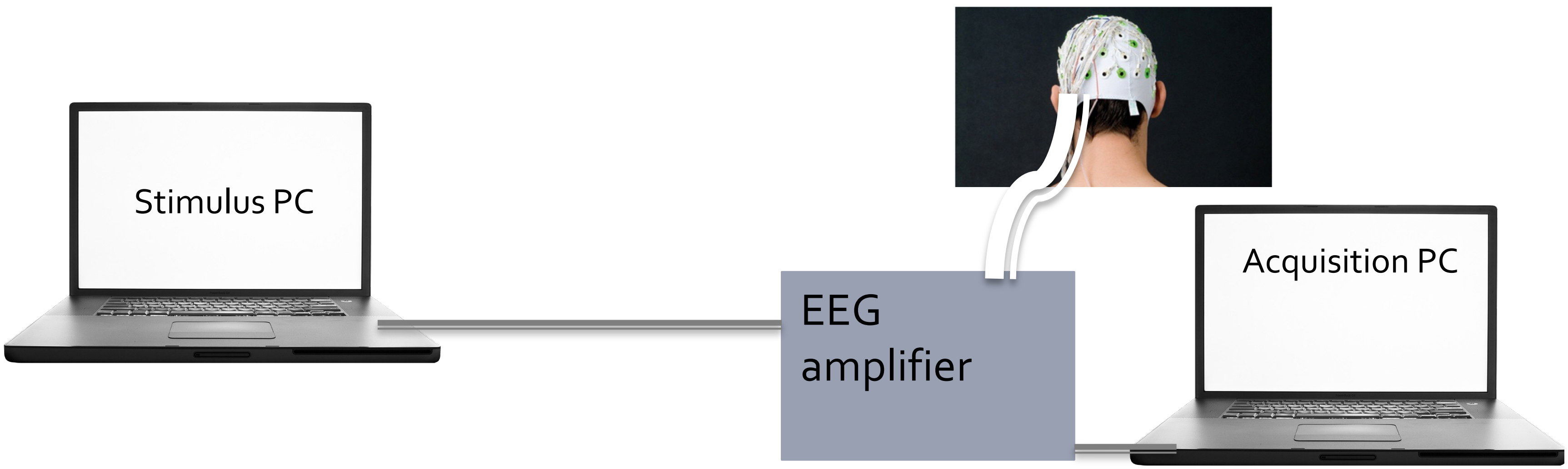
HOW often measured together?



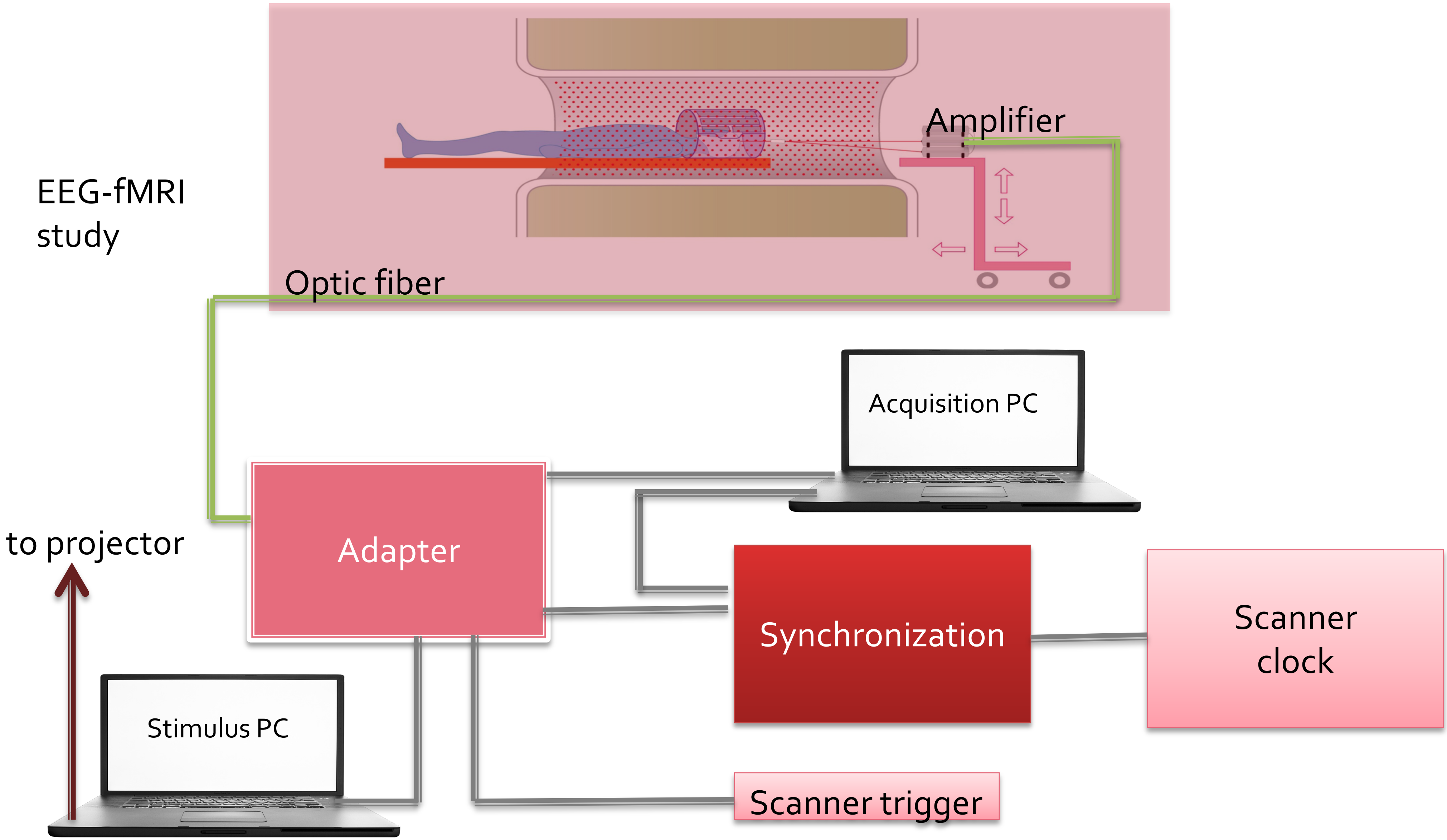
PUBMED search on 8/14/2016, keywords

EEG setup

EEG
study

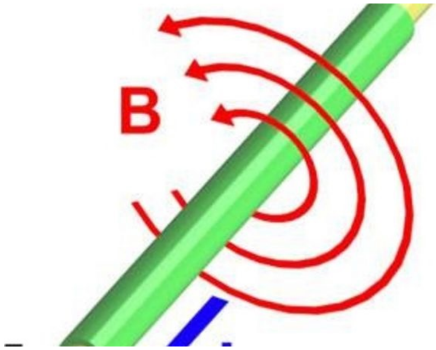


EEG-fMRI setup



Technical Issues

Electromagnetism
101



Maxwell's Laws.

• A changing magnetic field produces an electric field

BIG PROBLEM

• A changing electric field or current produces a magnetic field.

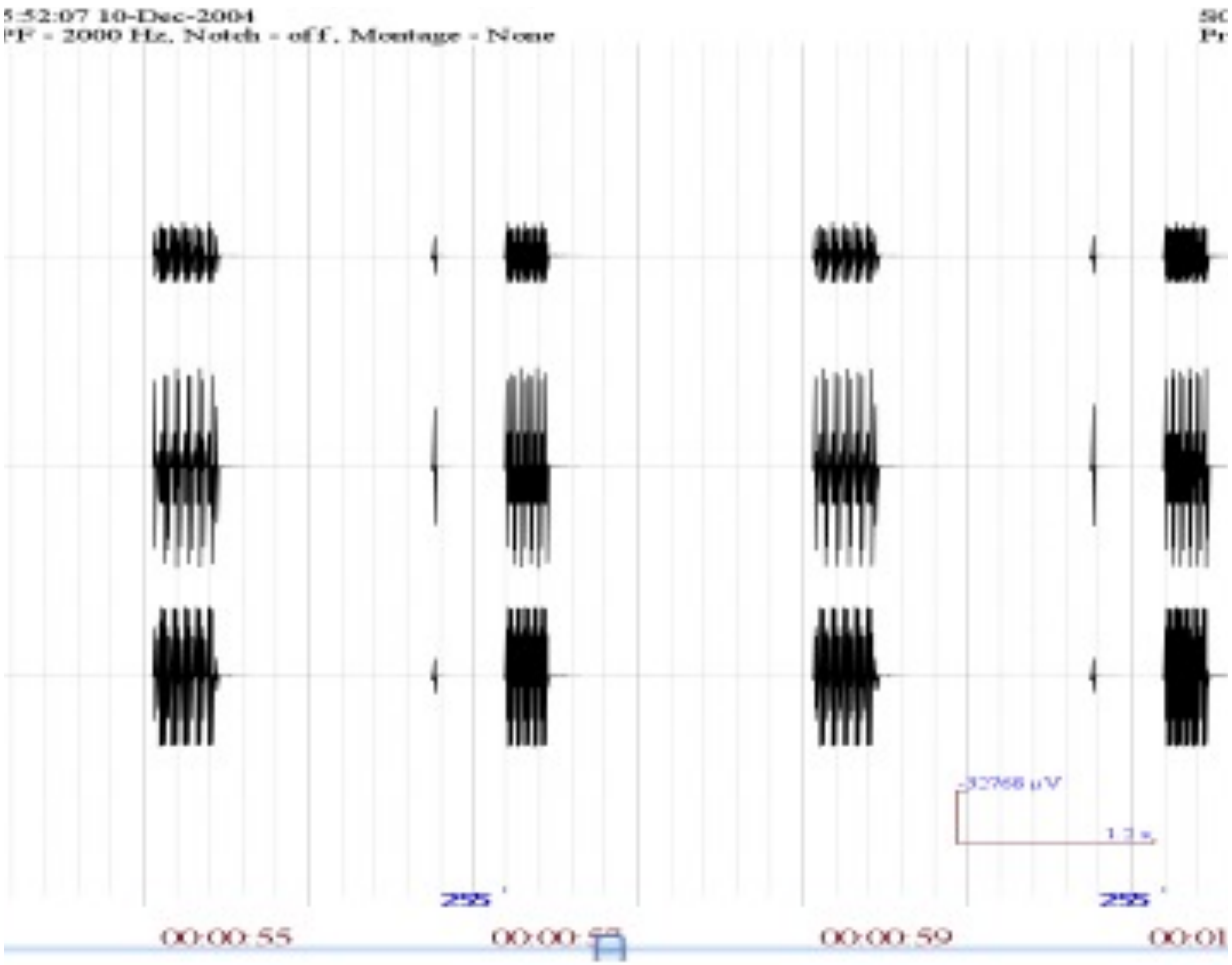
Luckily, the magnetic field change
Form the EEG does not affect the image quality!

THE not so good NEWS

- **MRI is noisy**
  - Electrical noise → MRI and EEG were not meant for each other …

Remember Maxwell's Law?

Simultaneous EEG-fMRI
- Technical issues



Example from
BOLD & Perfusion MRI sequence
optimized for EEG-fMRI acquisition
5 slices

Sources of artifacts:

- gradient artifact
- physiological noise:
  ballistocardiogram

Simultaneous EEG-fMRI
- Technical issues

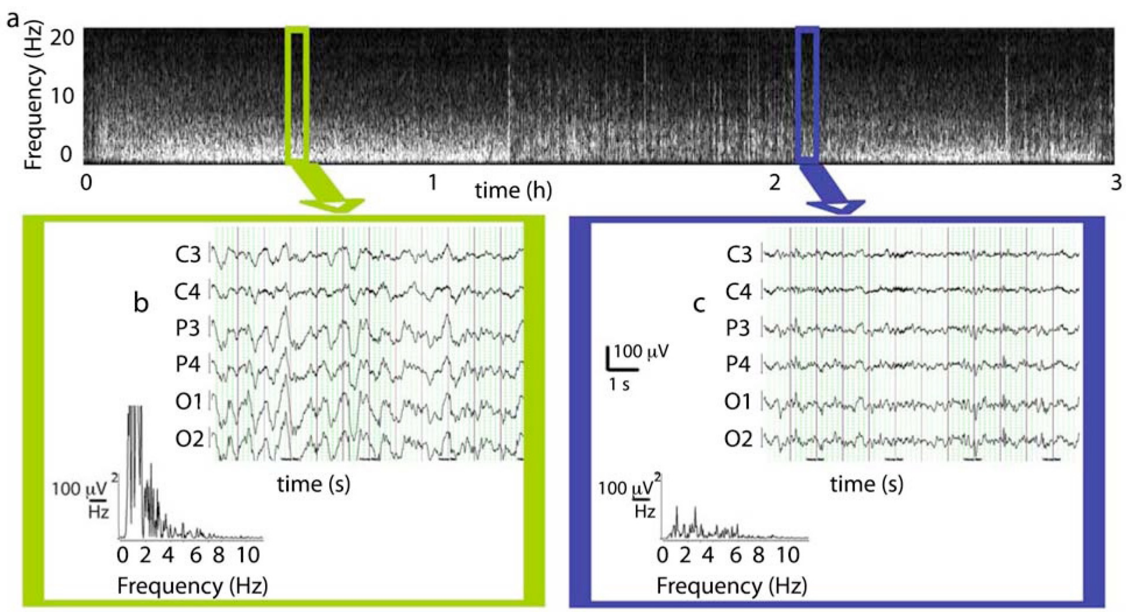
Approximate values of different signals

- Gradient artifact : ± 10mV
- EEG: ± 150μV
- BC artifact: ± 200μV
- Blink: ± 150μV
- Movement: < 1mV
- ECG: ± 20μV
- EMG: ± 50μV

- Helium pump: 40-60Hz and

THE good NEWS

- MRI compatible EEG equipment, leads and electrodes
  - Safe for the scanner
  - Safe for the subject



More on safety later

- Careful setup:
  - Equipment
  - Cables
  - Subject head

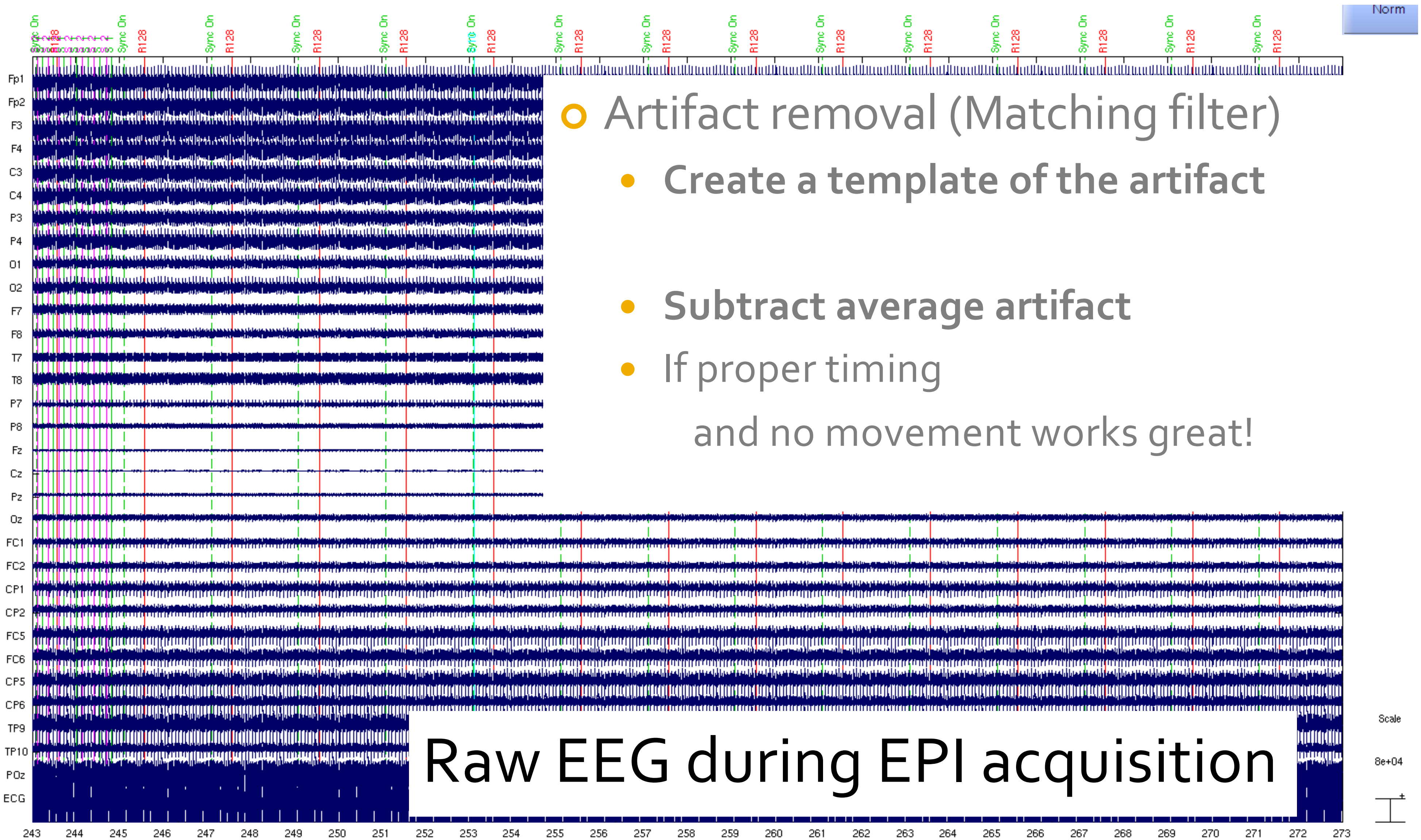
DATA acquisition

- Sample EEG at 5 kHz (or more)
- Slice TR at a frequency that is not of interest (and a round number)
- Low Pass Filter at 250Hz
- ~0.01 Hz high pass to avoid saturation (use DC only if enough range)
- Volume (or slice) marker
- Resolution: 0.5μV (make sure dynamic range covers the signal, depends on scanner and configuration)
- Clock synchronization

EEG DATA acquisition

- **Make sure amplifiers do not saturate**
  Adjust amplifier resolution
- **Keep electrodes' impedance low** (unless using high impedance equipment)
- **Keep cabling safe and fixed**
- **Have a good cardiac signal**
- **Adjust MR sequence**
- **Adjust experiment (ISI <> TR)**

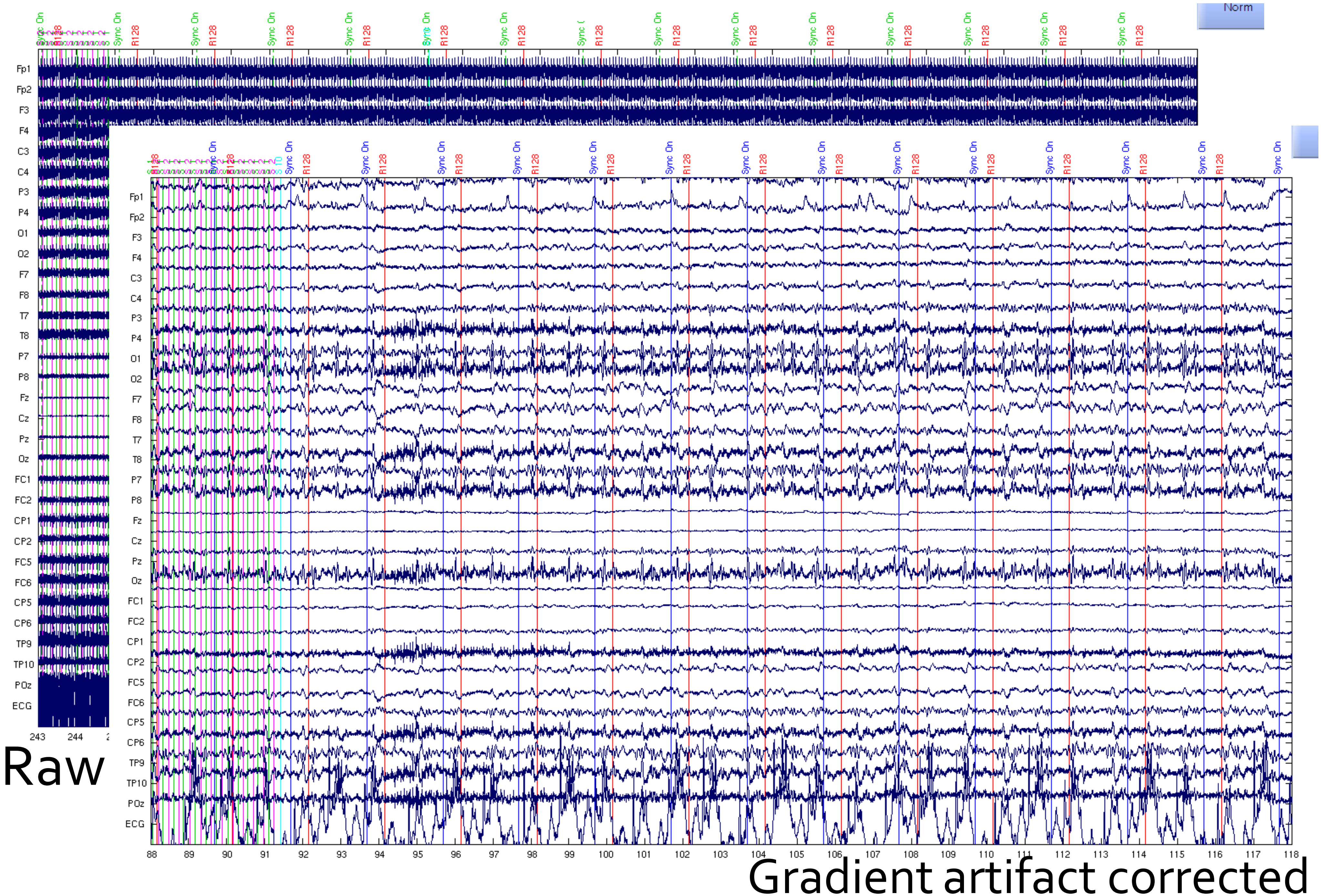
Gradient artifact removal



- Artifact removal (Matching filter)
  - **Create a template of the artifact**
  - **Subtract average artifact**
  - If proper timing

    and no movement works great!

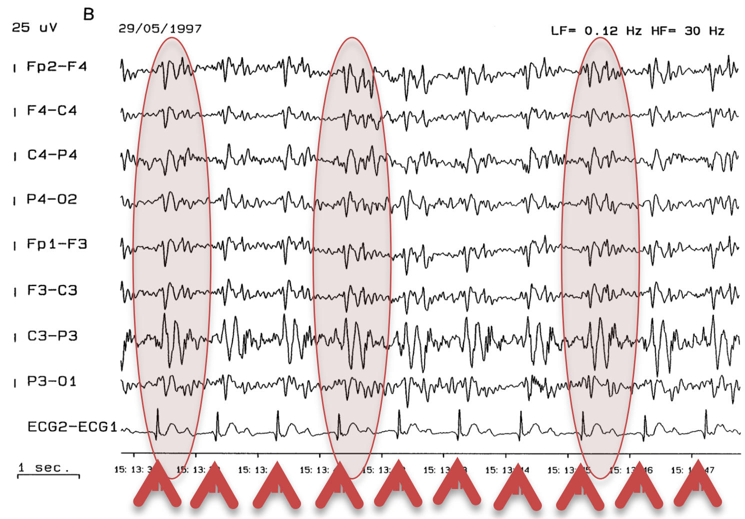
Raw EEG during EPI acquisition


Raw
Gradient artifact corrected
Norm
Fp1
Fp2
F3
F4
C3
C4
P3
P4
O1
O2
F7
F8
T7
T8
P7
P8
Fz
Cz
Pz
Oz
FC1
FC2
CP1
CP2
FC5
FC6
CP5
CP6
TP9
TP10
POz
ECG
Sync On
R128

Dr Jen Evans

Ballistocardiogram artifact removal

Matching filter (BV Analyzer) (Allen et al, 2000):
Detect R
Create a template
Subtract (allows for amplitude adjustment)



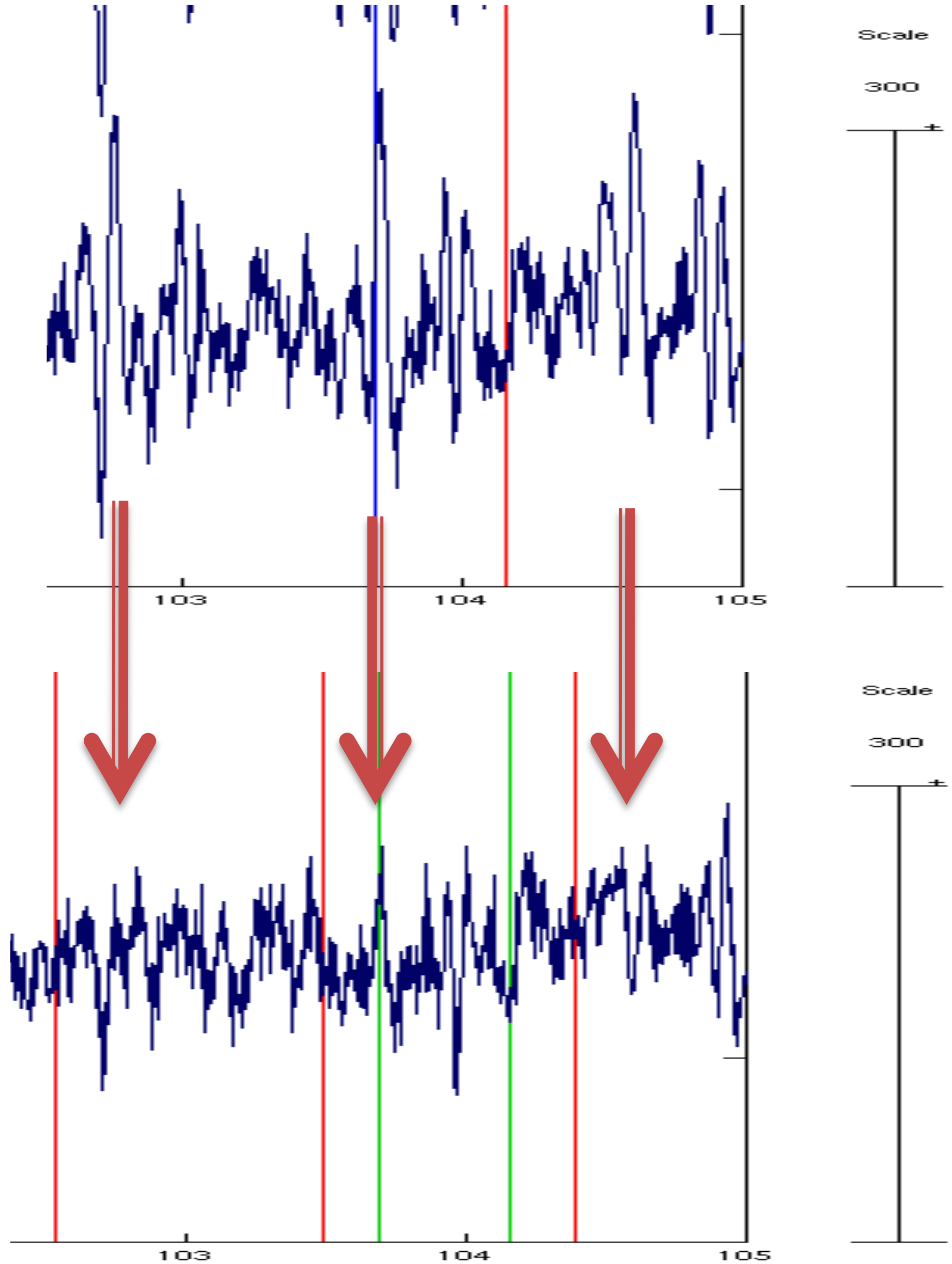
Single Value Decomposition (Neuroscan)
Run classification
Remove components
Reconstruct time series

Optimal base set (EEGLAB Niazy, 2005)
PCA to create bases
Fitting (adaptive algorithm)
Subtraction

Combinations
i.e → Liu, 2012 use ICA, SVD & mutual information (based on Peng, IEEE 2005)
software download: http://amri.ninds.nih.gov/cgi-bin/software

Gradient artifact corrected

Cardioballistogram corrected



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Grad

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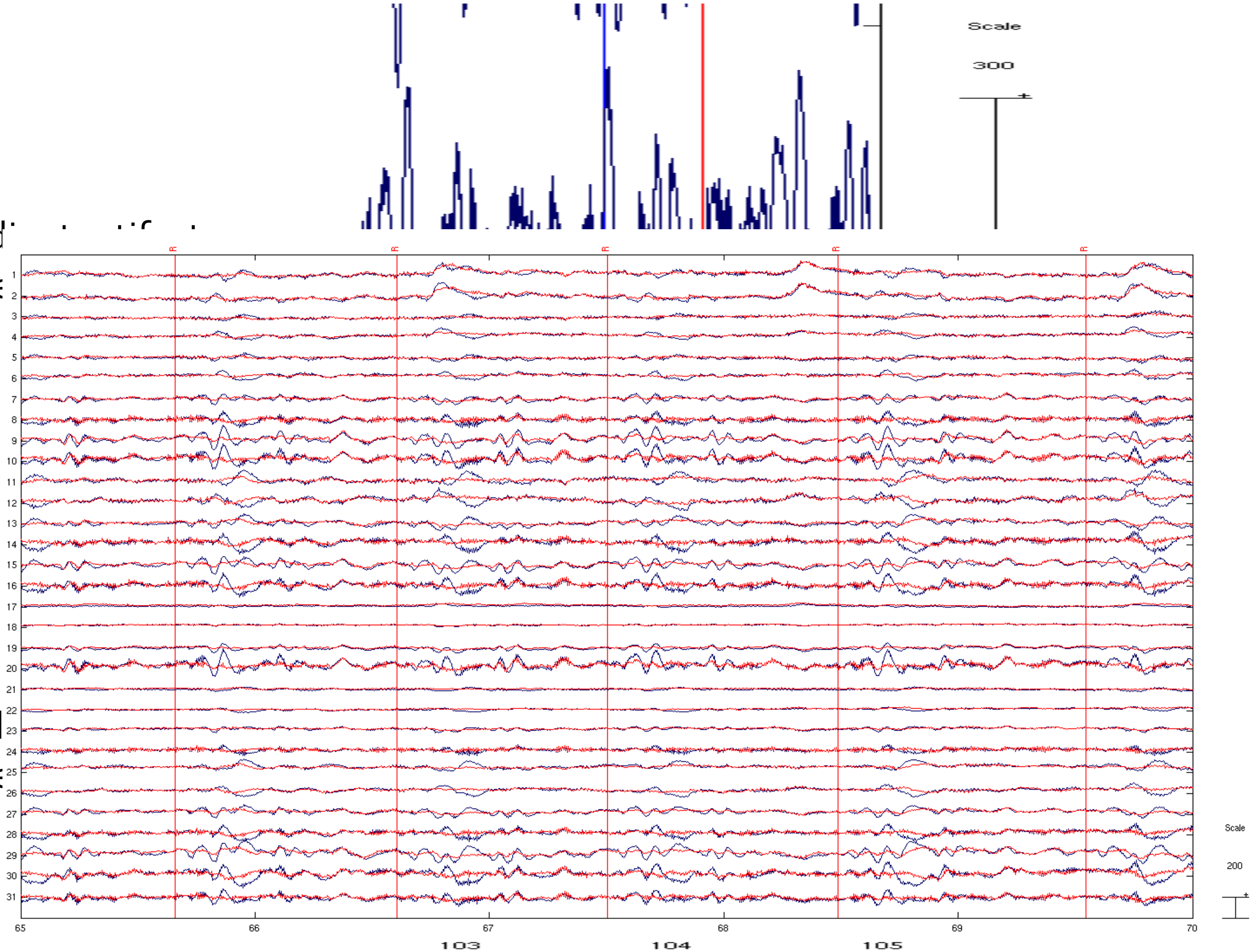

Card

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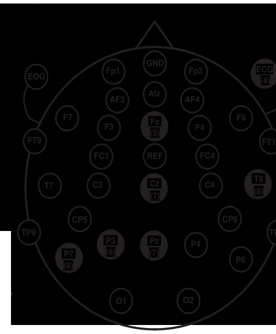
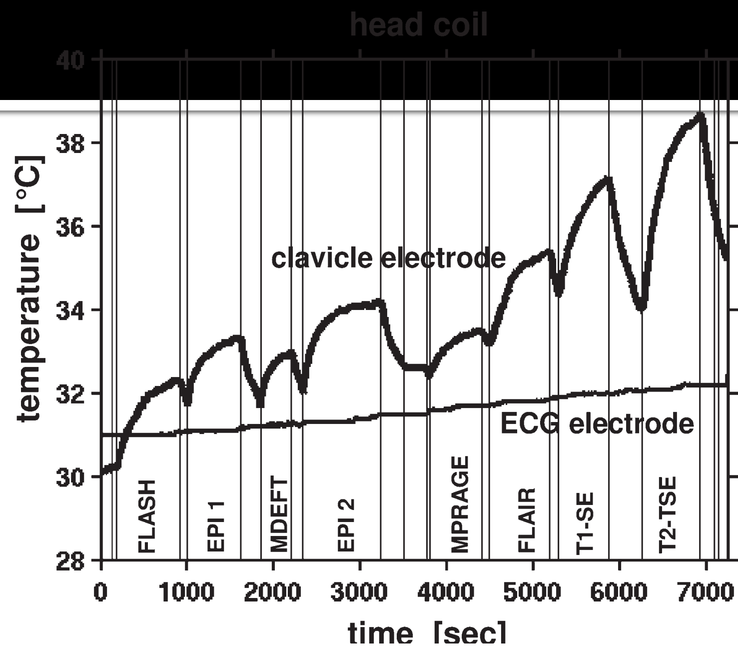
SAFETY considerations





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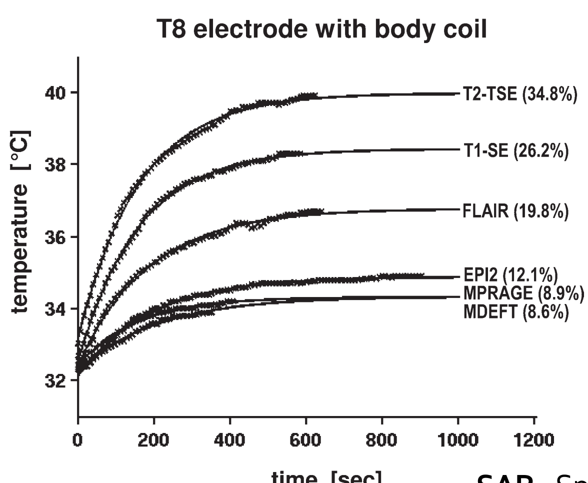


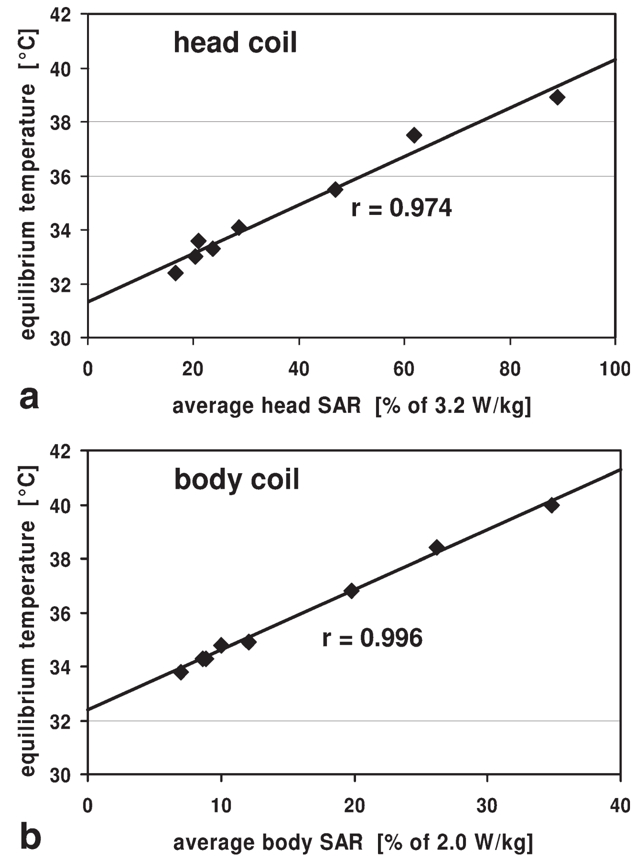


Figure 5. Relation between scanner-calculated average head (**a**) and body (**b**) SAR and fitted equilibrium temperatures for subject m90, clavicle electrode (a) and subject m85, T8 electrode (b) when using the head (a) and body (b) coil, respectively. The least-squares linear fit (solid line) shows a clear linear increase of the equilibrium temperature with average head (a) and body (b) SAR.

Simultaneous Electroencephalography-Functional MRI at 3 T: An Analysis of Safety Risks Imposed by Performing Anatomical Reference Scans With the EEG Equipment in Place

Ulrike Nöth, Laufs, Stoermer, and Deichmann JMRI 2012

SAR: Specific Absorption Rate (or the energy deposited in the body by the radio frequency transmission)

SAFETY considerations

- Sequences
  - EPIs (in most cases ok to run an MPRAGE for localization)
    - be aware of high res short TR EPIs (**pay attention to SAR**)
    - Special sequences require special safety testing

- Set up
  - Cables straight and in the center.
    - Avoid loops
  - Equipment as far back from iso-center as possible
    - (far front for EMG)
    - All scanners are **not** equal; gradients and coils affect electrodes' temperature
    - Be aware different body shapes and weight load coil differently

Interim Summary

- EEG measurements have:
  - Good temporal resolution
  - Poor spatial resolution

    (when measure non invasively)
- Electrical and hemodynamic responses are related
- Simultaneous EEG-fMRI requires special equipment
- **SAFETY PROCEDURES ARE KEY**
- Dimensionality reduction is needed for data integration

When do we want to measure EEG and fMRI simultaneously?

When is it important to measure simultaneously?

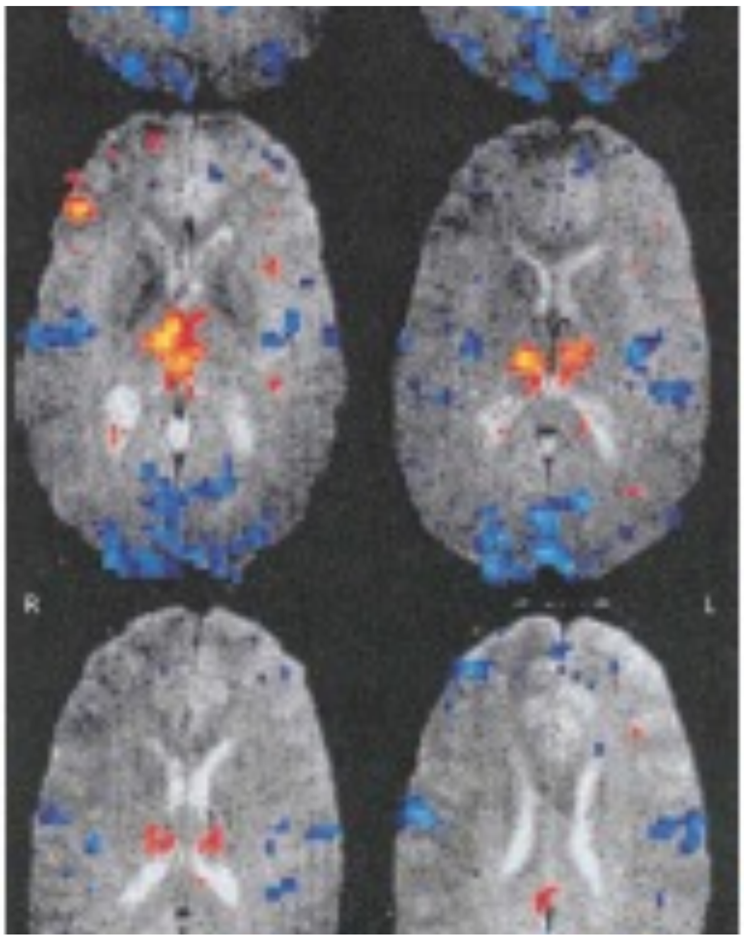
- **State dependent analysis**
  - Alertness
  - State vs Trait
  - Understanding origin of signals (BOLD; EEG)
- **Physiological markers defined by EEG**
  - Seizures
  - Sleep stages

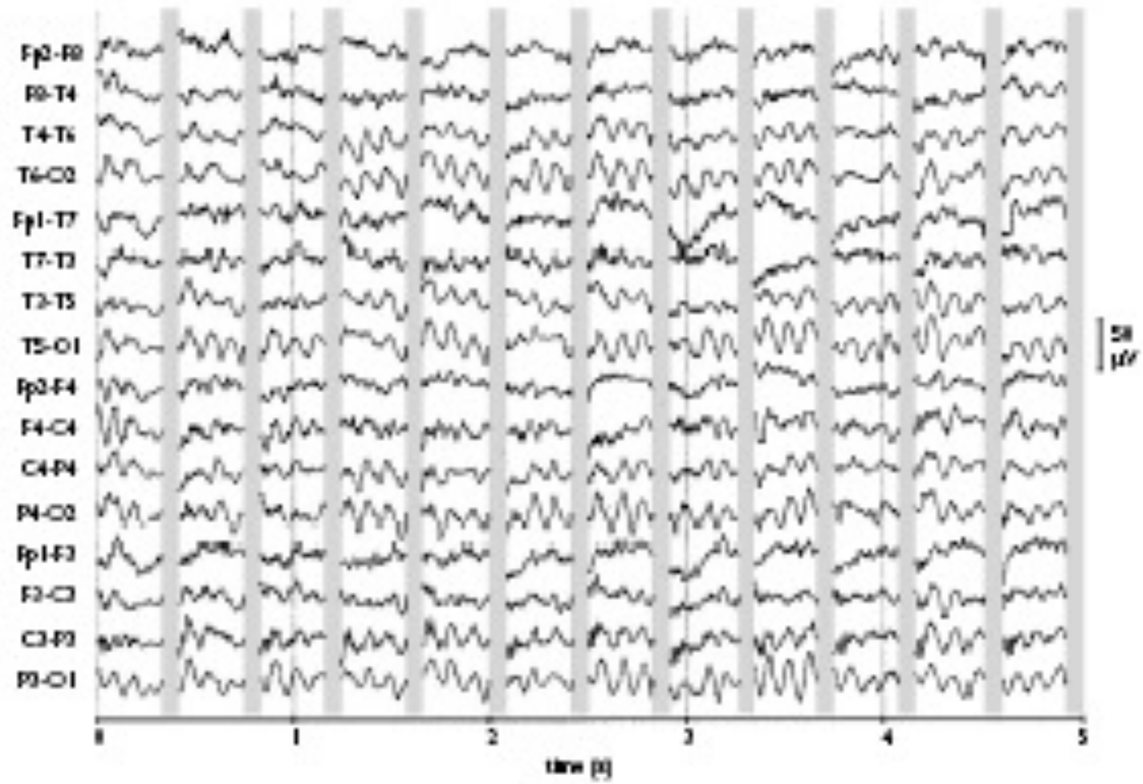
Type of studies

- Correlations of EEG and fMRI
  - In time domain
  - In frequency domain
- Multivariate methods
  - ICA
- Informing one with the other
  - Sorting data and perform analysis in one modality
- Mix analysis

EEG parameter as regressor

BOLD-EEG band-power correlations

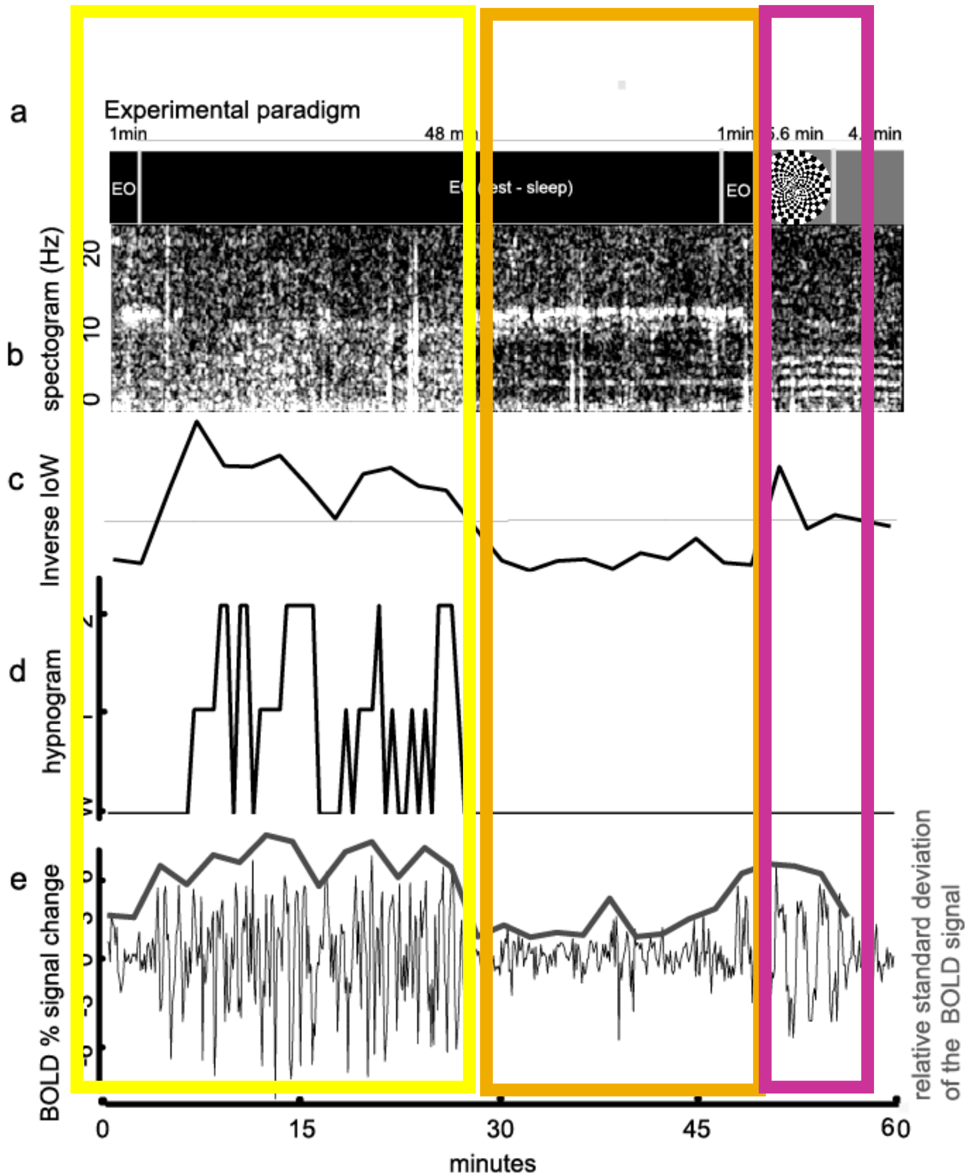




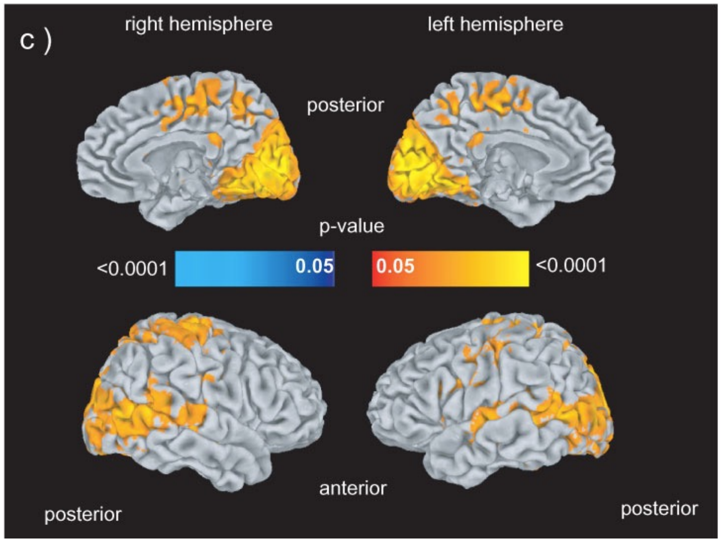
Goldman et al. 2002

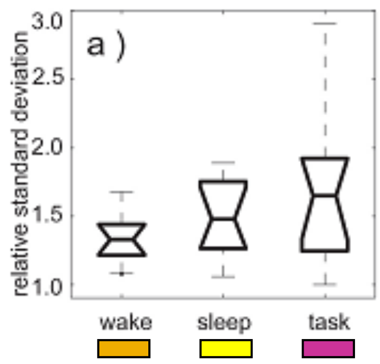
[Simultaneous **EEG** and **fMRI** of the alpha rhythm.]

Correlation between Amplitude of BOLD fluctuations and alertness Index derived from EEG



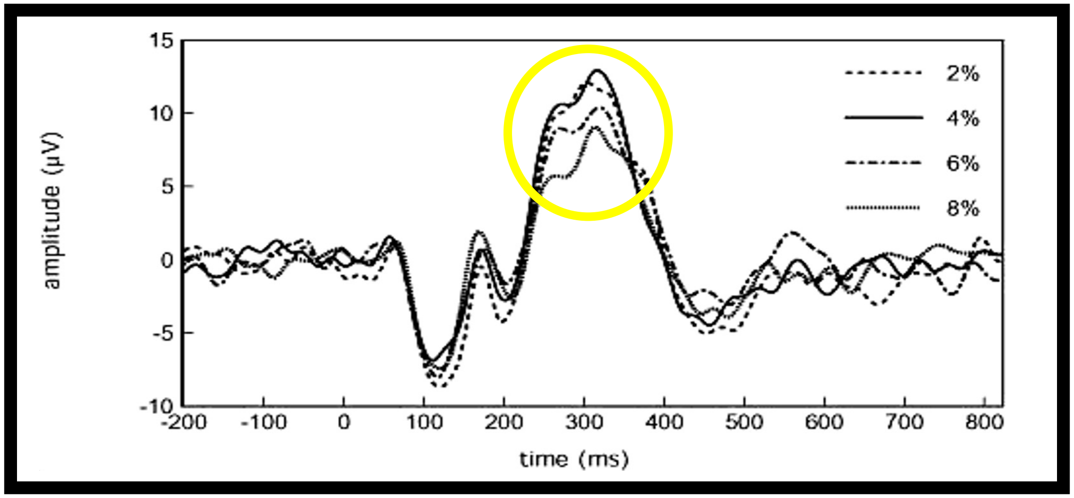
Horovitz et al HBM, 2008

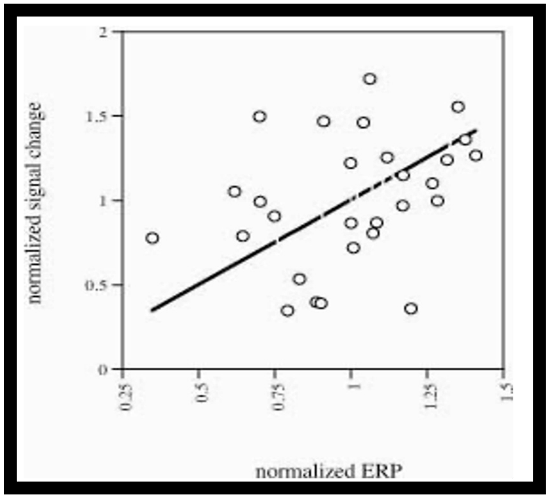


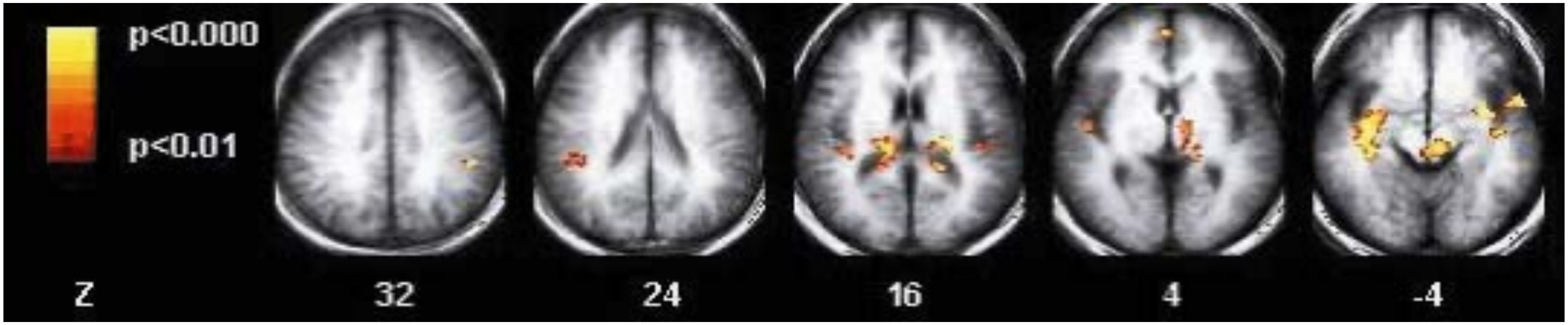


How to link time and space information?

Parametric studies and correlational analysis





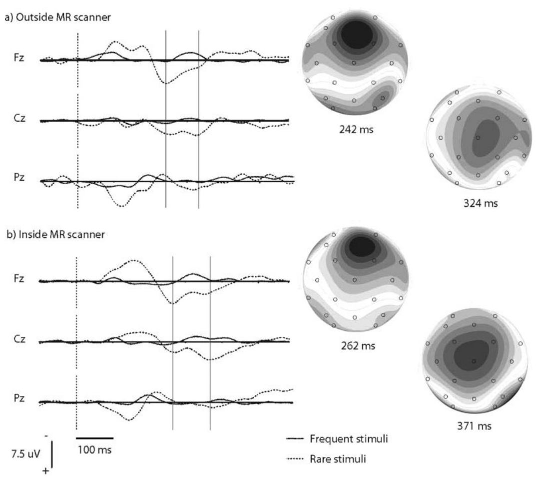


Correlation maps between fMRI signal change and P300 amplitude. Composite of 7 subjects.
Horovitz et al MRI, 2002

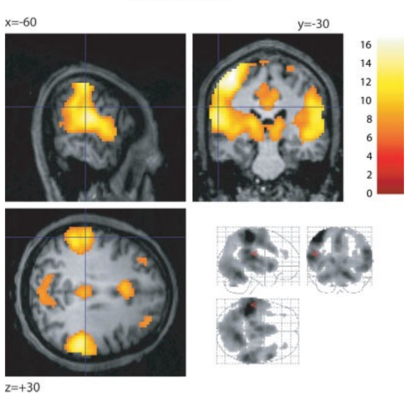
OLD DAYS: SAME SUBJECTS, EEG AND FMRI ON SEPARATE SESSONS

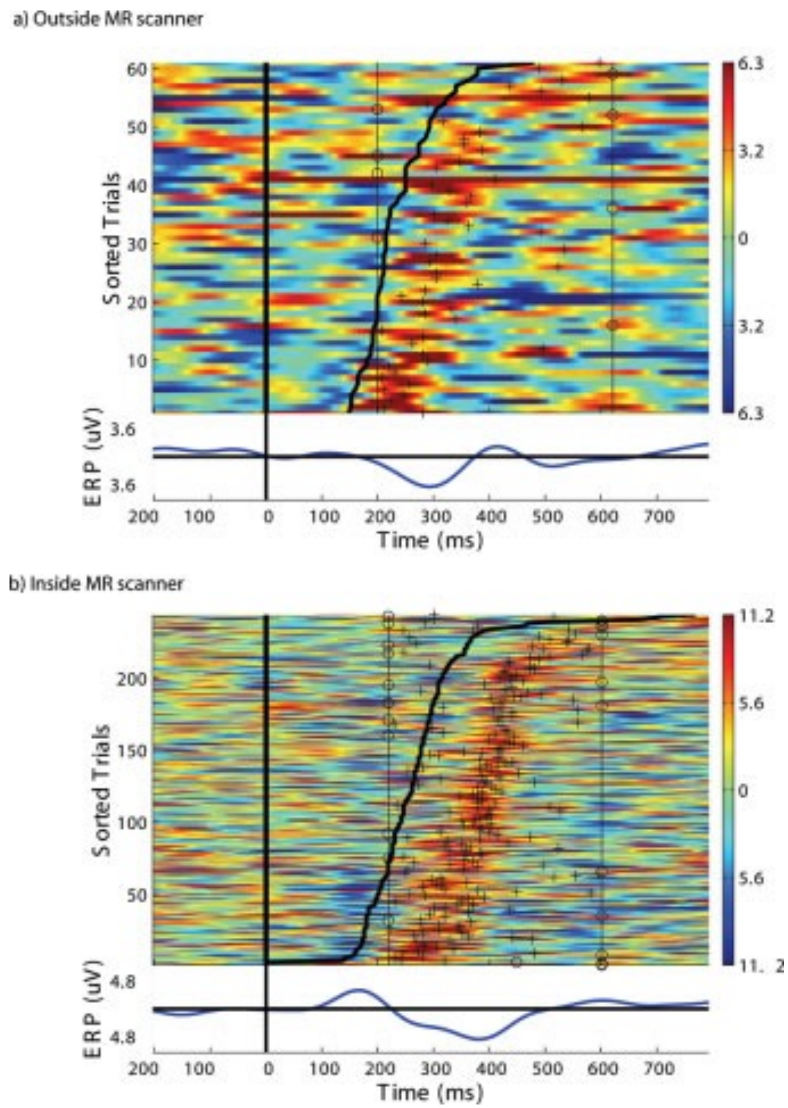
Single-Trial Analysis of Oddball Event-Related Potentials in Simultaneous EEG-fMRI

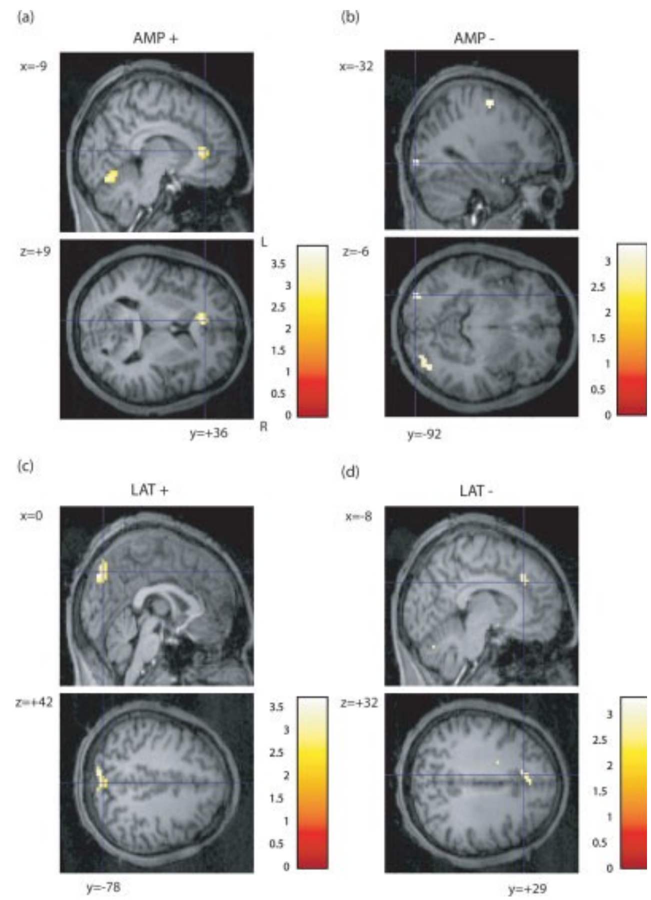
Benar et al. Human Brain Mapping 28:602–613 (2007)



Rare vs frequent

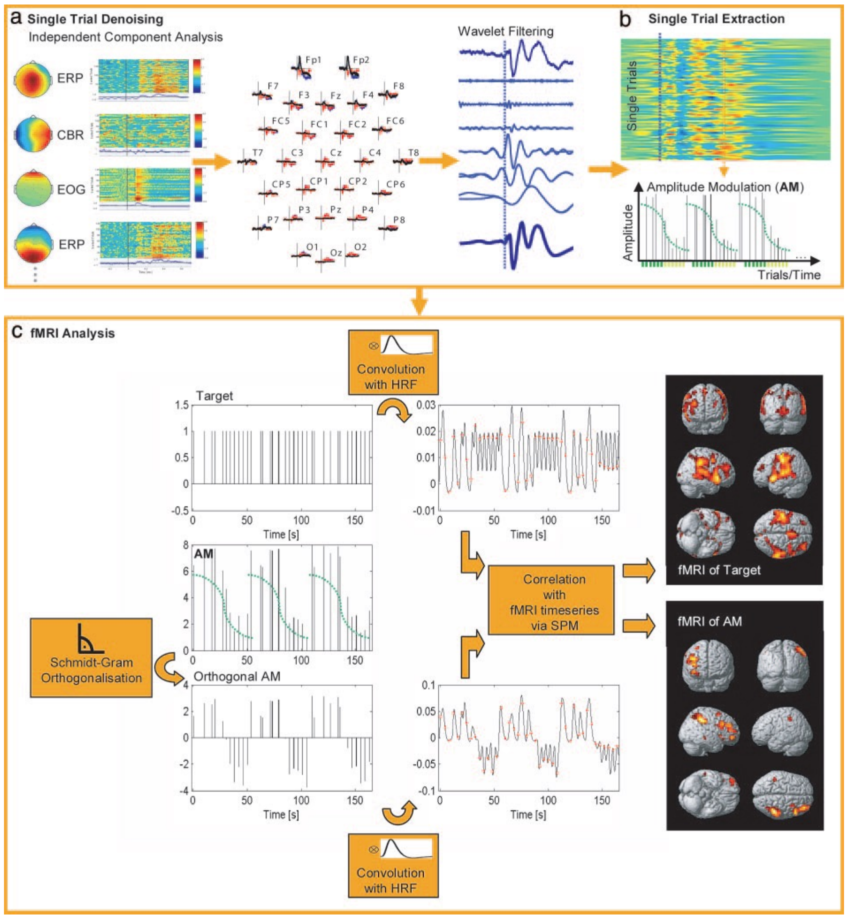


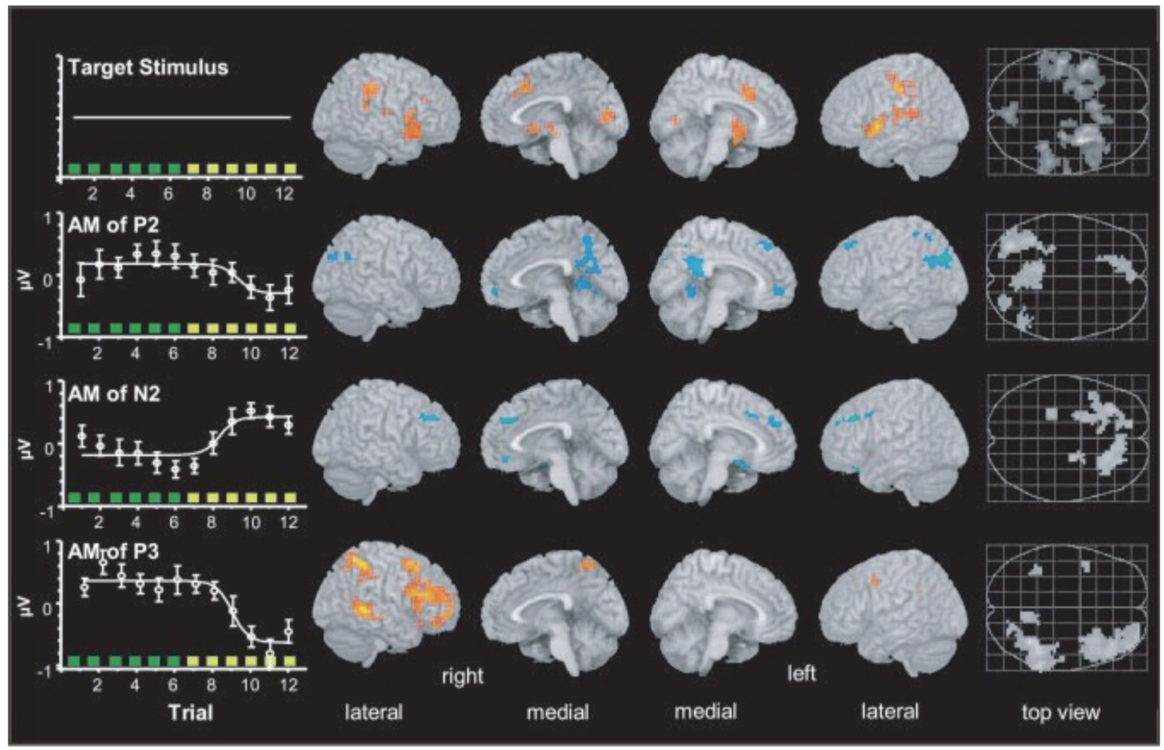




Assessing the spatiotemporal evolution of neuronal activation with single-trial event-related potentials and functional MRI

Tom Eichele PNAS 2005 vol. 102 no. 49





EEG to define states

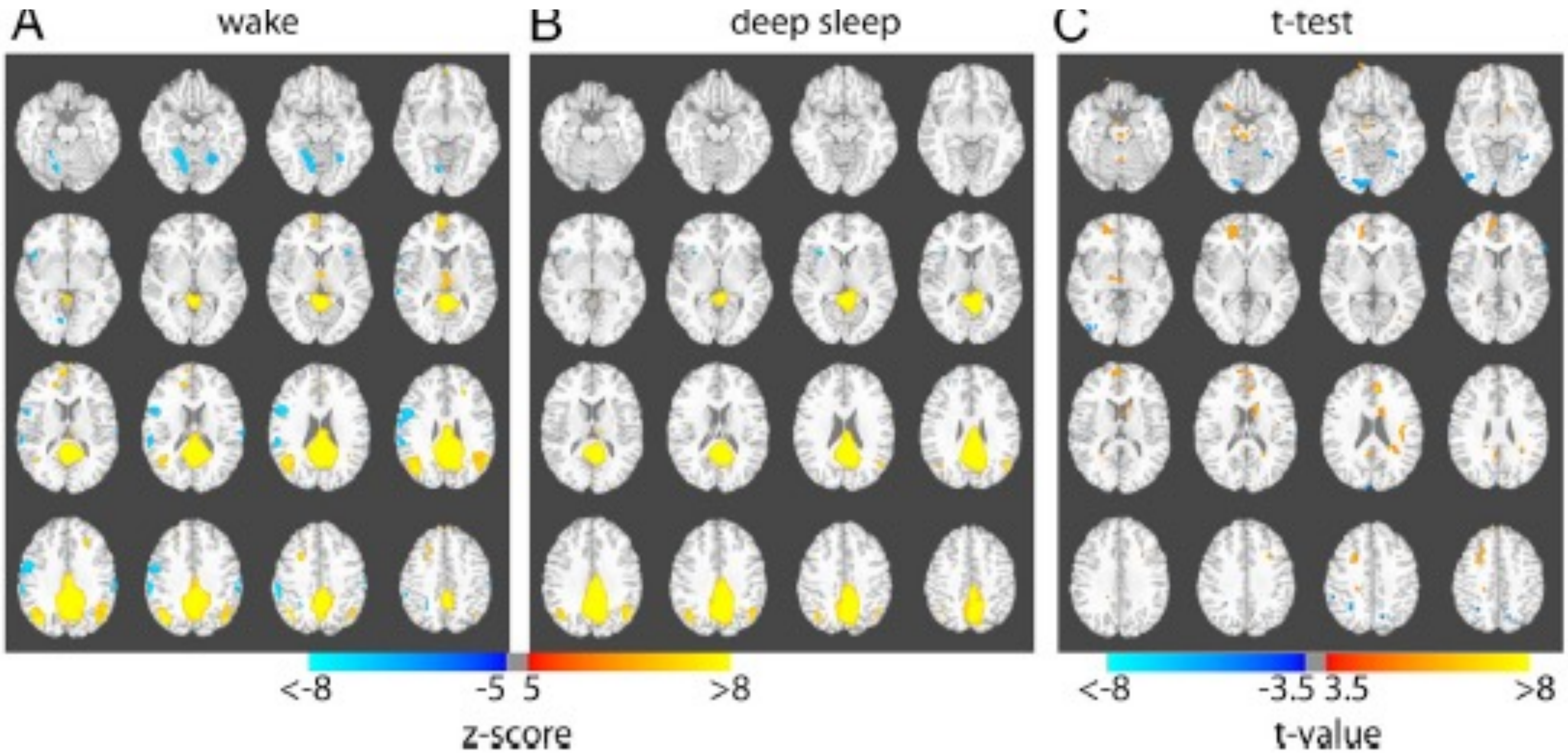
Use EEG to sort fMRI data

Changes in the level of consciousness

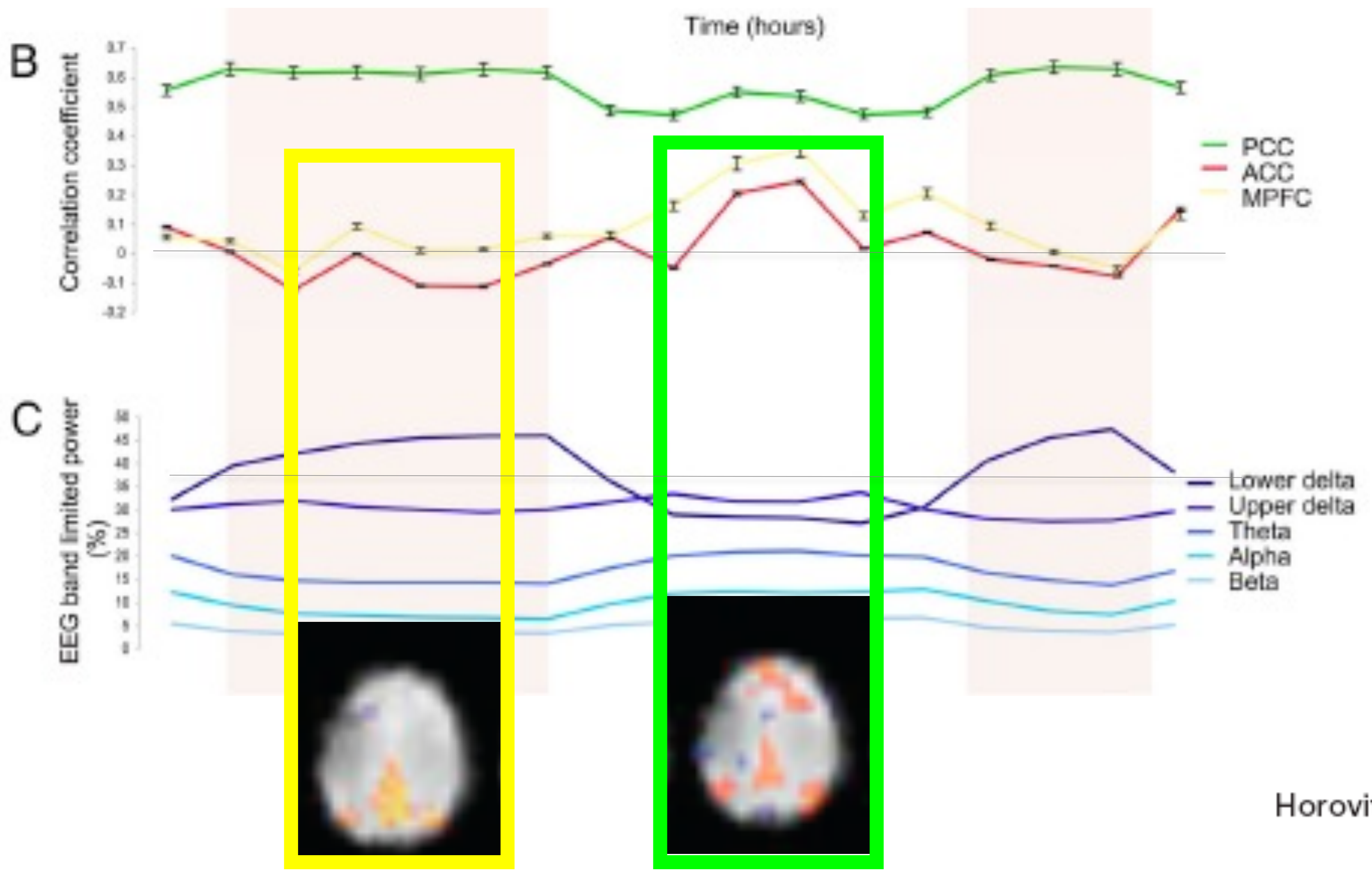
Decoupling of the brain's default mode network during deep sleep

11376–11381 | PNAS | July 7, 2009 | vol. 106 | no. 27

Silvina G. Horovitz[a,b,1], Allen R. Braun[c], Walter S. Carr[d], Dante Picchioni[e], Thomas J. Balkin[e], Masaki Fukunaga[b], and Jeff H. Duyn[b]



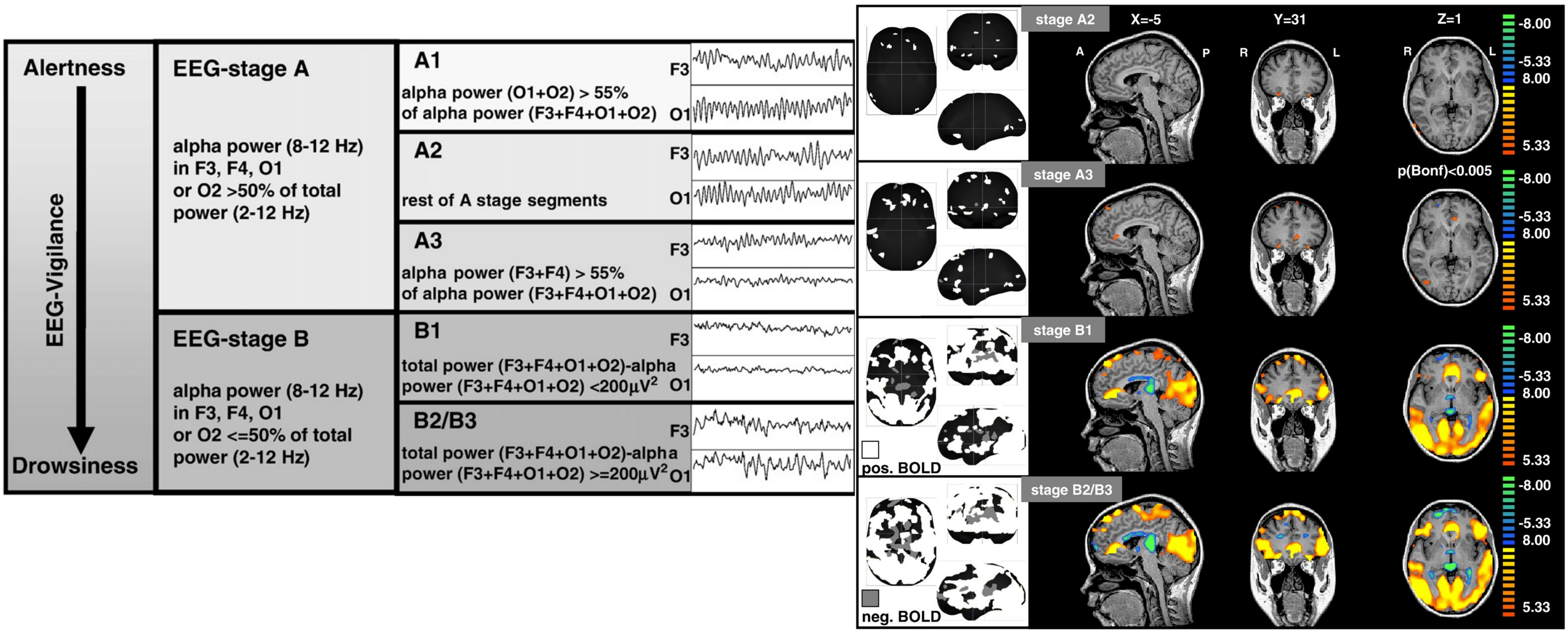
Do changes in connectivity over time have a physiological origin?



Horovitz et al.

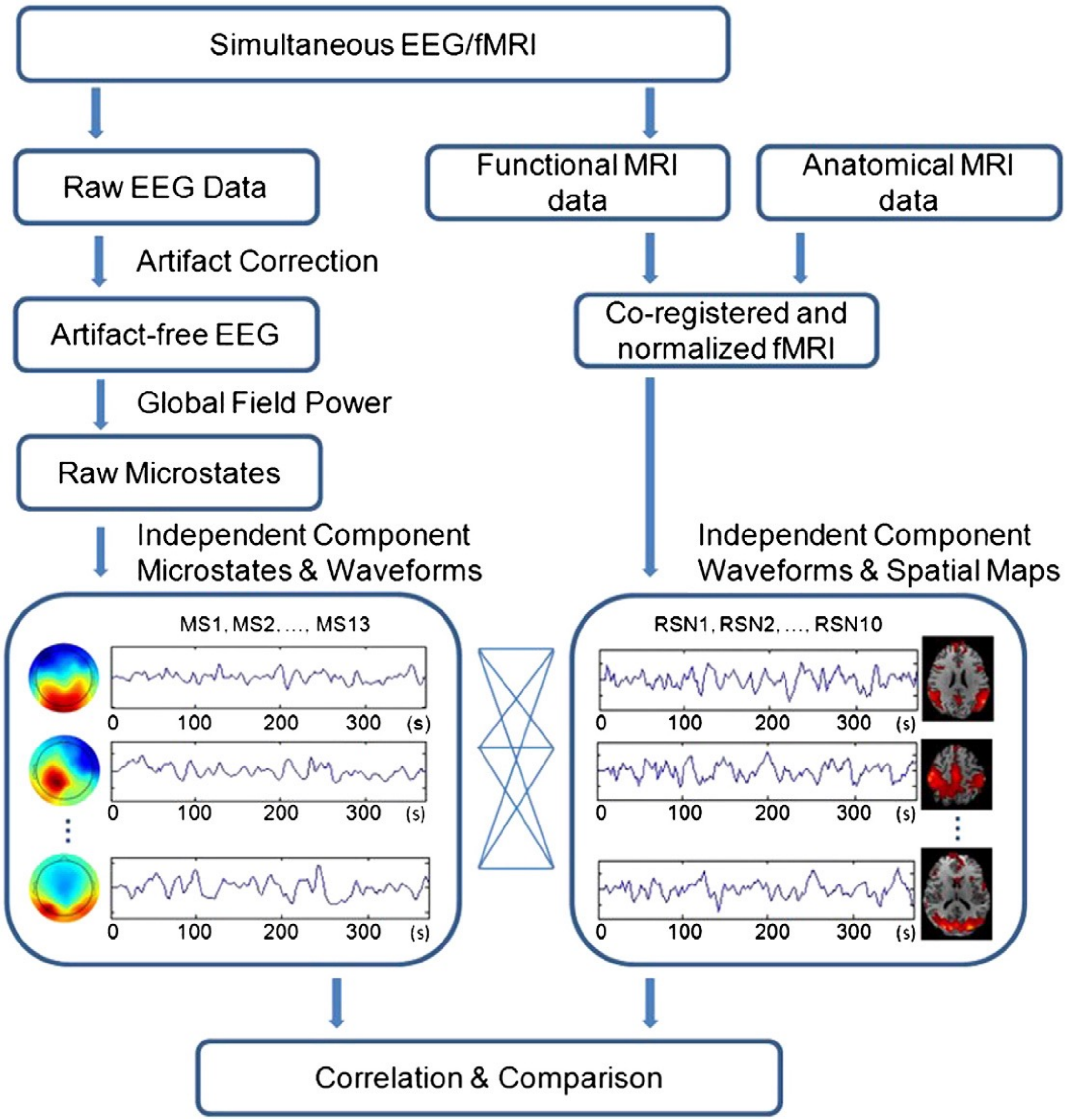
EEG-vigilance and BOLD effect during simultaneous EEG/fMRI measurement

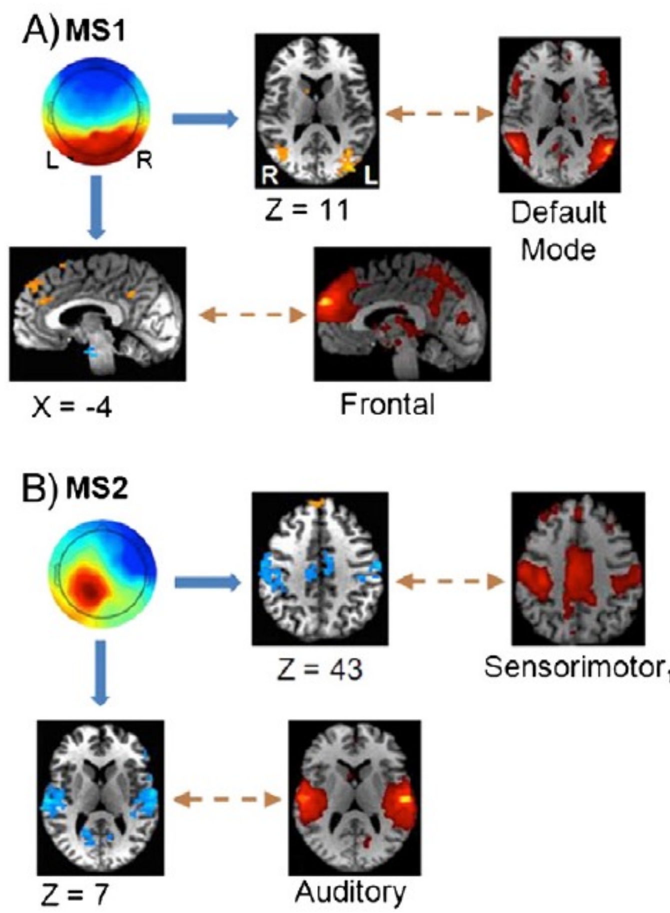
S. Olbrich et al. / NeuroImage 45 (2009) 319–



Spatiotemporal dynamics of the brain at rest- exploring EEG microstates as electrophysiological signatures of BOLD resting state networks.

Yuan H, Zotev V, Phillips R, Drevets WC, Bodurka J.
Neuroimage. 2012

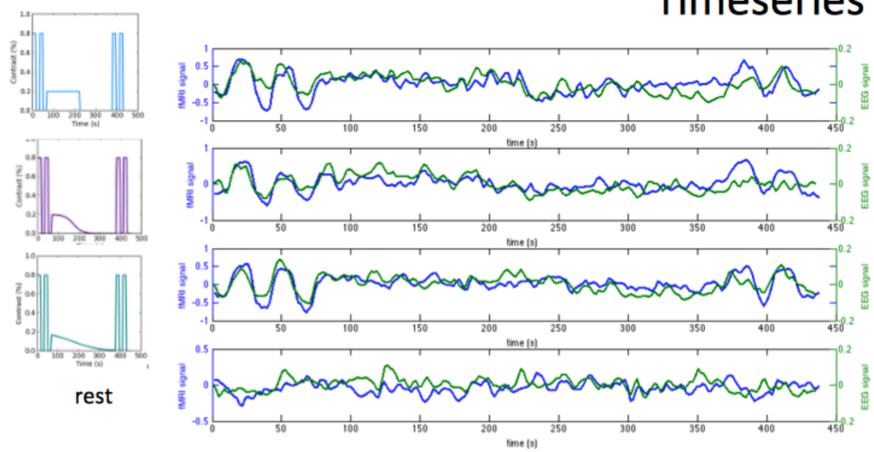




EEG to understand BOLD signal

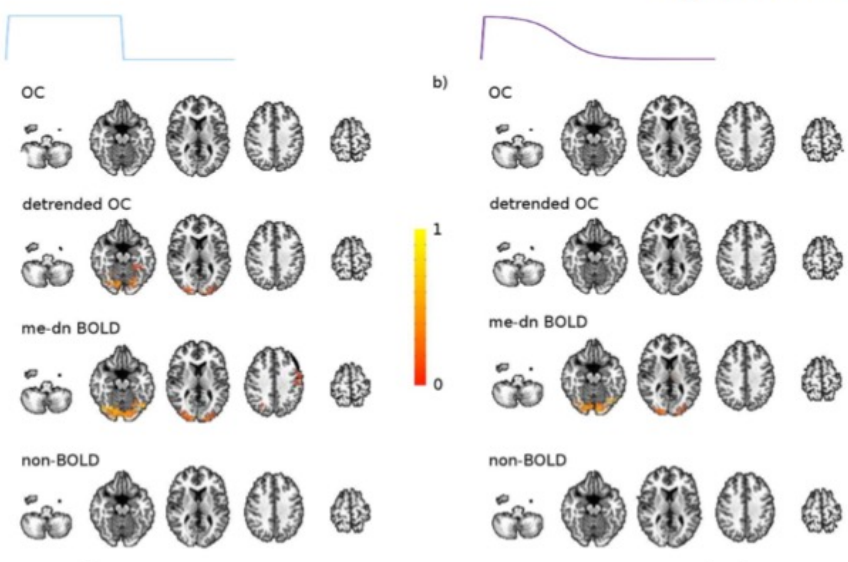
Correlations of simultaneously acquired SSVEPs with BOLD fMRI response

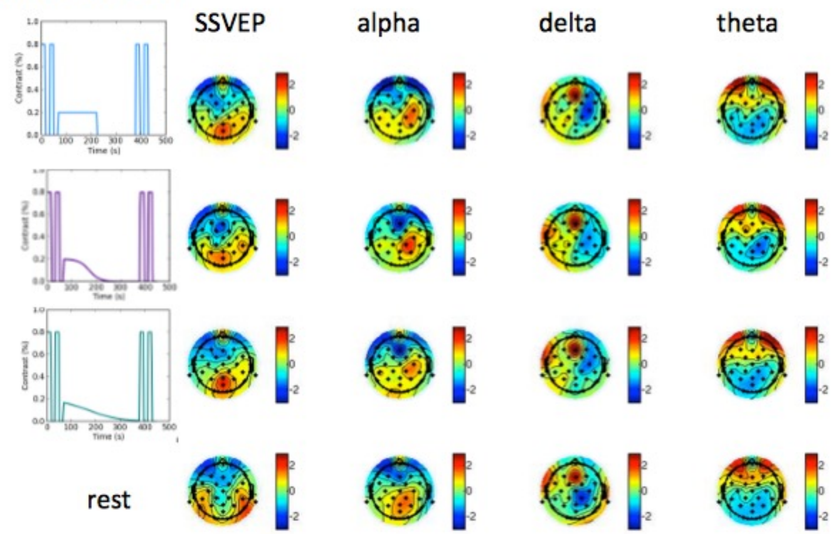
Timeseries



The graphs to the left show the group average MR (blue) and EEG (green) timeseries signals for each task. Excellent agreement is found between modalities. However, the amplitude of the last flanking blocks seems decreased in the SSVEP signal.

Spatial Localization





J.W Evans et al OHBM 2015

EEG & fMRI to study disease

intracranial recordings – fMRI

D.W. Carmichael et al. / NeuroImage 63 (2012) 301–309 305

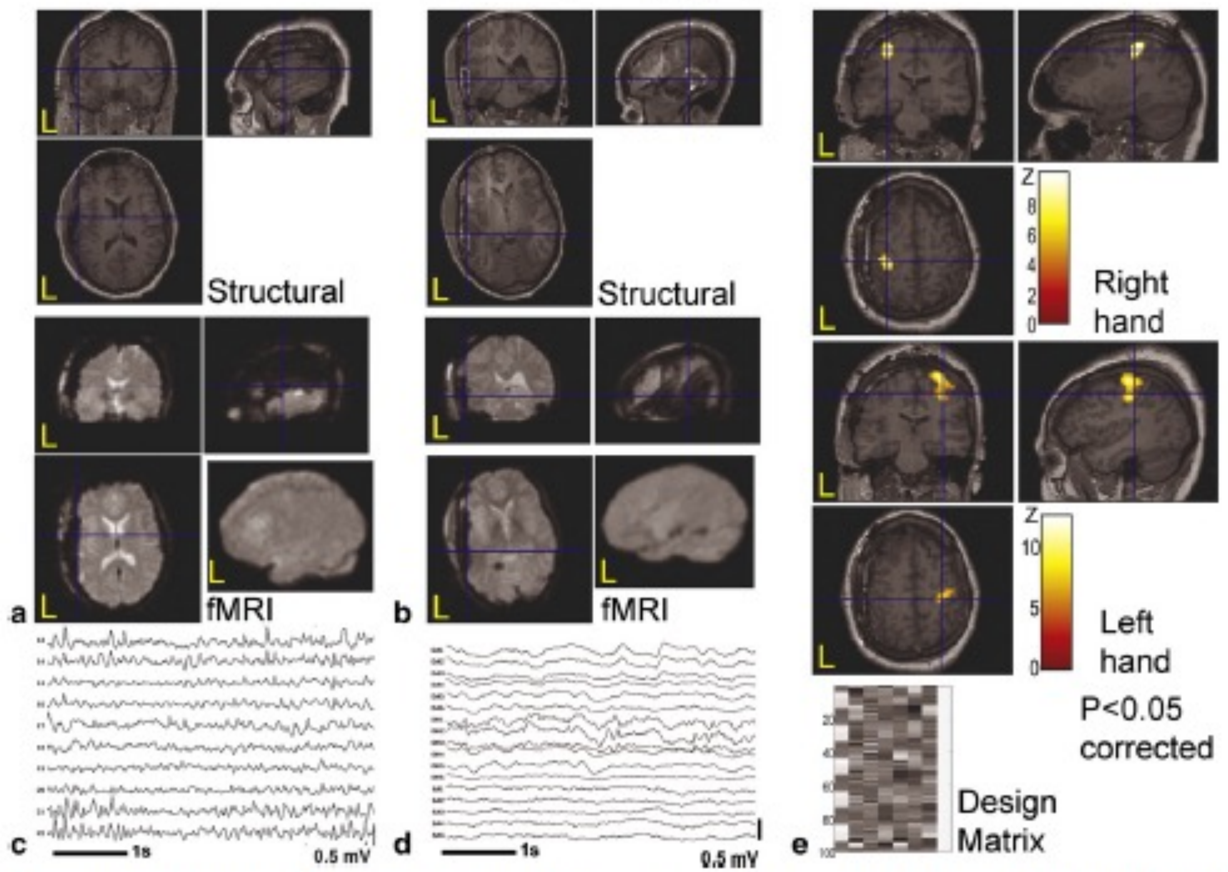


Fig. 3. Simultaneously acquired MRI and icEEG data quality; visual comparison. The same three orthogonal views are displayed of MRI structural (top left) and fMRI data (bottom middle left) in patient #1. The cross hairs indicate the displayed slices through the volume and are centred near the implanted electrode contacts. These are displayed overlaid on the reconstructed brain surface from the T1-weighted volumetric MRI. The fMRI data volume (bottom left) is also surface reconstructed to visualise image artefact levels. As in 'a' for patient #2. A segment of MRI scanner artefact corrected icEEG for patient #1. As in 'c' for patient #2. The results of the left vs. right hand finger tap task in patient #1 with the fMRI response visible immediately beneath the electrode contacts on the cortical surface.

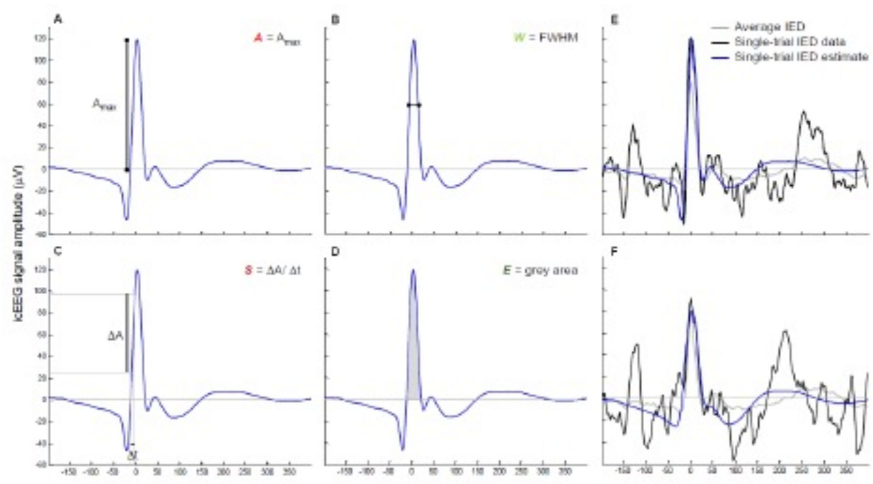
Simultaneous intracranial EEG–fMRI in humans: Protocol considerations and data quality D.W. Carmichael (2012)

A study of the electro-haemodynamic coupling using simultaneously acquired intracranial EEG and fMRI data in humans

T. Murta, L. Hu, T. Tierney, U.J. Chaudhary, M.C. Walker,
D.W. Carmichael, P. Figueiredo, L. Lemieux
NEUROIMAGE, 2016 (accepted Aug 3)

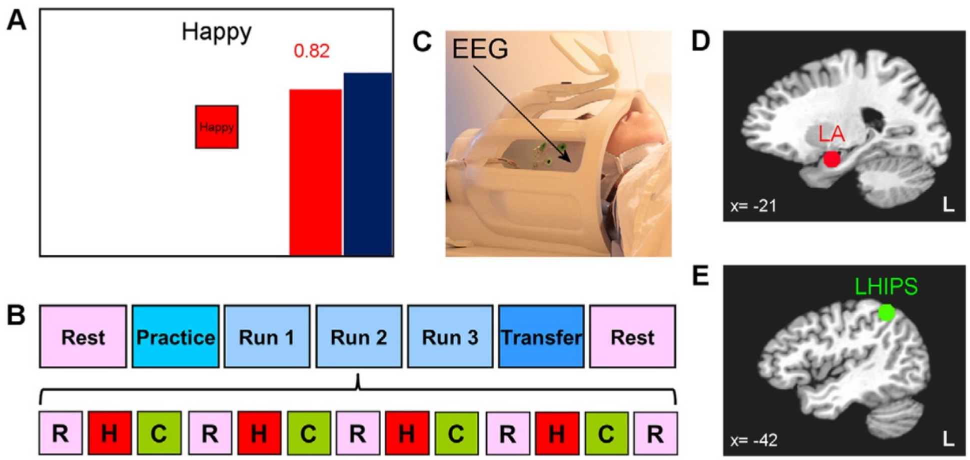
Highlights

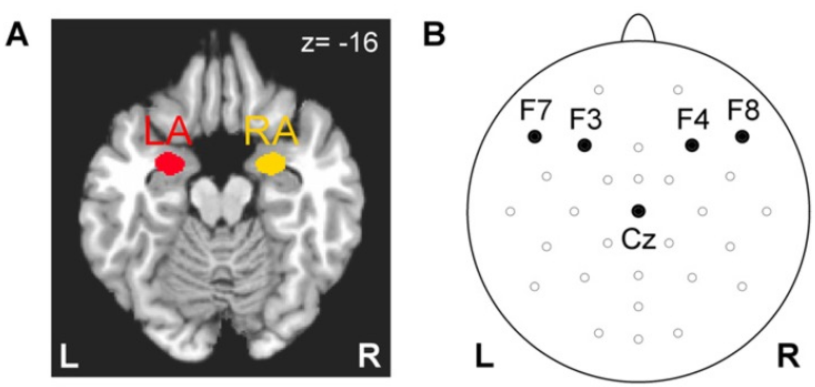
- First study of EEG morphology using simultaneous intracranial EEG-fMRI in humans.
- The duration of sharp waves is significantly correlated with the BOLD signal amplitude.
- BOLD amplitude reflects more field potential duration than neuronal synchrony.
- Sharp wave duration should be included in BOLD models of epileptic discharges.

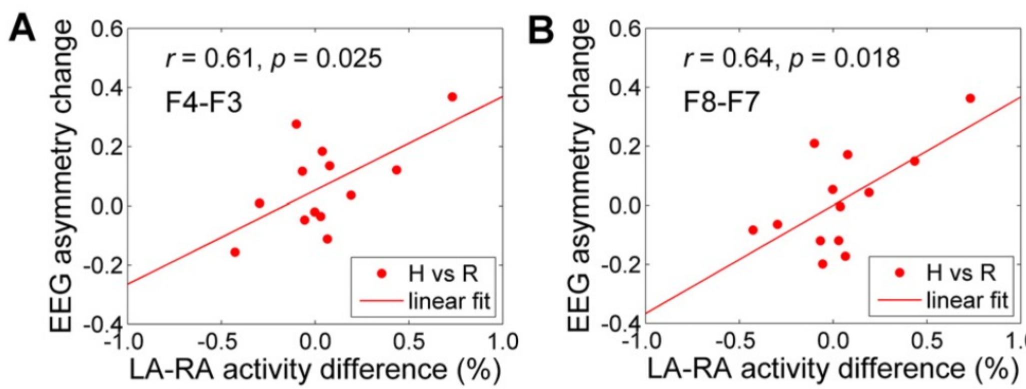


Use EEG to understand fMRI neurofeedback

Zotev et al. NeuroImage: Clinical 11 (2016) 224–238







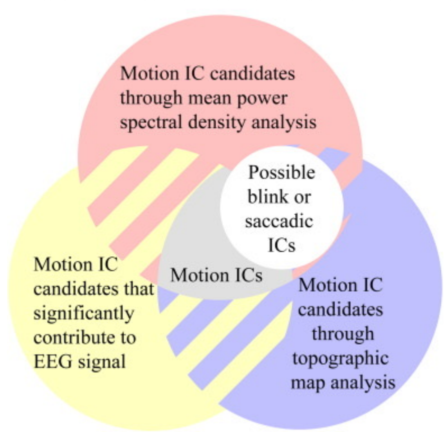
Automatic EEG-assisted retrospective motion correction for fMRI (aE-REMCOR).

Chung-Ki Wong, Vadim Zotev, Masaya Misaki, Raquel Phillips, Qingfei Luo, Jerzy Bodurka. Neuroimage 2016

Highlights

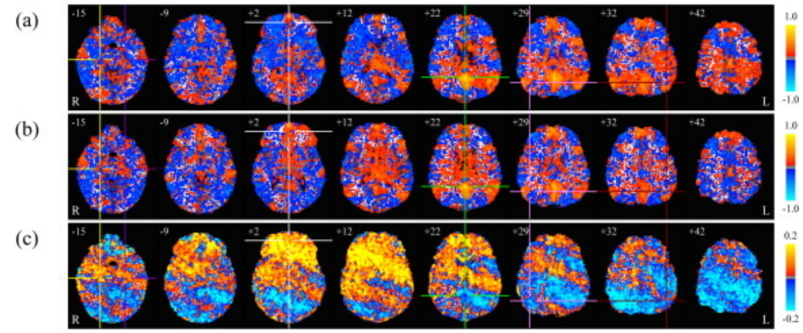
- aE-REMCOR is capable to automatically detect rapid head and cardioballistic motions.
- Motion effects can be corrected by aE-REMCOR on slice-by-slice basis in fMRI data.
- improve accuracy of the rs-fMRI connectivity analysis.
- aE-REMCOR provides incentive for conducting simultaneous EEG & fMRI.

Selection algorithm for motion ICs



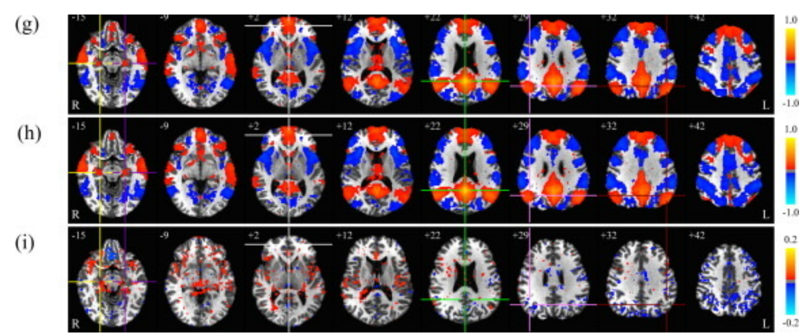
Resting state functional connectivity of default mode network

For the resting scan shown in Fig. 6



Resting state connectivity of the default mode network (DMN).
Top: Individual subject. (a)–(b): Correlation map without and with aE-REMCOR for the scan with significant rapid head movements (c) difference.

(g-h-i) Group results



Simultaneous EEG-fMRI summary

- Safety first!
- Quality control at experiment setup & data collection
    - Equipment setup
    - Pulse sequence
    - Task design
- EEG pre-processing
    - Gradient & ballistocardiogram artifacts
- Data integration
    - Dimensionality reduction
        - Spatial correlations
        - Regressions
        - Sorting data based on state
- Some applications
    - Understanding BOLD signal
    - Understanding Disease
    - Origins of EEG signals
    - State dependent studies