Functional neuroimaging:
from methods to applications

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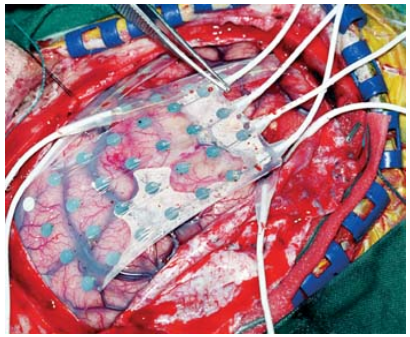
Overview

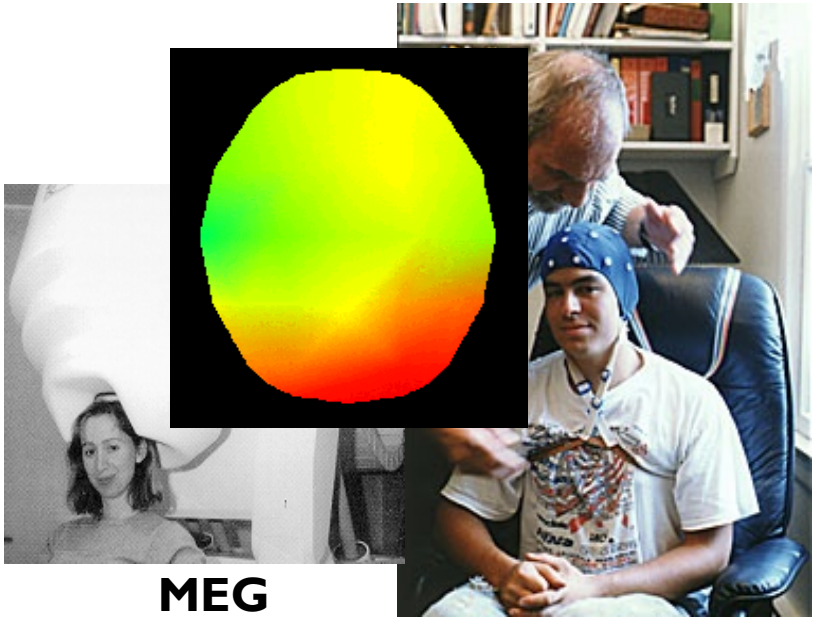
- fMRI basic principles
  - Background: functional brain imaging techniques
  - Brain haemodynamics and the BOLD effect
  - Image acquisition, image analysis and fMRI maps
- fMRI applications
  - (Pre-surgical) mapping of primary visual cortex
  - Neural correlates of faces at different orientations
- fMRI developments
  - Imaging with greater sensitivity at ultra high fields (7 Tesla)
  - Alternative, quantitative contrast mechanisms (ASL)
  - Multimodal, dynamic imaging (EEG-fMRI)
- Conclusion

Background

Functional brain imaging techniques



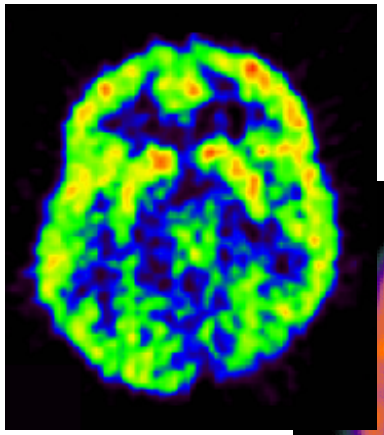
ECoG



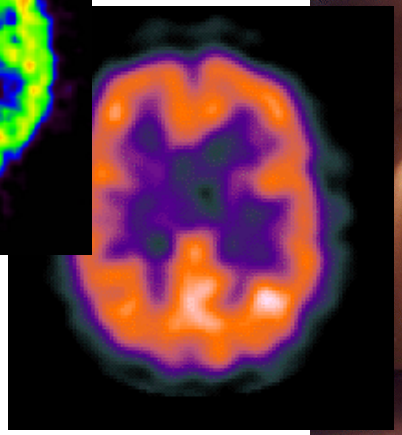
MEG

EEG

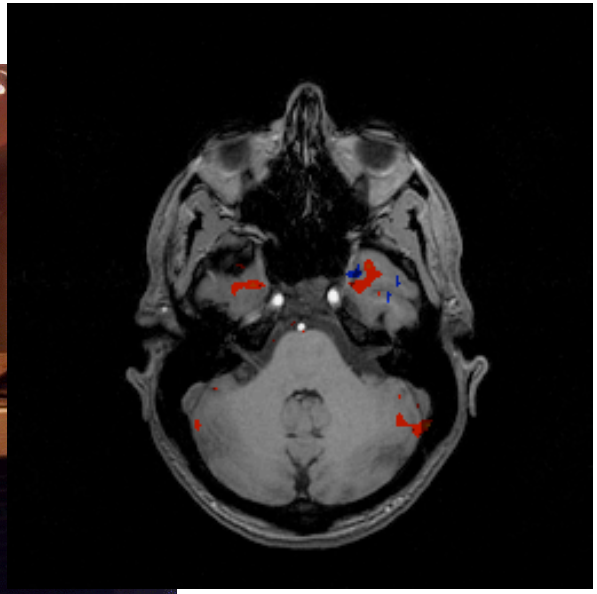
DOI



PET



SPECT



fMRI

Physiological correlates of neuronal activity

Neural activity:

Electrical and synaptic activity

↓

Metabolic response:

↑ $CMRO_2$ / glu =

Cerebral Metabolic Rate of O_2 / glucose

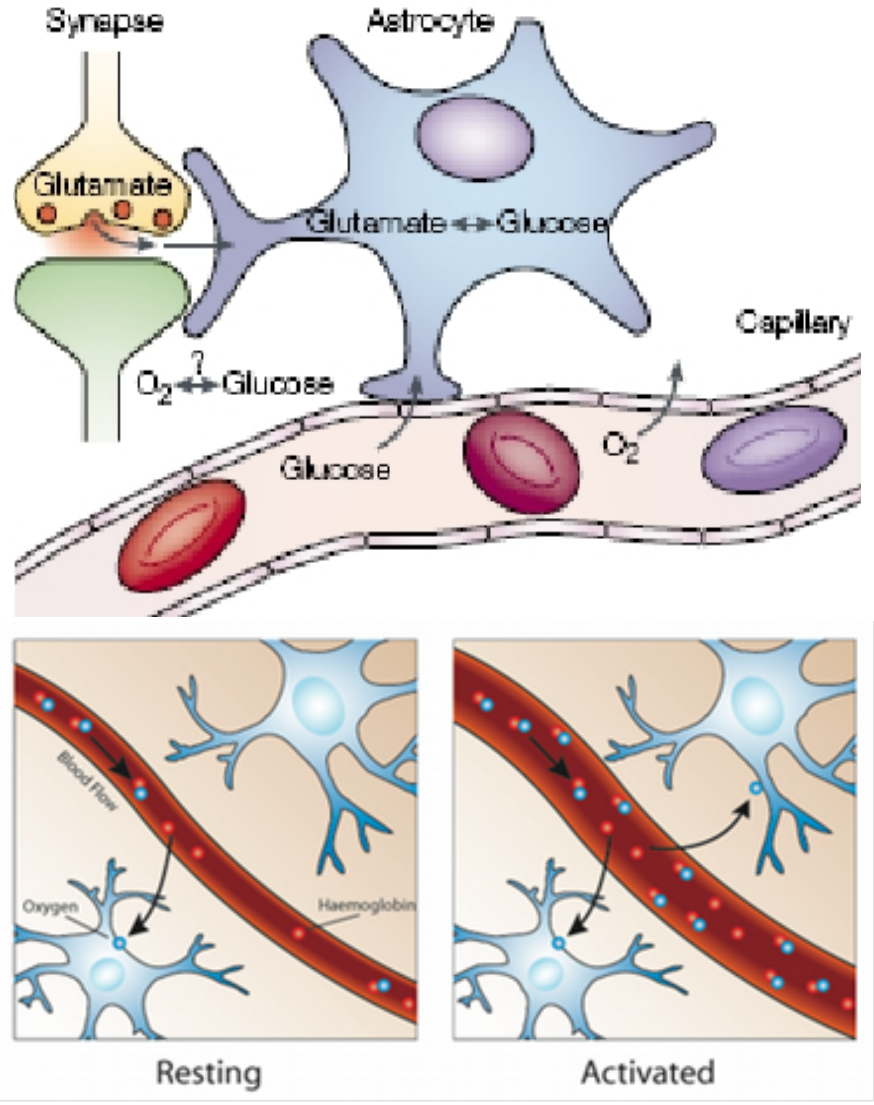
↓

Haemodynamic response:

↑ CBF = Cerebral Blood Flow (20 - 70%)

↑ CBV = Cerebral Blood Volume (5 - 30%)

↑ O_2sat = Blood oxygenation (~1-5%)

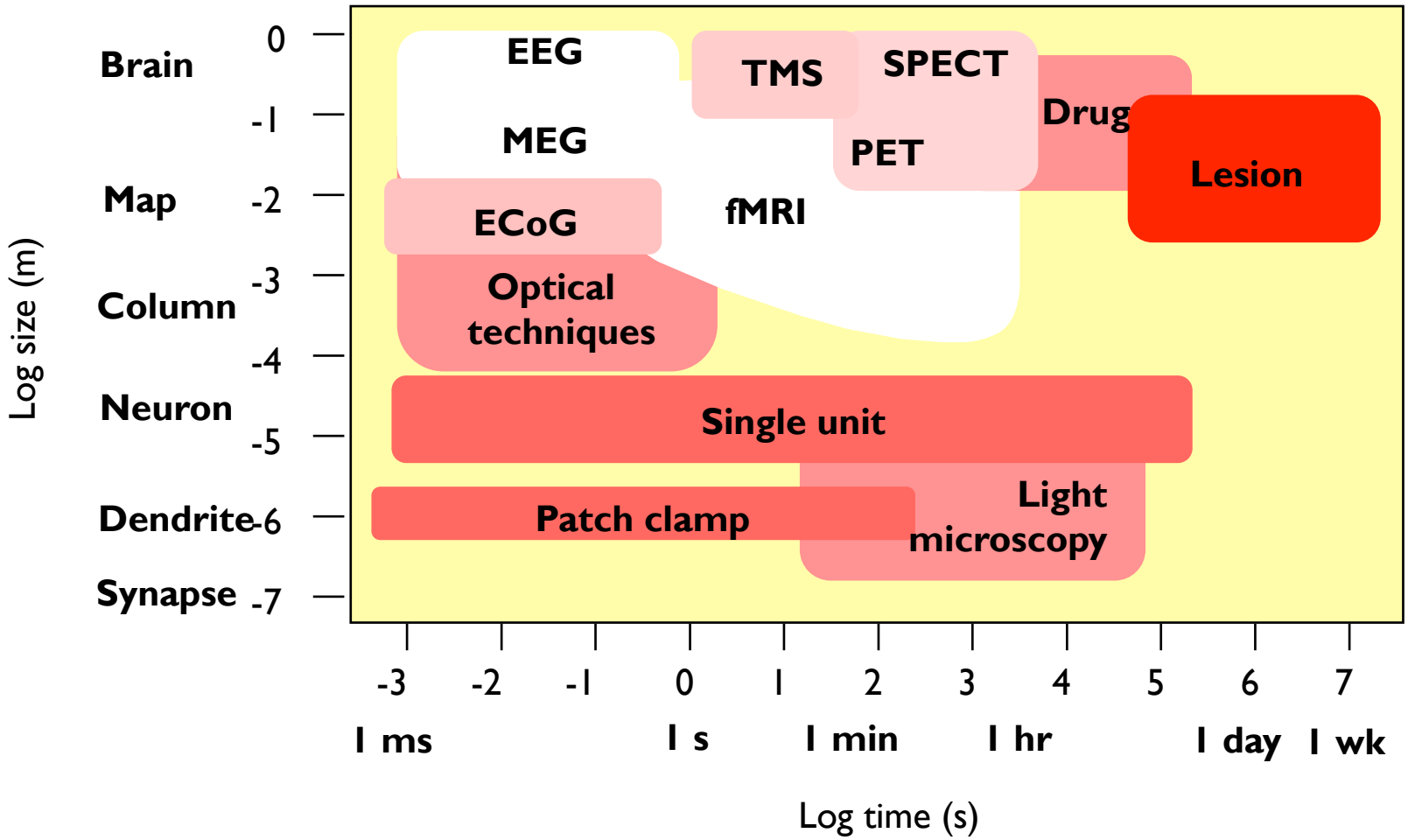


Heeger & Rees, Nat.Rev.Neurosci. 2002

Functional brain imaging techniques

In relation to other <u>neuroscience techniques</u>:

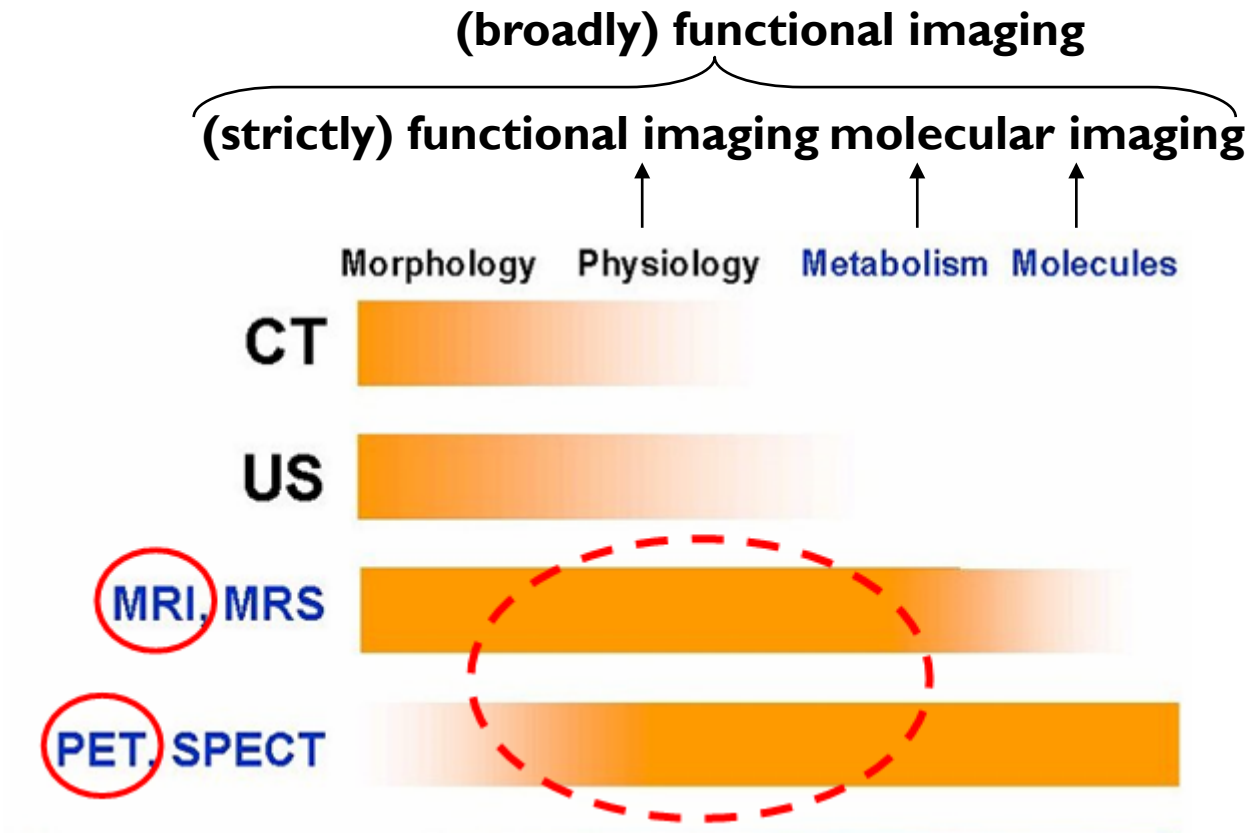
In terms of invasiveness and spatial/temporal resolution:



Functional brain imaging techniques

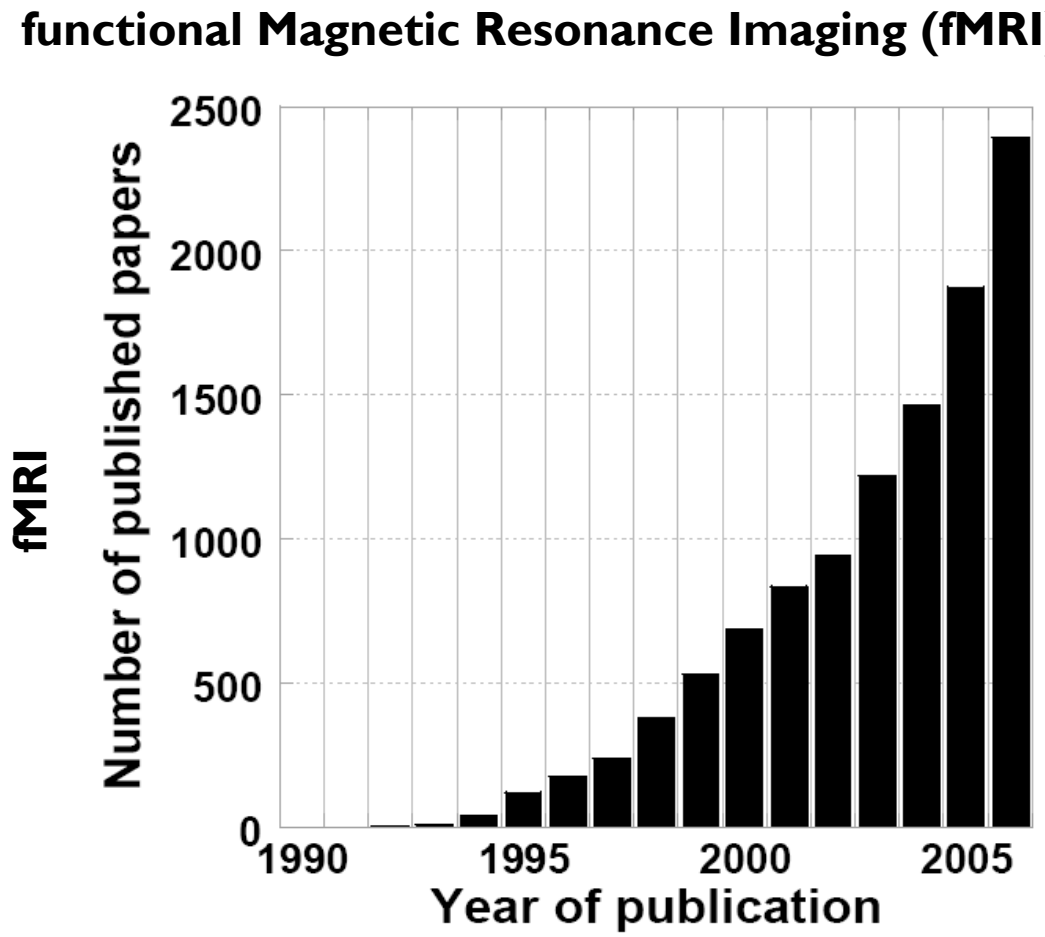
In relation to other <u>brain imaging techniques</u>:

In terms of contrast:



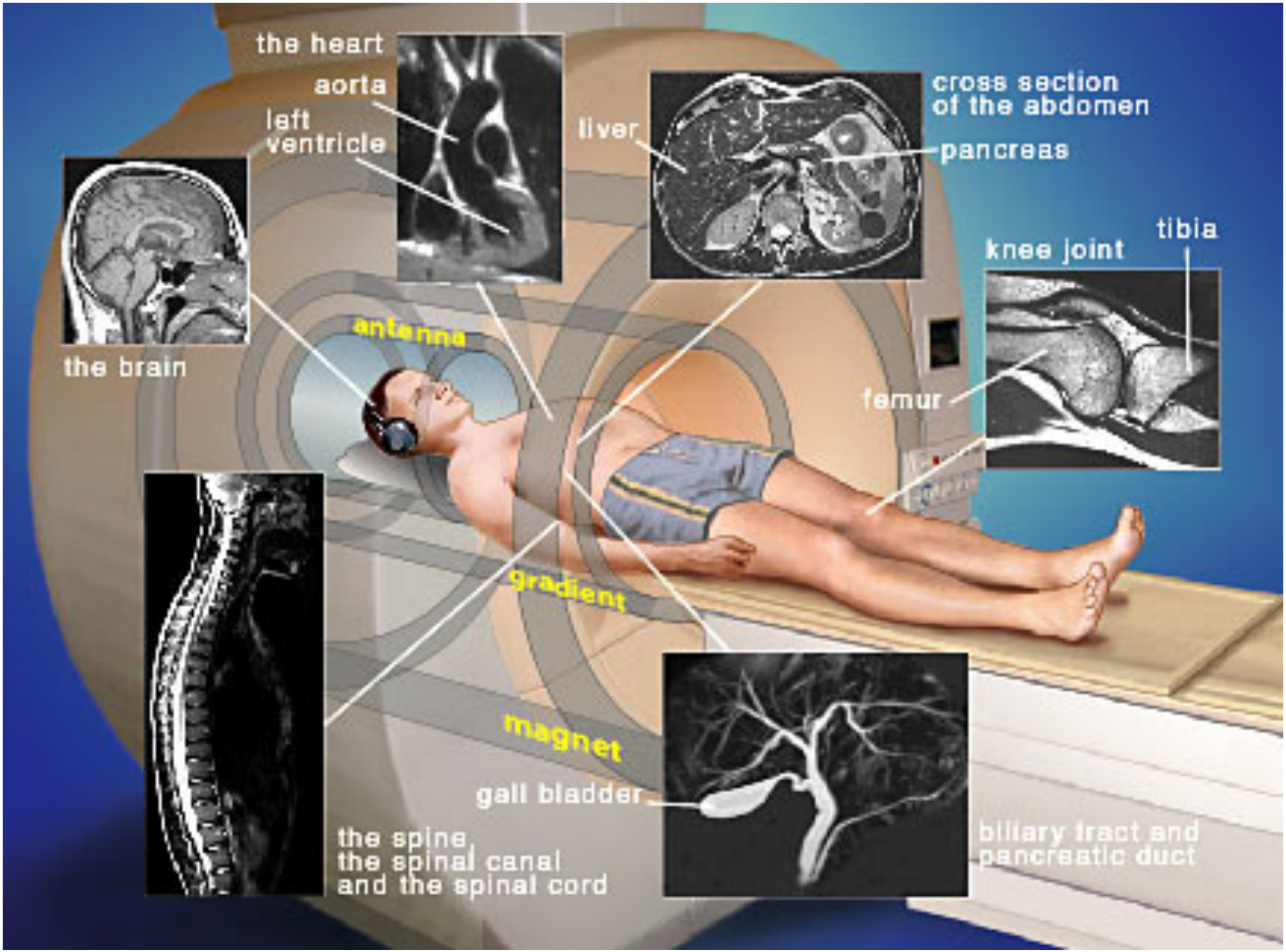
http://www.medical.siemens.com/

Functional brain imaging techniques



Based on a search on PubMed of papers using "fMRI' and/or "functional MRI' and/or 'functional magnetic resonance imaging' in the tile and/or abstract [Leite, 2006]

Methodology


the heart
aorta
left ventricle
cross section of the abdomen
liver
pancreas
knee joint
tibia
the brain
antenna
femur
gradient
magnet
gall bladder
the spine, the spinal canal and the spinal cord
biliary tract and pancreatic duct

The BOLD effect

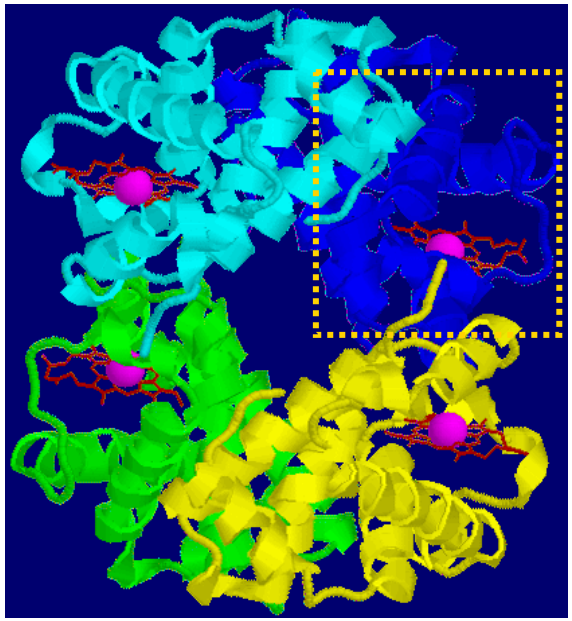
Oxy-Heamoglobin HbO_2

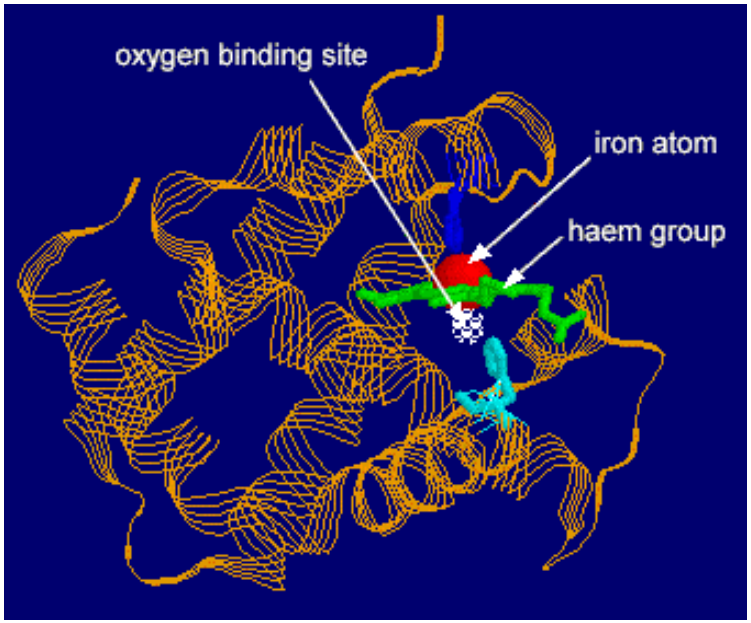
Vs

Deoxy-Heamoglobin dHb

$\Delta\chi$ (dHb – HbO_2)

≈ 0.08 ppm

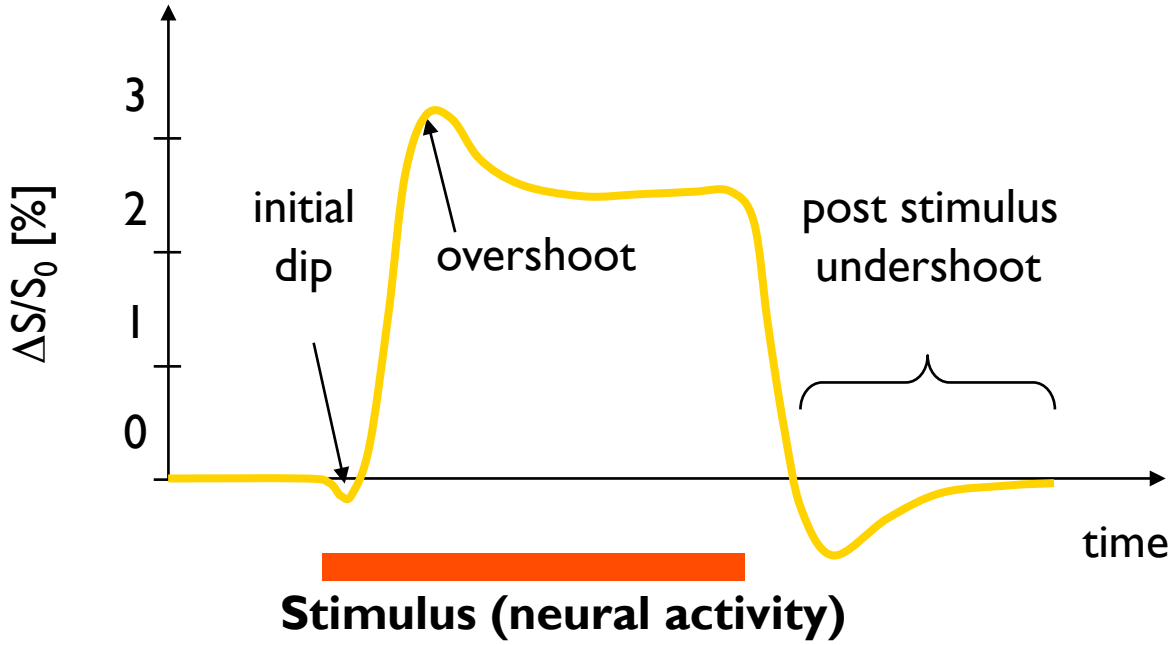




↑ neural activity

→ ↑ O2sat

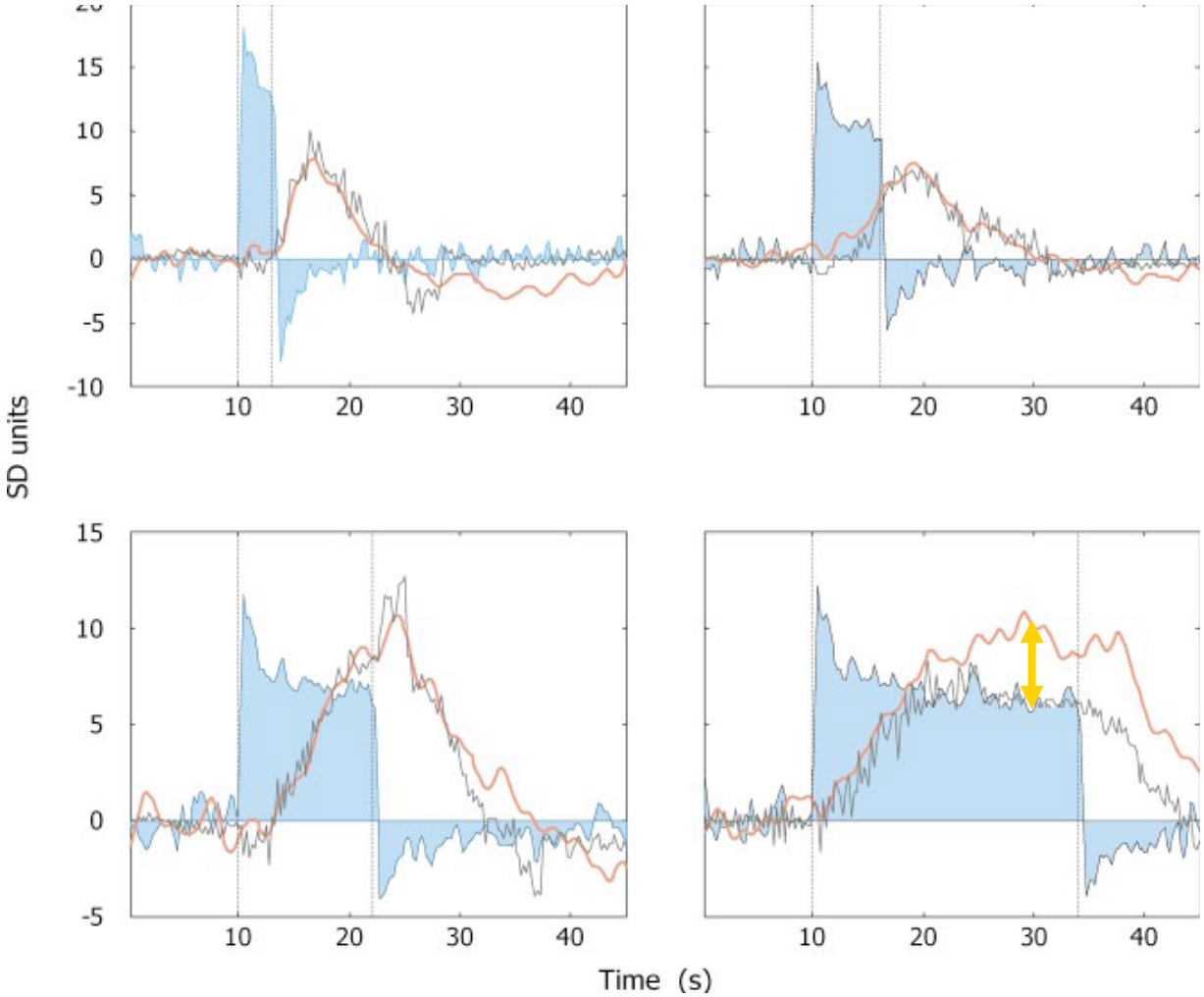
→ ↑ T2*-weighted signal:



The BOLD effect

Electrophysiological correlates:

BOLD response compared with LFP, as a function of stimulus duration:



BOLD

LFP

LTI

LFP =
Local Field Potential

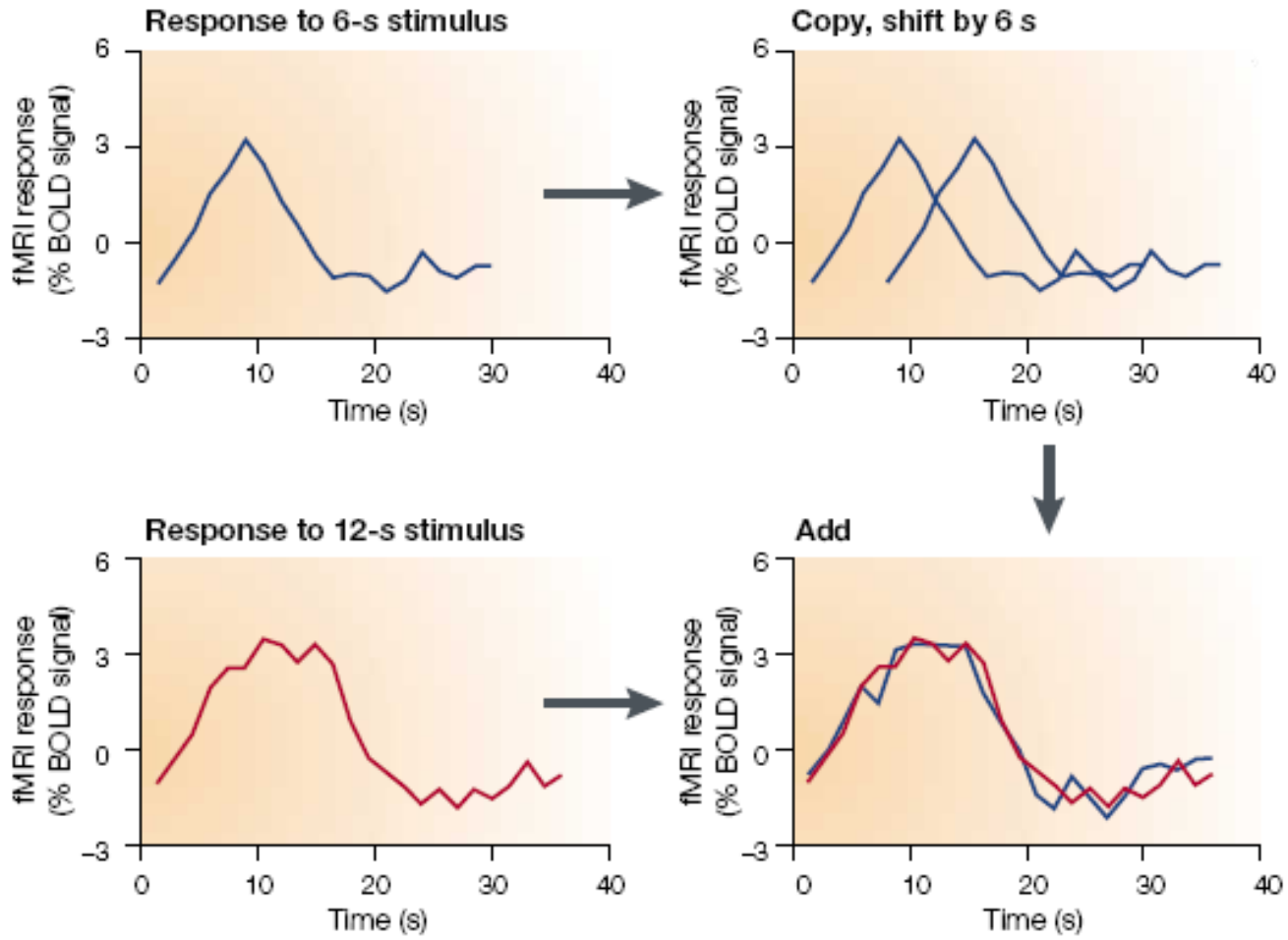
LTI =
Linear Time Invariant
BOLD prediction

Logothetis, 2004

The BOLD effect

Linear behaviour:

BOLD response summation (using the linear transformation model):

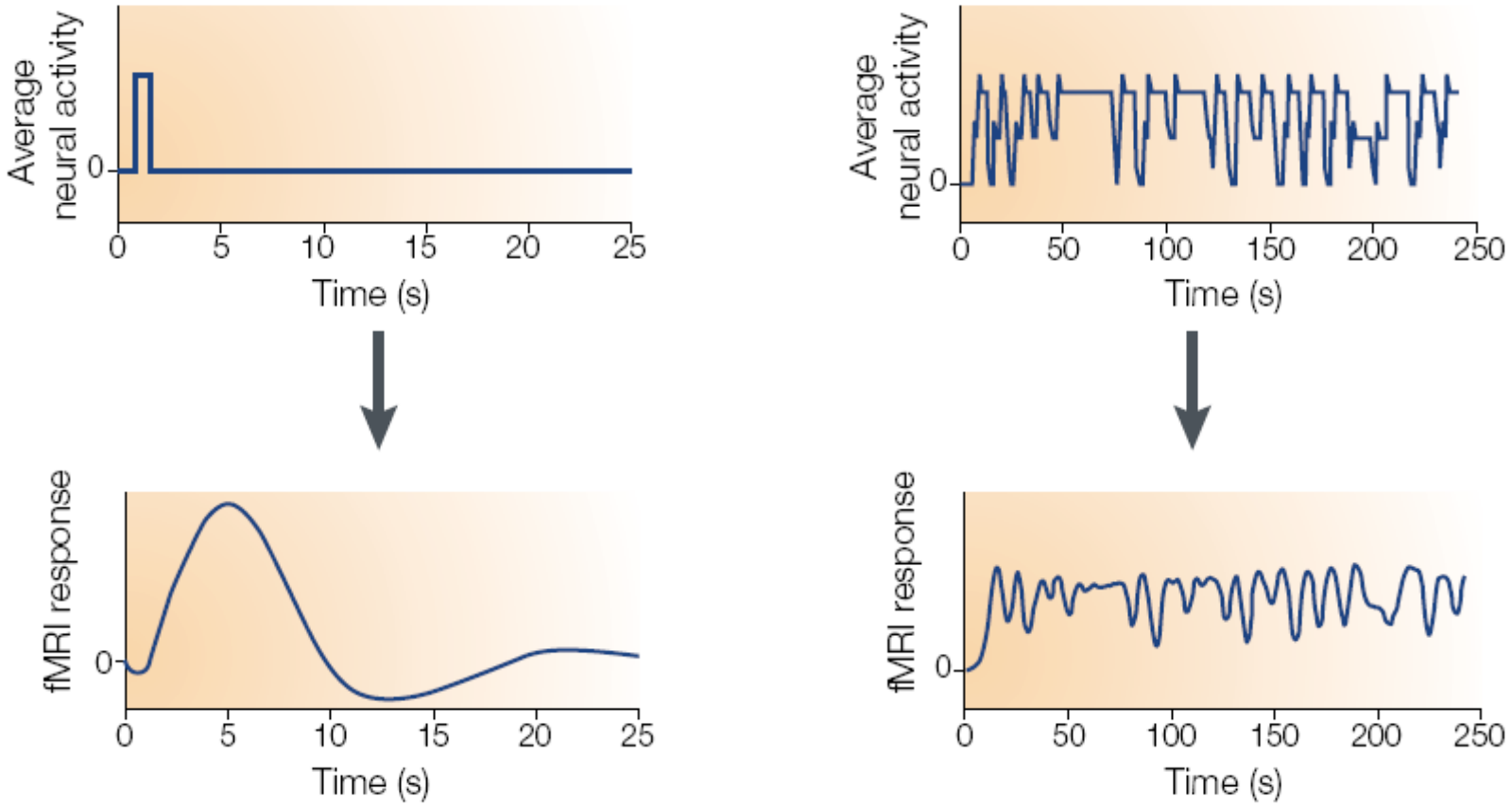


Heeger & Rees, Nat.Rev.Neurosci. 2002

The BOLD effect

Linear behaviour:

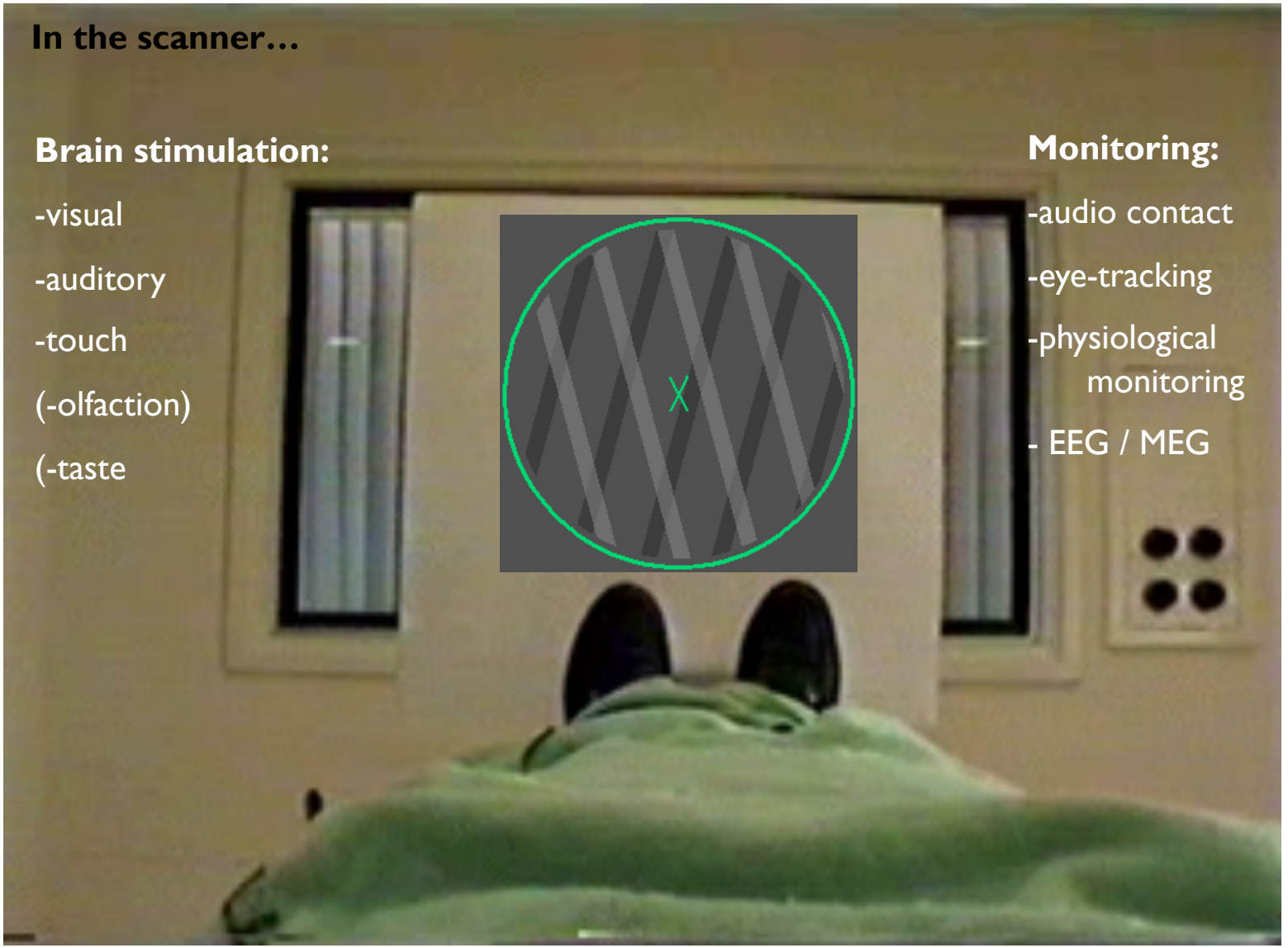
BOLD response summation (using the linear transformation model):



Heeger & Rees, Nat.Rev.Neurosci. 2002

fMRI experimental setup

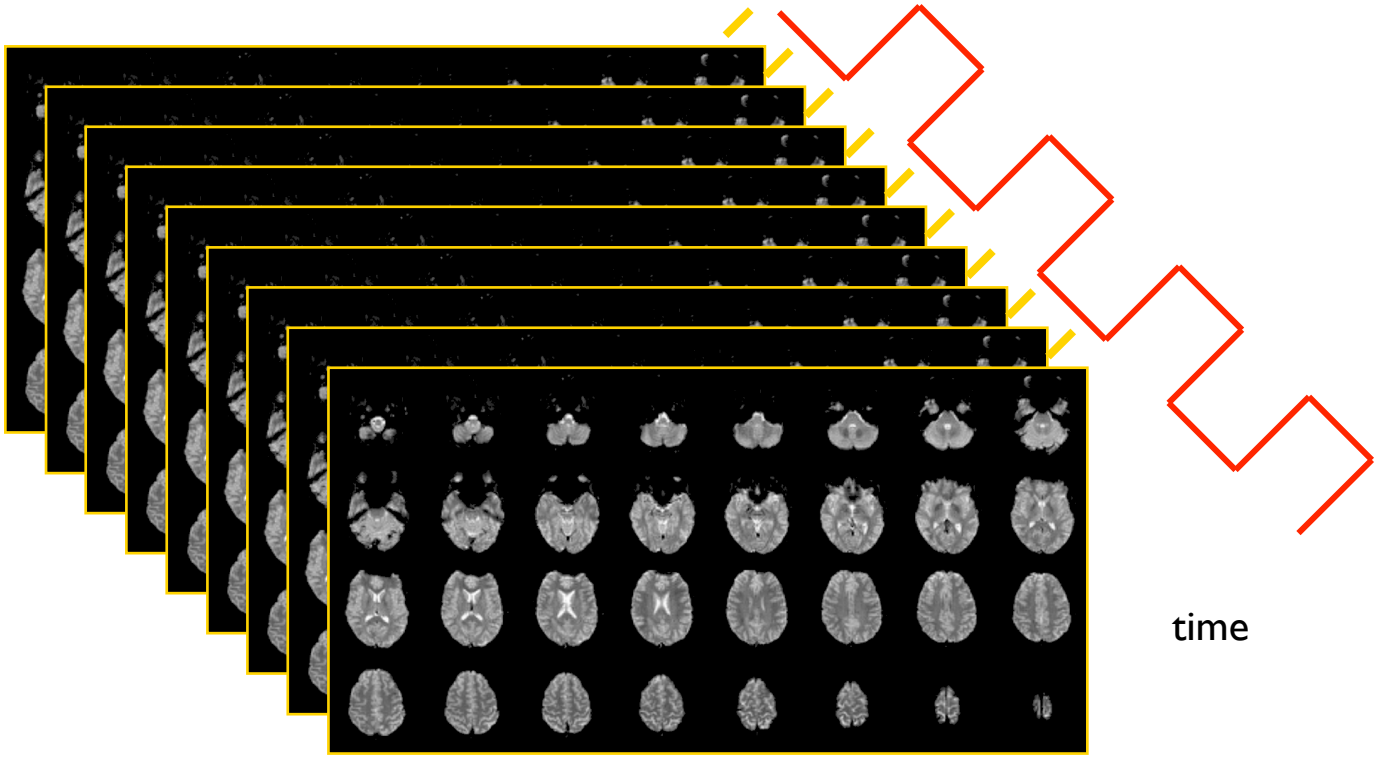
fMRI experimental setup

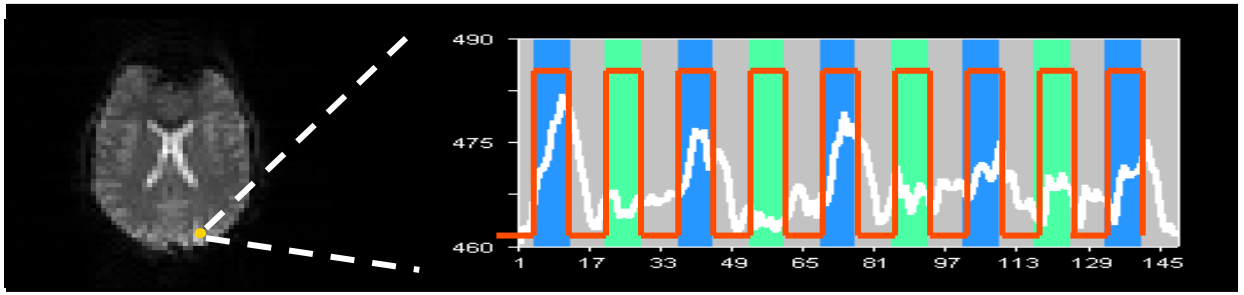


fMRI image acquistion

Typical parameters:

1.5 / 3.0 Tesla system; T2*-weighted BOLD; GE-EPI, TE = 50 / 30 ms
TR = 1000 – 3000 ms; ~30 axial slices; ~2-4 mm3 voxel resolution

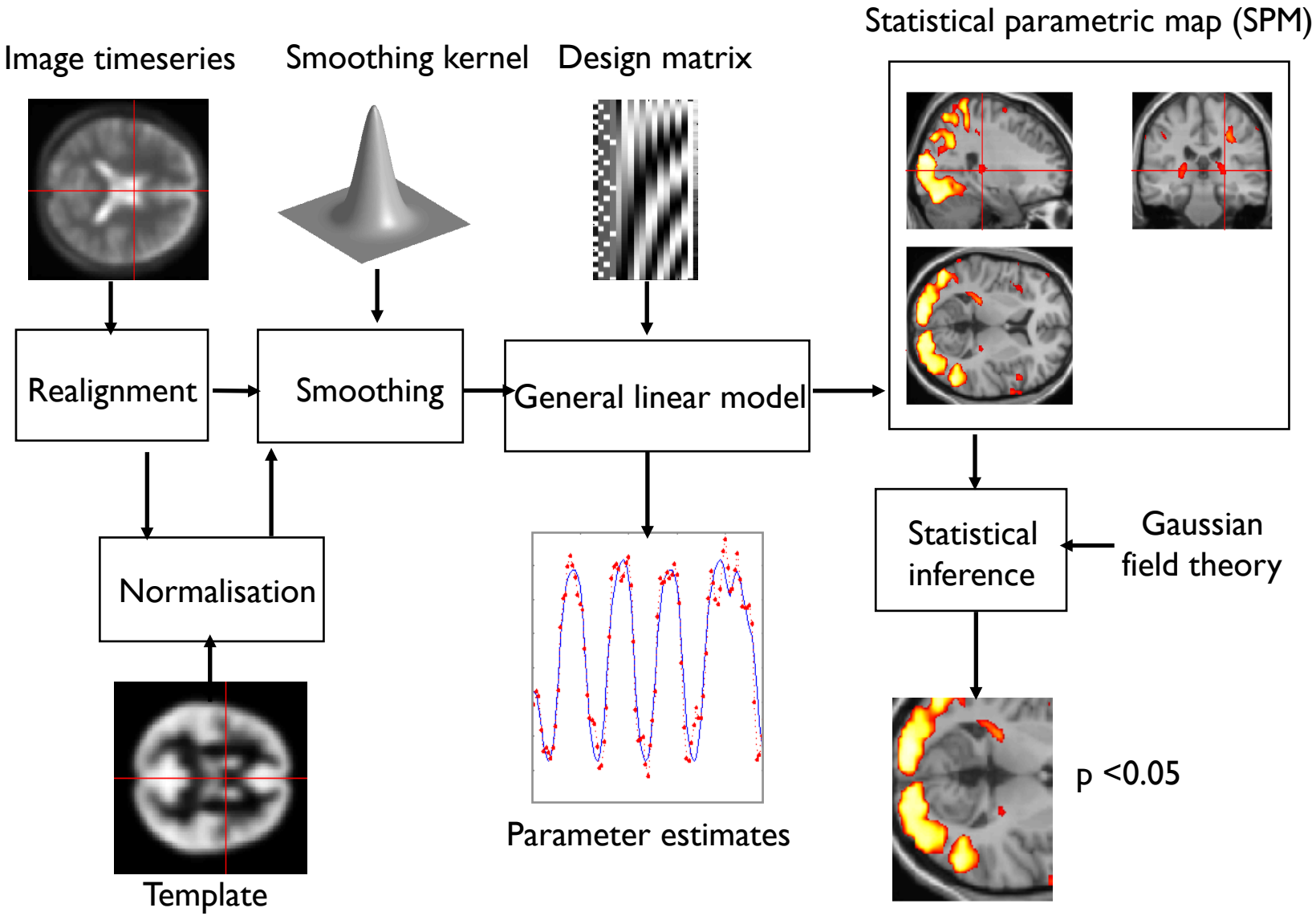




Figueiredo 2008

fMRI image analysis

The statistical parametric mapping (SPM) approach:

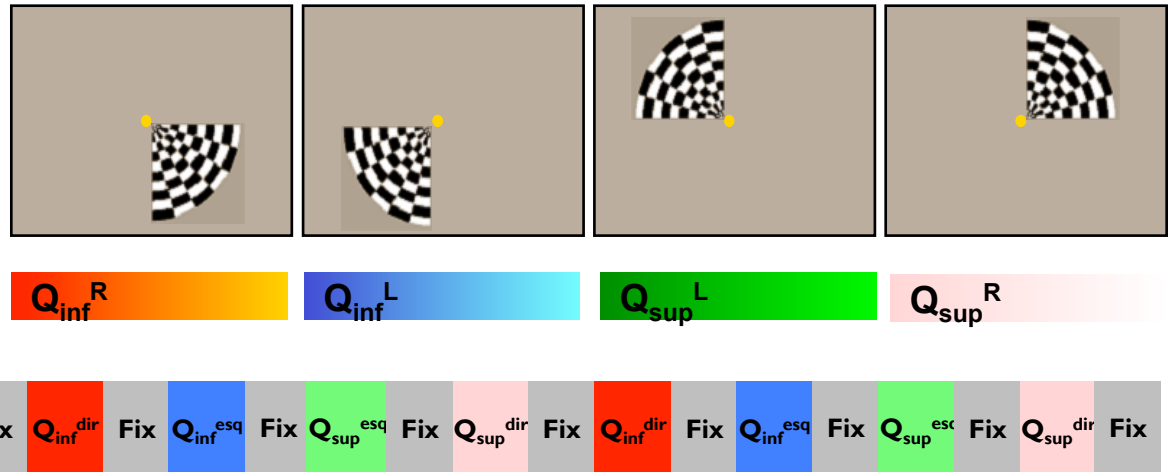


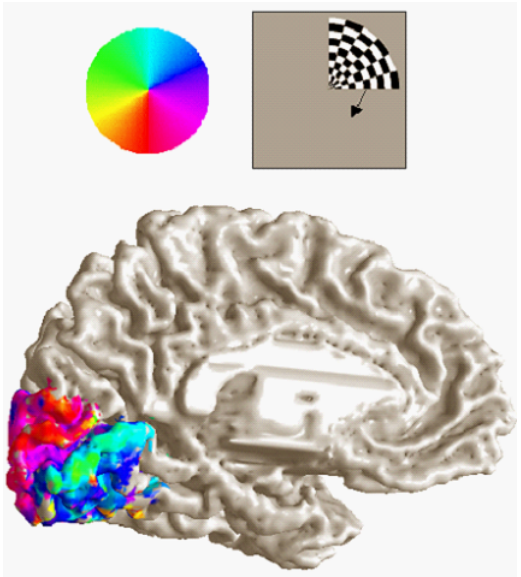
Applications

Retinotopic quadrant mapping

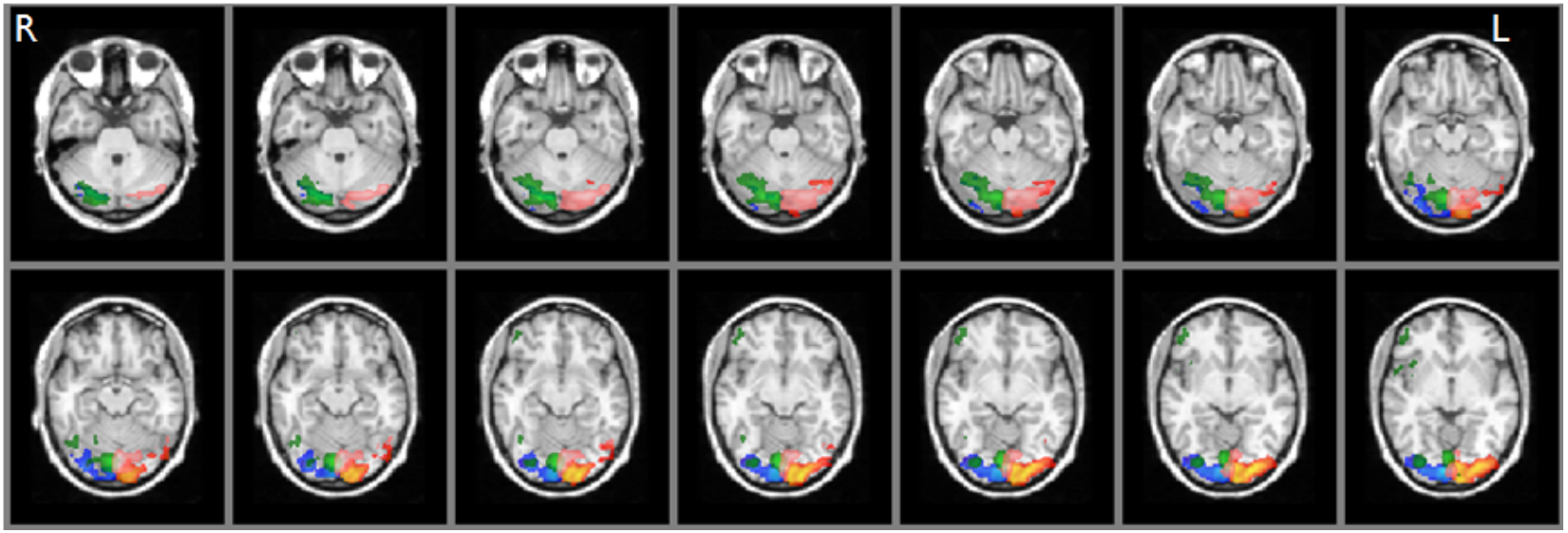
Control subject:

Stimuli





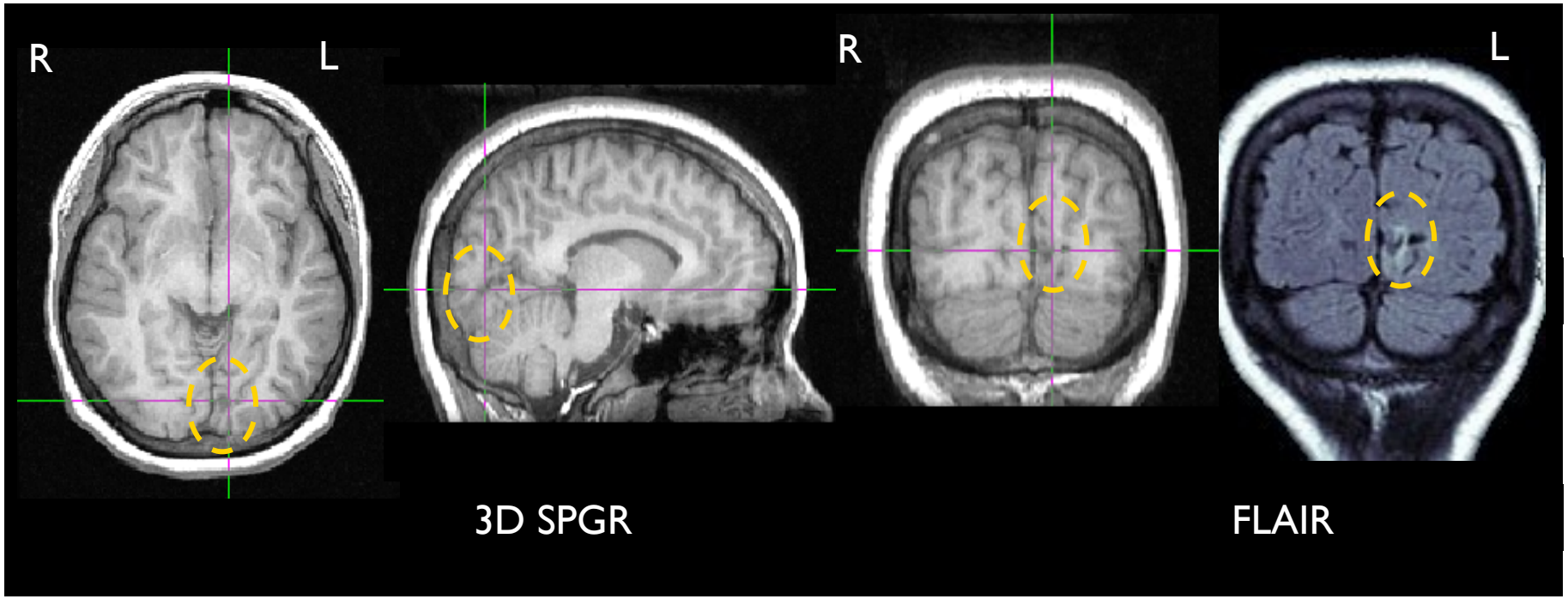
Activation maps



Cruz et al., HBM 2009

Focal epilepsy case study

Patient IL: congenital focal cortical dysplasia in left occipital cortex, with pharmaco-resistant epilepsy, indicated for surgical treatment of epilepsy



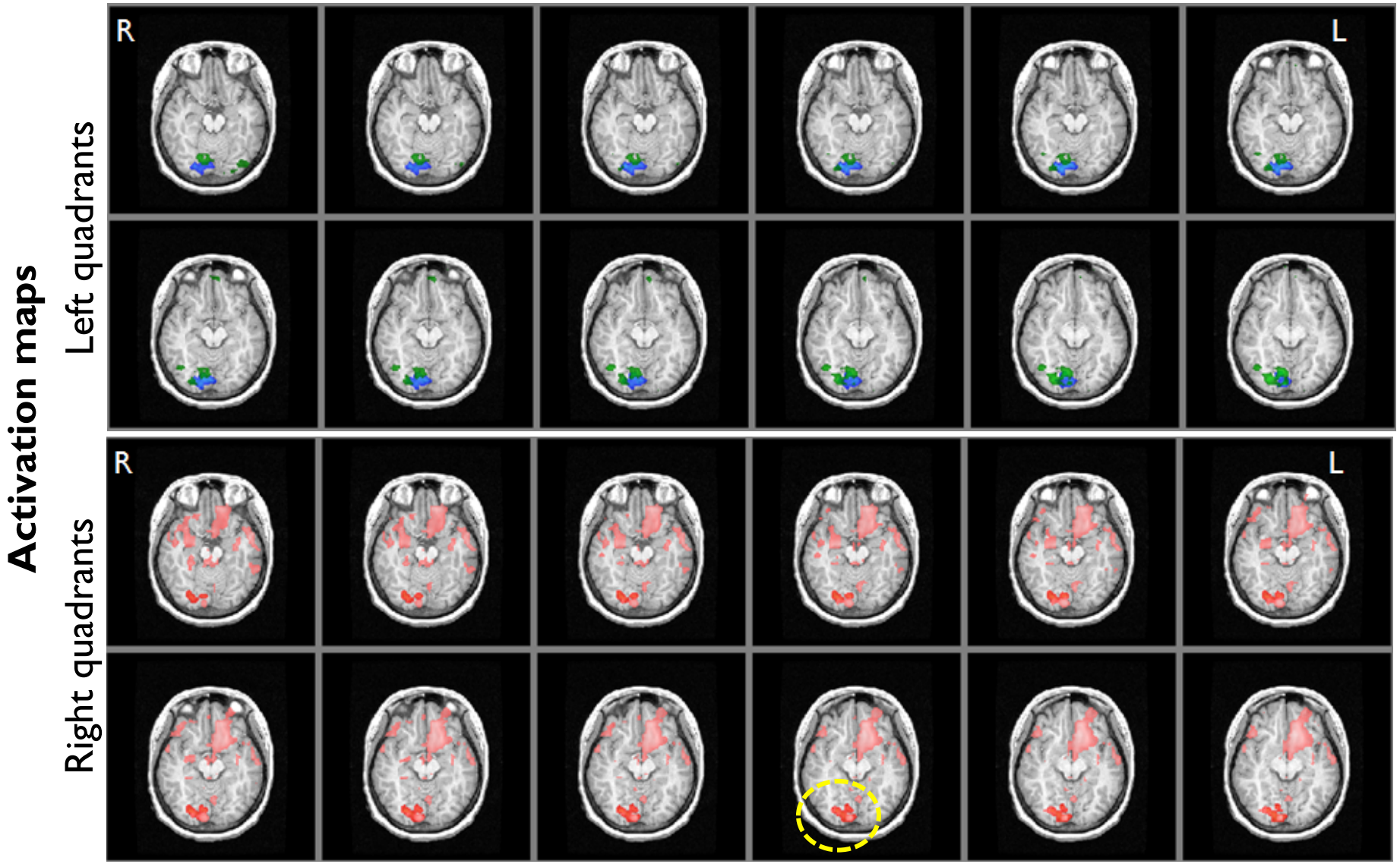
Aim of the fMRI study:

To identify eloquent cortical tissue in the neighbourhood of the lesion, in order to assist surgical resection planning and post-surgical outcome prediction.

Courtesy of Dr. Alberto Leal.

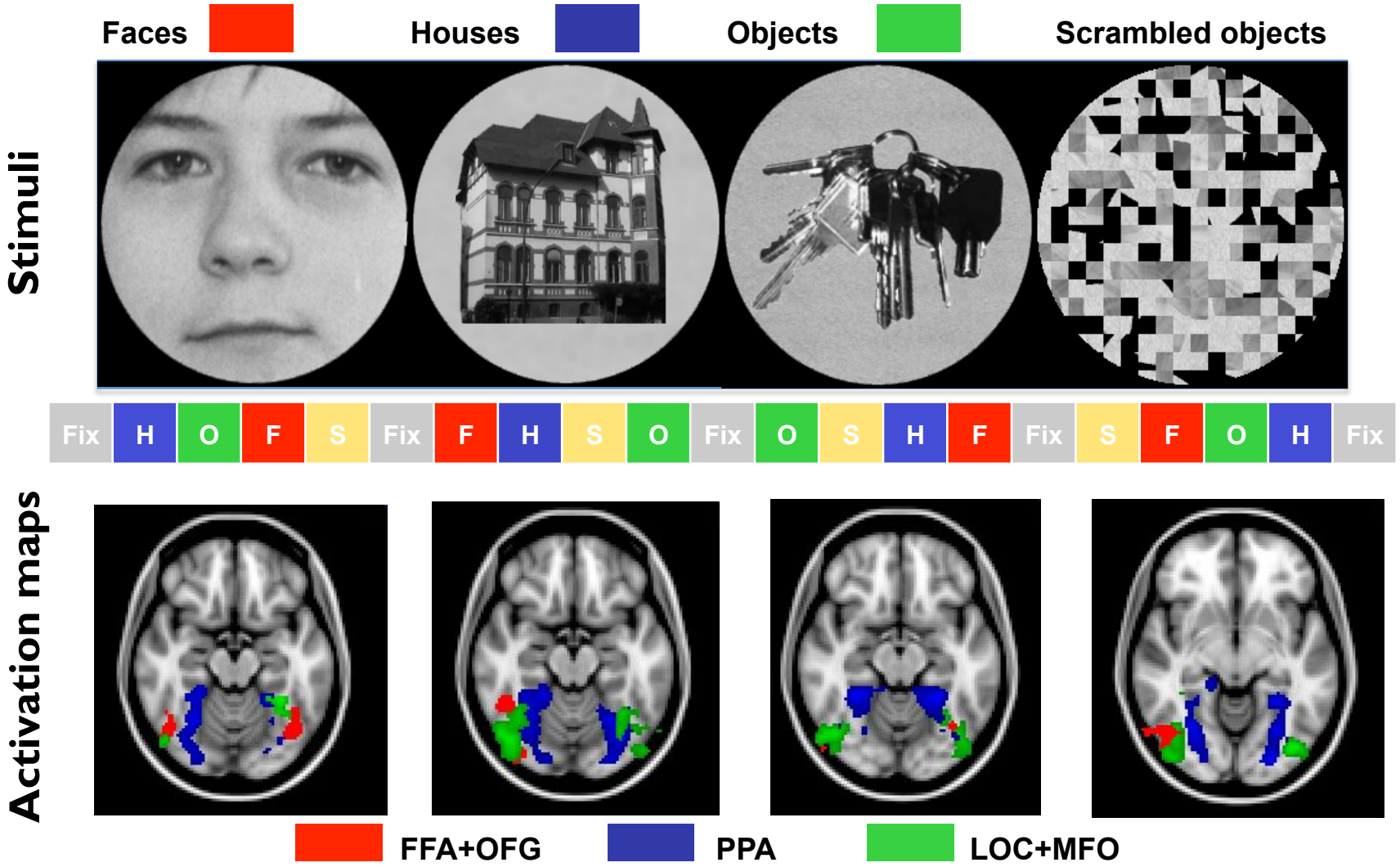
Retinotopic quadrant mapping

Patient IL:



Neural correlates of faces, places and objects

Localizer experiment:

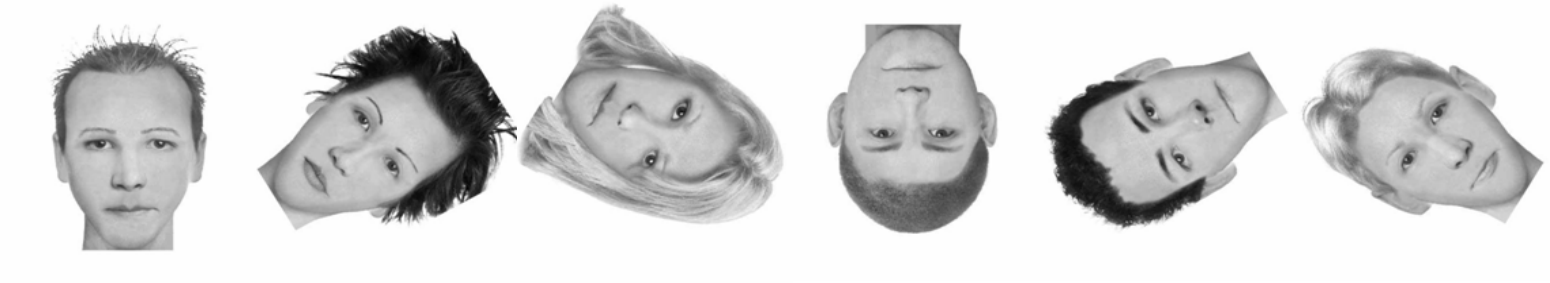


Leite et al., HBM 2010

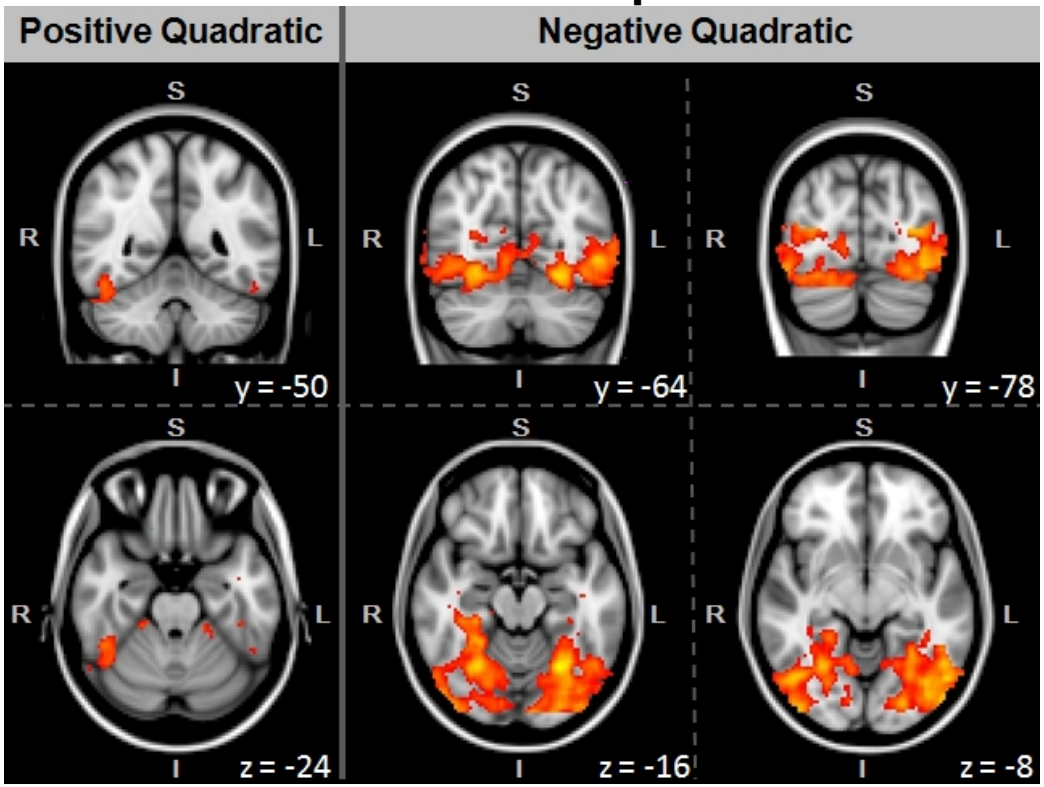
Neural correlates of faces at different orientations

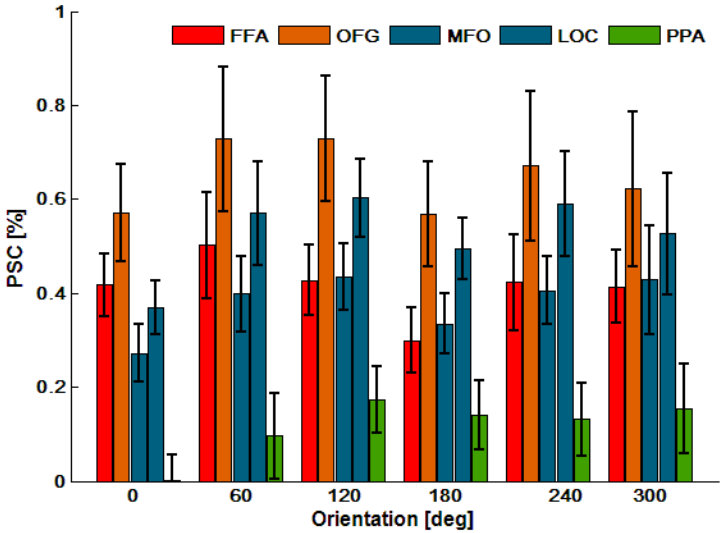
Investigating the effect of face orientation:

Stimuli



Activation maps





Leite et al., HBM 2010

Imaging at ultra-high field (7 Tesla)

fMRI vs MRI: trade-off between time and space

MRI

-structural imaging

-high spatial resolution (~1x1x1mm^3)

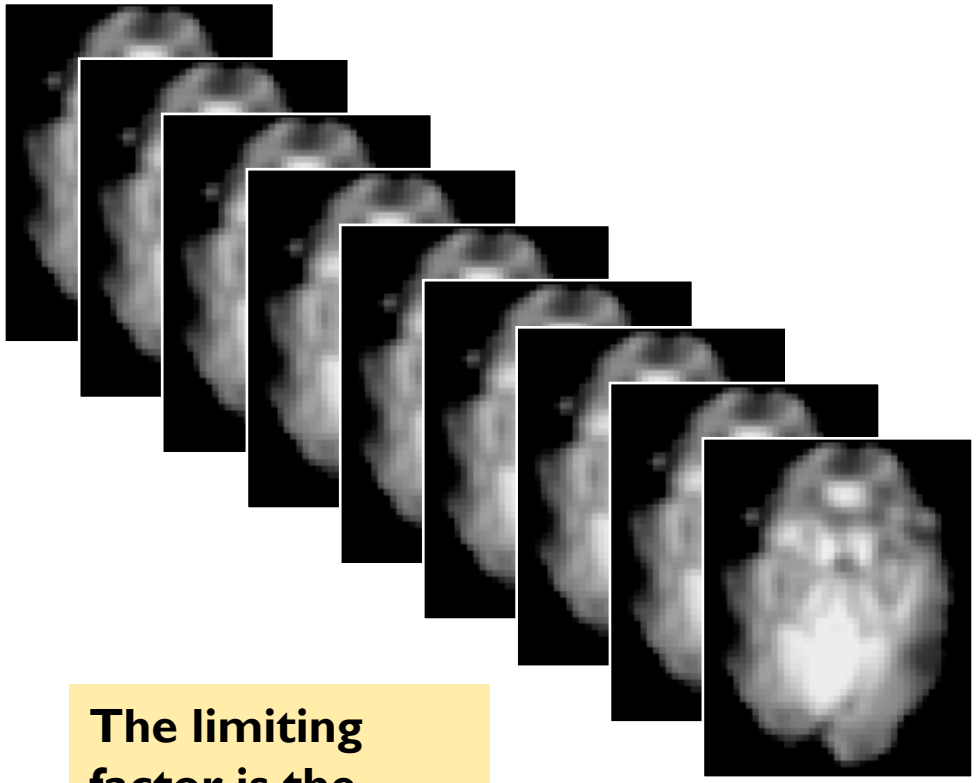
-1 brain volume ~ 5-20 minutes

fMRI

-functional imaging

-low spatial resolution (~3x3x3mm^3)

-1 brain volume ~ 1-3 seconds

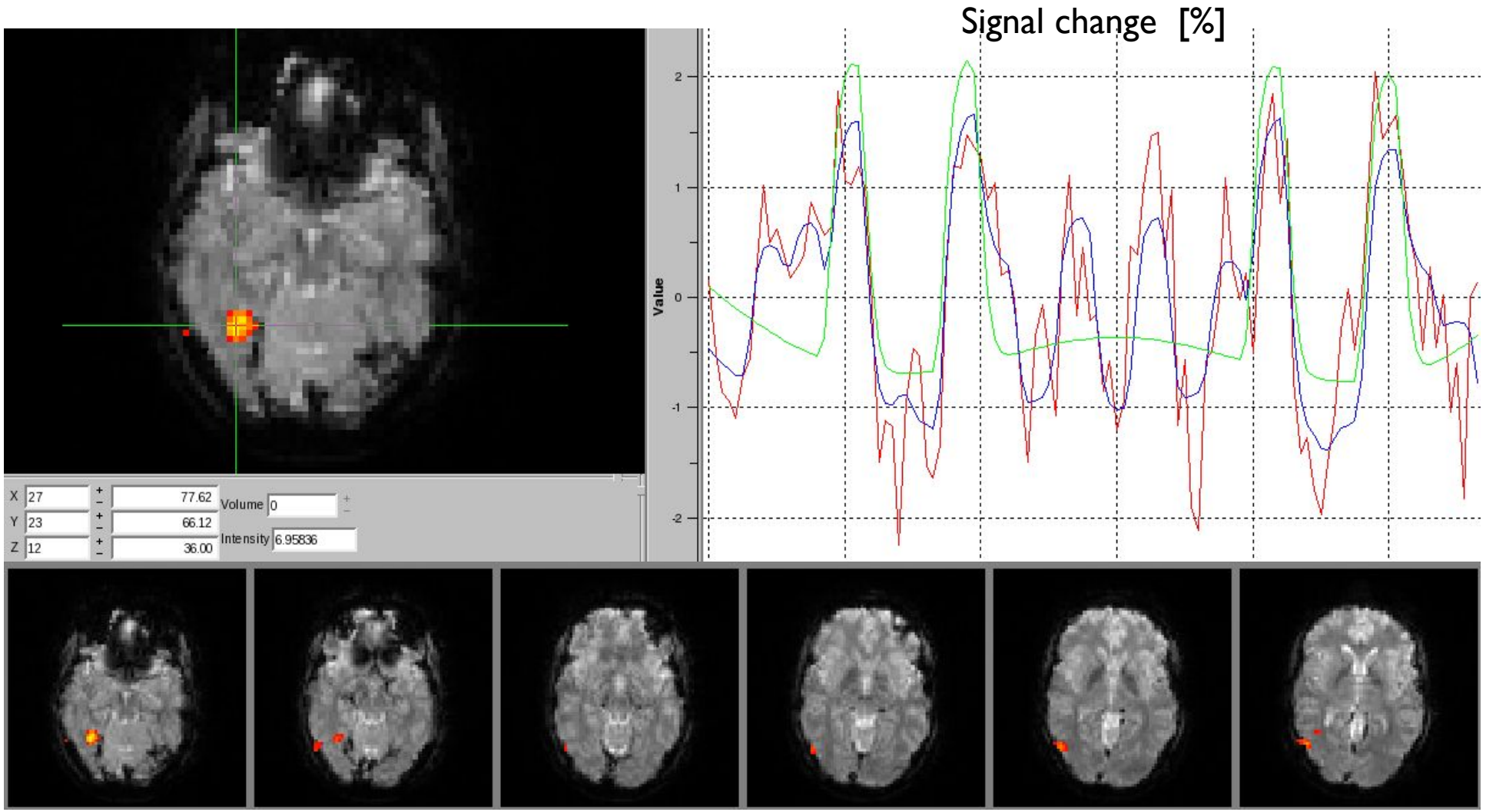


The limiting factor is the SNR…

Going towards higher field strengths: $SNR \propto B_0^f$, f>2

Localizer for face fusiform area (FFA)

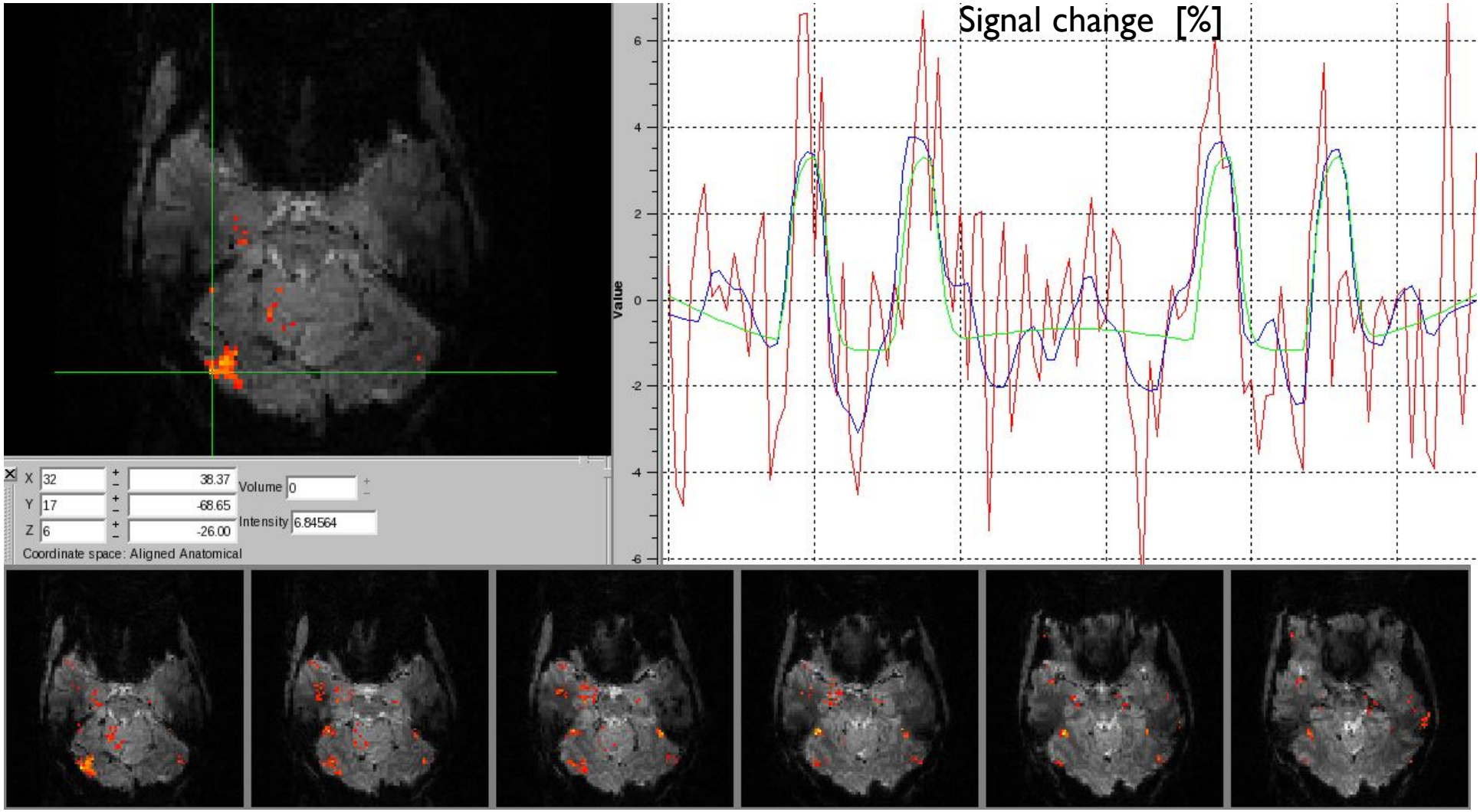
B0 = 3 T: 3 x 3 x 3 mm^3



Going towards higher field strengths: $SNR \propto B_0^f$, f>2

Localizer for face fusiform area (FFA)

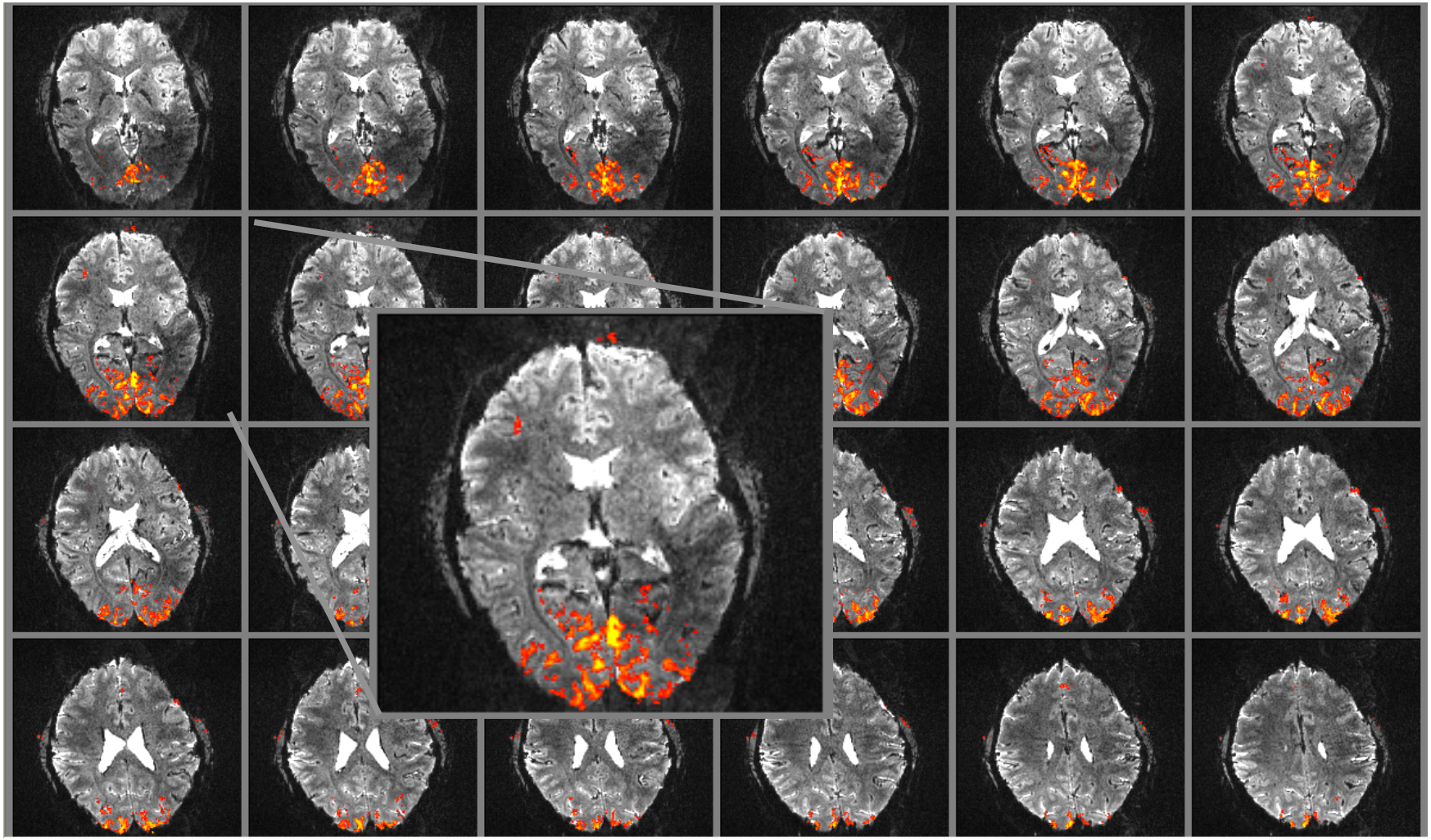
B0 = 7 T: 2 x 2 x 2 mm^3



Going towards higher field strengths: $SNR \propto B_0^f$, $f>2$

Flashing checkerboard stimulation for V1

B_0 = 7 T: 1 x 1 x 1 mm^3 fMRI data set using GRAPPA, TE = 28 ms, speed-up factor 2

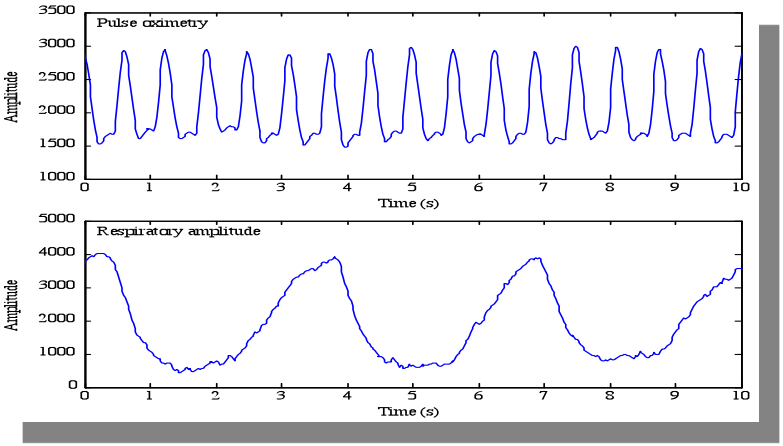


Courtesy of Van der Zwaag, CIBM.

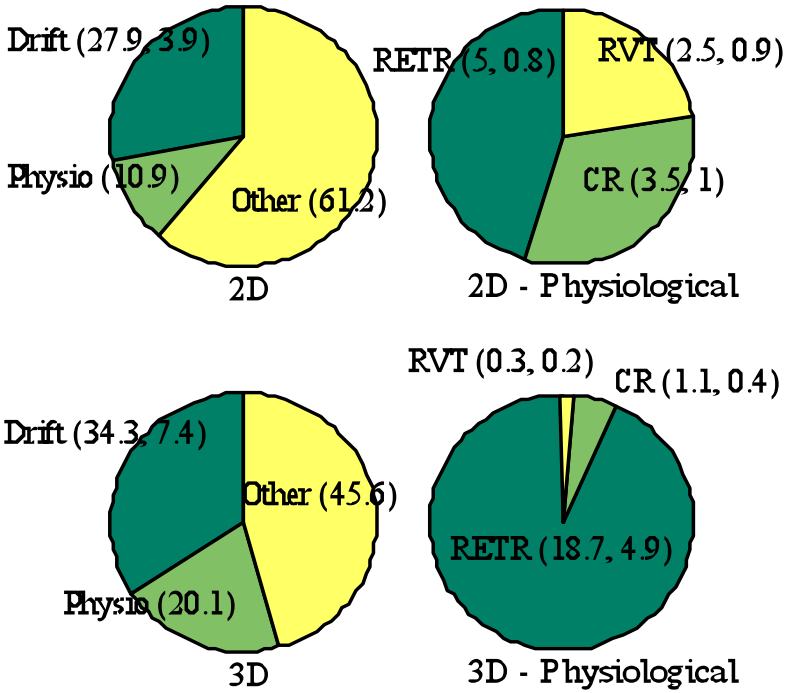
Imaging at ultra-high field (7 Tesla)

Physiological noise contribution and correction, using 2D and 3D acquisitions

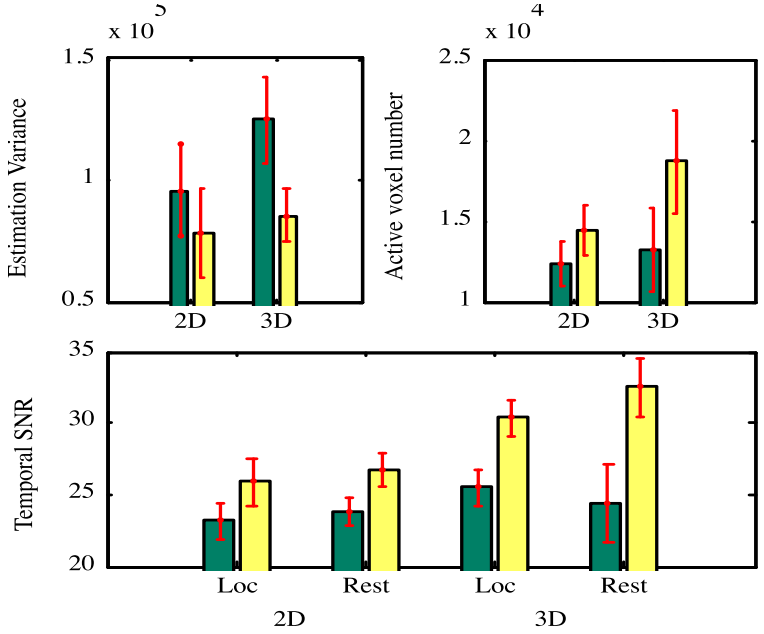
Respiration and HR

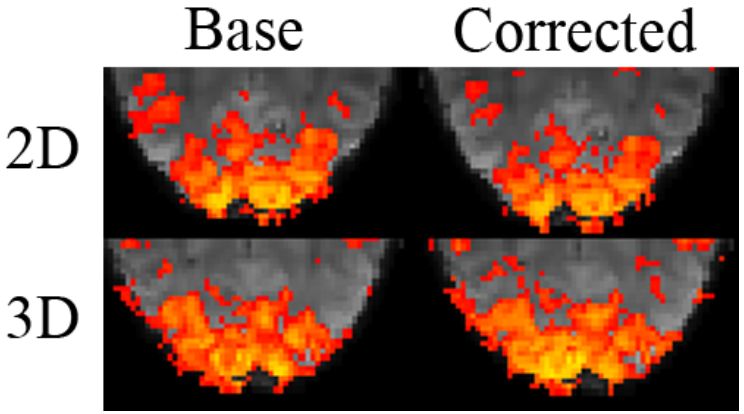


Physiological noise contributions



Physiological noise correction

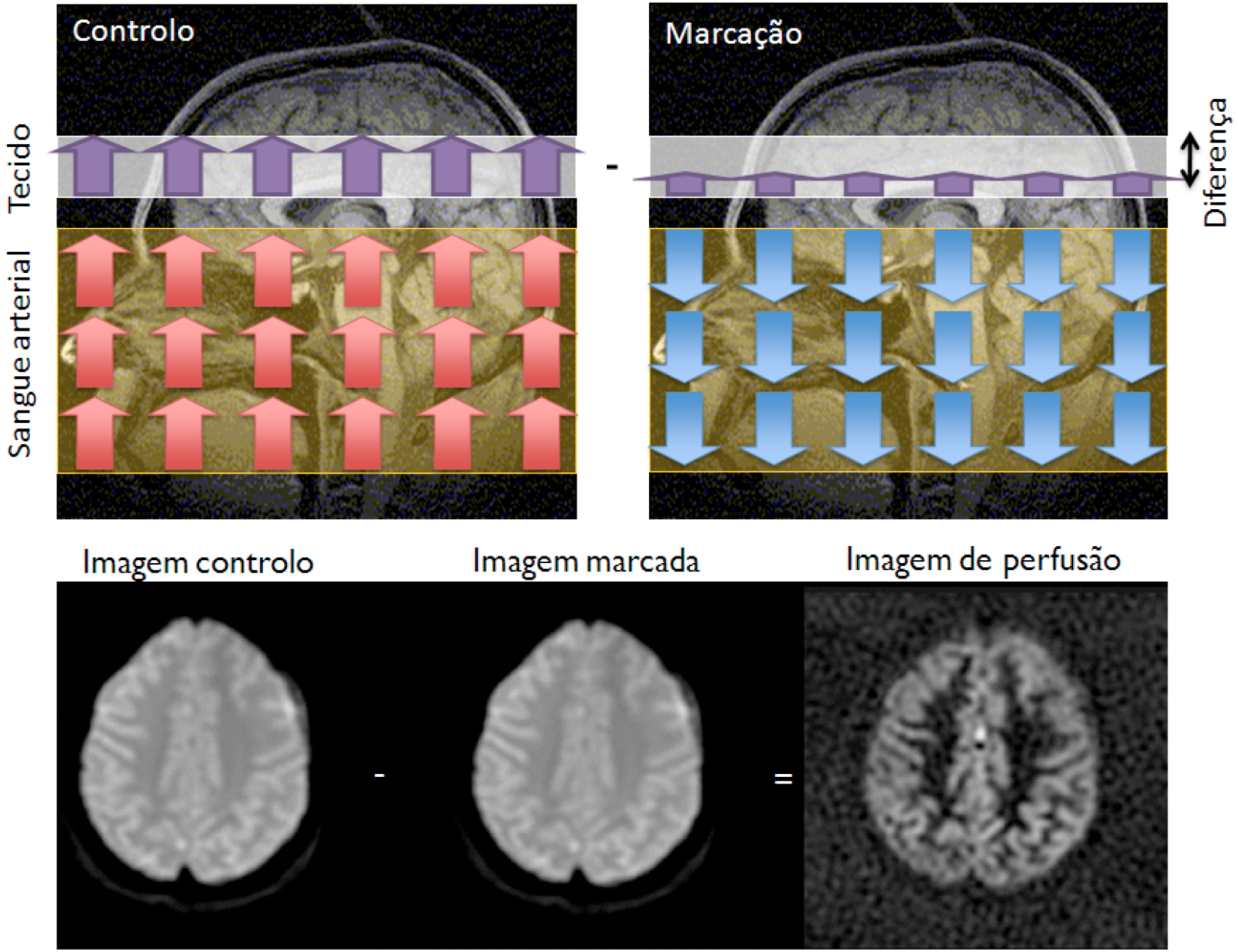




Jorge et al., ISMRM 2011; Jorge et al., HBM 2011

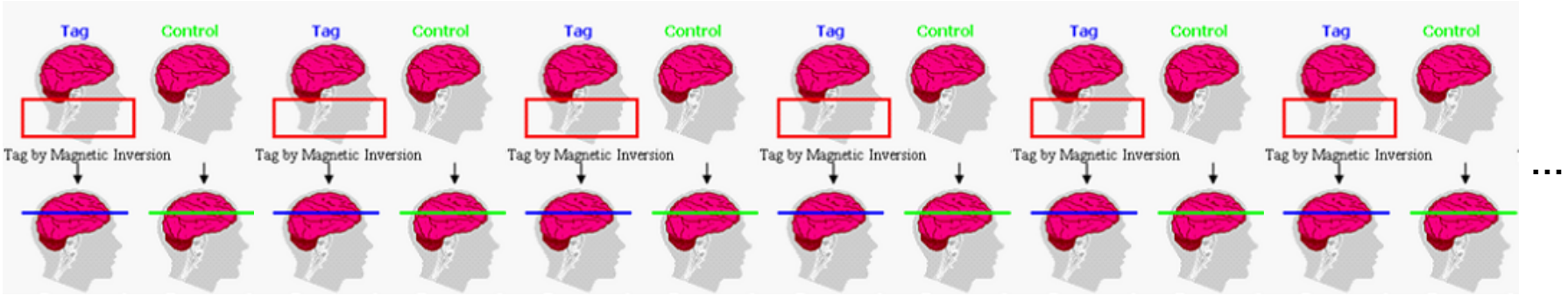
Alternative, quantitative contrast mechanisms (ASL)

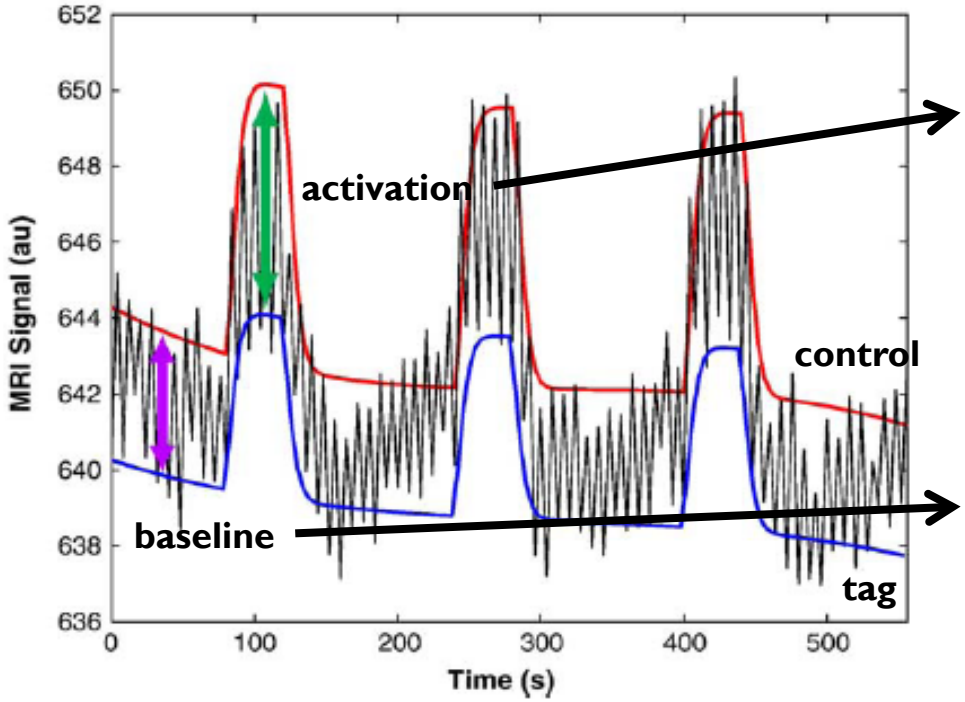
Perfusion imaging: arterial spin labeling (ASL)

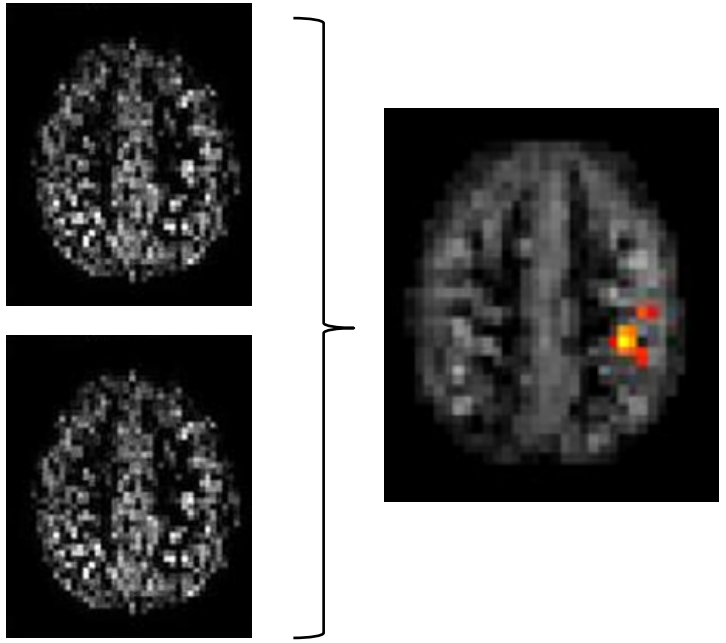


Figueiredo 2010

Simultaneous ASL-BOLD fMRI







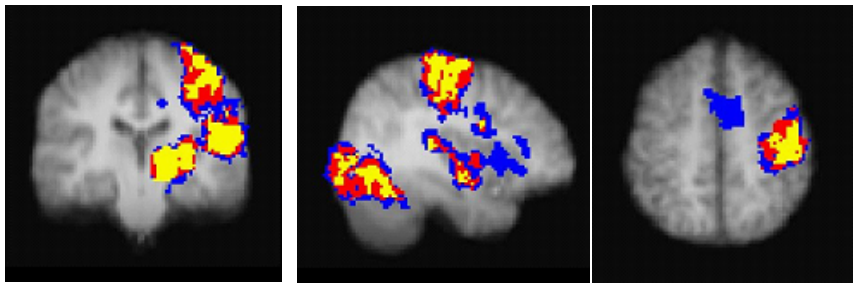
Liu 2007

ASL vs BOLD fMRI

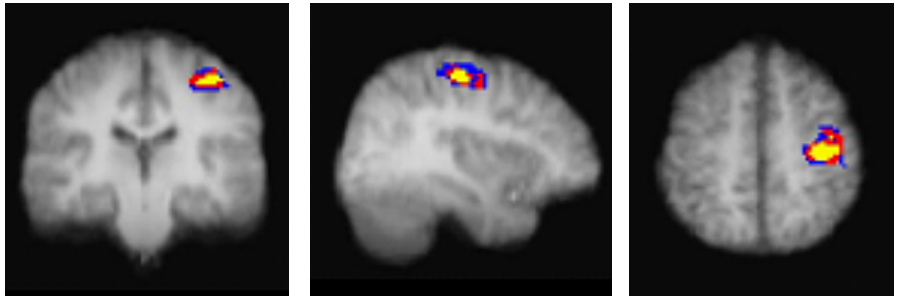
Better reproducibility:

Within-subject

BOLD



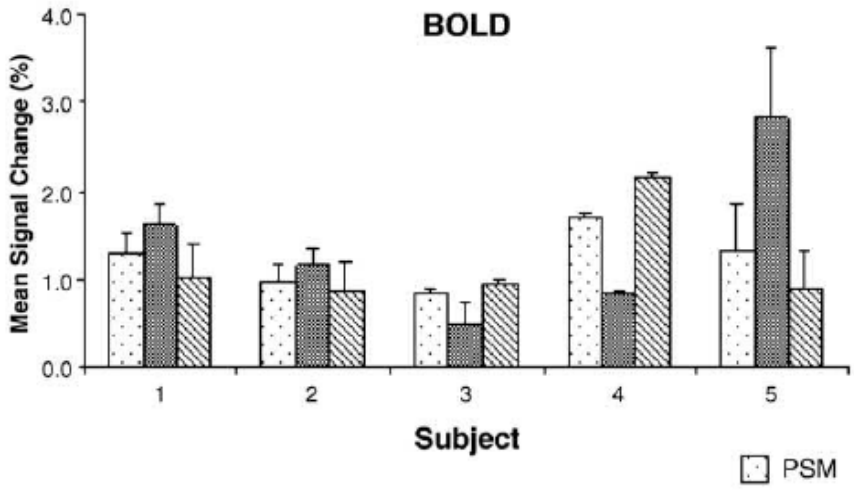
ASL

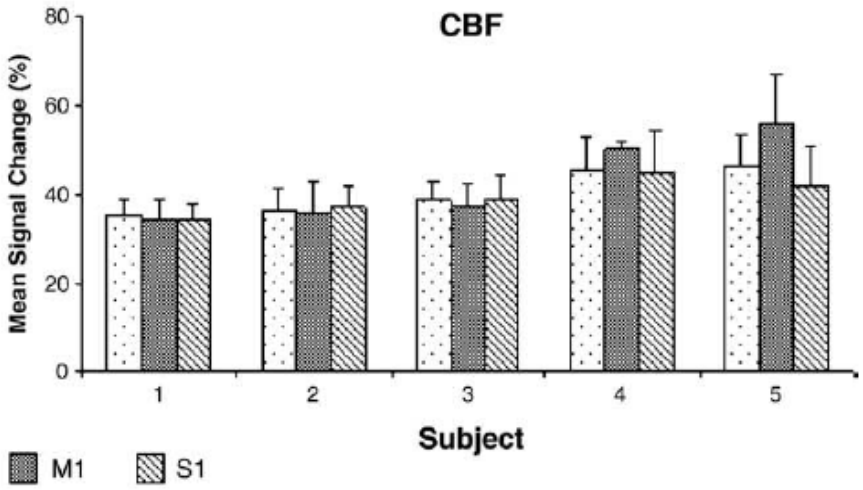


1 session 2 sessions 3 sessions

ASL is more consistent than BOLD across sessions.

Between-subject





PSM M1 S1

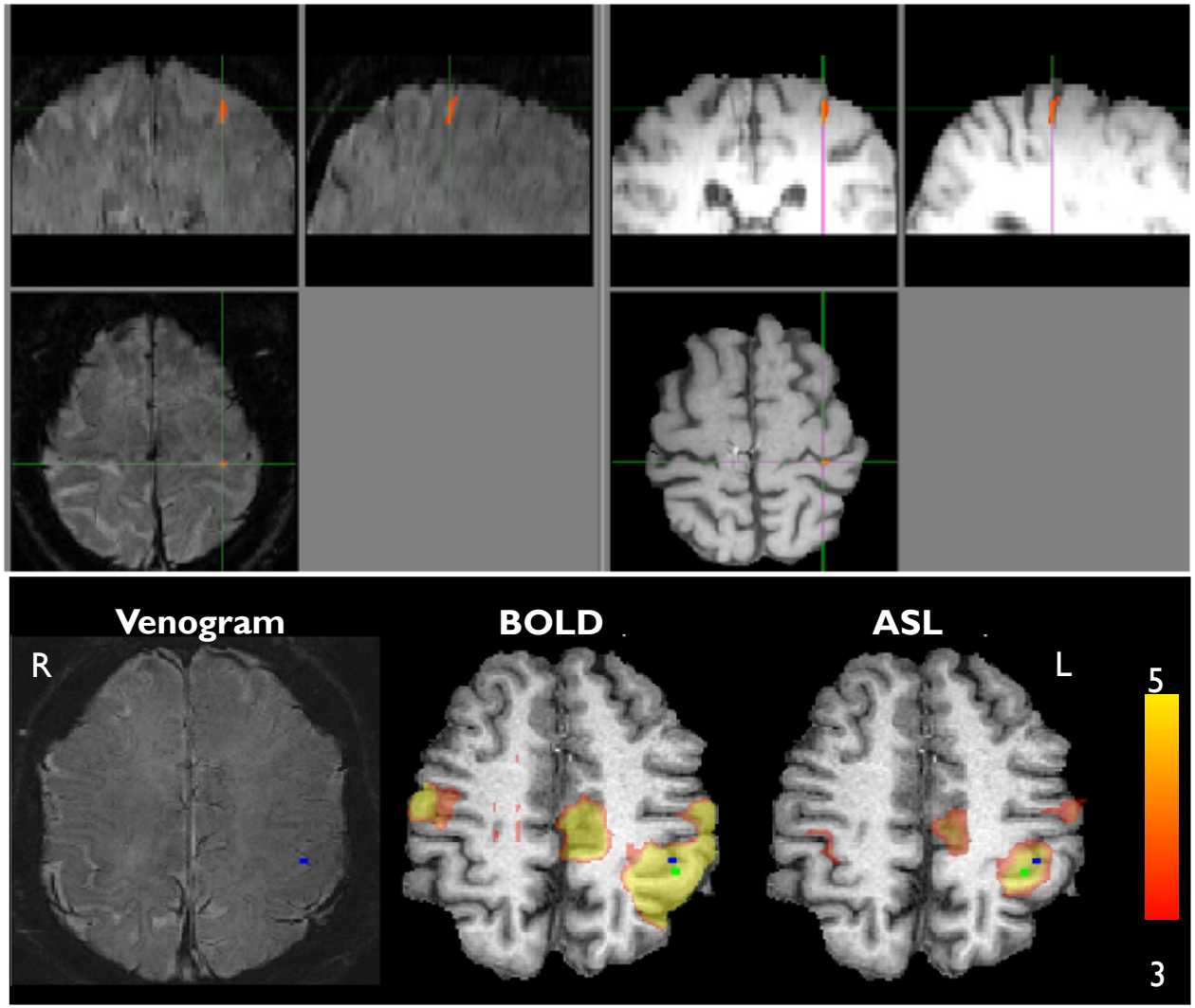
ASL is less variable than BOLD across subjects.

Tjandra et al., Neuroimage 2005

ASL vs BOLD fMRI

Better spatial specificity:

Activity peak of BOLD is closer to the nearest draining venule than that of ASL.

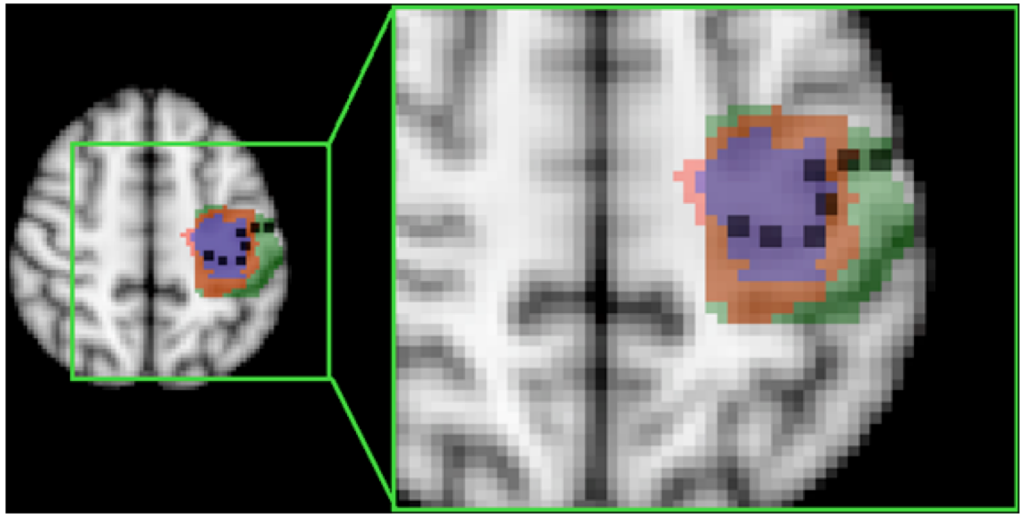


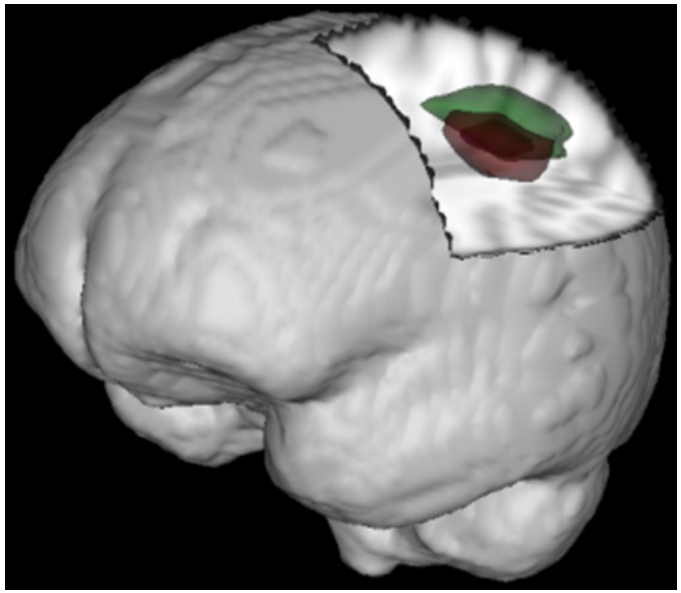
Tjandra et al., Neuroimage 2005

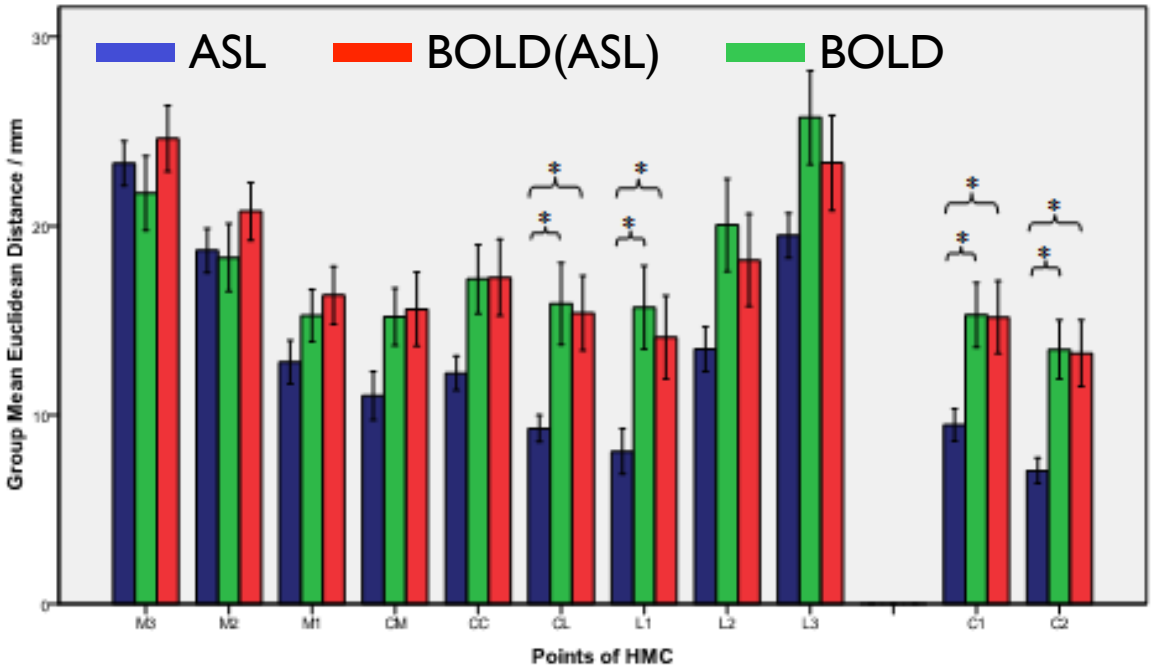
ASL vs BOLD fMRI

Better anatomical specificity:

Localization of the hand motor area obtained using ASL fMRI was less variable and closer to the hand motor cortex anatomical landmarks than the one produced by both simultaneous BOLD-ASL fMRI and standard BOLD fMRI.







Pimentel et al., ISMRM 2010.

Quantitative ASL

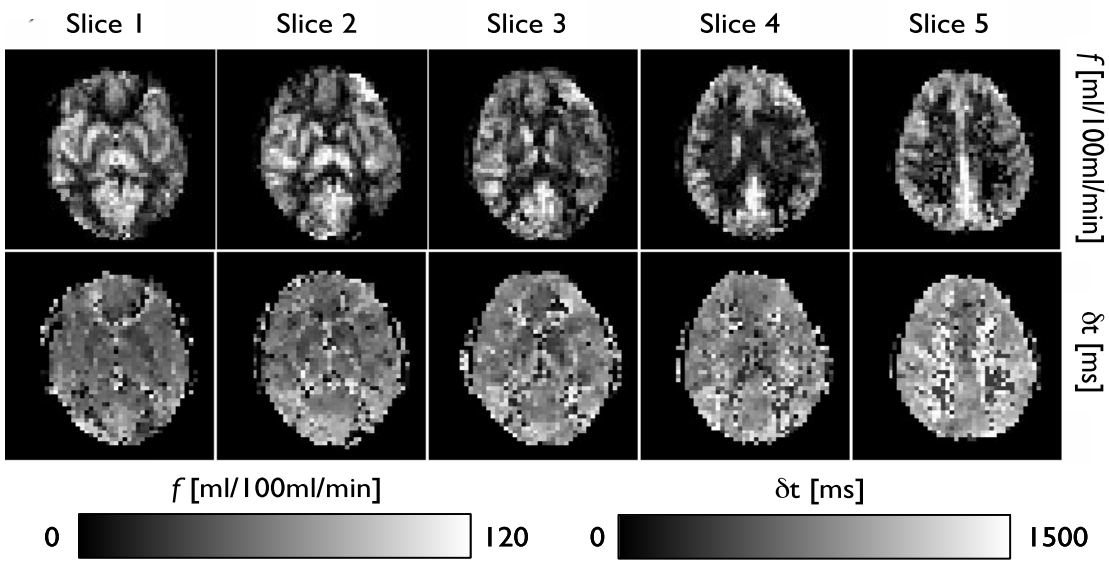
Perfusion (and arterial transit time) quantification:

Pixel-by-pixel quantification

based on multiple inversion time acquisitions and kinetic modeling and estimation

Figueiredo et al., JMRI 2005

Santos et al., EMBC 2010

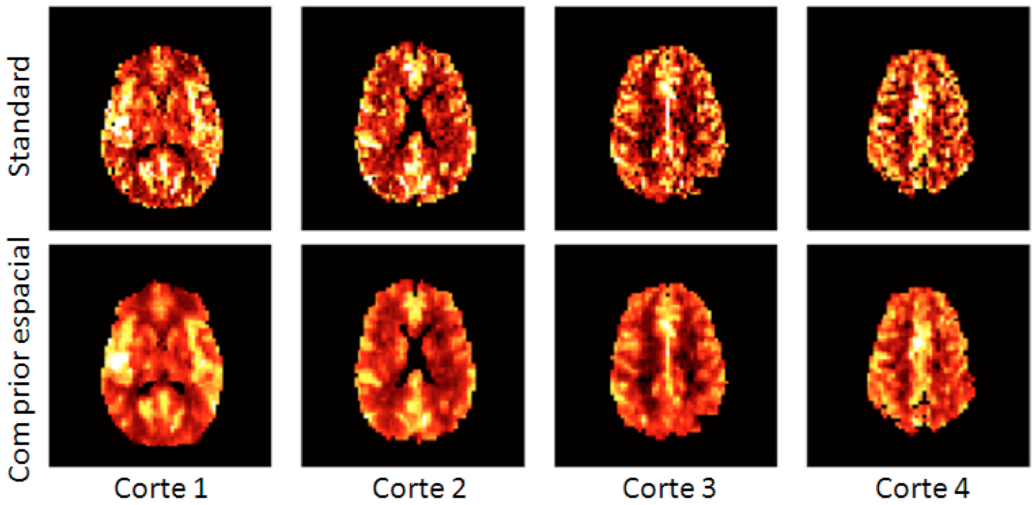


Bayesian estimation methods

incorporating spatial a priori information

Santos et al., ISBI 2011

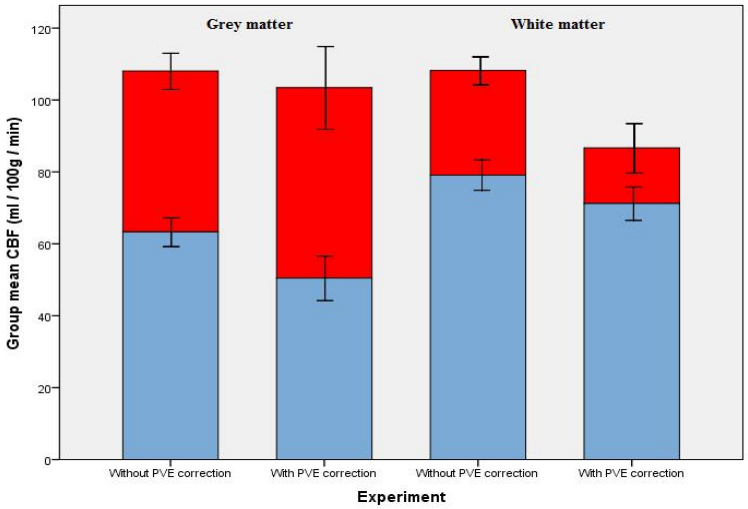
Santos et al., ISMRM 2011

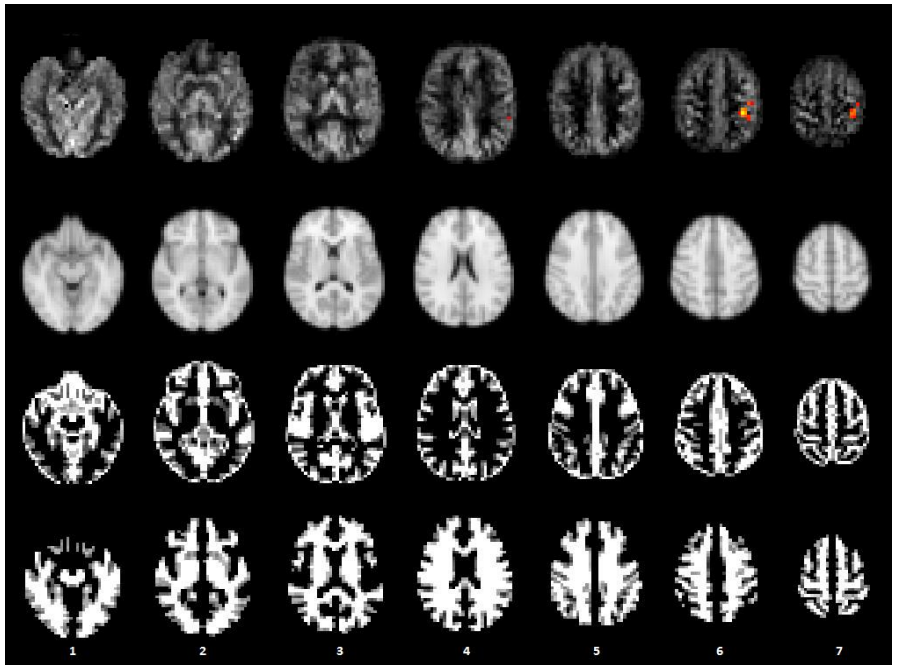


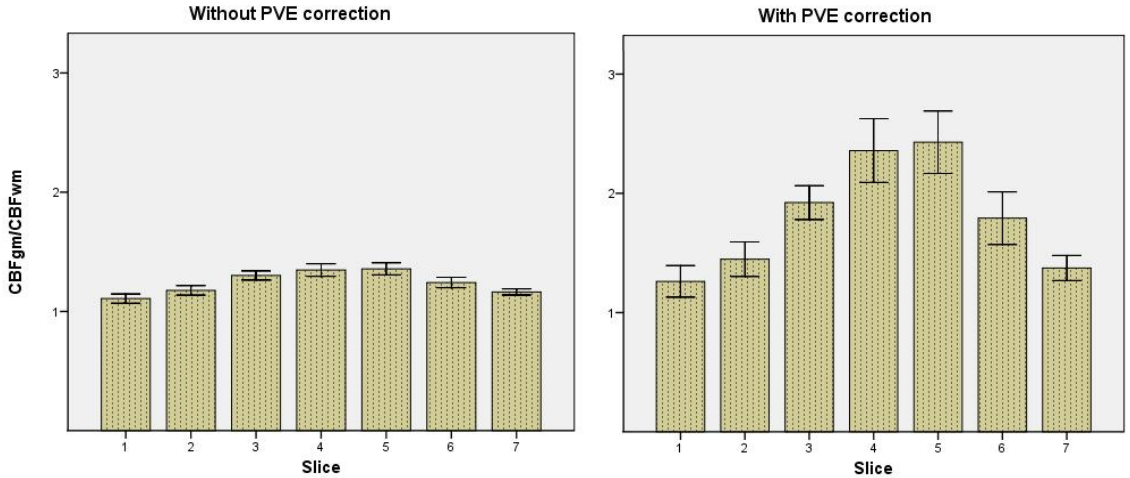
Quantitative ASL

Perfusion change quantification:

Partial volume correction







Pimentel et al., ISMRM 2010

ASL advantages and disadvantages

ASL vs BOLD fMRI:

+ potentially quantitative

+ more direct relationship with haemodynamic response

+ better spatial specificity

+ better reproducibility

- very low SNR

- lower temporal resolution…

- limited brain coverage…

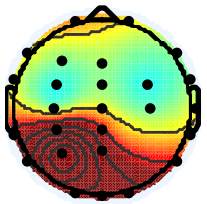
Multimodal imaging in epilepsy (EEG-fMRI)

EEG-fMRI integration in epileptic seizures

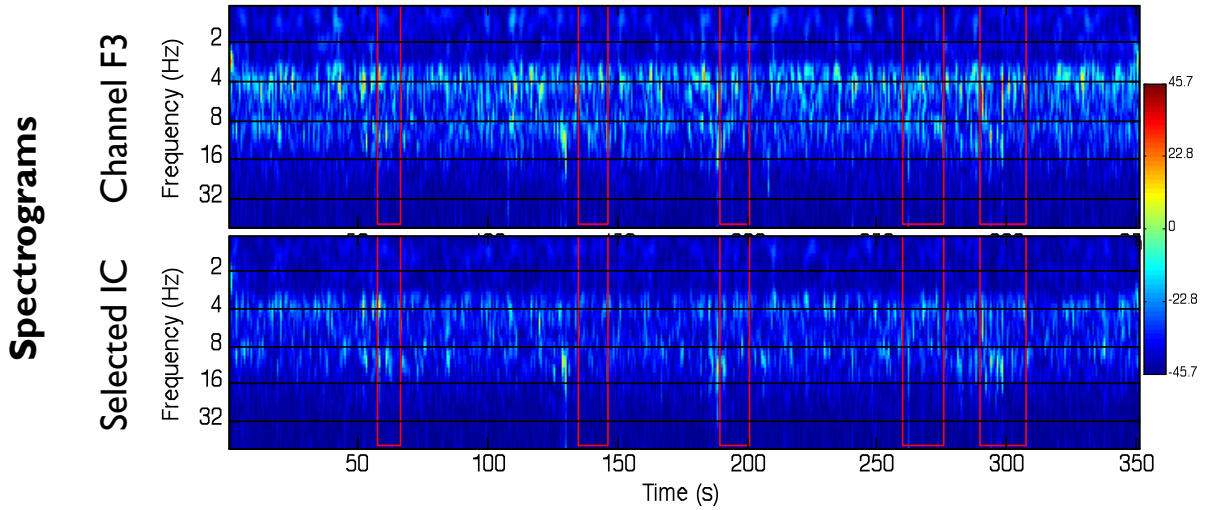
EEG to fMRI transfer function:

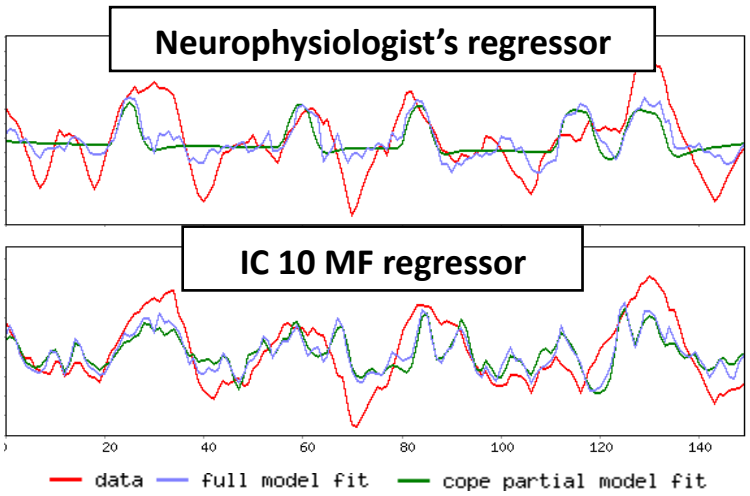
ICA decomposition of EEG data

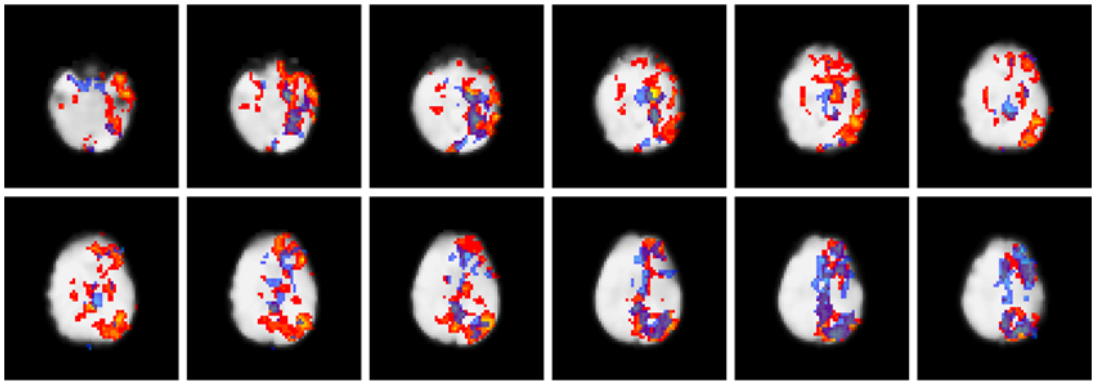
Selected IC topography:

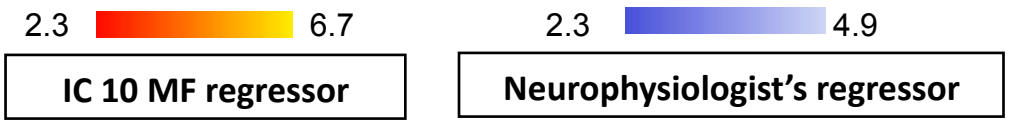


Mean frequency: $r_{MF}(t) = r_{uMF}(t) / r_{TP}(t)$









Leite et al., HBM 2011

Dynamic imaging of epileptic seizures

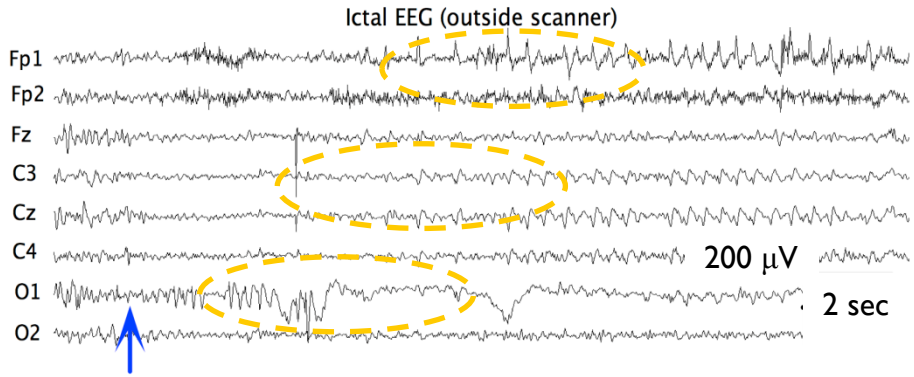
Case study:

2-year-old male patient

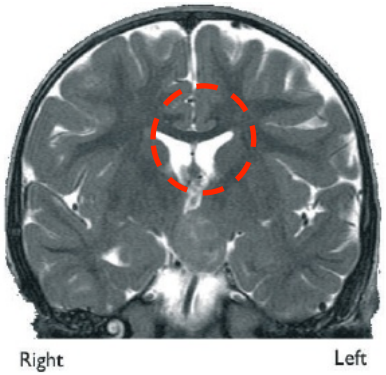
medically intractable gelastic epilepsy associated with a HH

formal indication for epilepsy surgery (through disconnection approach)

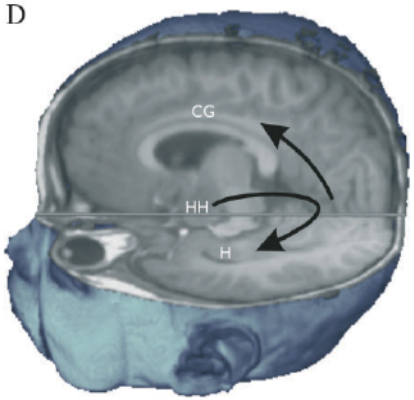
EEG of typical seizure:



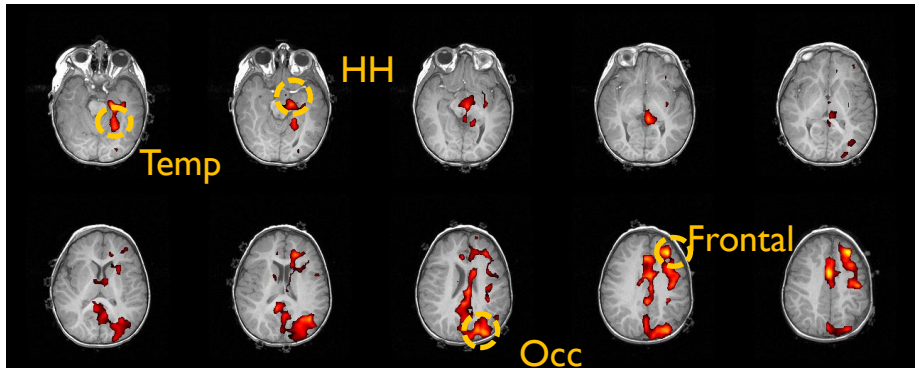
T_2-w image of HH:



Possible seizure propagation pathway:



fMRI activation map during seizures:



Leal et al., Epilepsia 2009

Dynamic imaging of epileptic seizures

Investigation of seizure propagation by Dynamic Causal Modelling (DCM):

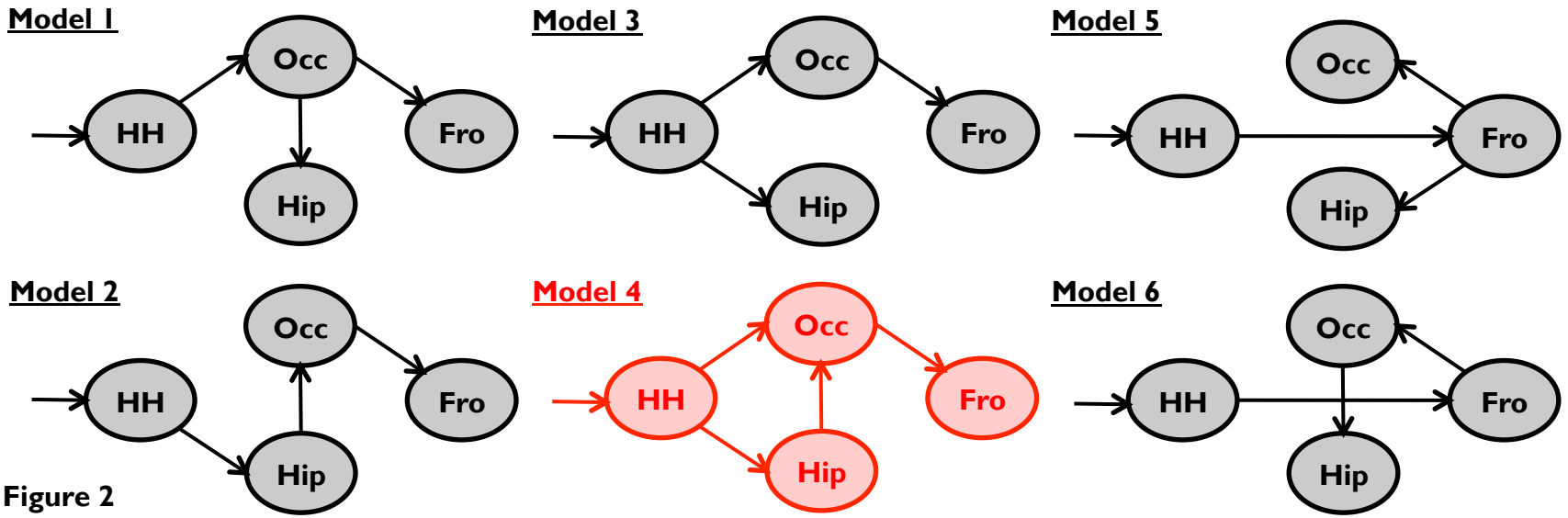


Figure 2

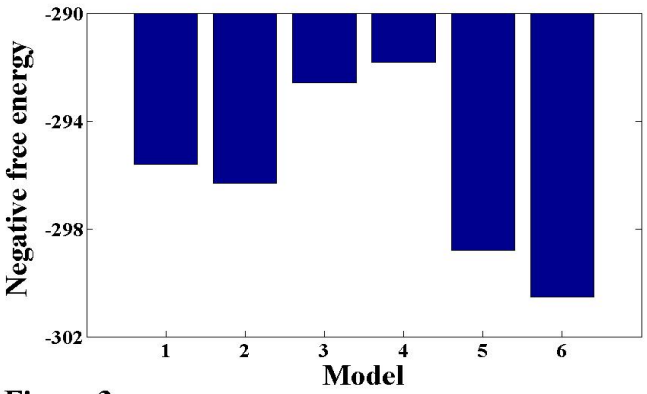
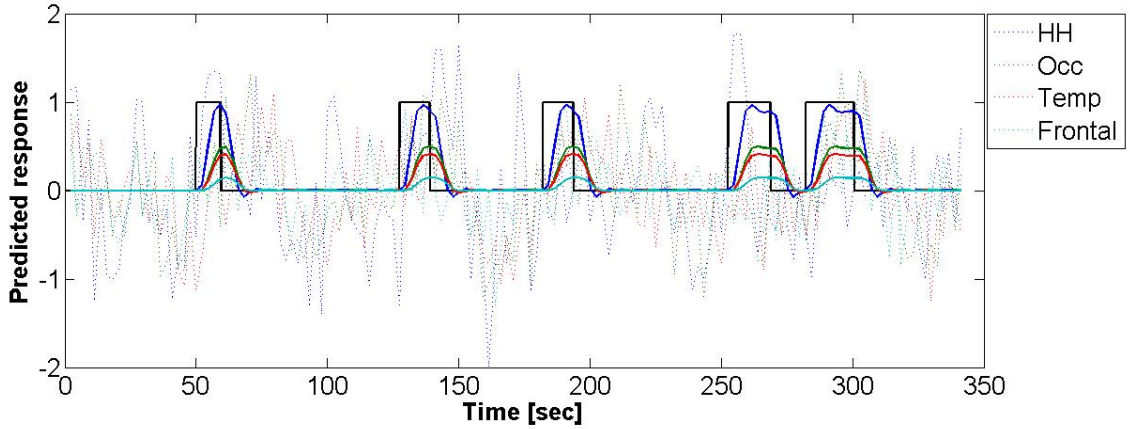


Figure 3



Figueiredo et al., ISMRM 2010

Conclusion

Conclusion

We can map brain activity non-invasively with:

- spatial resolution ~2x2x2 mm3
- temporal resolution ~1-3 sec

We need more sensitive, reproducible, quantitative and dynamic measures:

- Stronger magnetic fields…
- Alternative contrast mechanisms: perfusion…
- Multi-modal imaging approaches…

We need alternative / complementary analysis approaches:

- Data-driven analysis:

- PCA, ICA, …

- Connectivity analysis:

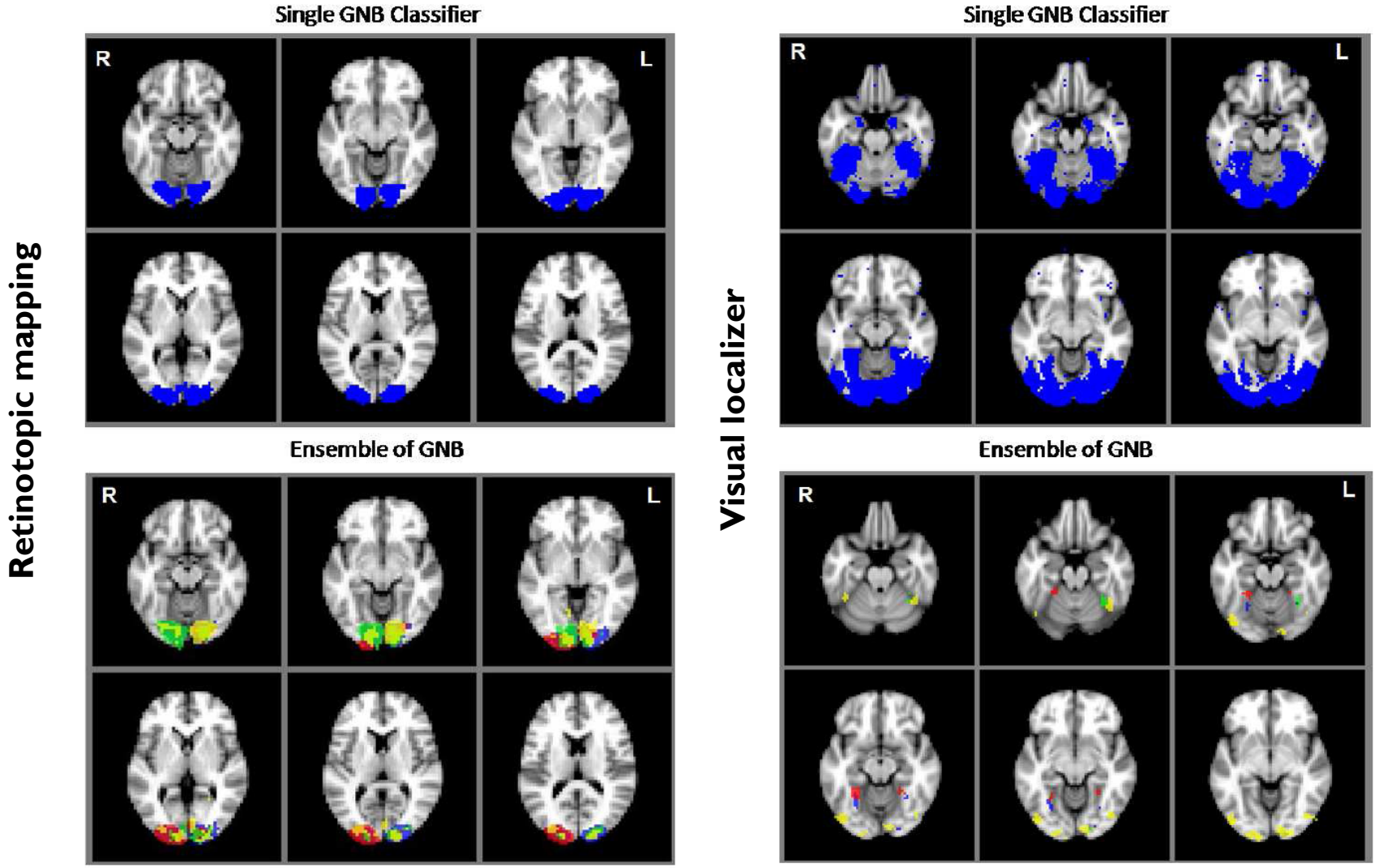
- Structural connectivity: e.g., DTI
- Functional connectivity: e.g., ICA
- Effective connectivity: e.g., DCM

- Multi-variate analysis:

- machine learning methods (e.g., SVMs), …

Brain decoding by machine learning

Decoding visual stimuli using ensembles of classifiers:



Cabral et al., ISBI 2011.

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