Seventeen Years of Functional MRI

Peter A. Bandettini, Ph.D.

Section on Functional Imaging Methods

Laboratory of Brain and Cognition

http://fim.nimh.nih.gov

&

Functional MRI Facility

http://fmrif.nimh.nih.gov

1. A bit of history of MRI and functional MRI

2. Basics of functional MRI contrast and methods

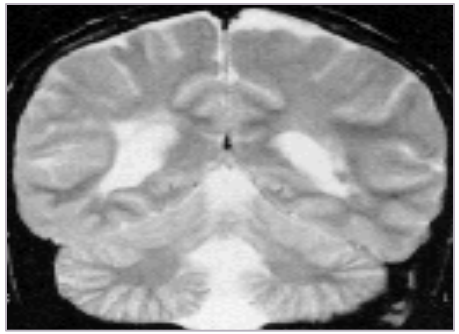
3. Basic and cutting edge applications

Magnetic Resonance Imaging

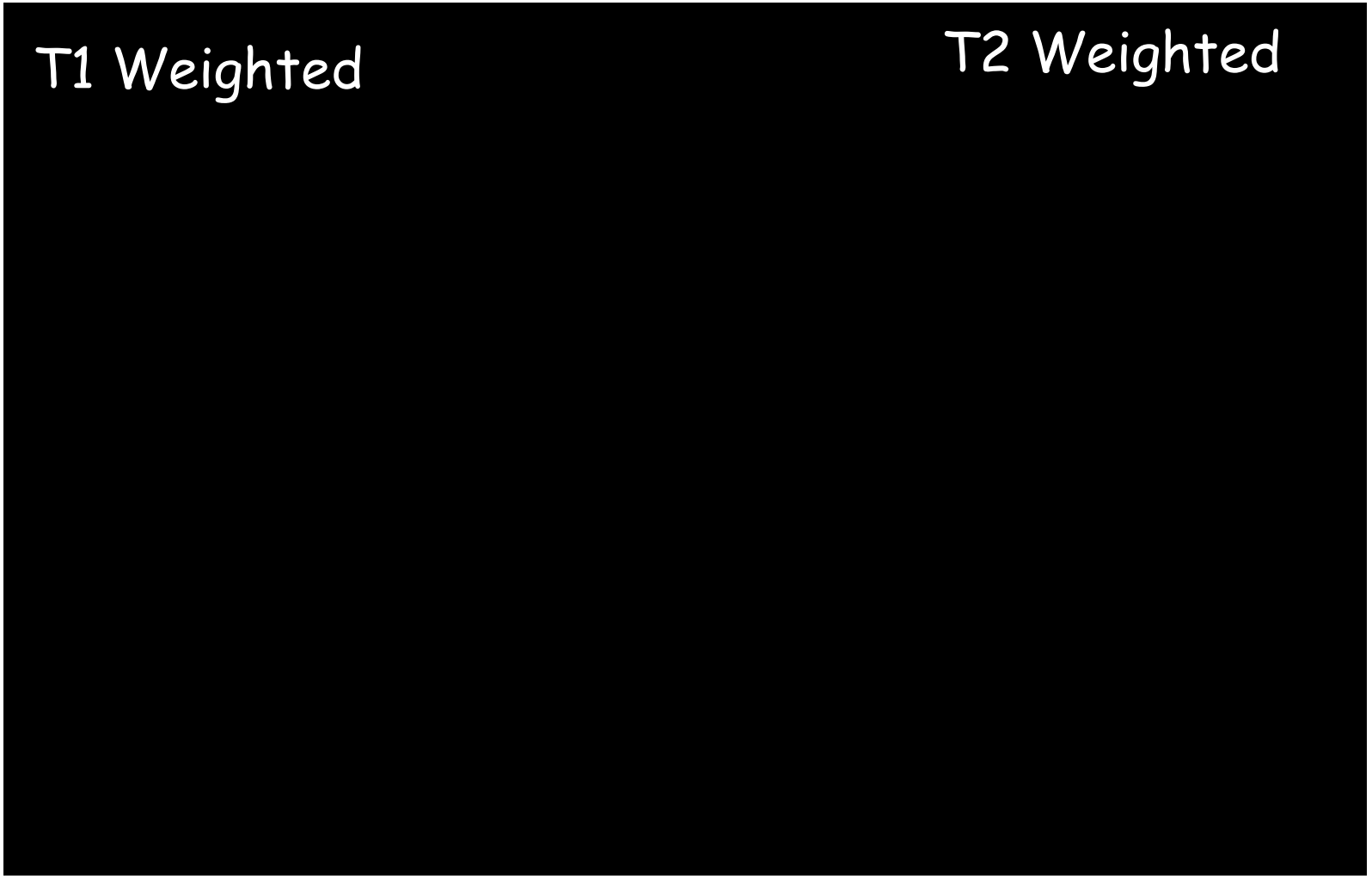
1984

Water: 42 MHz/Tesla

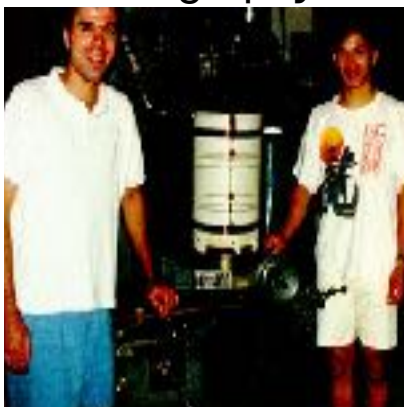
1.5 Tesla = 63 MHz
3 Tesla = 126 MHz
7 Tesla = 294 MHz



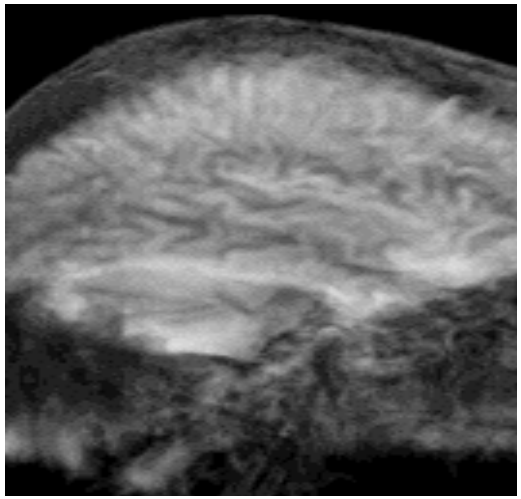
MRI Images with Different Contrast Weighting

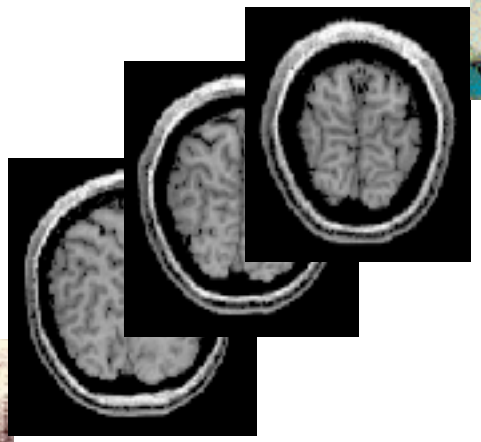


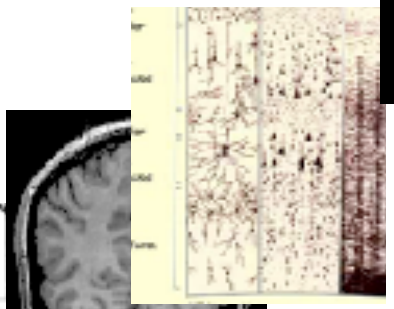
Venography

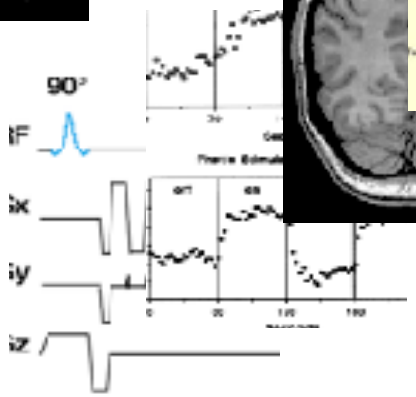


Fiber Track Imaging









Anatomy

Angiography

Perfusion

1. A bit of history of MRI and functional MRI

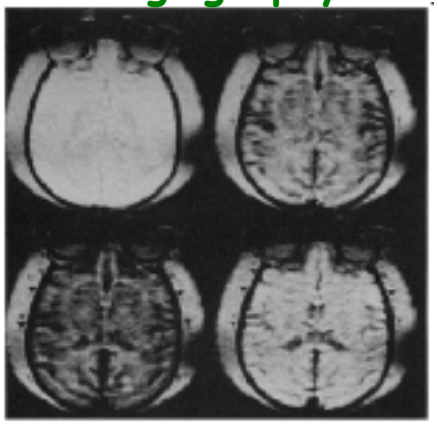
2. Basics of functional MRI contrast and methods

3. Basic and cutting edge applications

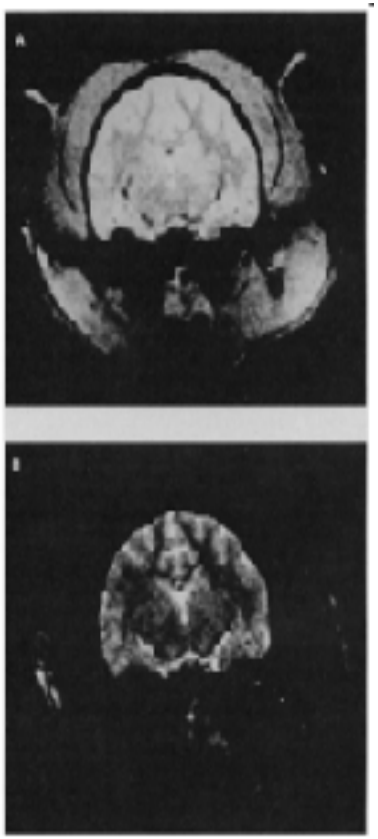
metabolic imaging (NAA)

(1990) Science, 250, 53-61.

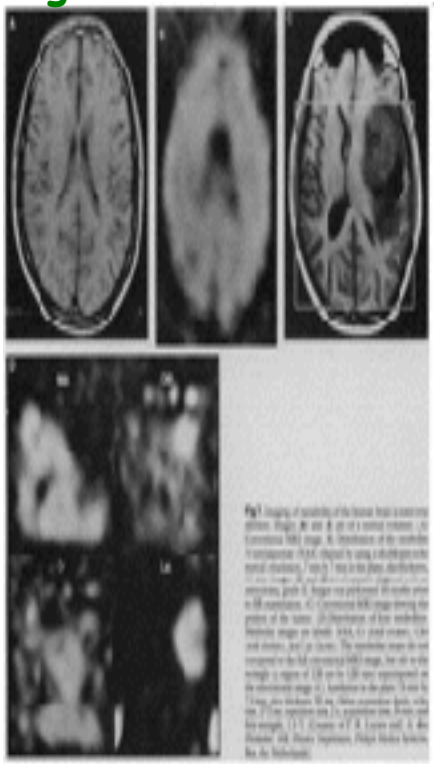
angiography



Diffusion



magnetization transfer



Gadolinium perfusion

NAA choline

creatine lactate

Magnetic Properties of Blood

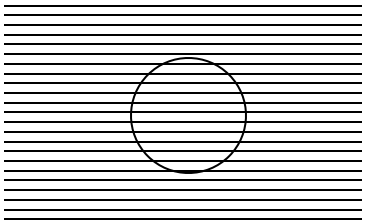
L. Pauling, C. D. Coryell, Proc.Natl. Acad. Sci. USA 22, 210-216, **1936**.

K.R. Thulborn, J. C. Waterton, et al., Biochim. Biophys. Acta. 714: 265-270, **1982**.

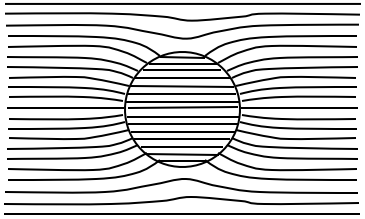
S. Ogawa, T. M. Lee, A. R. Kay, D. W. Tank, Proc. Natl. Acad. Sci. USA 87, 9868-9872, **1990**.

Turner, R., Lebihan, D., Moonen, C. T. W., Despres, D. & Frank, J. Magnetic Resonance in Medicine, 22, 159-166, **1991**.

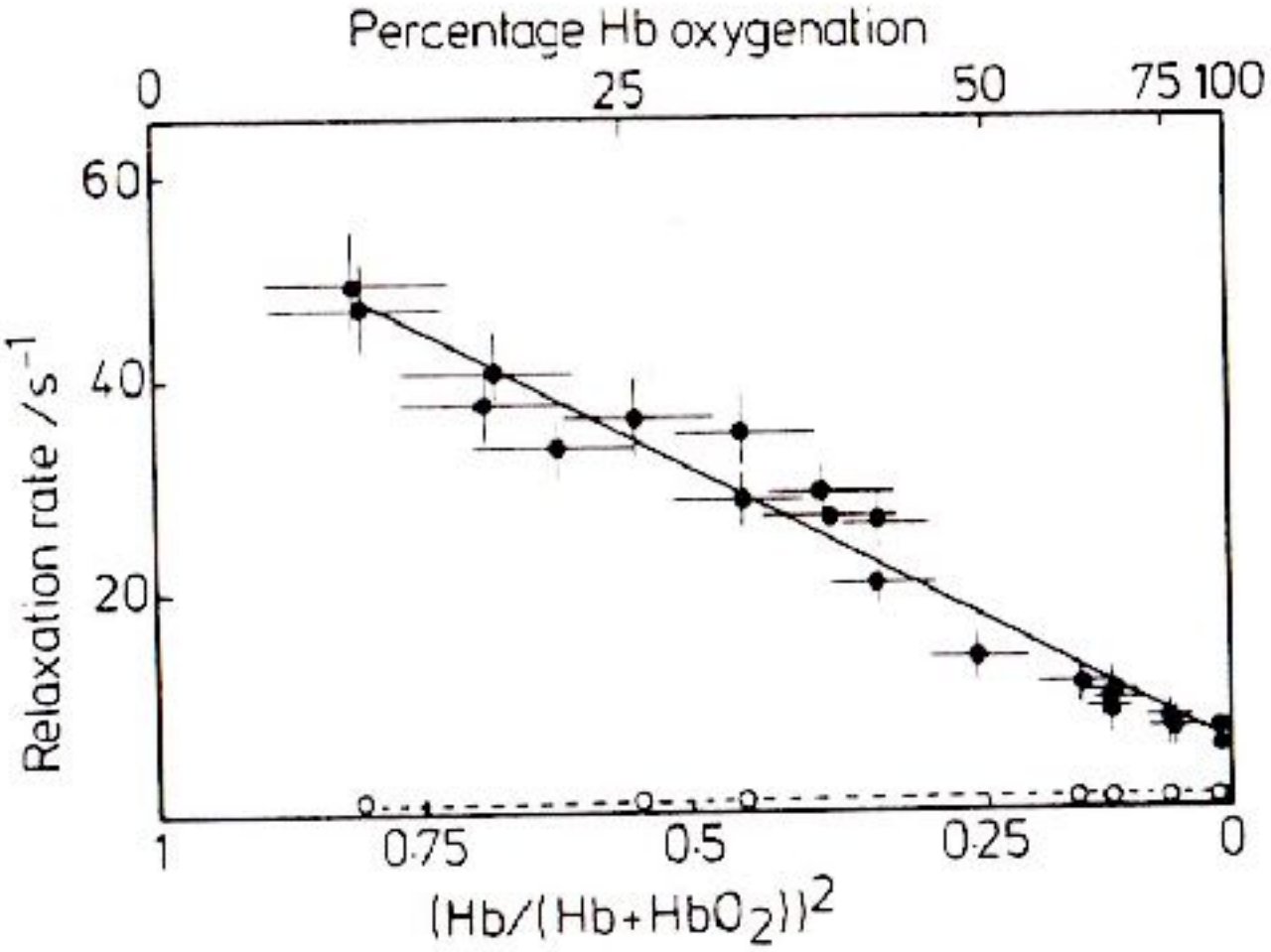
oxygenated



deoxygenated



red blood cells



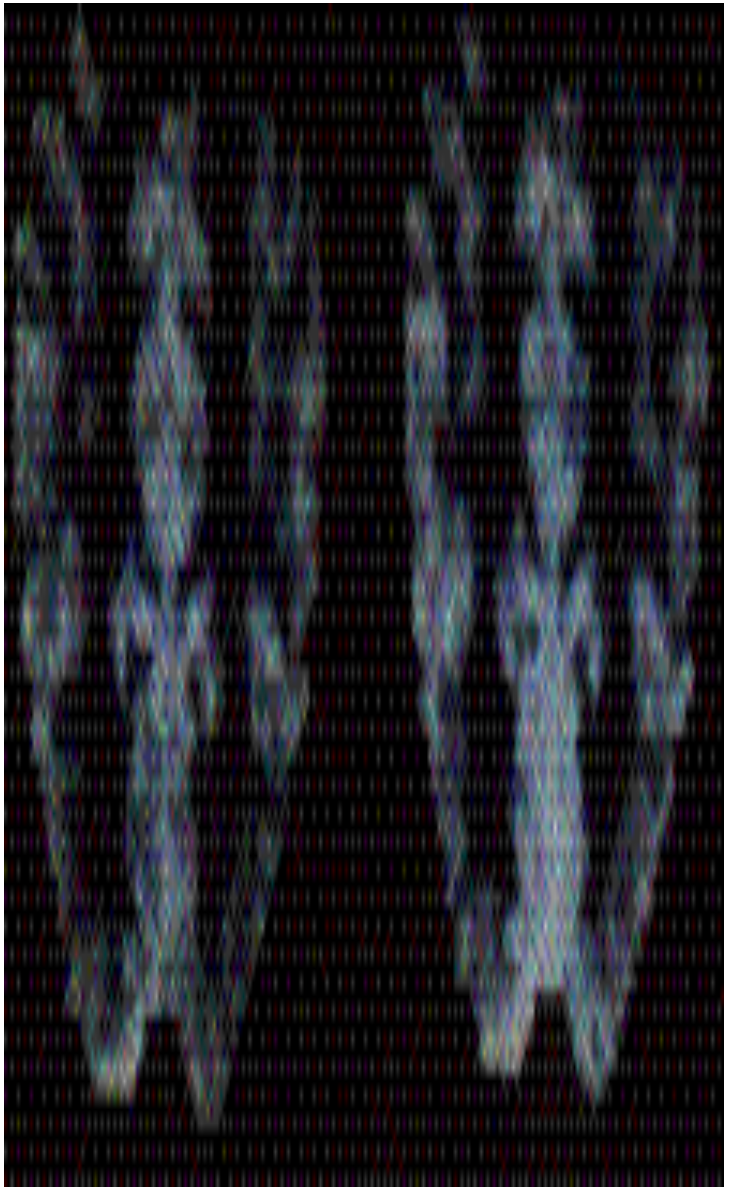
K. R. Thulborn, J. C. Waterton, P. M. Matthews, G. K. Radda, Biochimica et Biophysica Acta, 714, 265-270, 1982

in vivo

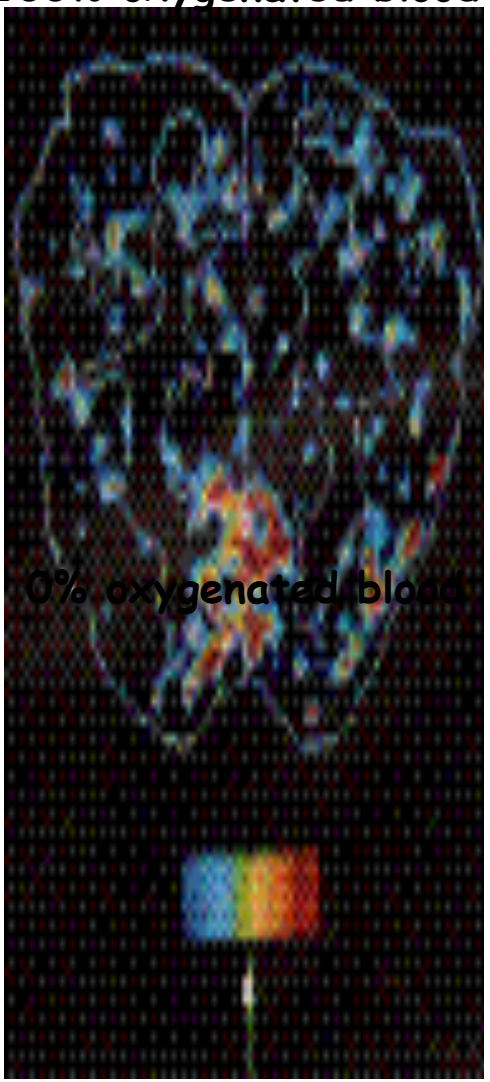
in vitro

100% O_2

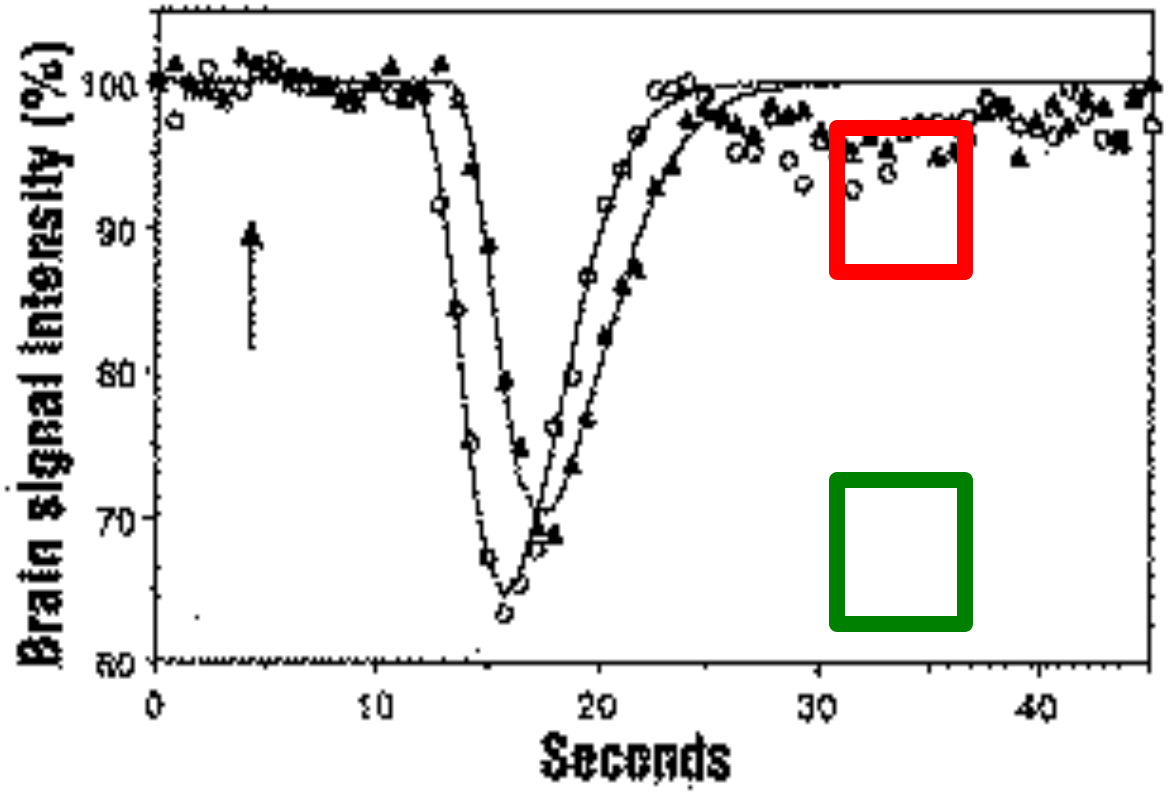
20% O_2

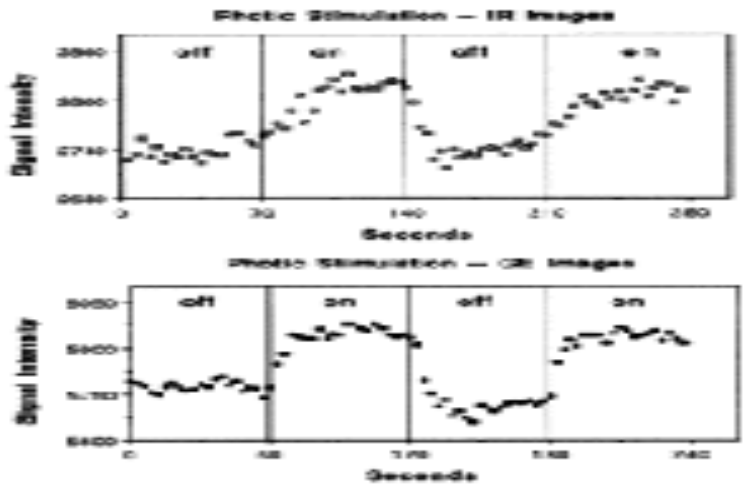


100% oxygenated blood



S. Ogawa, T.-M. Lee, A. S. Nayak, P. Glynn, Magn. Reson. Med, 14, 68-78 (1990)





R. Turner, D. LeBihan, C.T.W. Moonen, D. Despres, J. Frank, Magn. Reson. Med, 22, 159-166 (1991)

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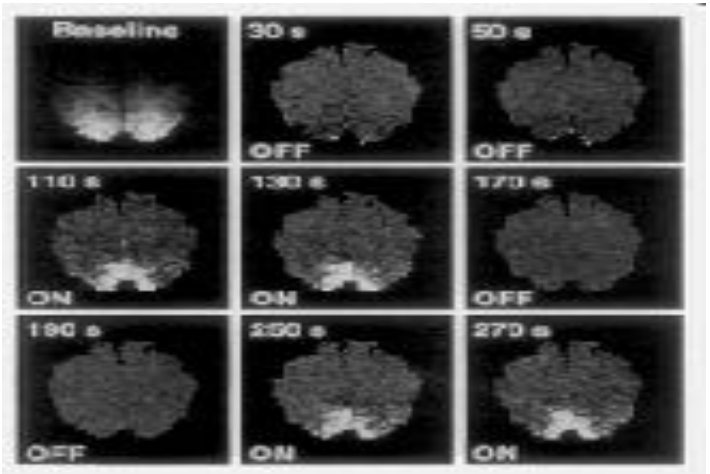
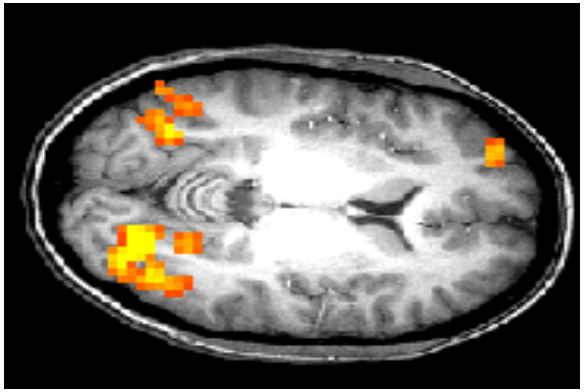
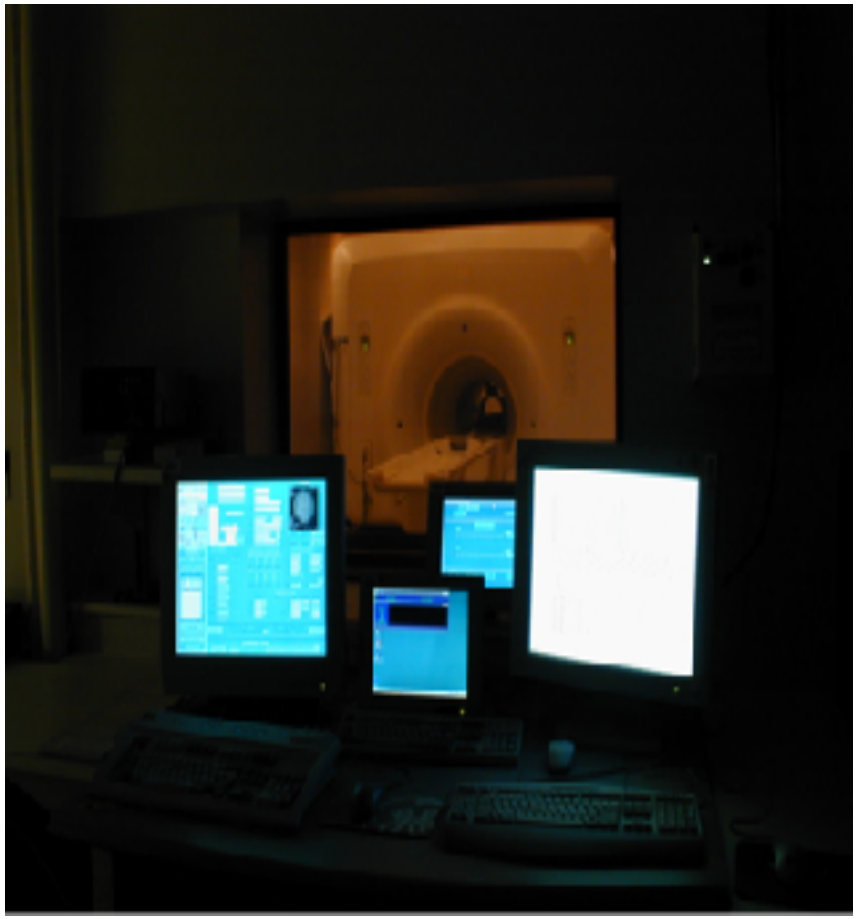
Blood Volume Imaging

Susceptibility Contrast agent bolus injection and time series collection of T2* or T2 - weighted images



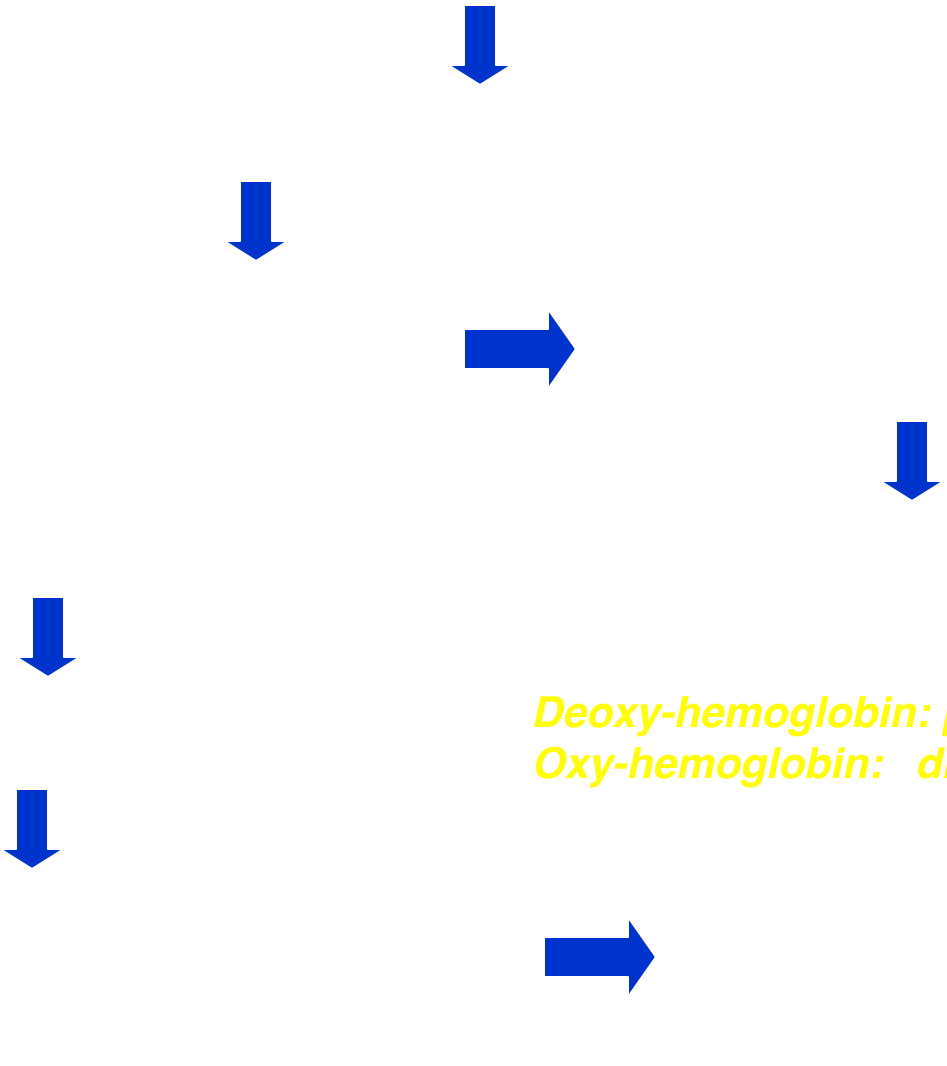


Kwong et al.



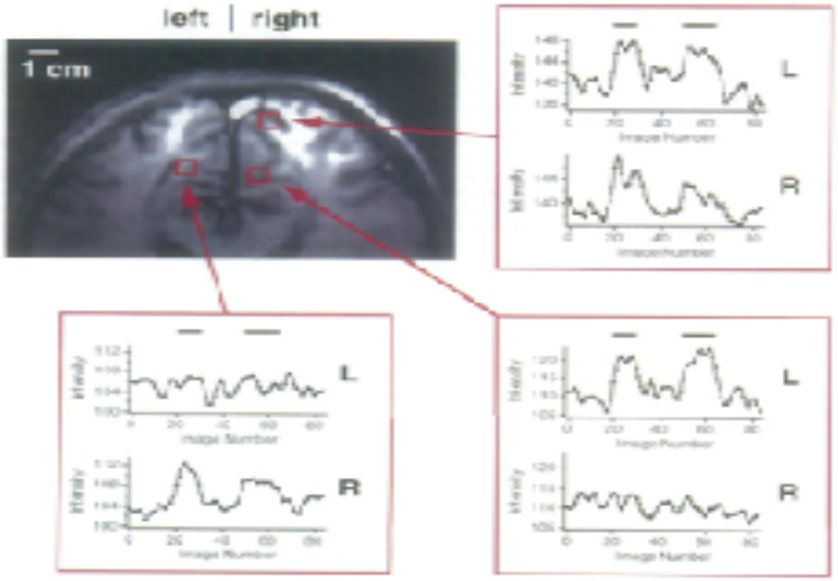
K. K. Kwong, et al, (1992) "Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation." Proc. Natl. Acad. Sci. USA. 89, 5675-5679.

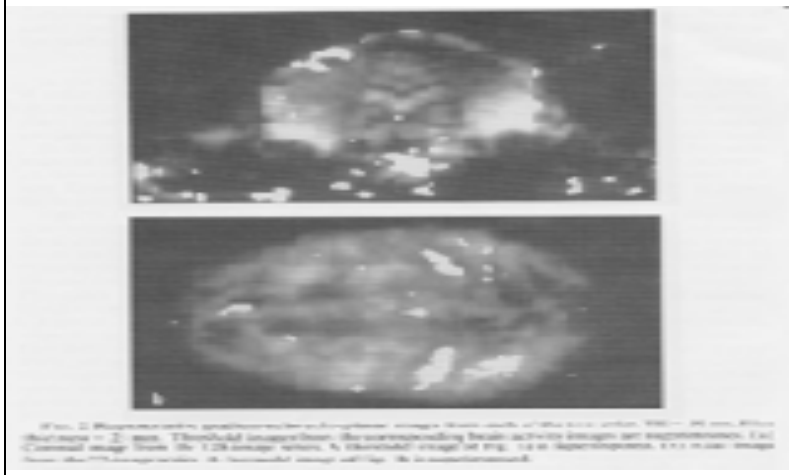
BOLD Contrast in the Detection of Neuronal Activity

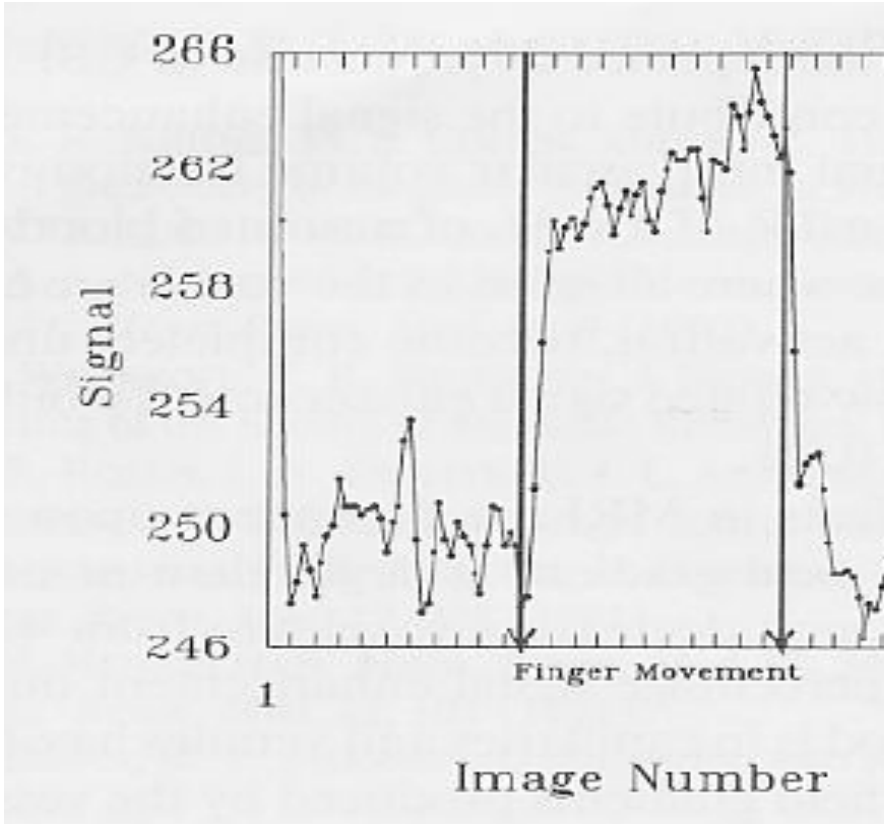


Deoxy-hemoglobin: paramagnetic
Oxy-hemoglobin: diamagnetic

Ogawa et al.

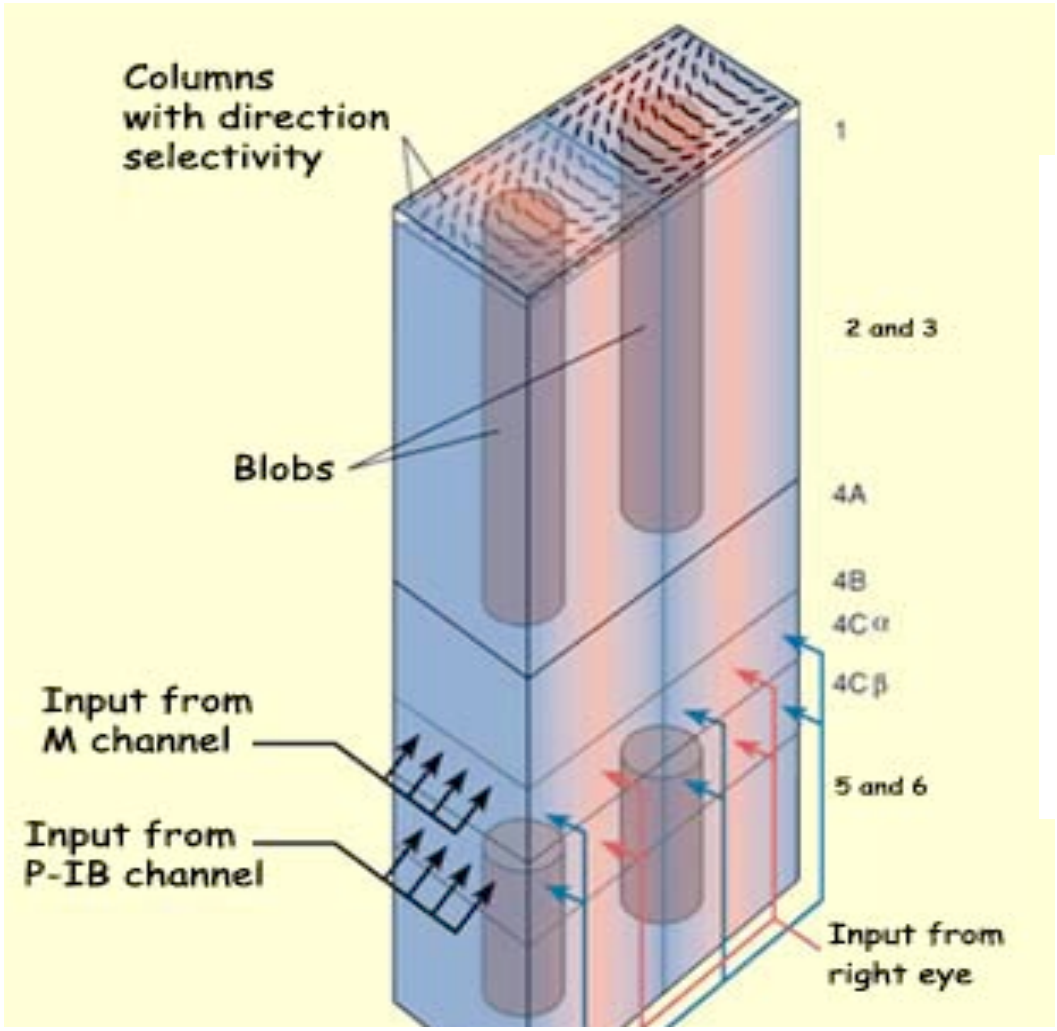


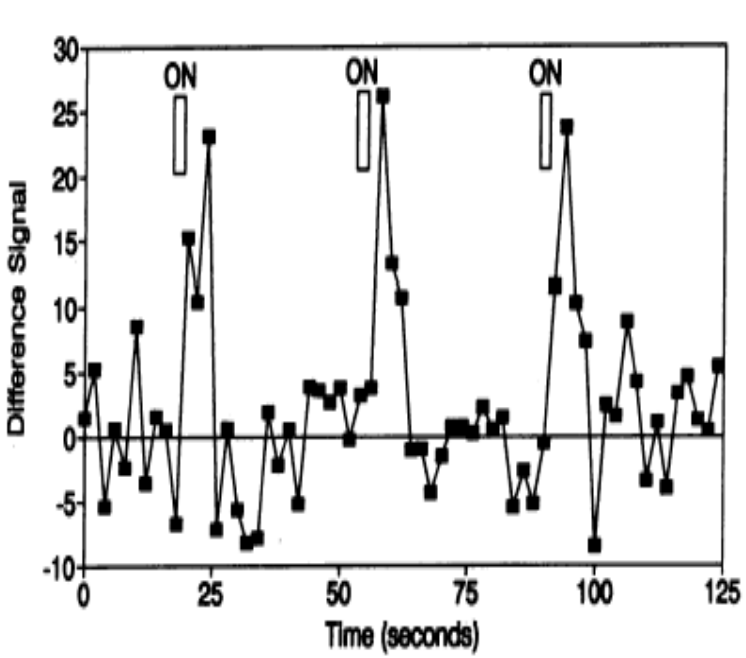




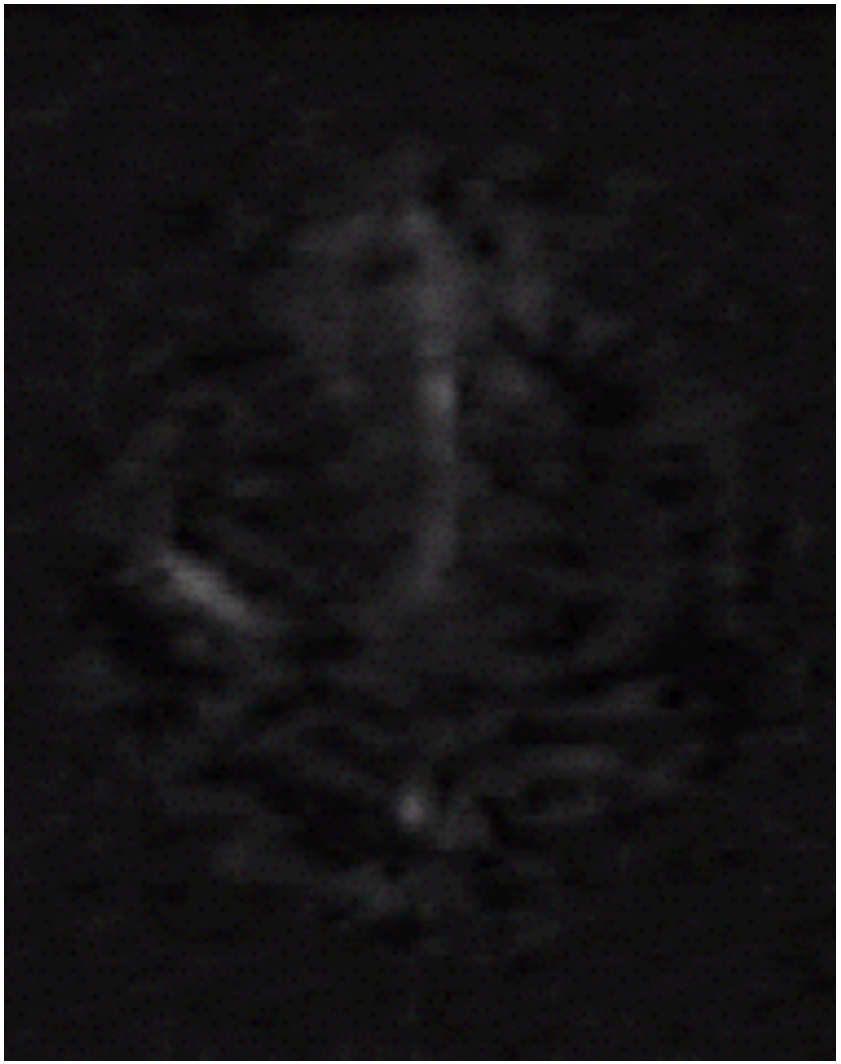
S. Ogawa, et al., (1992) "Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. Proc. Natl. Acad. Sci. USA." 89, 5951-5955.

Bandettini et al.





P. A. Bandettini, et al., (1992) "Time course EPI of human brain function during task activation." Magn. Reson. Med 25, 390-397.



1991

Blamire et al.

•Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

1992…Perfusion using Arterial Spin Labeling

Williams, D. S., Detre, J. A., Leigh, J. S. & Koretsky, A. S. (1992) "Magnetic resonance imaging of perfusion using spin-inversion of arterial water." **Proc. Natl. Acad. Sci. USA 89, 212-216.**

Edelman, R., Siewert, B. & Darby, D. (1994) "Qualitative mapping of cerebral blood flow and functional localization with echo planar MR imaging ans signal targeting with alternating radiofrequency (EPISTAR)." **Radiology 192, 1-8.**

Kim, S.-G. (1995) "Quantification of relative cerebral blood flow change by flow-sensitive alternating inversion recovery (FAIR) technique: application to functional mapping." **Magn. Reson. Med. 34, 293-301.**

Kwong, K. K. et al. (1995) "MR perfusion studies with T1-weighted echo planar imaging."**Magn. Reson. Med. 34,878-887.**

Contrast in Functional MRI

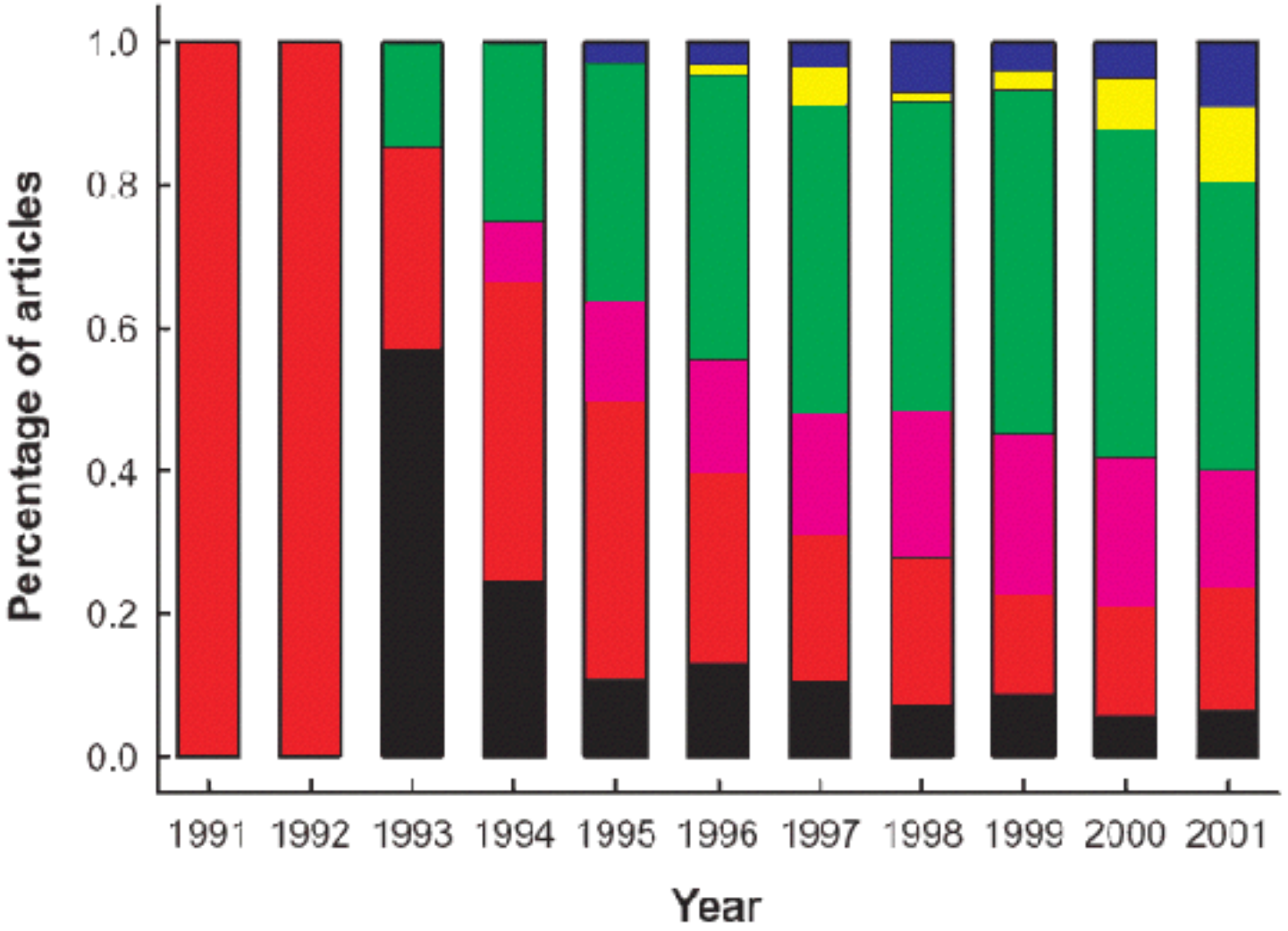
- Blood Volume
- Blood Oxygenation Changes
- Blood Perfusion

fMRI Contrast

- Volume (gadolinium)
- BOLD
- Perfusion (ASL)
- $\Delta CMRO_2$
- ΔVolume (VASO)
- Neuronal Currents
- Diffusion coefficient
- Temperature

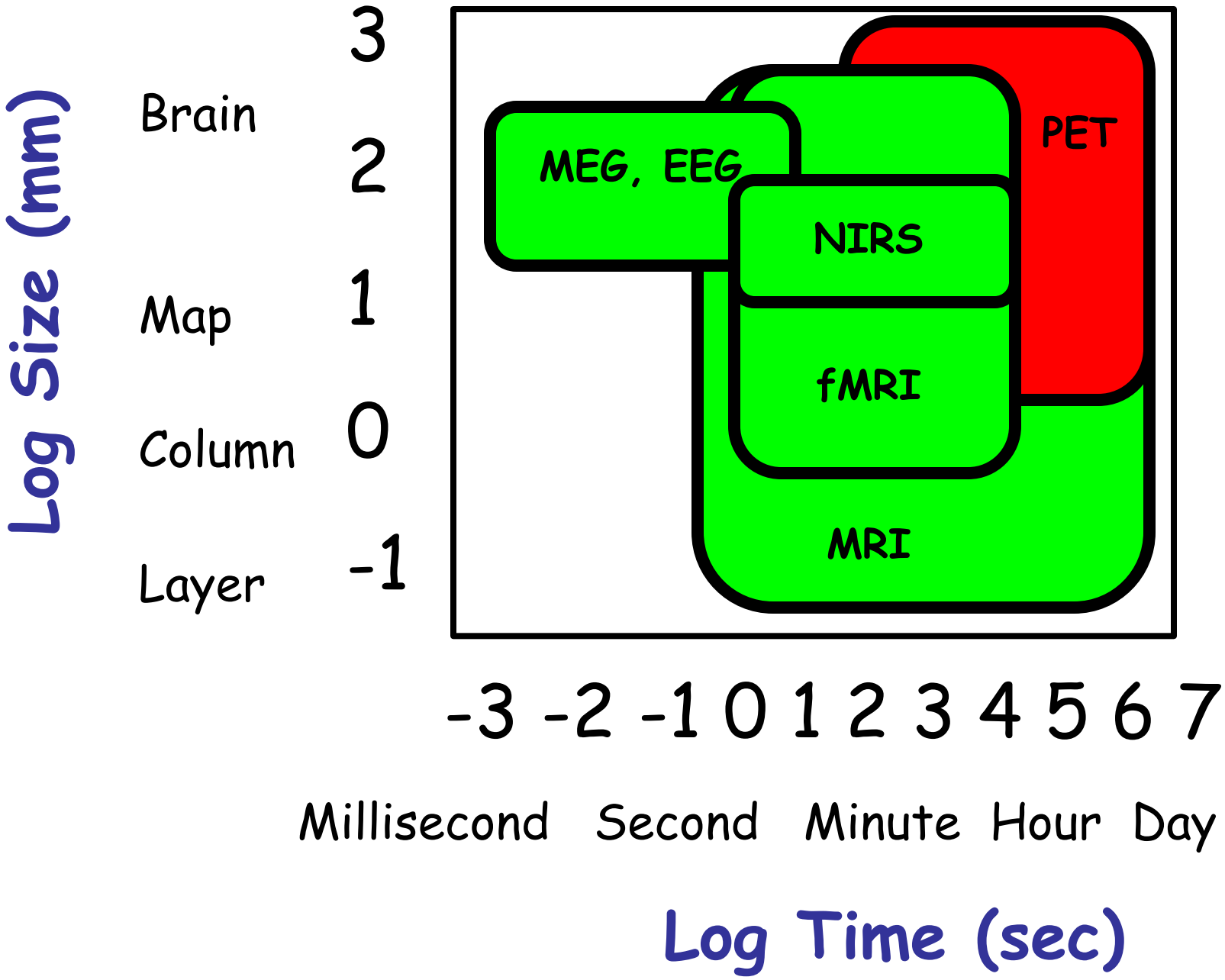
Scopus: Articles or Reviews Published per Year

"fMRI" or "functional MRI"



Motor (black)
Primary Sensory (red)
Integrative Sensory (violet)
Basic Cognition (green)
High-Order Cognition (yellow)
Emotion (blue)

J. Illes, M. P. Kirschen, J. D. E. Gabrielli, Nature Neuroscience, 6 (3)m p.205

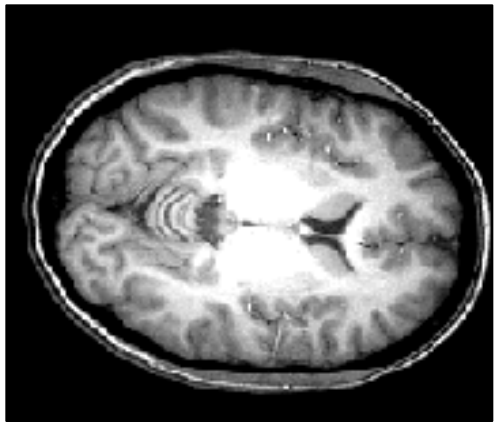

Log Size (mm)
3
Brain
2
Map
1
Column
0
Layer
-1
MEG, EEG
PET
NIRS
fMRI
MRI
-3 -2 -1 0 1 2 3 4 5 6 7
Millisecond Second Minute Hour Day
Log Time (sec)

Topics Studied with fMRI at the NIH

- Epilepsy
- Visual processing
- Mood disorders
- Learning
- Habituation
- Plasticity
- Motor Function
- Auditory processing
- Attention
- Language
- Speech
- Stroke
- Social Interaction
- Development
- Aging

MRI vs. fMRI

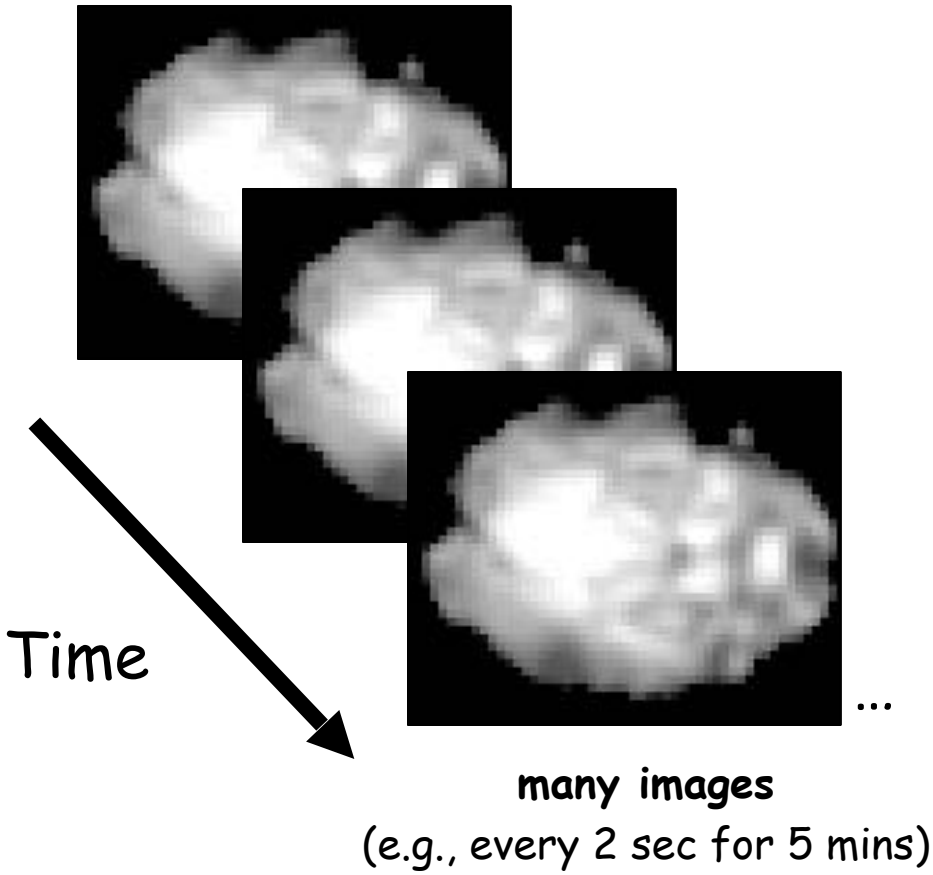
MRI



one image

high resolution
(1 mm or less)

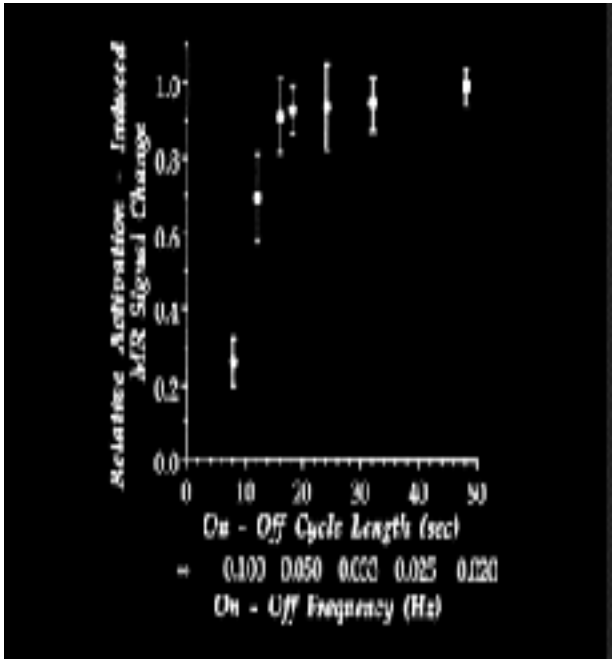
fMRI

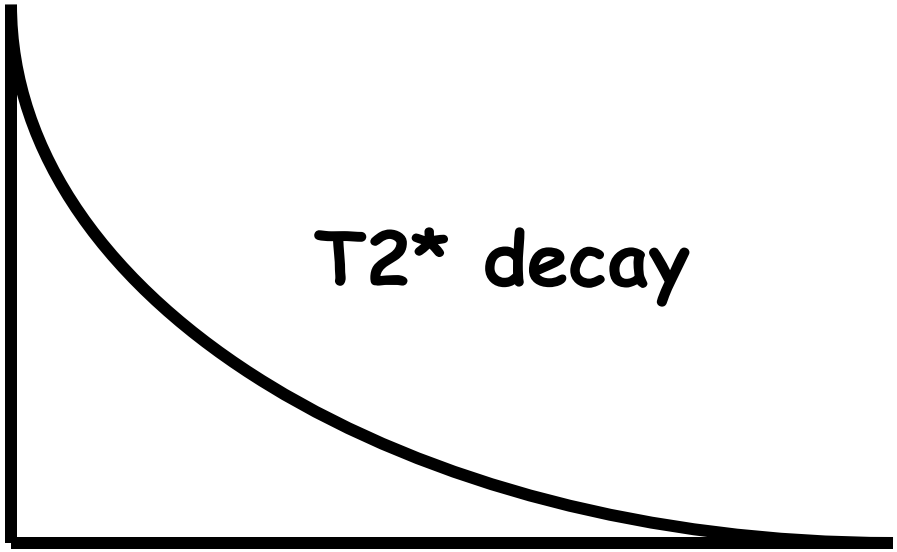


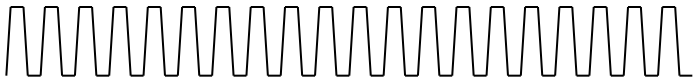
many images
(e.g., every 2 sec for 5 mins)

low resolution
(1.5 to 4 mm)

Single Shot Echo Planar Imaging (EPI)

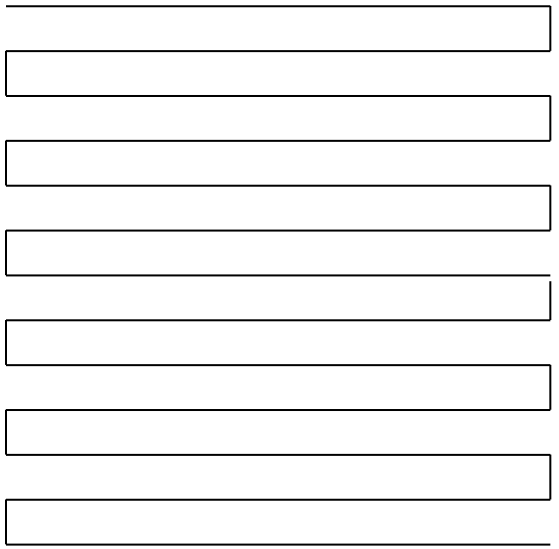


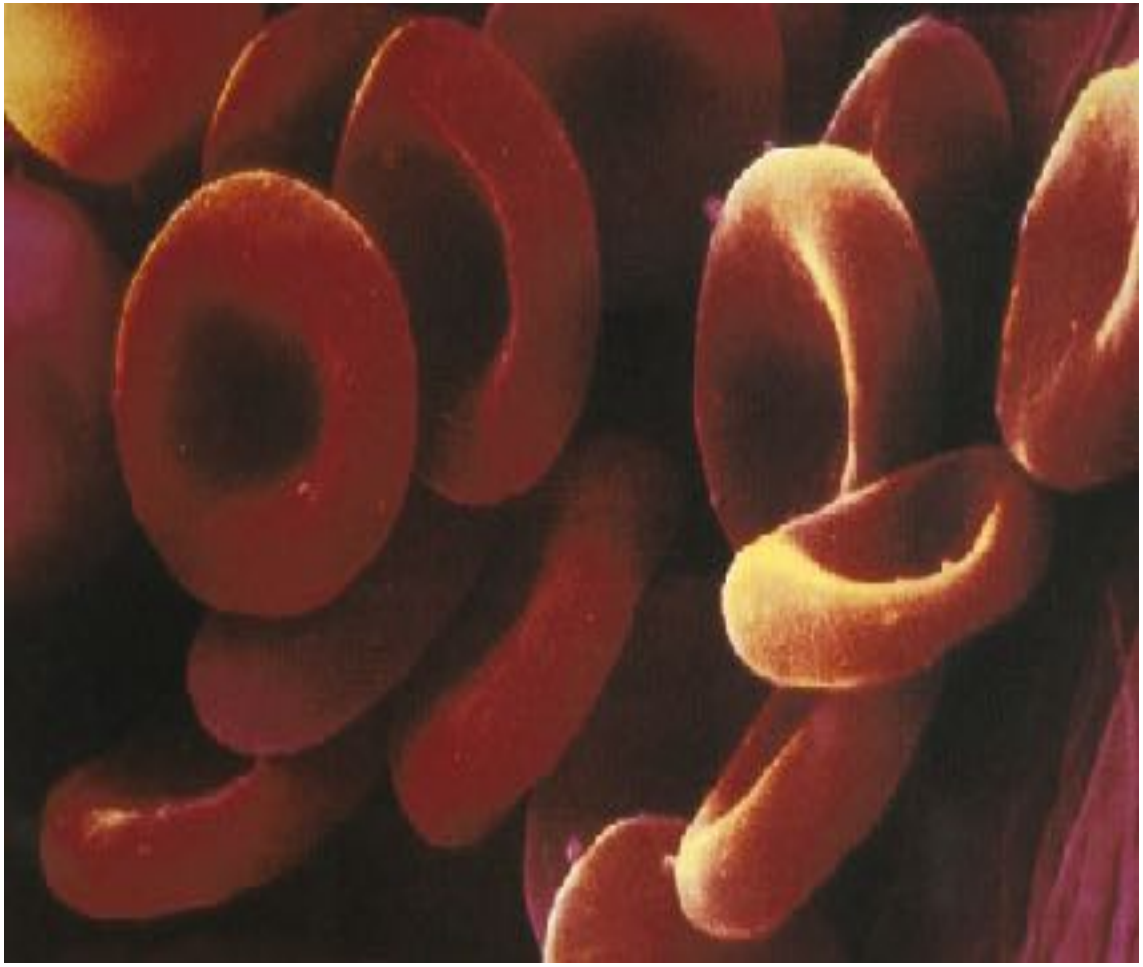




EPI Readout Window

≈ 20 to 40 ms

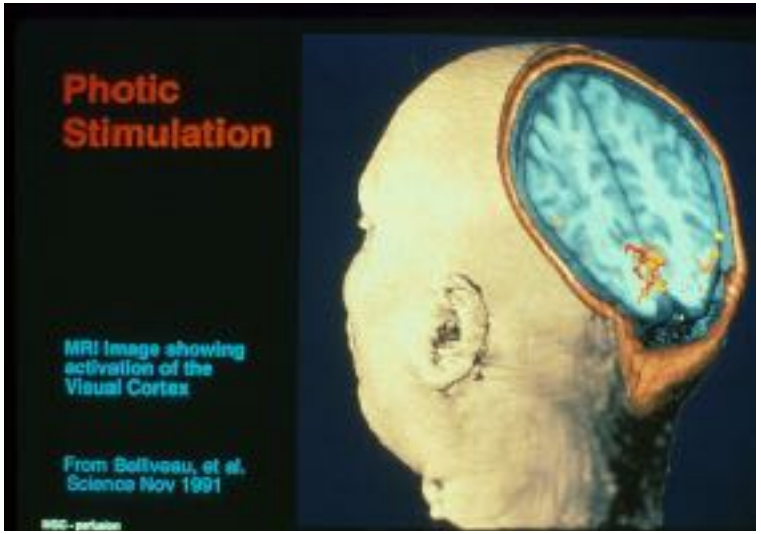




August, 1991

1991-1992

1992-1999



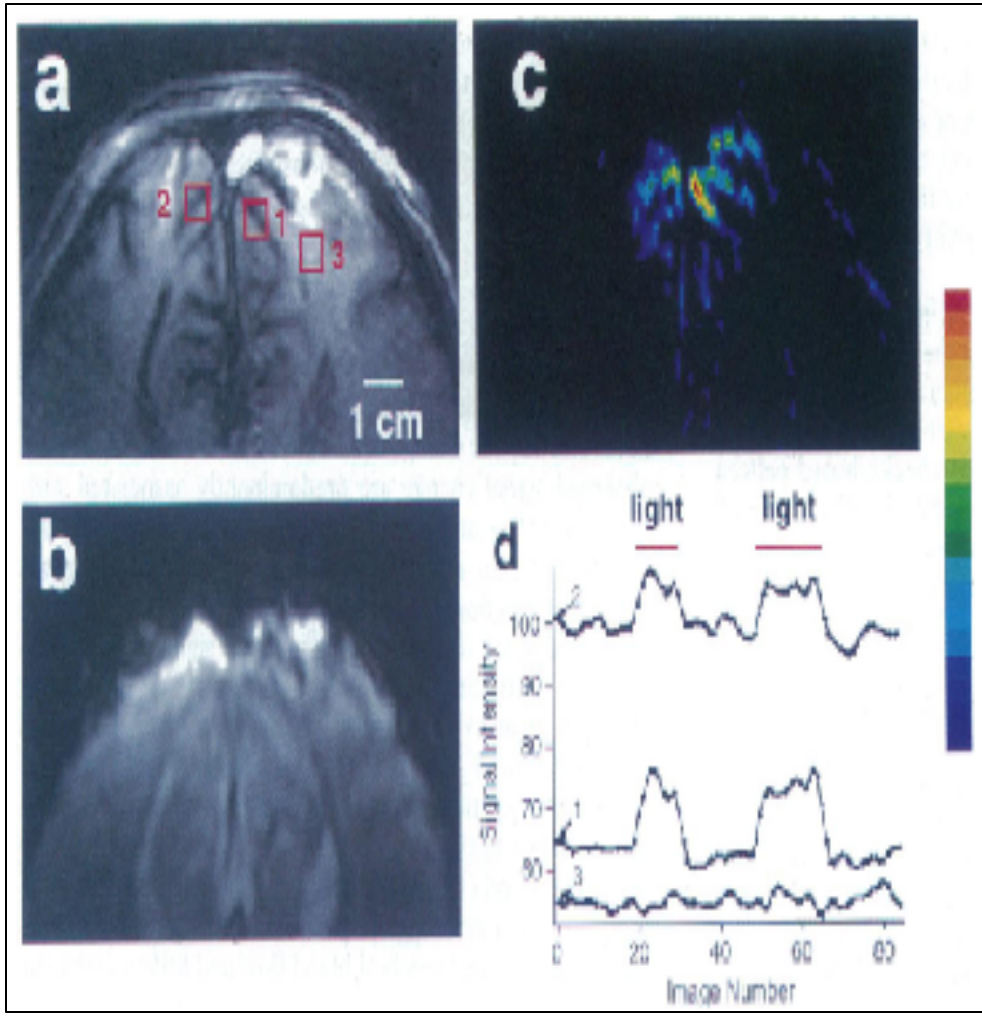
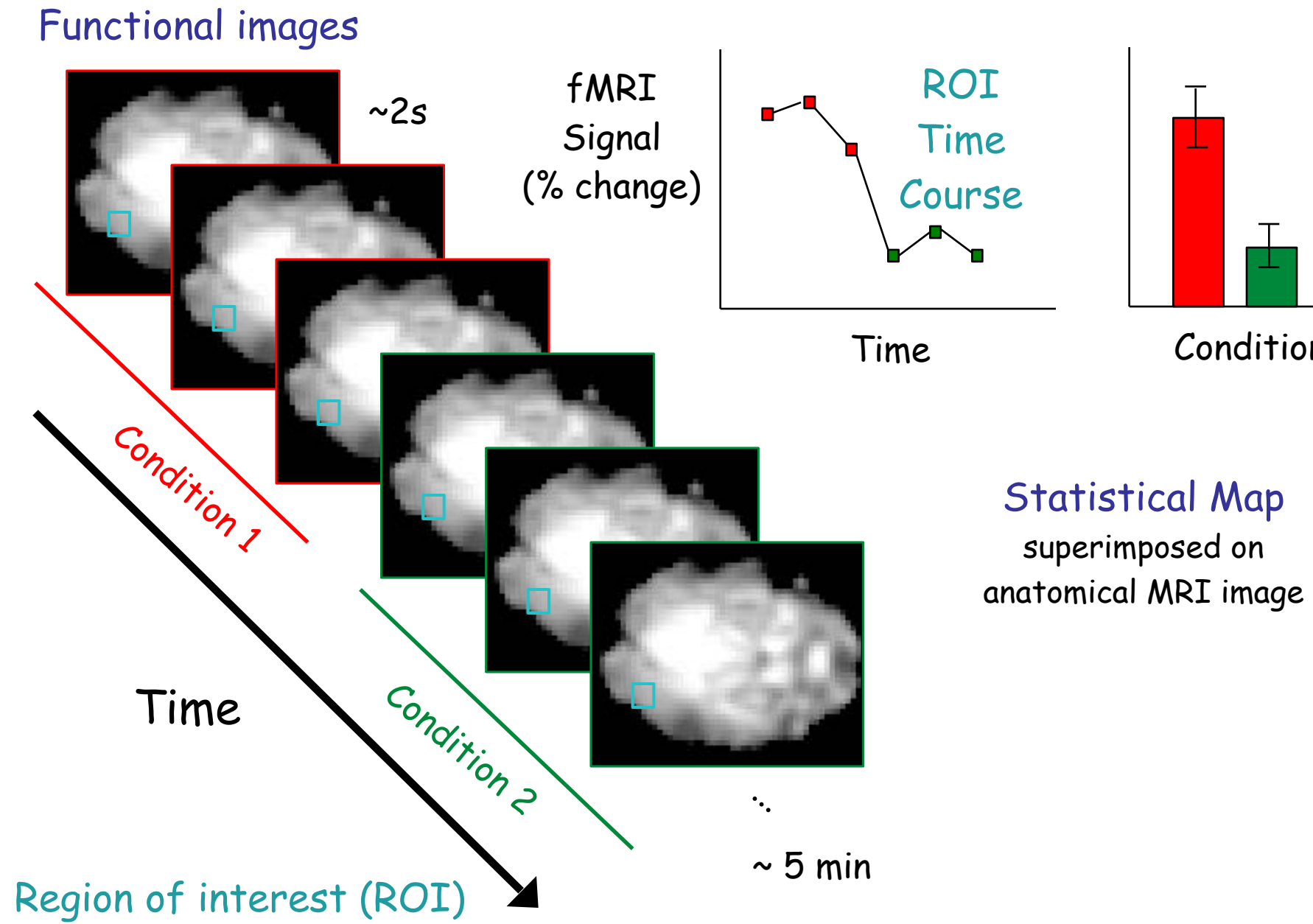


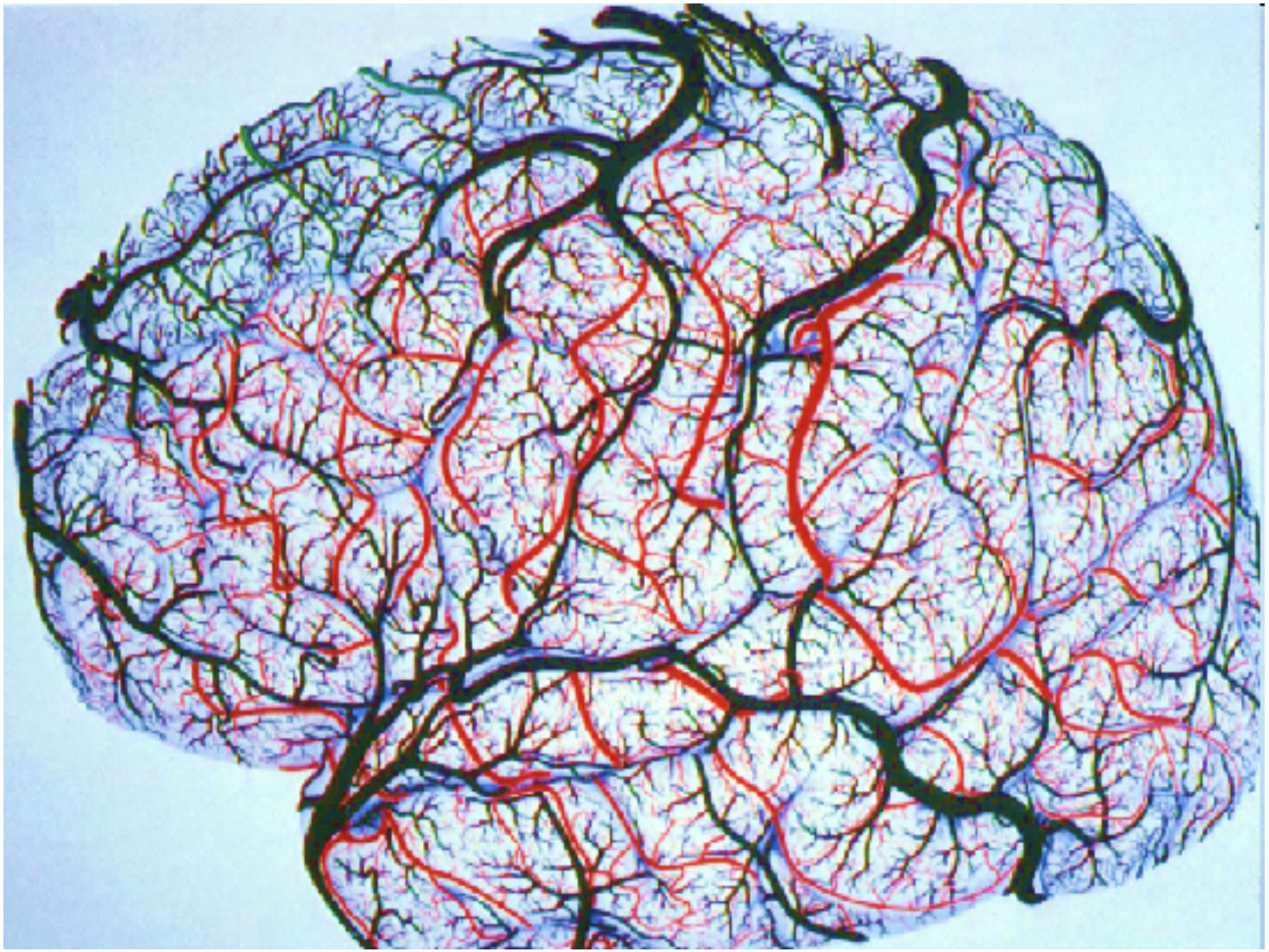
FIG. 2. Intrinsic signal changes produced by photic stimulation in oblique brain images along the calcarine fissure. (*a*) T_1-weighted image of the brain taken with the slice axis oriented parallel to the calcarine fissure. The occipital pole is at the top of the image. (*b*) Gradient echo image (FISP sequence; TE = 40 ms) at the same anatomical location. (*c*) Pseudocolor map of the difference in signal intensity produced by photic stimulation. (*d*) Time course of changes in signal intensity for regions indicated by the three boxes outlined in *a*.

Activation Statistics



fMRI Setup

Courtesy, Robert Cox, Scientific and Statistical Computing Core Facility, NIMH



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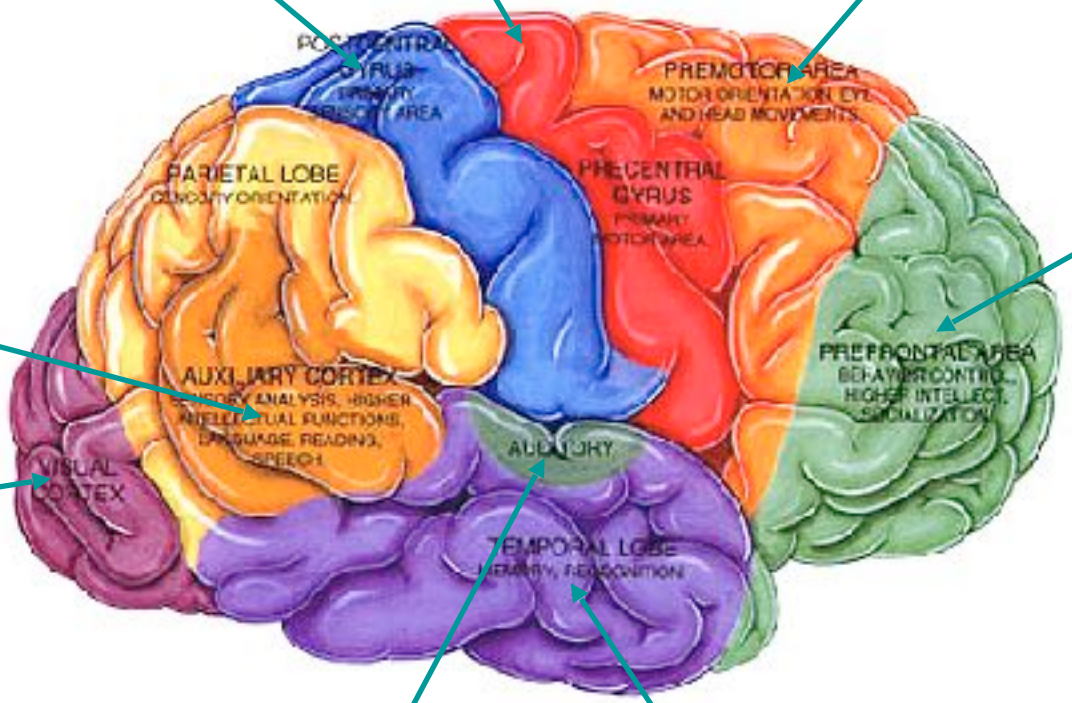
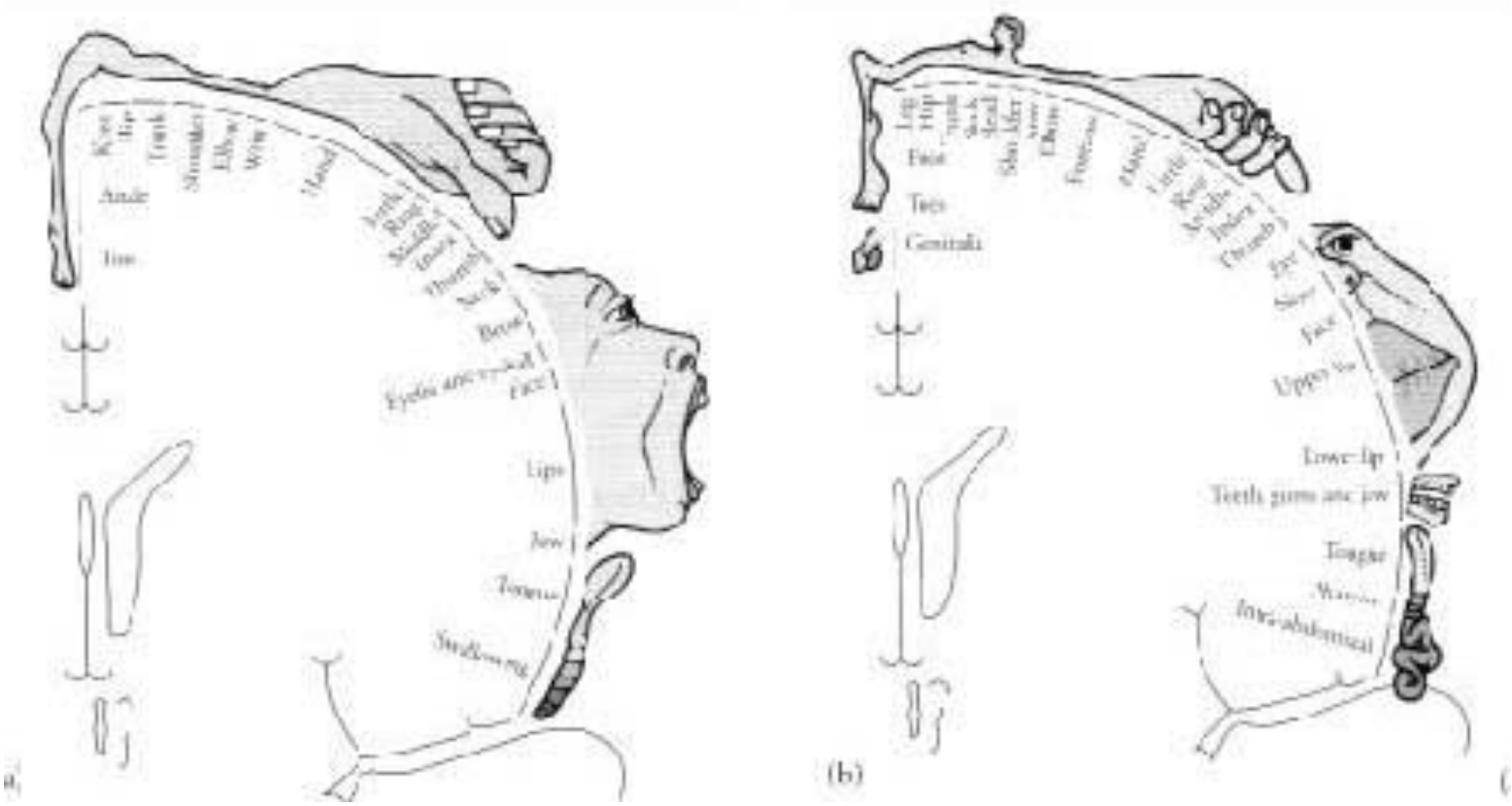
Motor Cortex

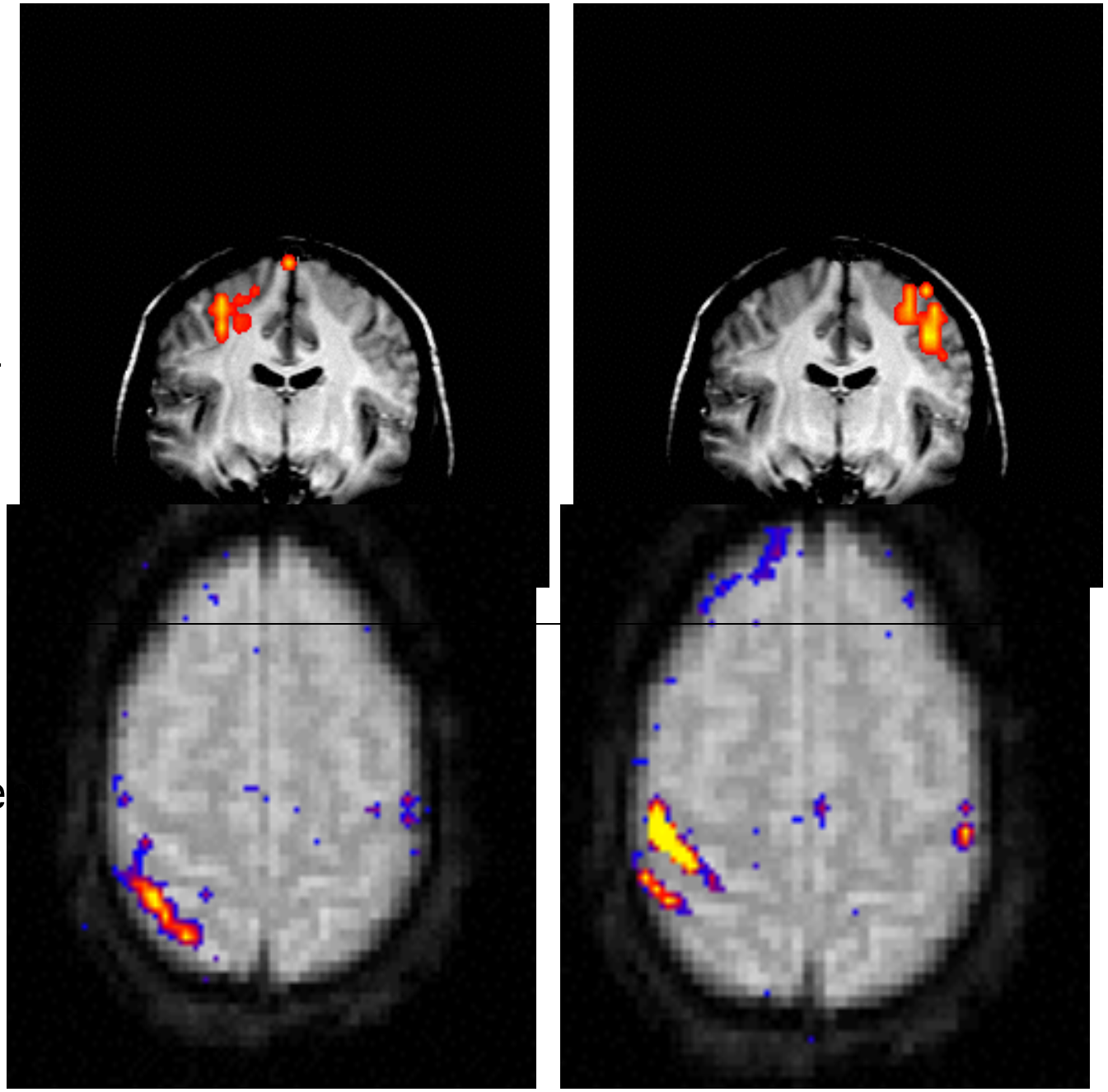
Brain Function

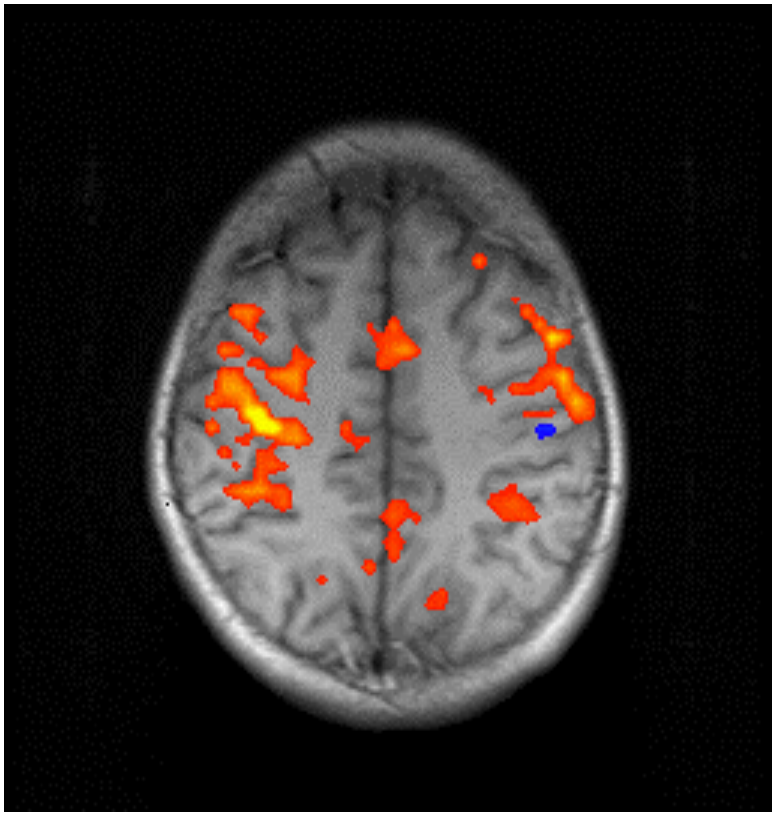


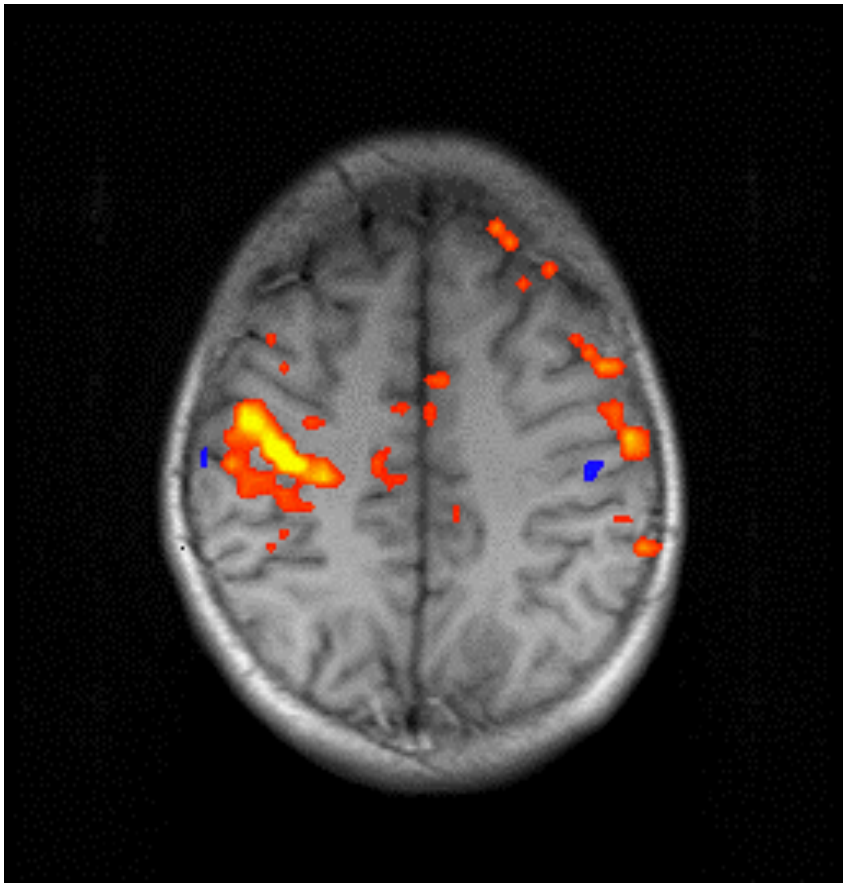

Ankle
Toe
Lips
Jaw
(b)

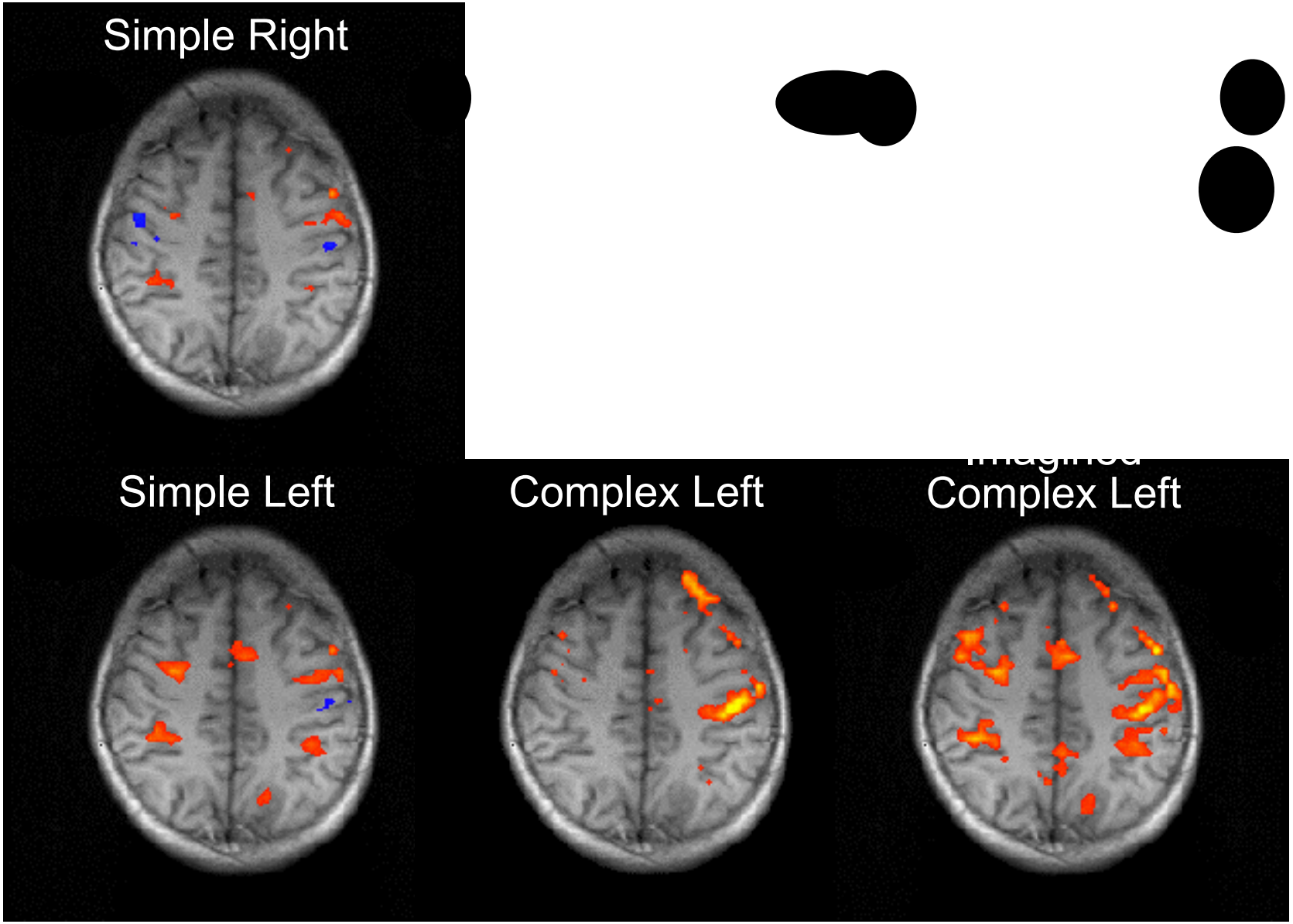
Toe movement

Finger moveme



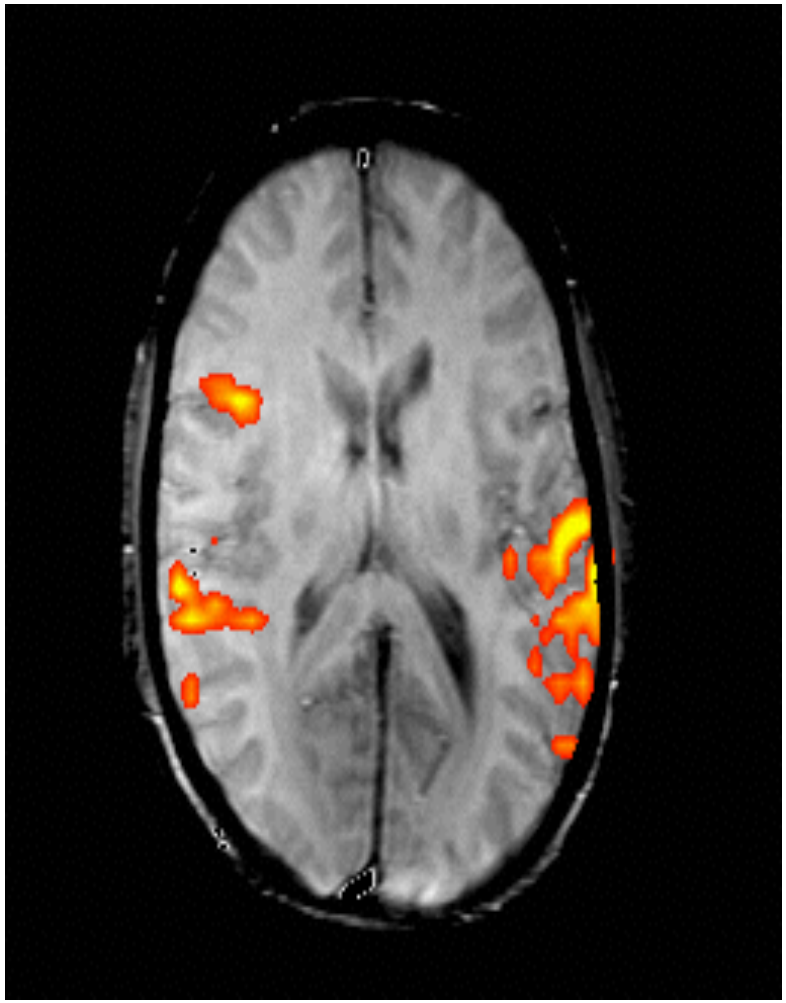


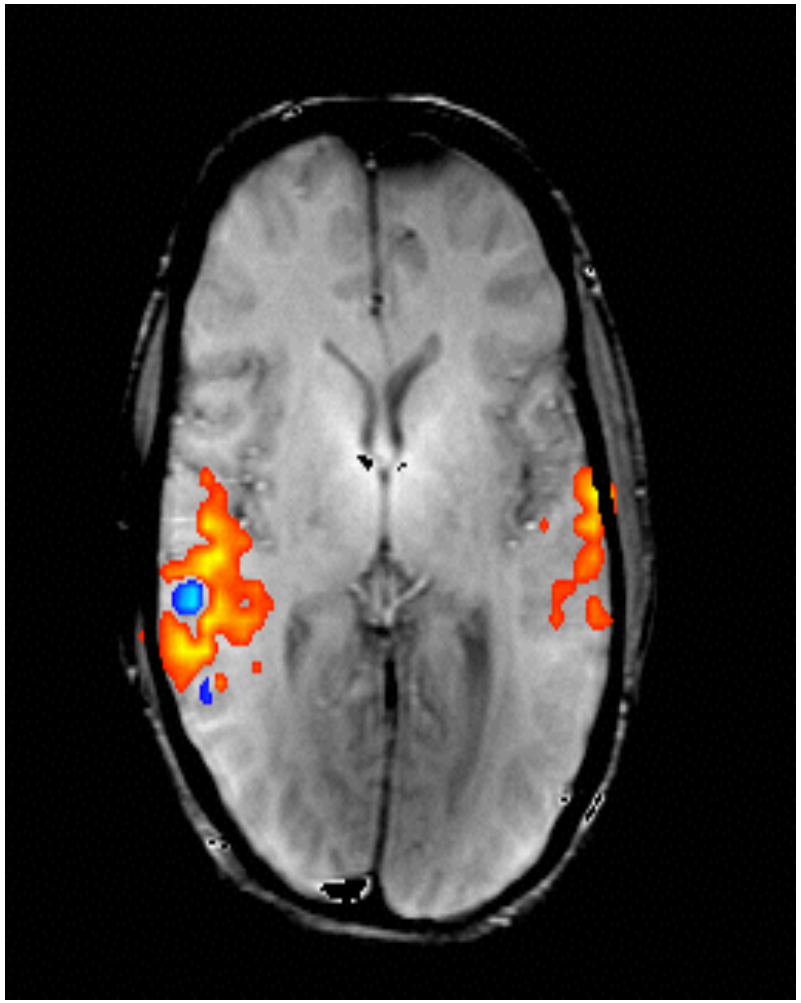



Simple Right
Simple Left
Complex Left
Complex Left

Presurgical Mapping

Left Foot Tumor Right Foot Right Hand

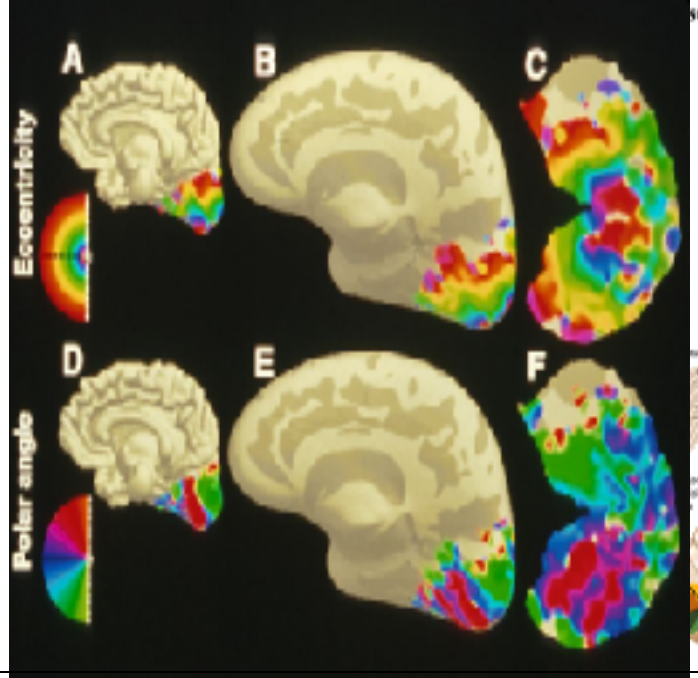


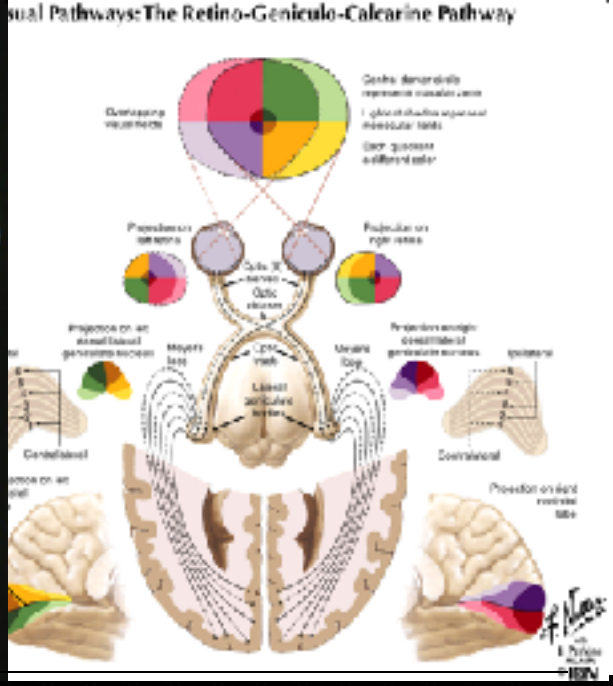


fMRI O-15 PET

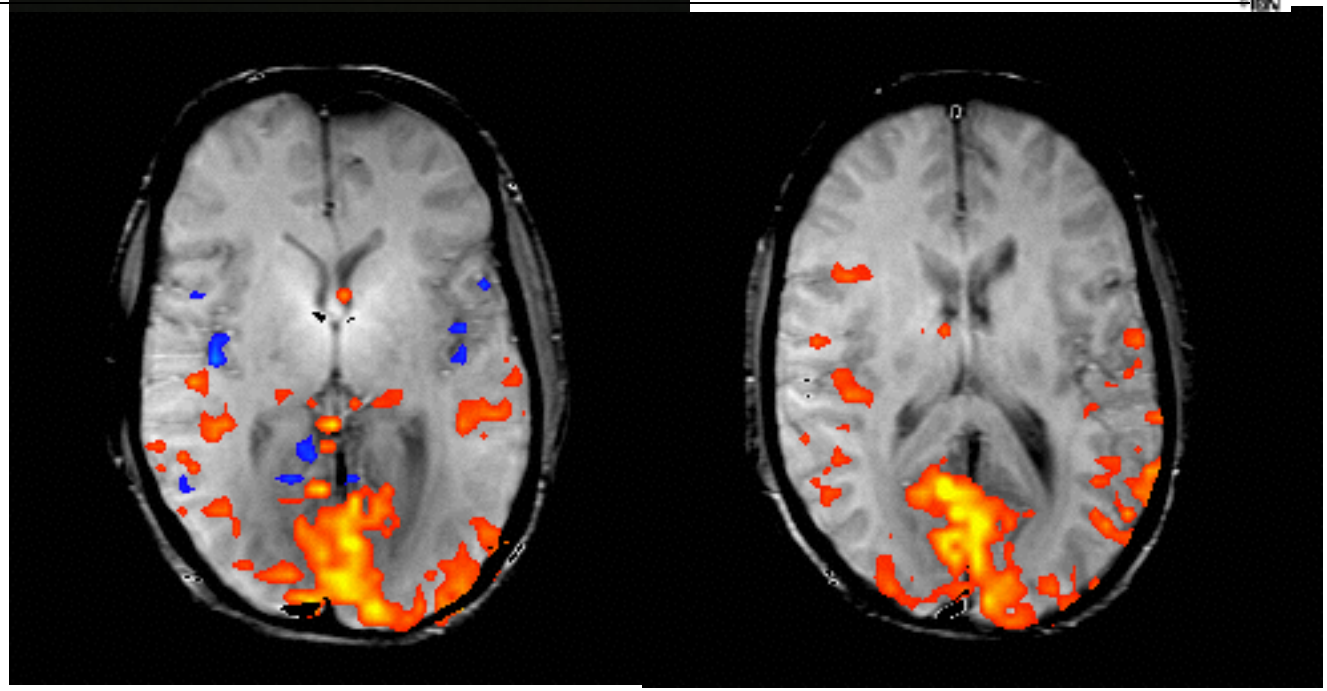
Visual and Auditory Processing

Reading





Listening



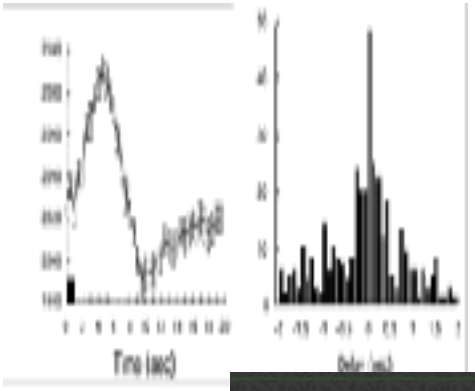
Multi-sensory integration

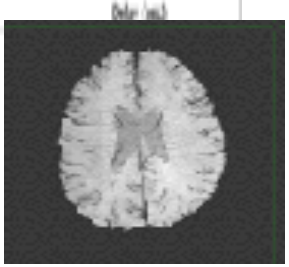
M.S. Beauchamp et al.,

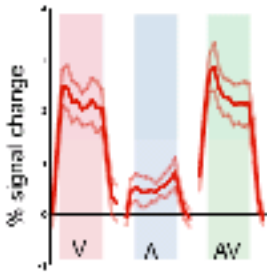
Visual

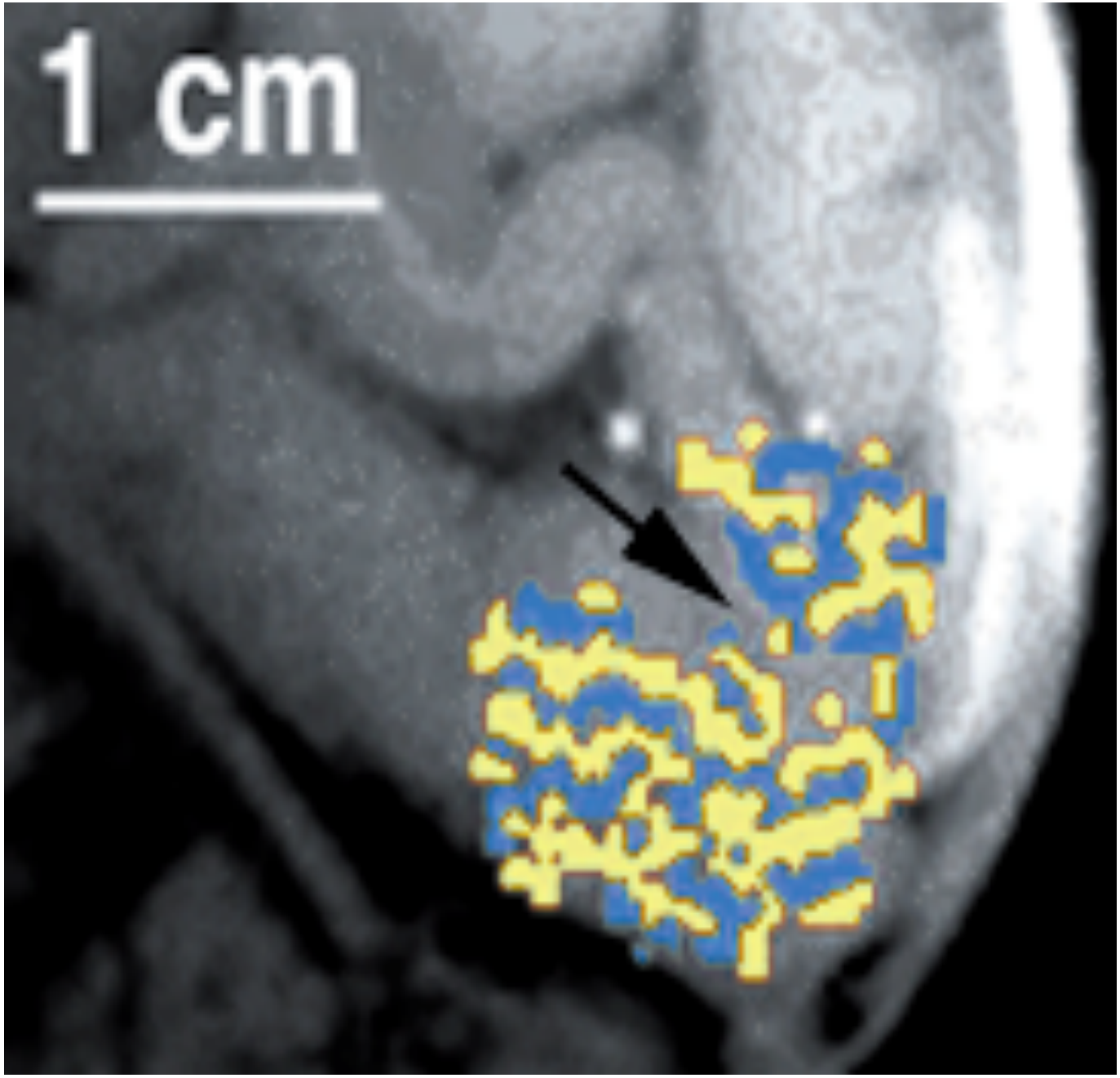
Auditory

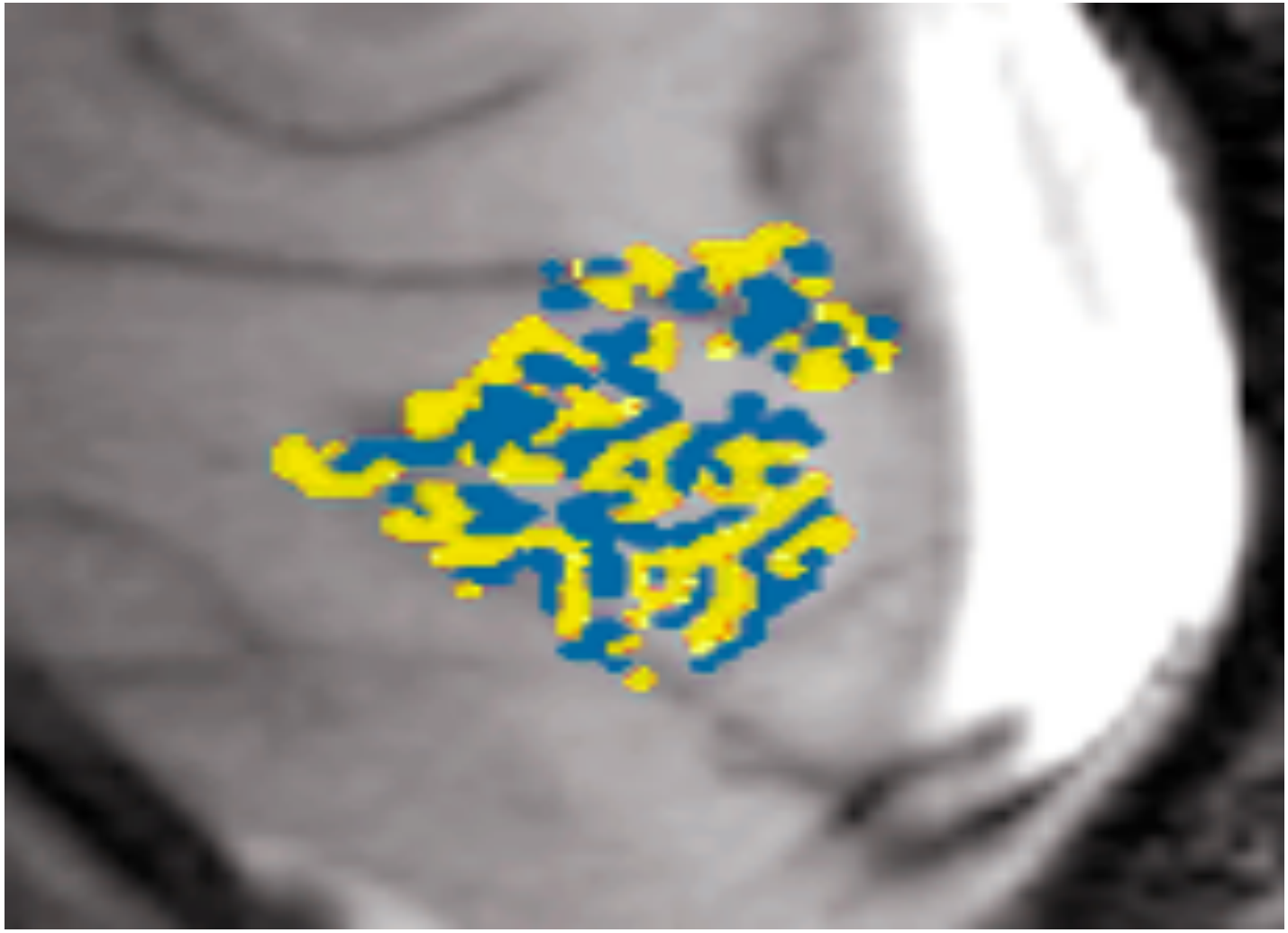
Multisensory







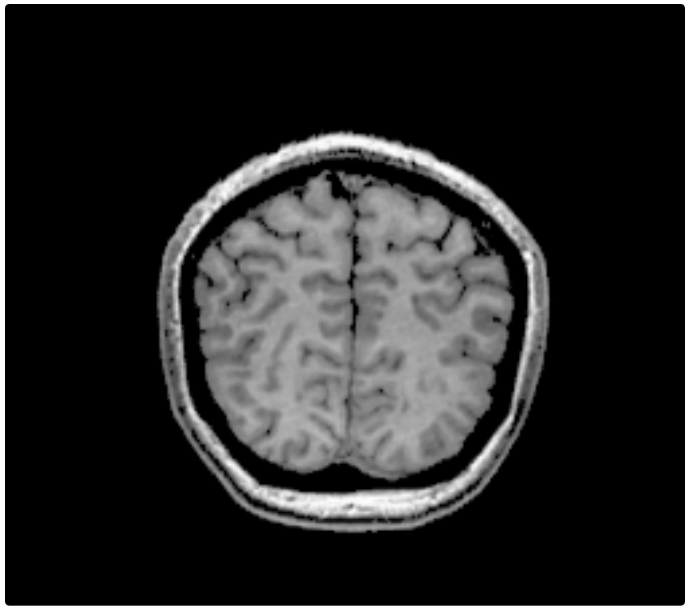

1 cm

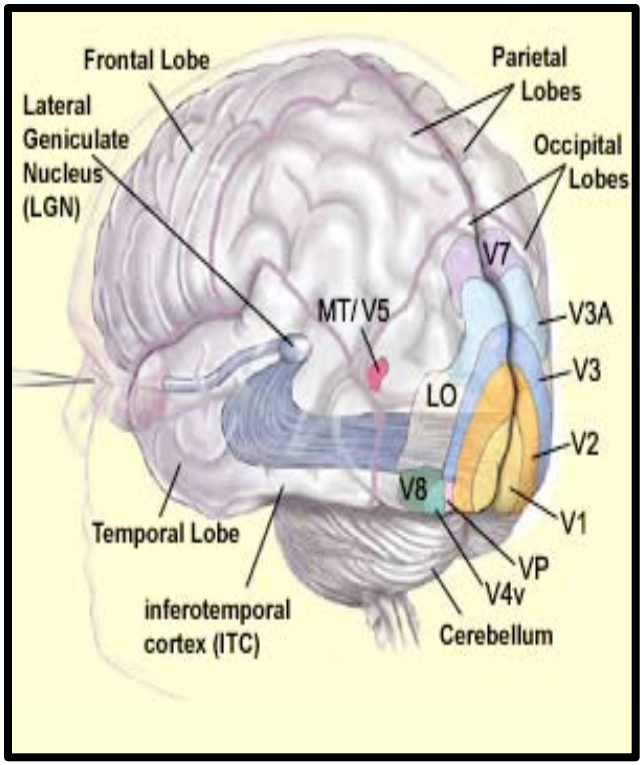


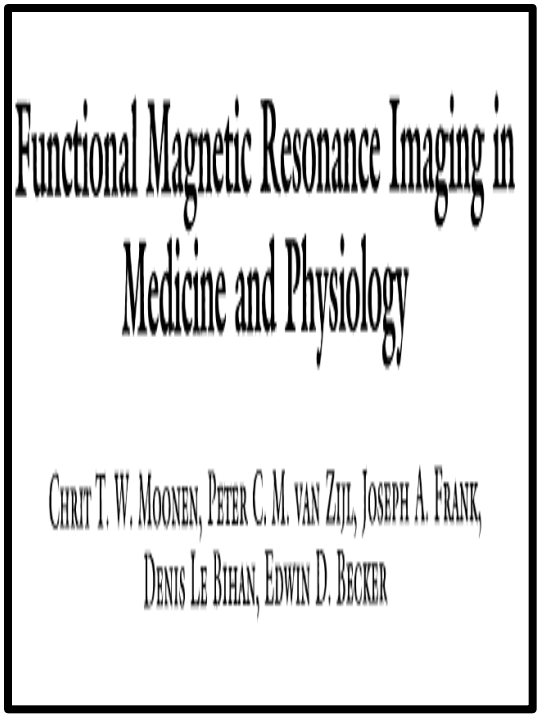
Visual Processing

(spatial resolution)

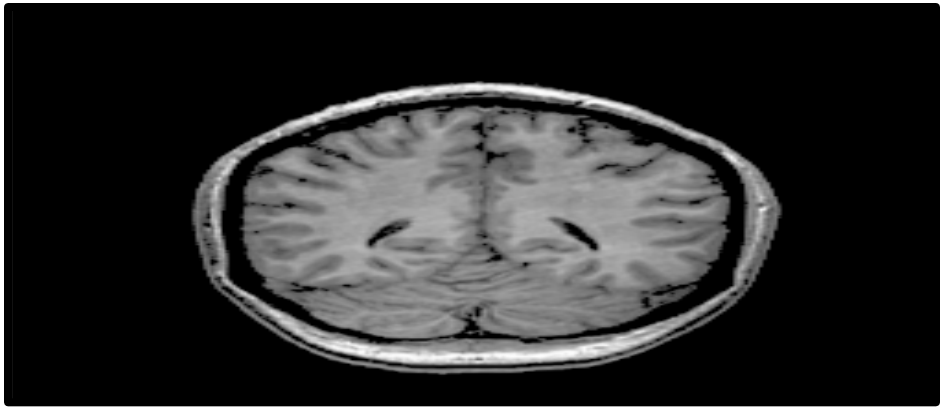
Visual Cortex Organization



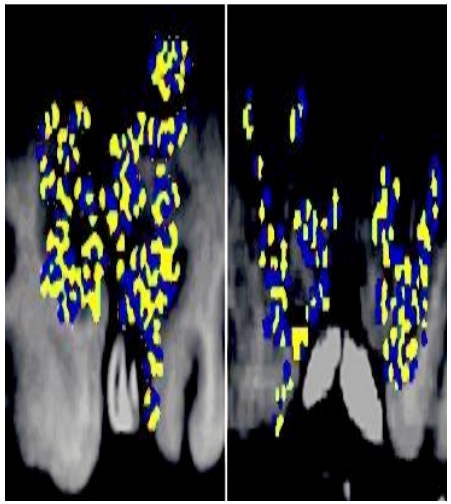




http://www.thebrain.mcgill.ca



ODC Maps using fMRI



1 cm

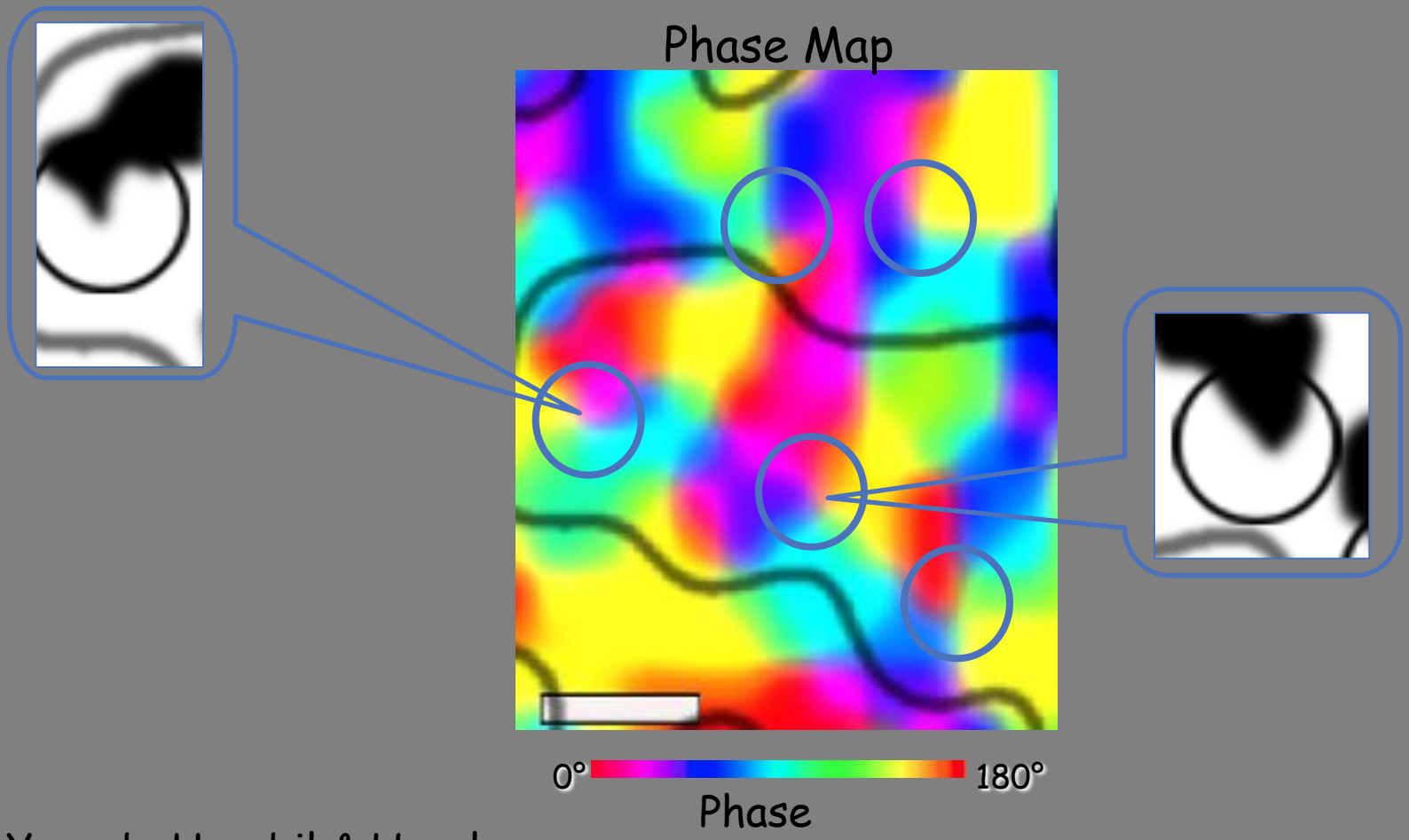
calcarine

• Identical in size, orientation, and appearance to those obtained by optical imaging[1] and histology[3,4].

Menon et al.

[1]Malonek D, Grinvald A. *Science* 272, 551-4 (1996).
[3]Horton JC, Hocking DR. *J Neurosci* 16, 7228-39 (1996).
[4]Horton JC, et al. *Arch Ophthalmol* 108, 1025-31 (1990).

Orientation Columns in Human V1 as Revealed by fMRI at 7T



Yacoub, Ugurbil & Harel
University of Minnesota / CMRR

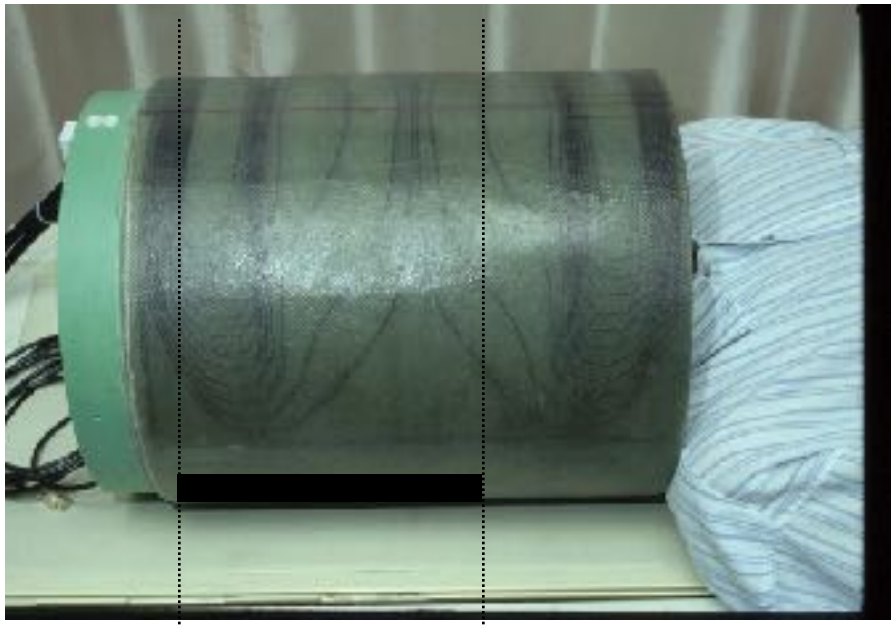
HBM 2006: Thursday, June 15, 2006 at 9:30

Scalebar = 0.5 mm

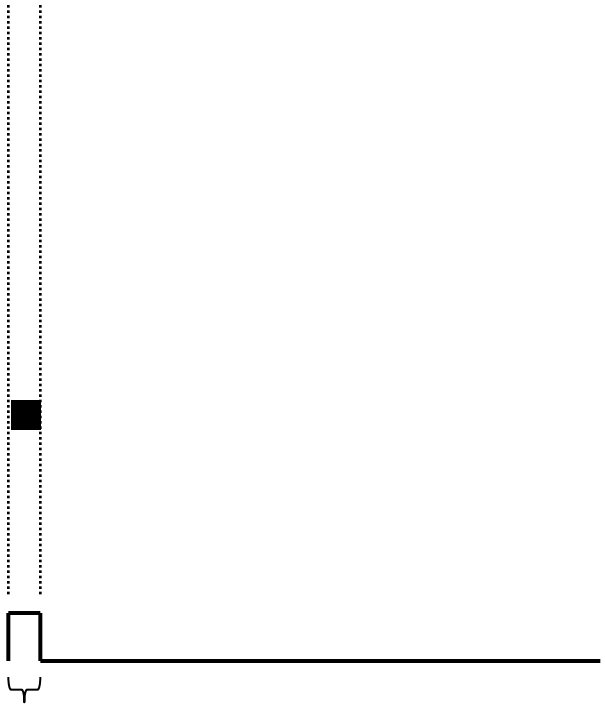
Temporal Resolution

The BOLD Signal

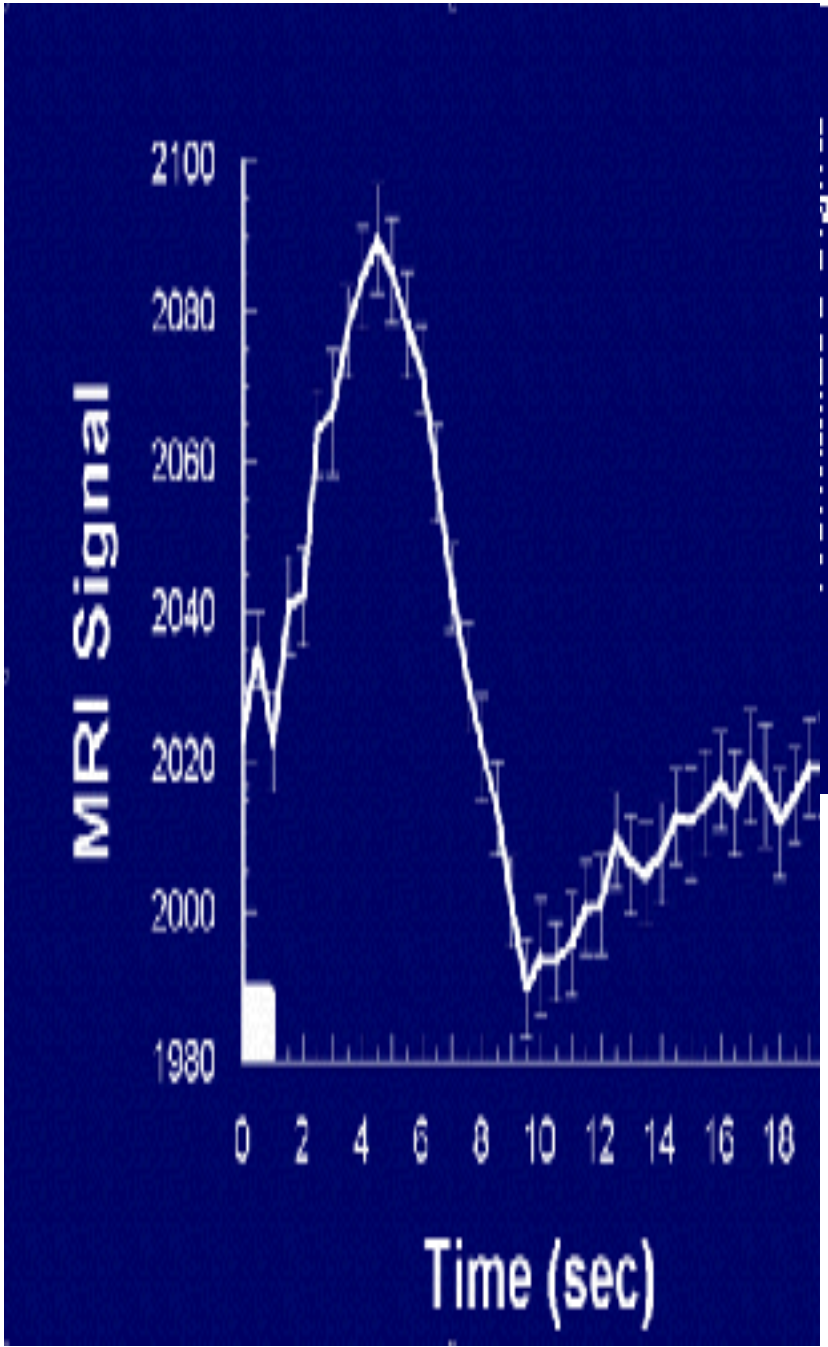
Blood Oxygenation Level Dependent (BOLD) signal changes

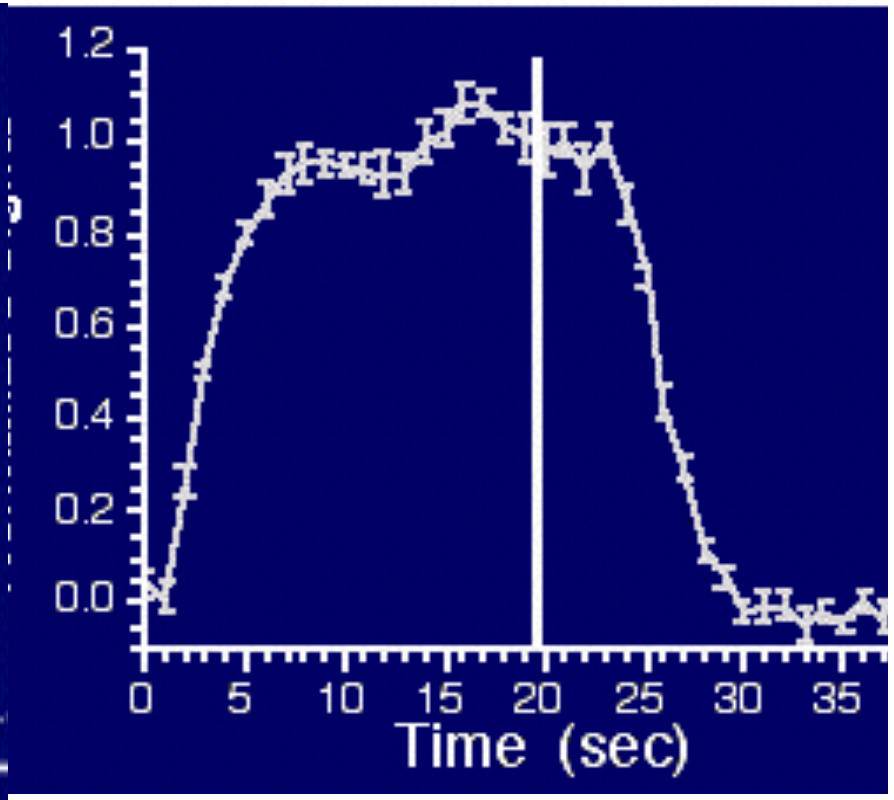


task



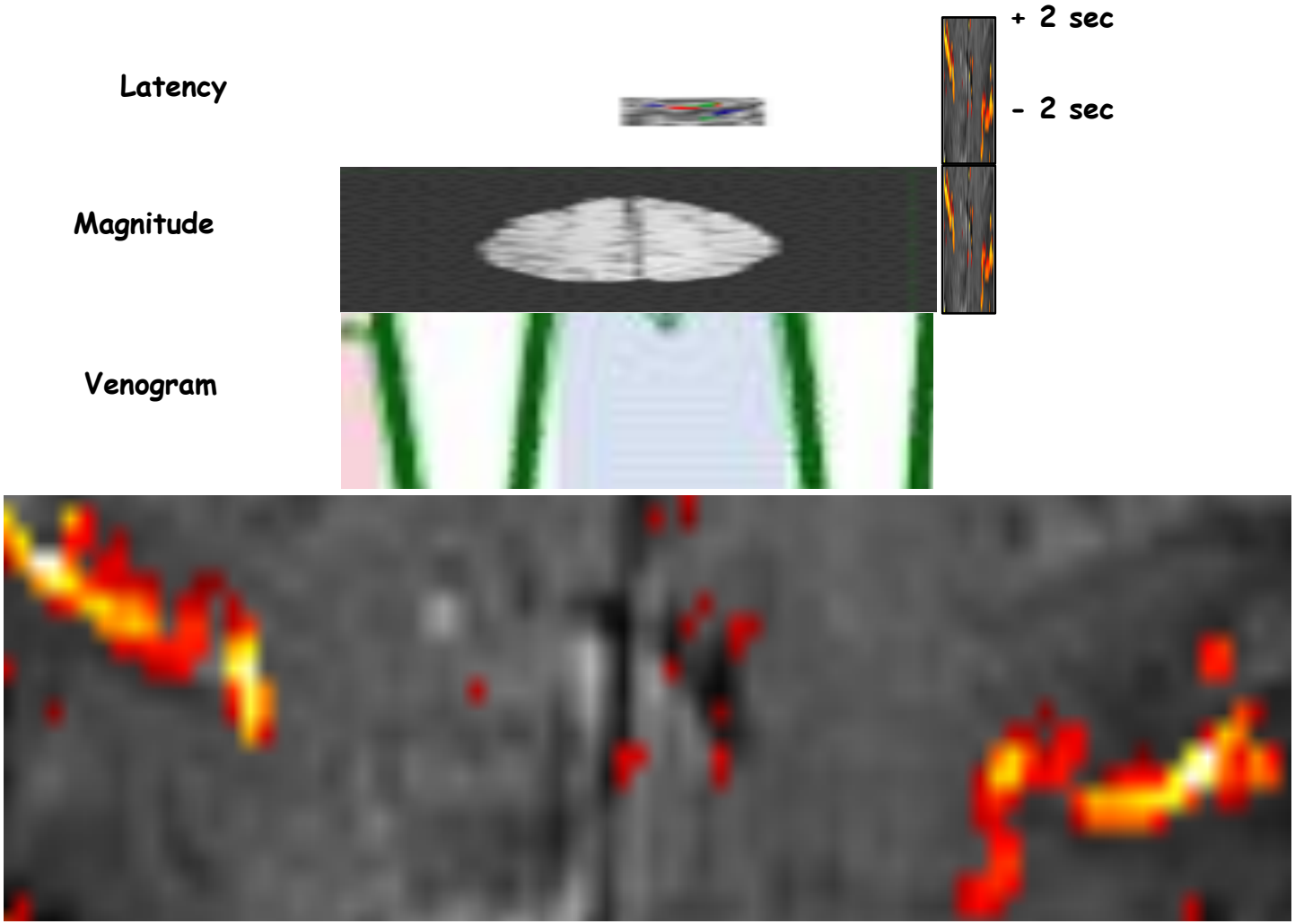
task



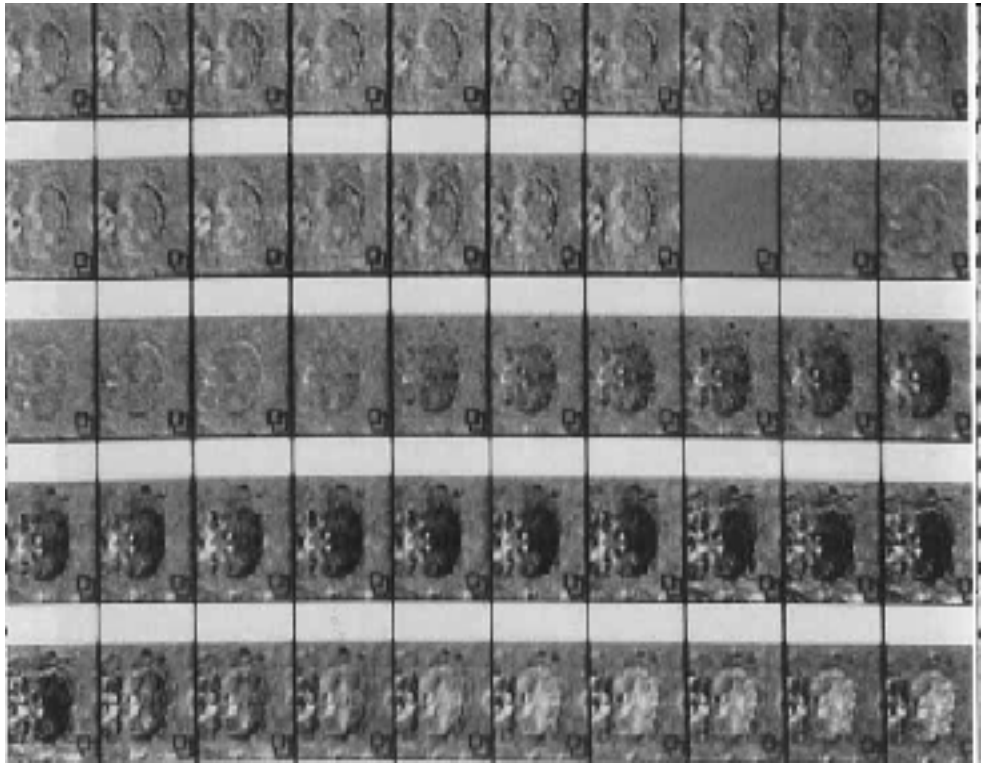


P. A. Bandettini, Functional MRI temporal resolution in "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

Latency Variation…

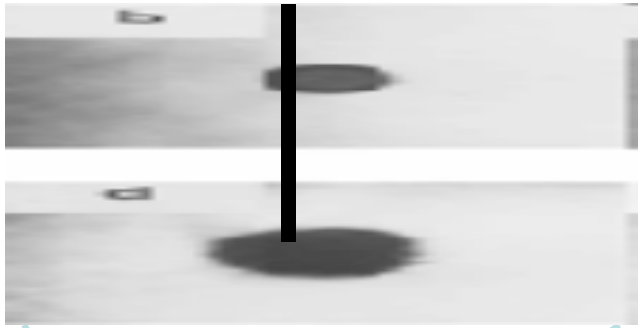


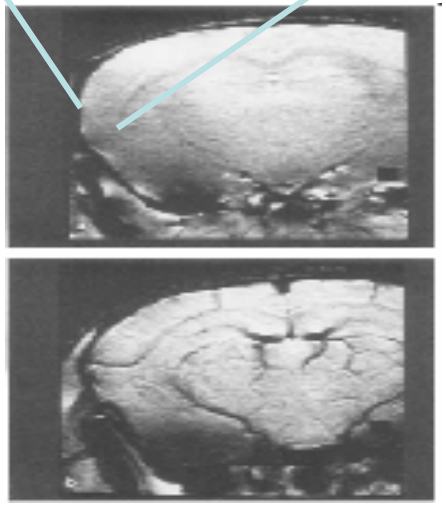
P. A. Bandettini, (1999) "Functional MRI" 205-220.



Word vs. Non-word

0°, 60°, 120° Rotation



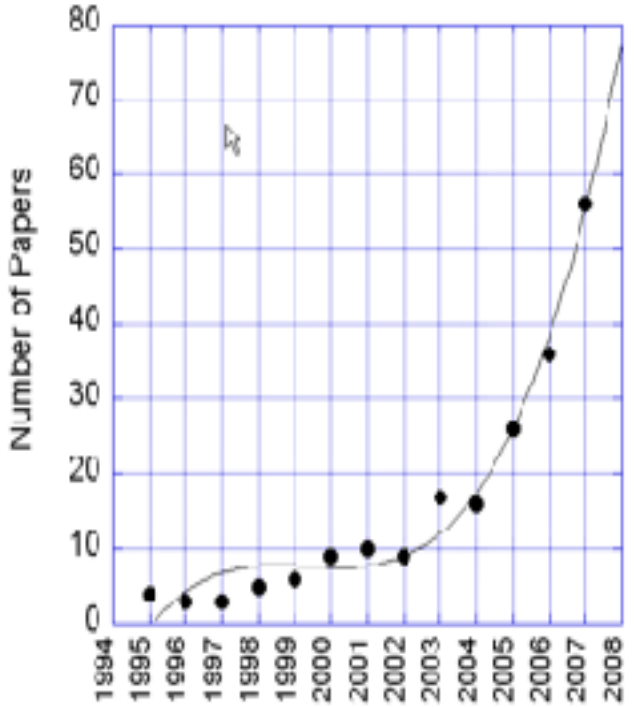


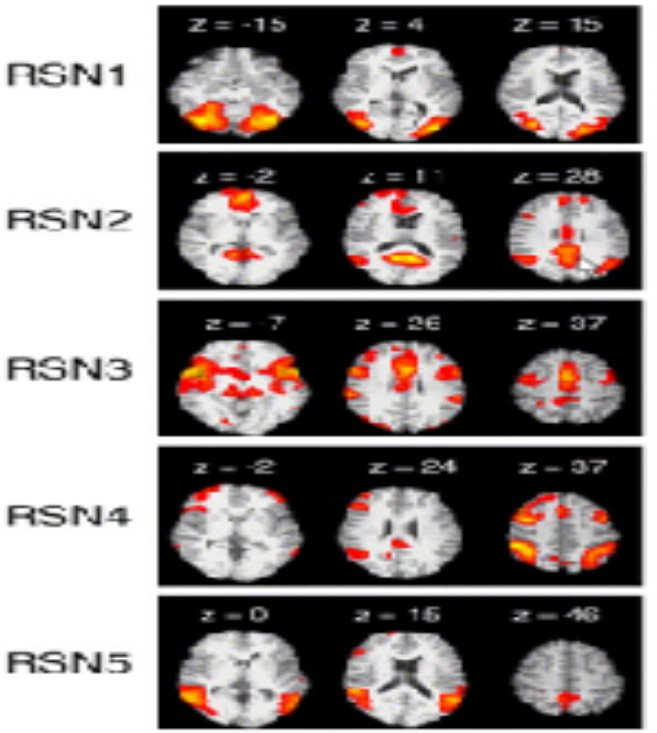
Bellgowan, et al (2003), PNAS 100, 15820–15283

"Resting State" Fluctuations

Hasson, et al (2004), Science, 303, 1634-1640

Resting State Correlations





Activation:
correlation with reference function

Rest:
seed voxel in motor cortex

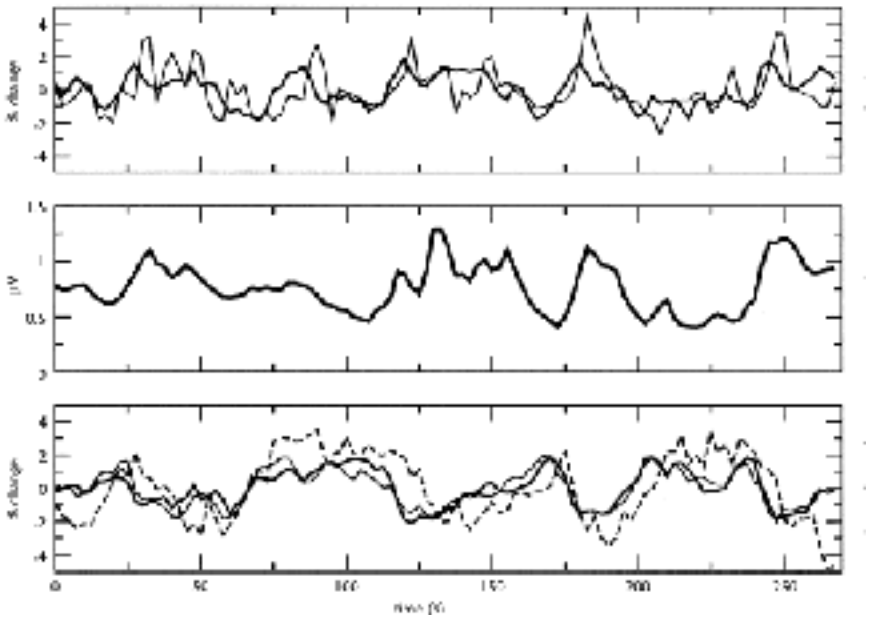
B. Biswal et al., MRM, 34:537 (1995)

BOLD correlated with 10 Hz power during "Rest"

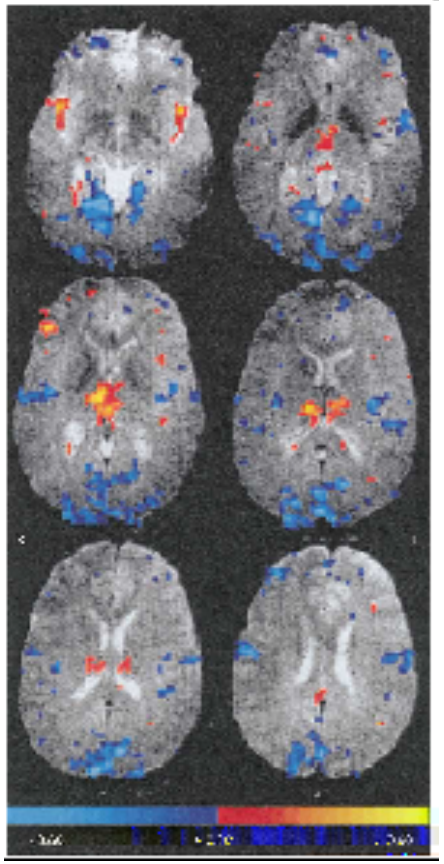
Positive

10 Hz power

Negative



Goldman, et al (2002), Neuroreport

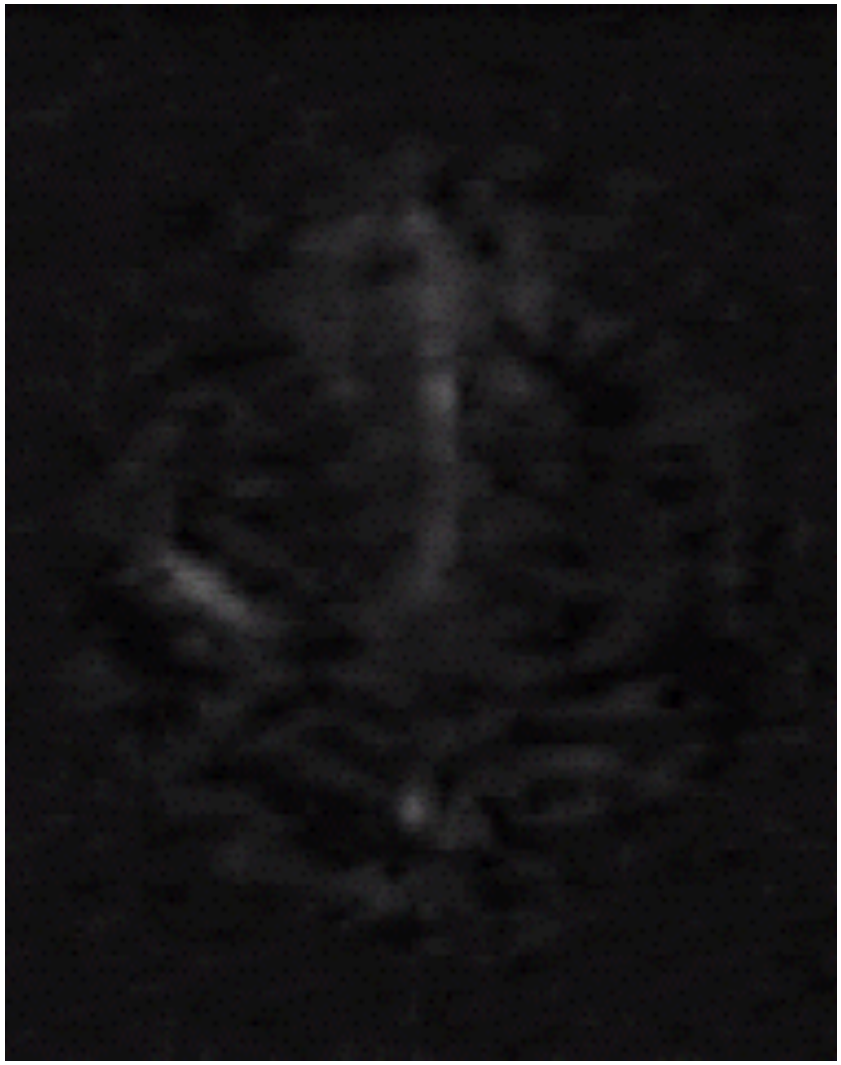


Resting state networks identified with ICA

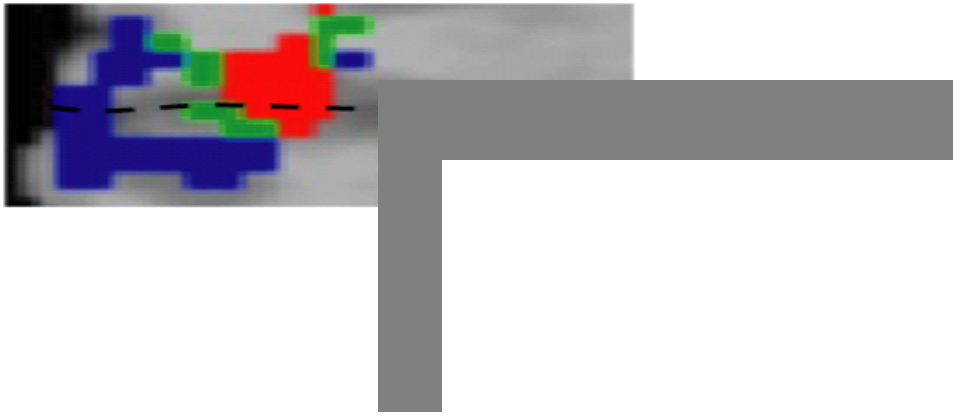
M. DeLuca, C.F. Beckmann, N. De Stefano, P.M. Matthews, S.M. Smith, fMRI resting state networks define distinct modes of long-distance interactions in the human brain. NeuroImage, 29, 1359-1367

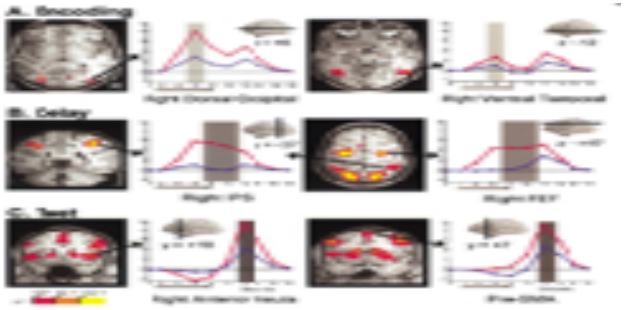
"Brain Reading"

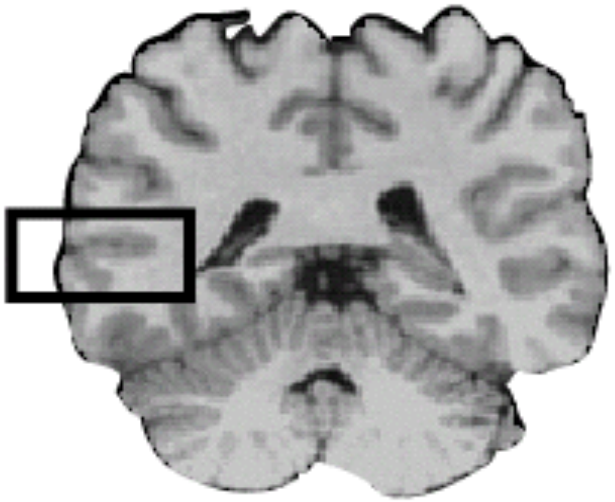
Methodology



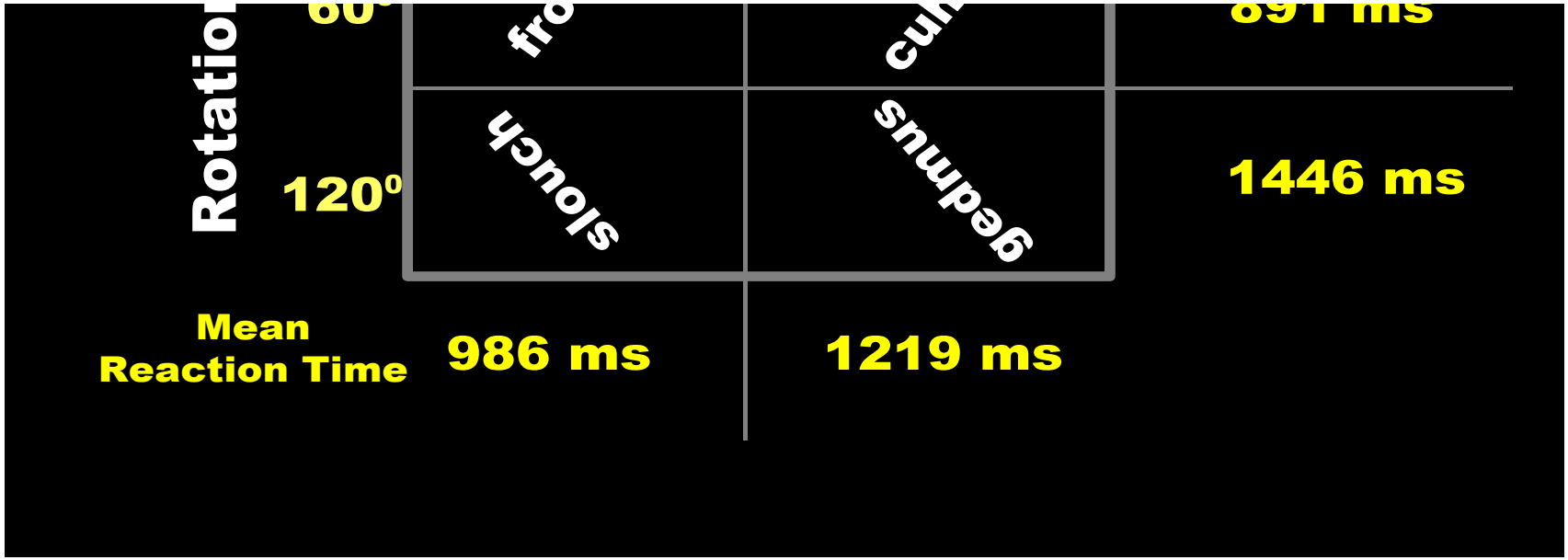
Mapping ⟷ "Reading"







Visual object categories distinguished by widely distributed inferotemporal activity pattern



Haxby et al. (2001)

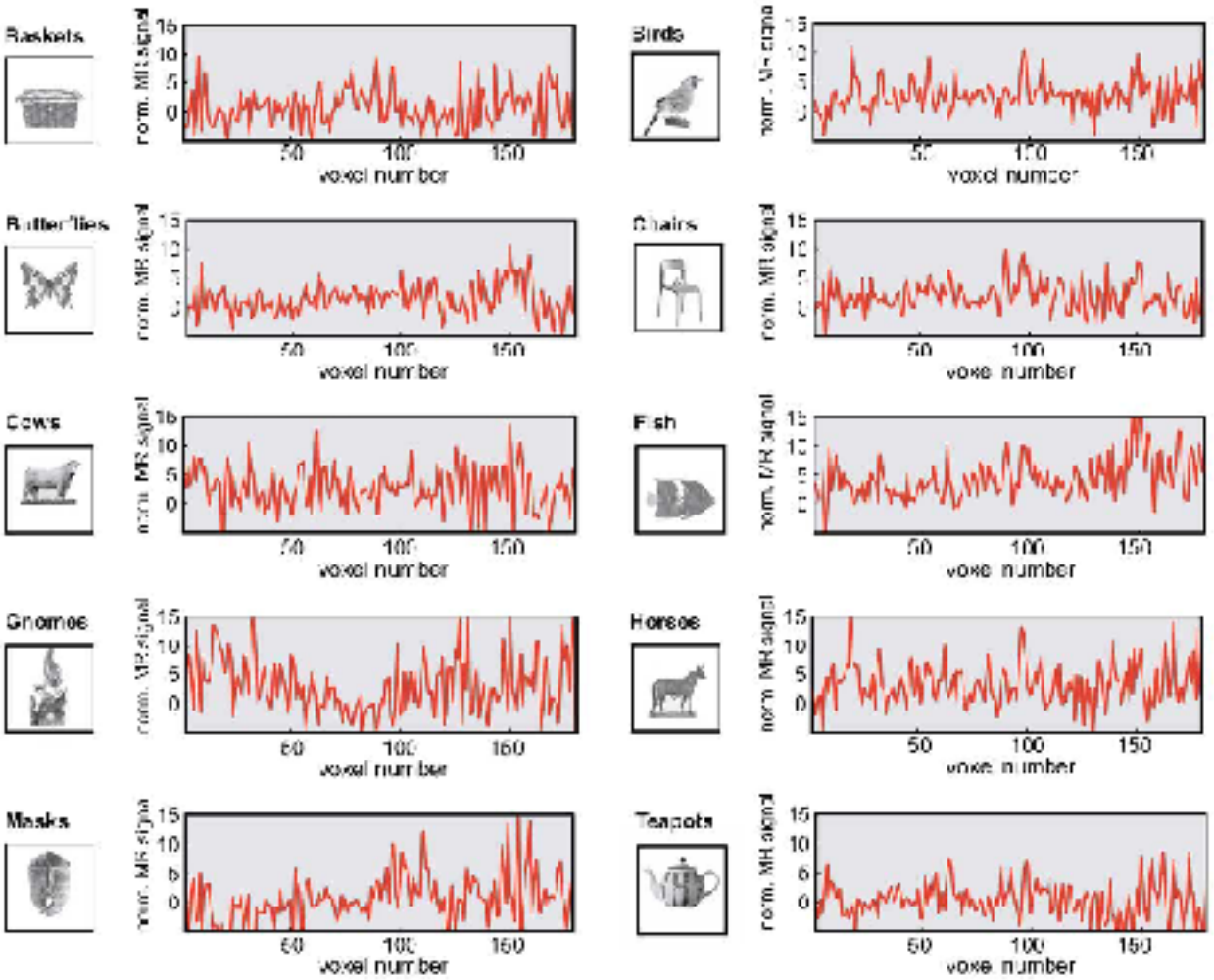
Functional magnetic resonance imaging (fMRI) "brain reading": detecting and classifying distributed patterns of fMRI activity in human visual cortex

David D. Cox[a,b,*] and Robert L. Savoy[a,c,d]

[a]Rowland Institute for Science, Cambridge, MA 02142, USA
[b]Athinoula A. Martinos Center for Biomedical Imaging, Charlestown, MA 02129, USA
[c]Myon Pictor, Inc., P.O. Box 132, Arlington, MA 02476, USA

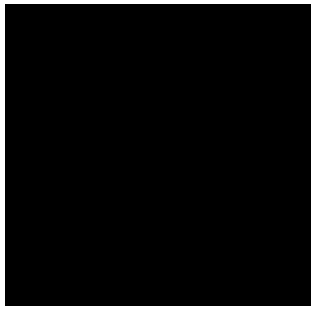
Received 15 July 2002; accepted 10 December 2002

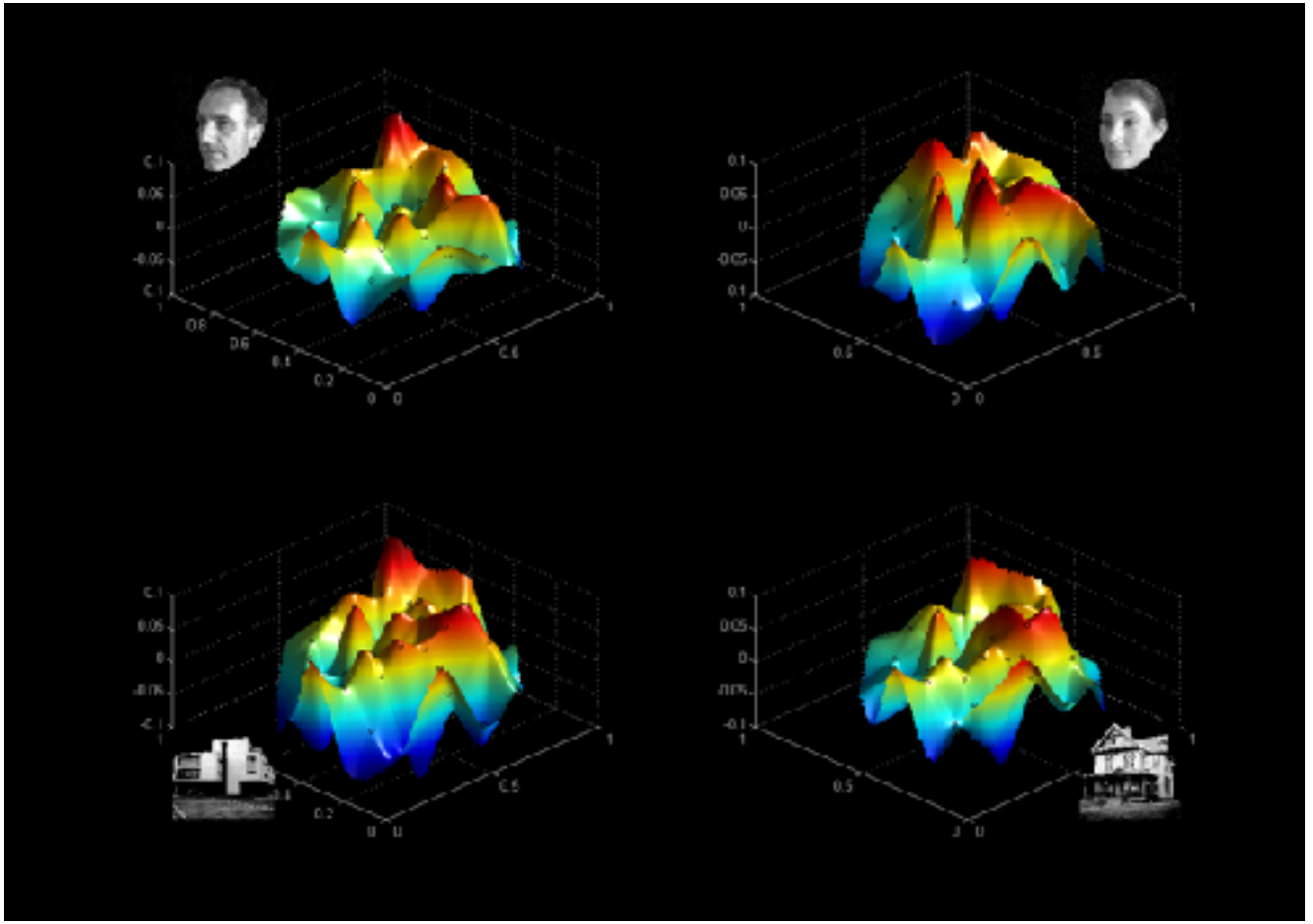
NEUROIMAGE 19 (2): 261-270 Part 1 JUN 2003



"searchlight" ROI

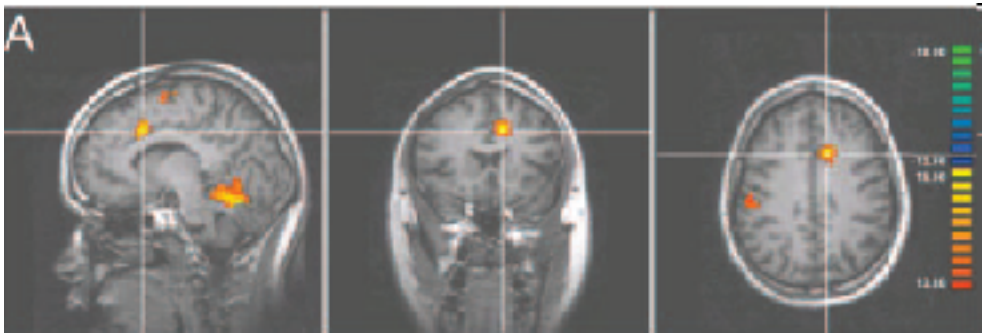
Mulitvariate analysis

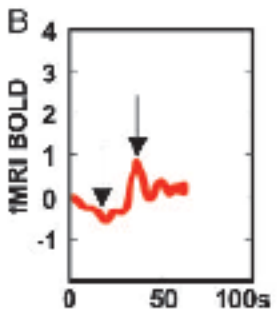


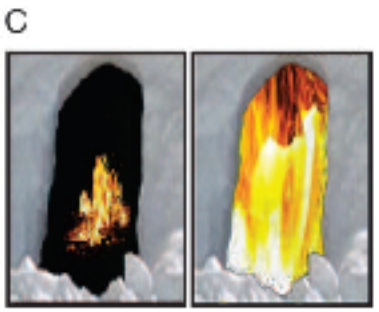


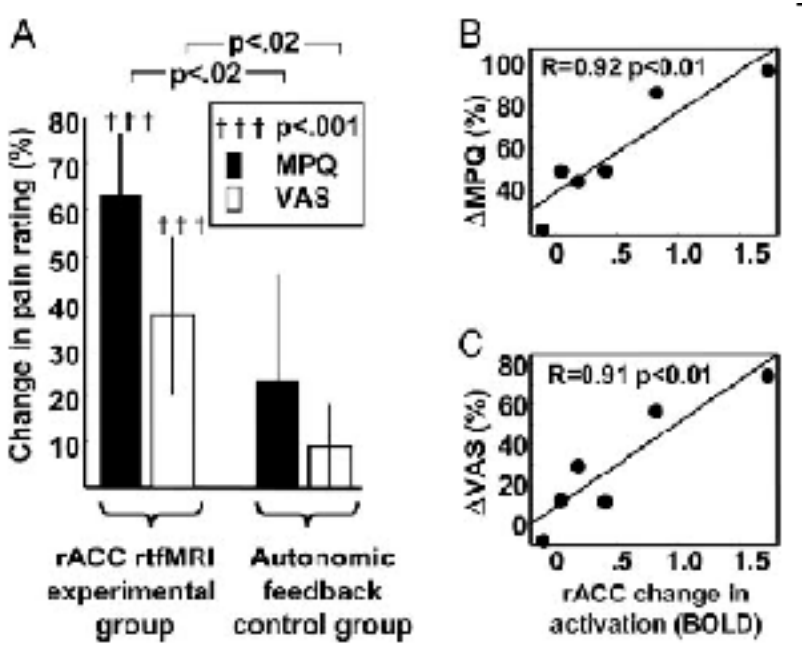
N. Kriegeskorte, R. Goebel, P. Bandettini, Proc. Nat'l. Acad. Sci. USA, 103, 3863-3868 (2006)

Real time fMRI feedback to reduce chronic pain









Control over brain activation and pain learned by using real-time functional MRI, R. C. deCharms, et al. PNAS, 102; 18626-18631 (2005)

Current Uses of fMRI

Understanding normal brain organization and changes

- -networks involved with specific tasks (low to high level processing)
- -changes over time (seconds to years)
- -correlates of behavior (response accuracy, performance changes...)

Clinical research

- -correlates of specifically activated networks to clinical populations
- -presurgical mapping
- -epileptic foci mapping
- -drug effects

Potential uses of fMRI

Complementary use for clinical diagnosis

- -utilization of clinical research results

Clinical treatment and assessment

- -drug, therapy, rehabilitation, biofeedback

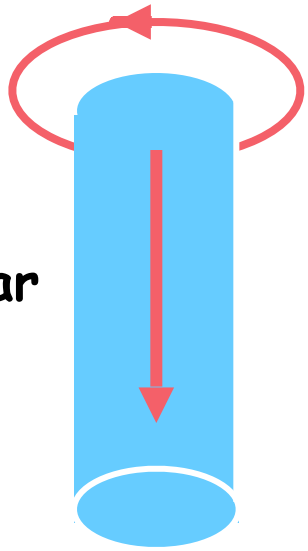
Non clinical uses

- -complementary use with behavioral results
- -lie detection
- -prediction of behavior tendencies (many contexts)
- -brain/computer interface

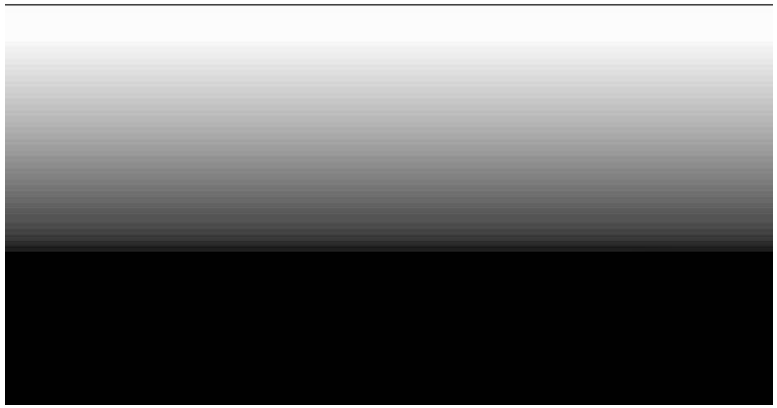
Section on Functional Imaging Methods & Functional MRI Facility Jan 19, 2007

Back row: Wenming Luh, Niko Kriegeskorte, Rasmus Birn, Tyler Jones, Sean Marrett
Middle row: Jon West, Kay Kuhns, Anthony Boemio, Peter Bandettini, Joey Dunsmoor, Doug Ruff, Kevin Murphy
Front row: Dorian Van Tassel, Jerzy Bodurka, Adam Thomas, Marieke Mur, David Knight

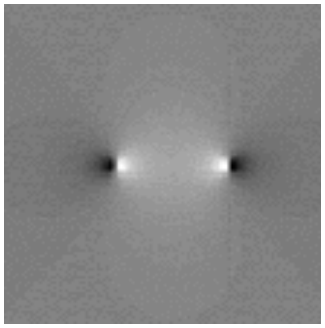
Magnetic Field



Intracellular Current



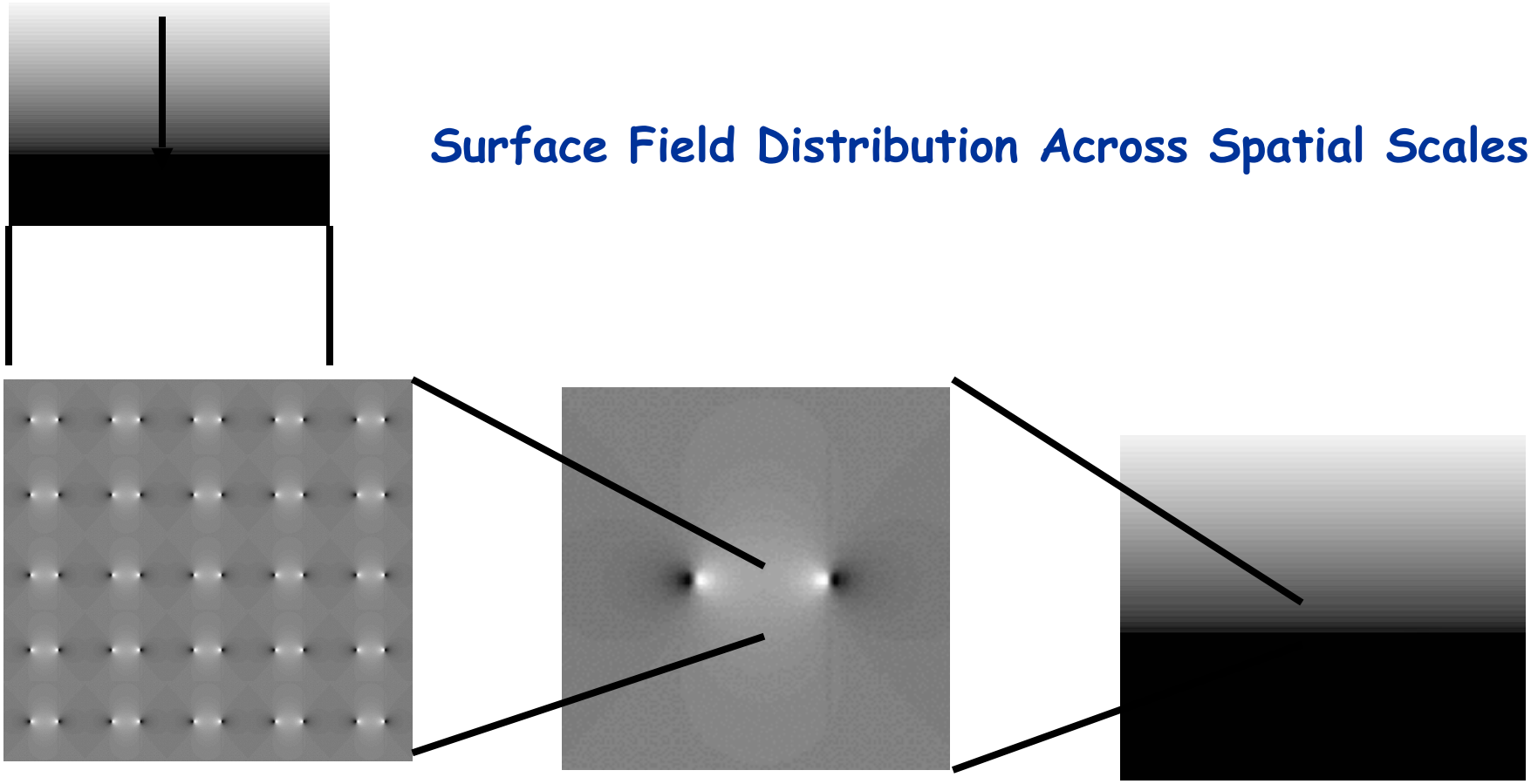
Surface Fields



100 fT at on surface of skull

J.P. Wikswo Jr et al. J Clin Neuronphy 8(2): 170-188, 1991

Surface Field Distribution Across Spatial Scales

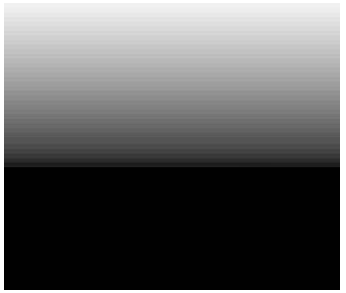


Adapted from: J.P. Wikswo Jr et al.

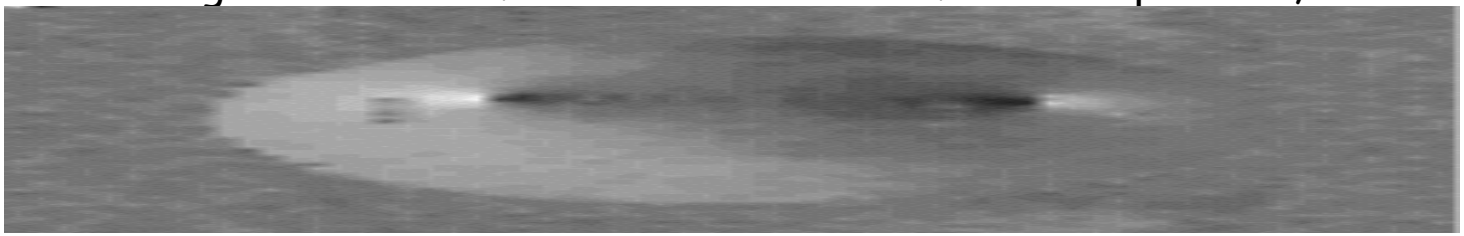
J Clin Neurophy 8(2): 170-188, 1991

Magnetic field associated with a bundle of dendrites

Because B_{MEG}=100fT is measured by MEG on the scalp

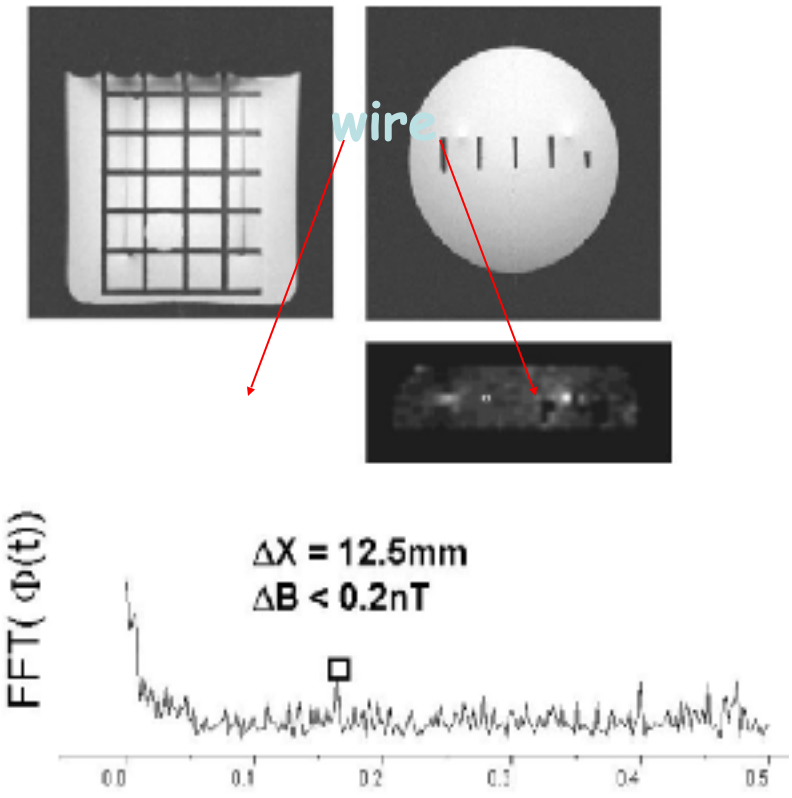


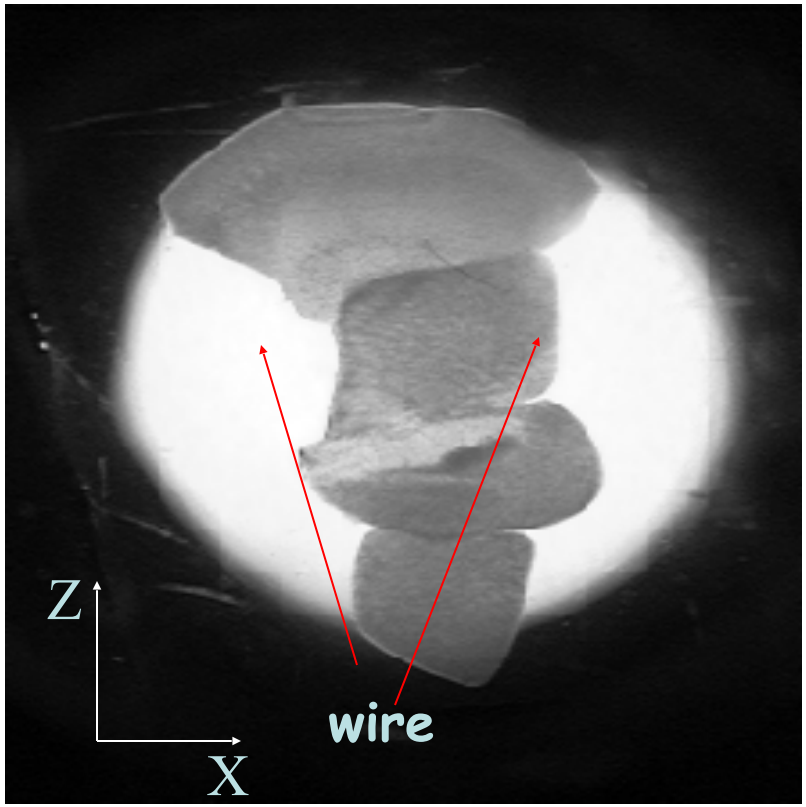
at least 50,000 neurons (0.002 fT (per dendrite) x 50,000 = 100 fT), must coherently act to generate such field. These bundles of neurons produce, within a typical voxel, 1



$B_{MRI} \approx 0.2nT$

Current Phantom Experiment

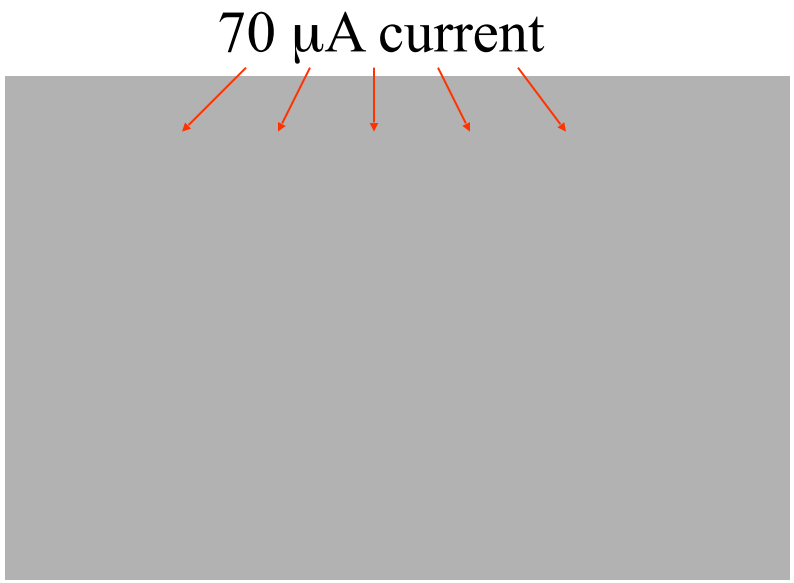




calculated B_c || B_0

$\Delta\phi \cong 20^0$

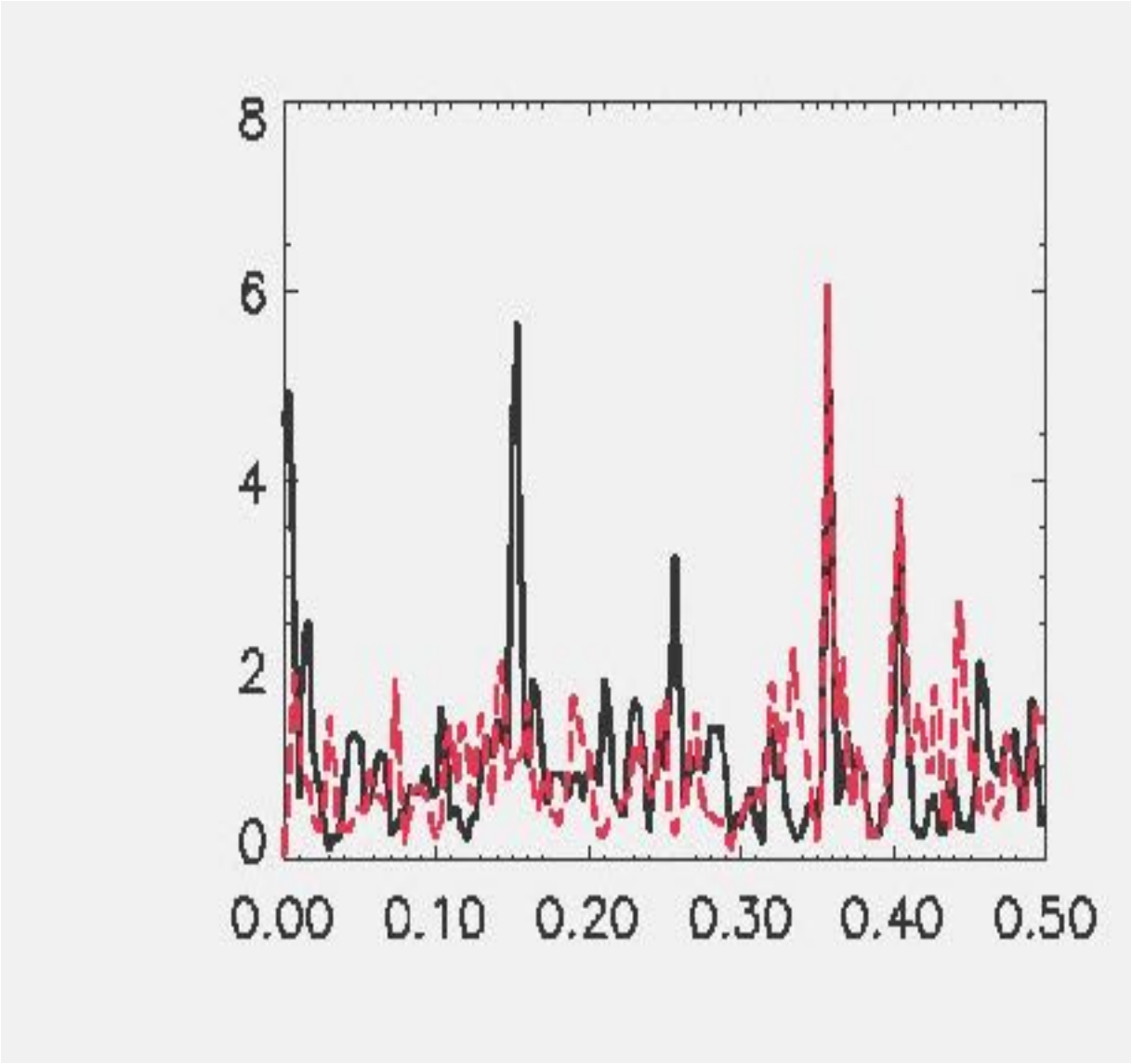
Measurement



Single shot GE EPI

Correlation image

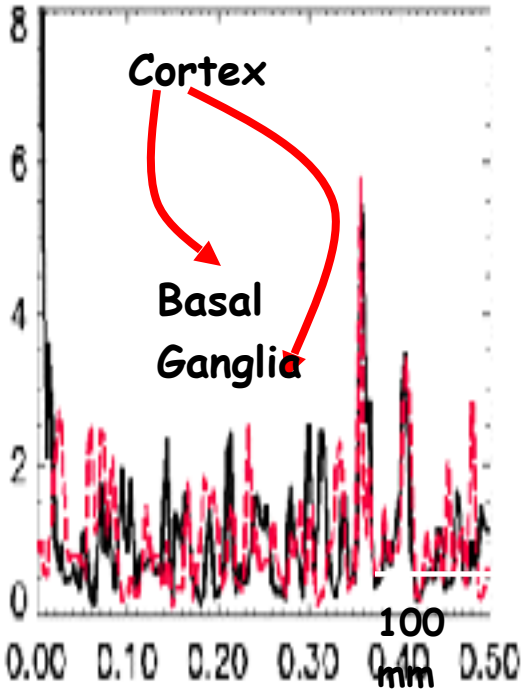
J. Bodurka, P. A. Bandettini. Magn. Reson. Med. 47: 1052-1058, (2002).



J. Bodurka, P. A. Bandettini. Magn. Reson. Med. 47: 1052-1058, (2002).

in vitro model

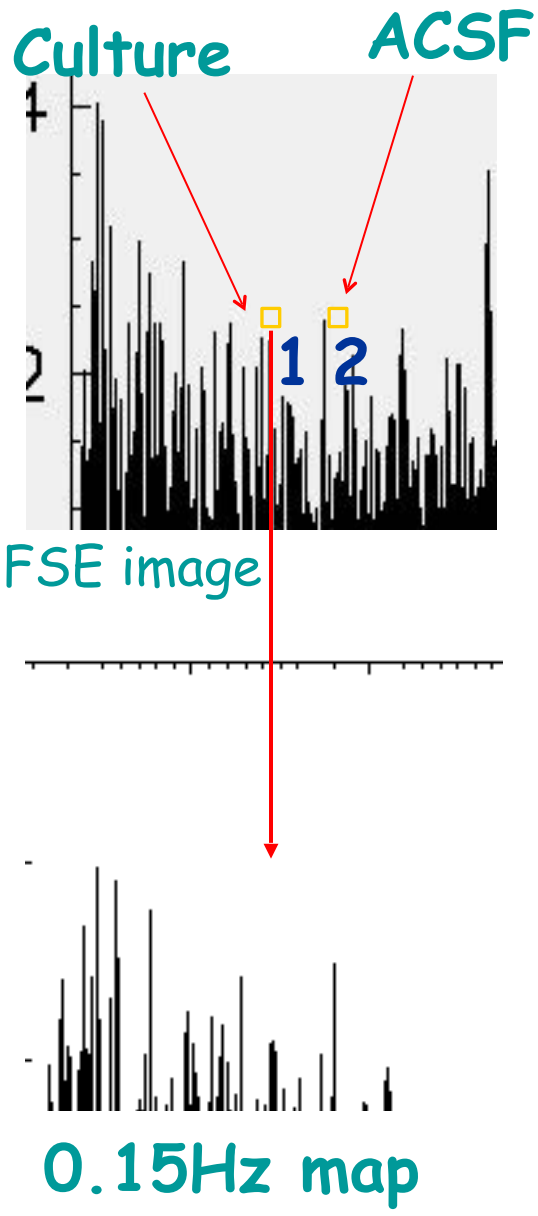
Organotypic (no blood supply or hemoglobin traces) sections of newborn-rat somato-sensory Cortex &Basal Ganglia

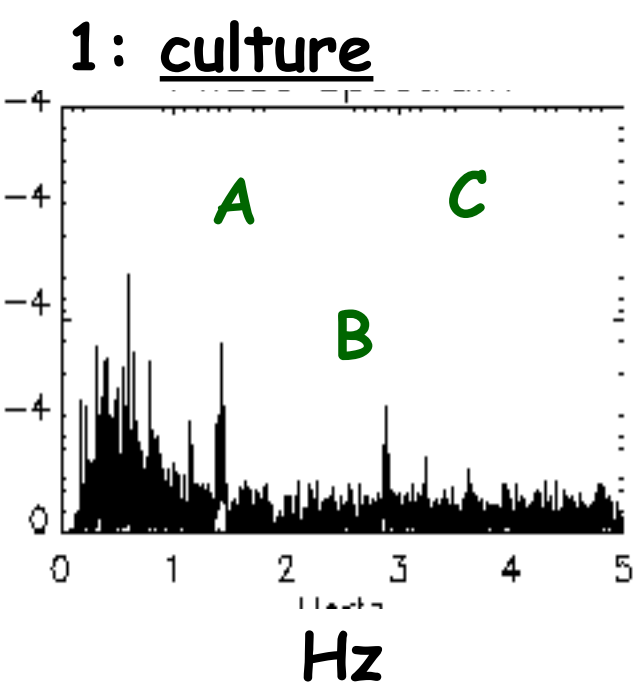


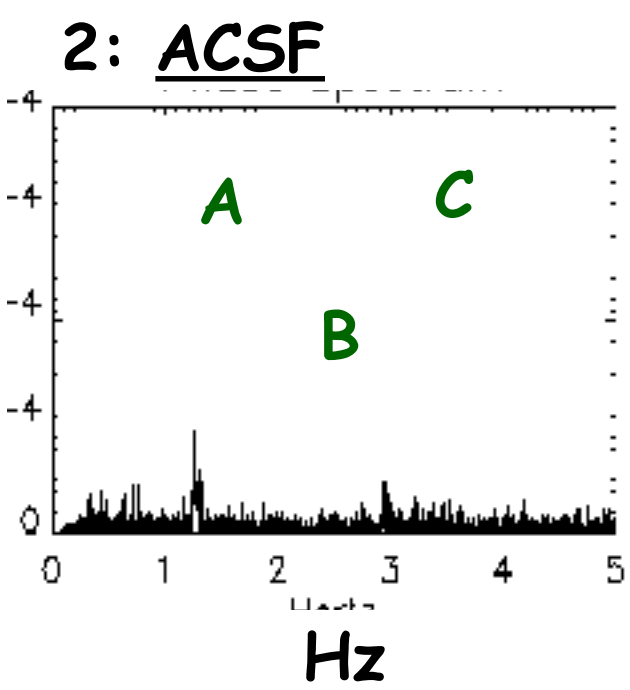
- Size: in-plane:~1-2mm^2, thickness: 60-100μm
- Neuronal Population: 10,000-100,000
- Spontaneous synchronized activity < 2Hz
- Epileptiform activity
- Spontaneous beta freq. activity (20-30Hz)
- Network Activity Range: ~ 0.5-15μV

Plenz, D. et al. Neurosci 70(4): 861-924, 1996

3 Tesla data







Active condition: black line

Inactive condition: red line

A: 0.15 Hz activity, on/off frequency

B: activity

C: scanner noise (cooling-pump)

7 Tesla data

TTX

Power decrease between PRE & TTX EEG : ~ 81%

Decrease between PRE & TTX MR phase: ~ 70%

Decrease between PRE & TTX MR magnitude: ~ 8%

N. Petridou, D. Plenz, A. C. Silva, J. Bodurka, M. Loew, P. A. Bandettini, Proc. Nat'l. Acad. Sci. USA. 103, 16015-16020 (2006).