What more information can we extract from the FMRI time series?

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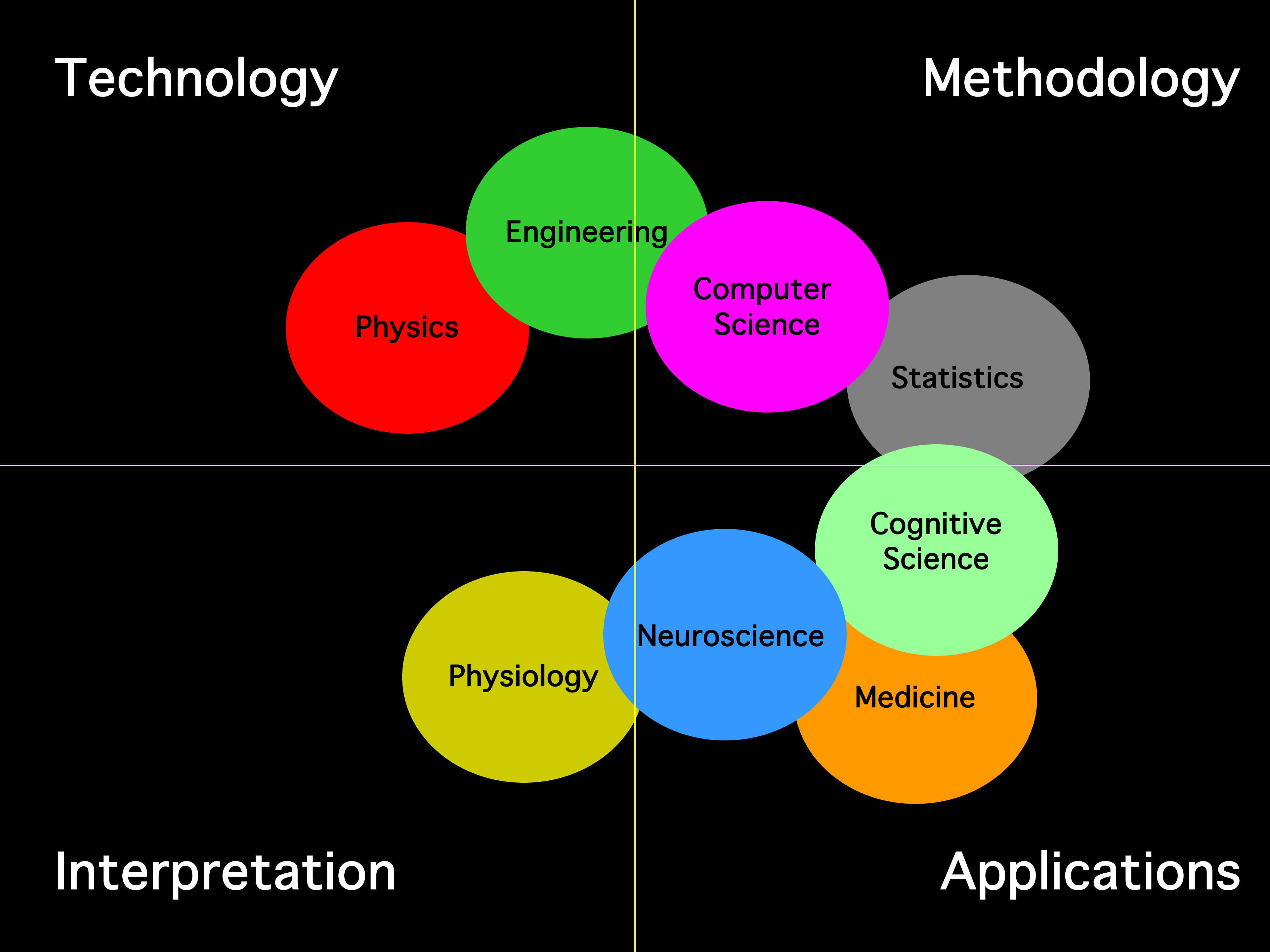
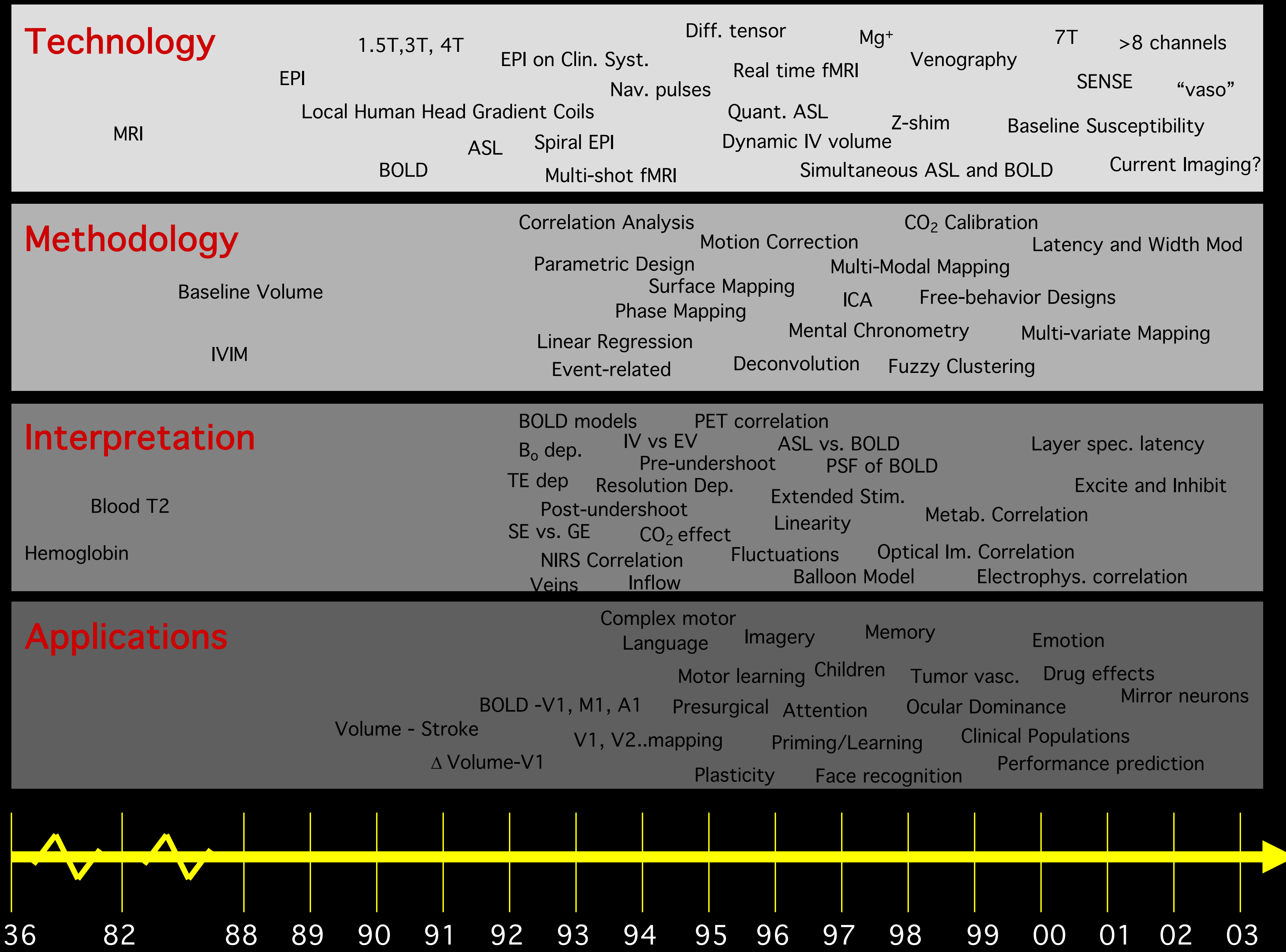
Unit on Functional Imaging Methods
&
3T Neuroimaging Core Facility

Laboratory of Brain and Cognition
National Institute of Mental Health

BOLD Contrast


Technology
Methodology
Engineering
Physics
Computer Science
Statistics
Cognitive Science
Neuroscience
Physiology
Medicine
Interpretation
Applications


Technology
MRI
EPI
1.5T,3T, 4T
Local Human Head Gradient Coils
BOLD
ASL
EPI on Clin. Syst.
Spiral EPI
Multi-shot fMRI
Nav. pulses
Diff. tensor
Real time fMRI
Quant. ASL
Dynamic IV volume
Simultaneous ASL and BOLD
Mg^{+}
Z-shim
Venography
7T
SENSE
Baseline Susceptibility
>8 channels
"vaso"
Current Imaging?
Methodology
Baseline Volume
IVIM
Correlation Analysis
Parametric Design
Surface Mapping
Phase Mapping
Linear Regression
Event-related
Motion Correction
Deconvolution
CO_2 Calibration
Multi-Modal Mapping
ICA
Mental Chronometry
Free-behavior Designs
Fuzzy Clustering
Latency and Width Mod
Multi-variate Mapping
Interpretation
Blood T2
Hemoglobin
BOLD models
B_o dep.
TE dep
Post-undershoot
SE vs. GE
NIRS Correlation
Veins
IV vs EV
Pre-undershoot
Resolution Dep.
CO_2 effect
Inflow
PET correlation
ASL vs. BOLD
PSF of BOLD
Extended Stim.
Linearity
Fluctuations
Balloon Model
Optical Im. Correlation
Metab. Correlation
Electrophys. correlation
Layer spec. latency
Excite and Inhibit
Applications
Volume - Stroke
∆ Volume-V1
BOLD -V1, M1, A1
V1, V2..mapping
Complex motor
Language
Motor learning
Presurgical
Plasticity
Imagery
Children
Attention
Priming/Learning
Face recognition
Memory
Tumor vasc.
Ocular Dominance
Clinical Populations
Performance prediction
Emotion
Drug effects
Mirror neurons
36
82
88
89
90
91
92
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01
02
03

What more information can we extract from the FMRI time series?

- Event-related developments
- Linearity (Neuronal and/or Hemodynamic?)
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

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- Event-related developments
- Linearity (Neuronal and/or Hemodynamic?)
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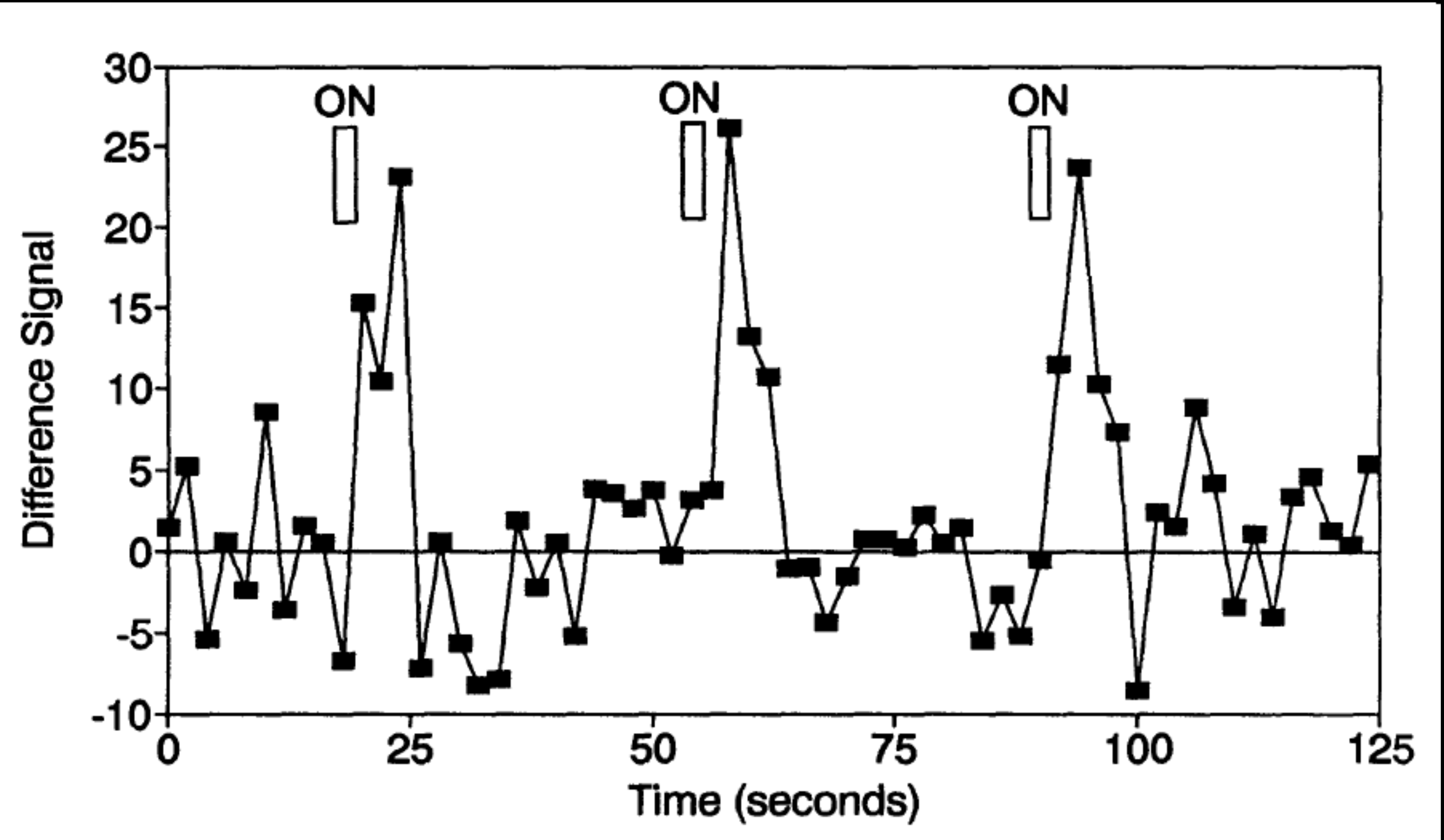
First Event-related fMRI Results



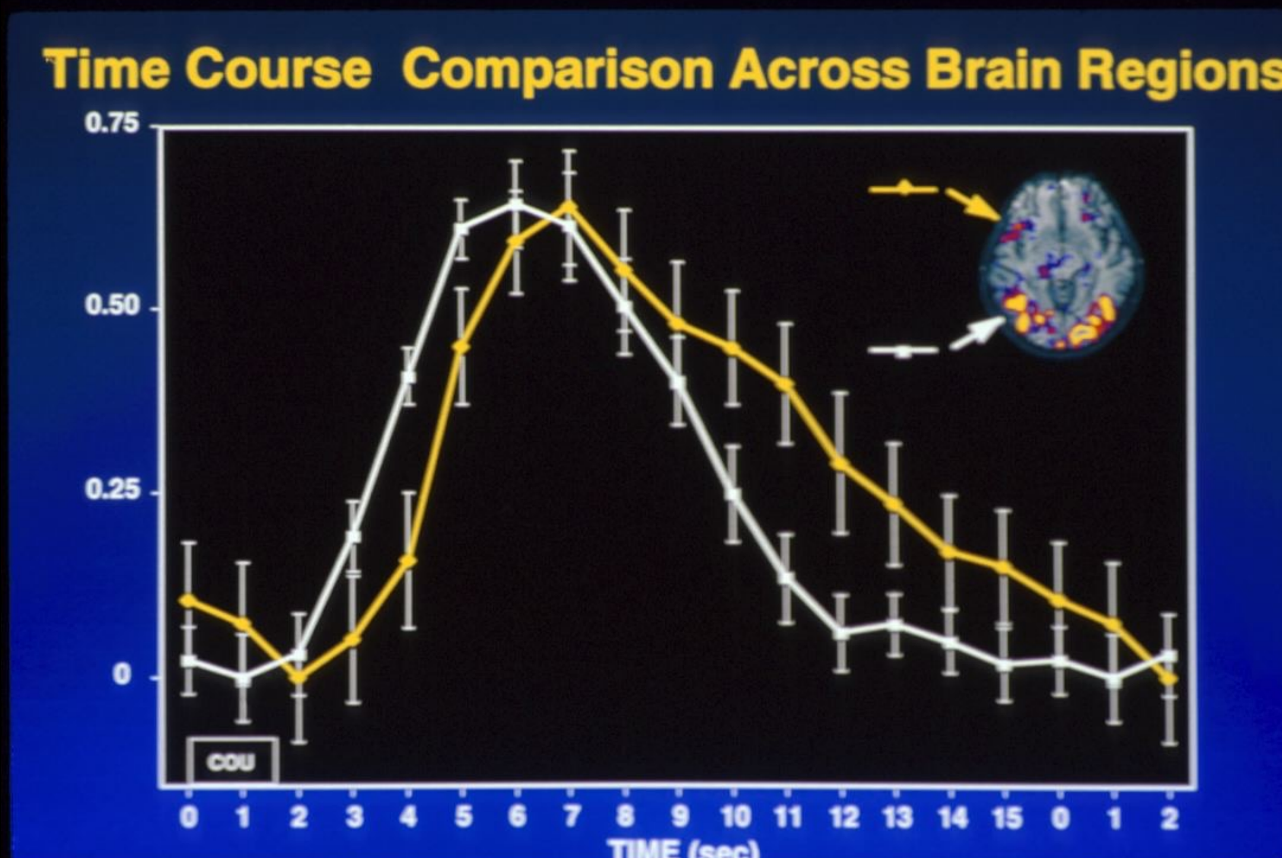
Blamire, A. M., et al. (1992). "Dynamic mapping of the human visual cortex by high-speed magnetic resonance imaging." Proc. Natl. Acad. Sci. USA 89: 11069-11073.

Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 14878–14883, December 1996
Neurobiology

Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging

(neuroimaging/single trial/language/prefrontal)

Randy L. Buckner[†‡§¶], Peter A. Bandettini[†‡], Kathleen M. O'Craven[†‖], Robert L. Savoy[†‖],
Steven E. Petersen[**††], Marcus E. Raichle[§**††], and Bruce R. Rosen[†‡]



Visual Cortex

ISI, SD

20, 20

12, 2

10, 2

ISI, SD

8, 2

6, 2

4, 2

2, 2

P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

Motor Cortex

ISI, SD

20, 20

12, 2

10, 2

ISI, SD

8, 2

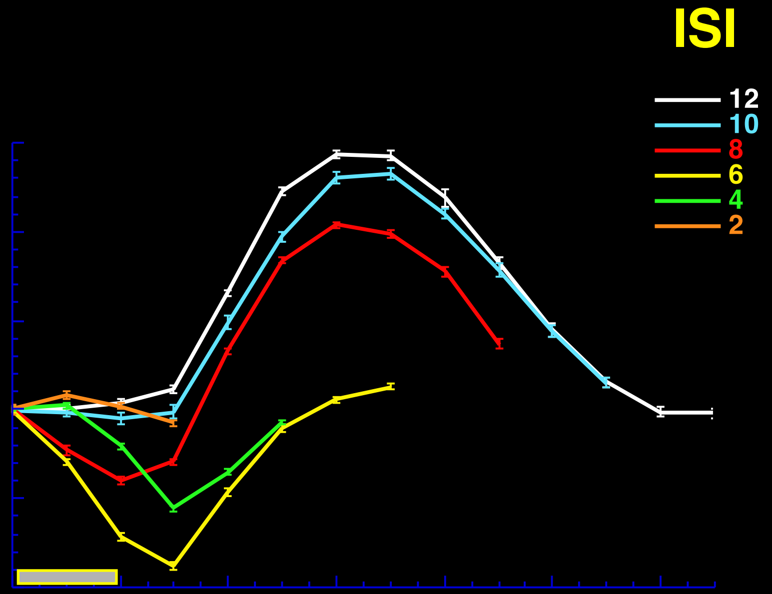
6, 2

4, 2

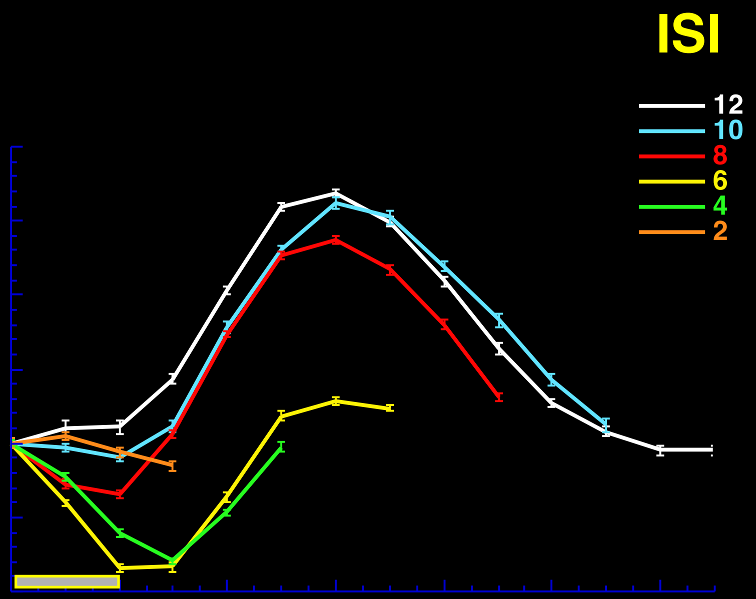
2, 2

P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

Motor Cortex

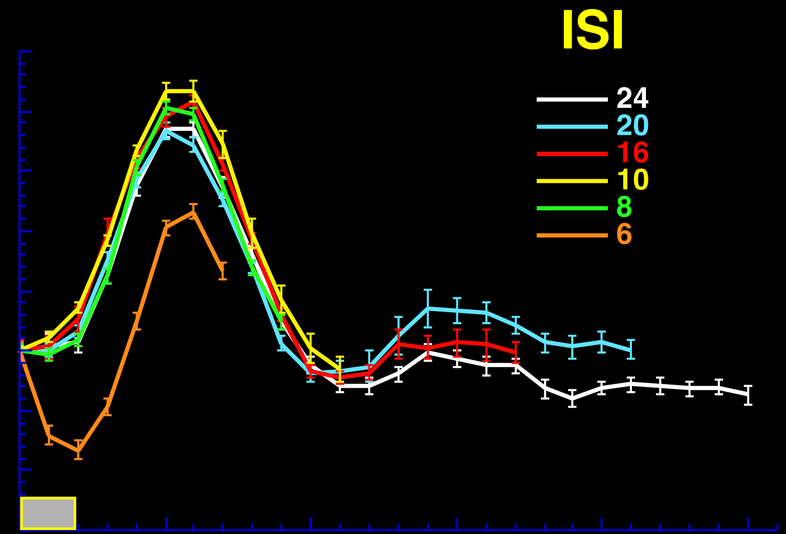


Visual Cortex

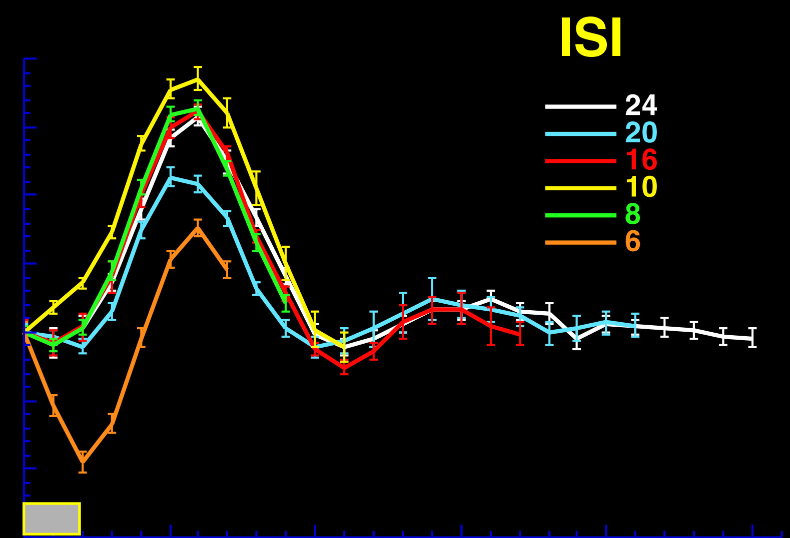


P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

Motor Cortex

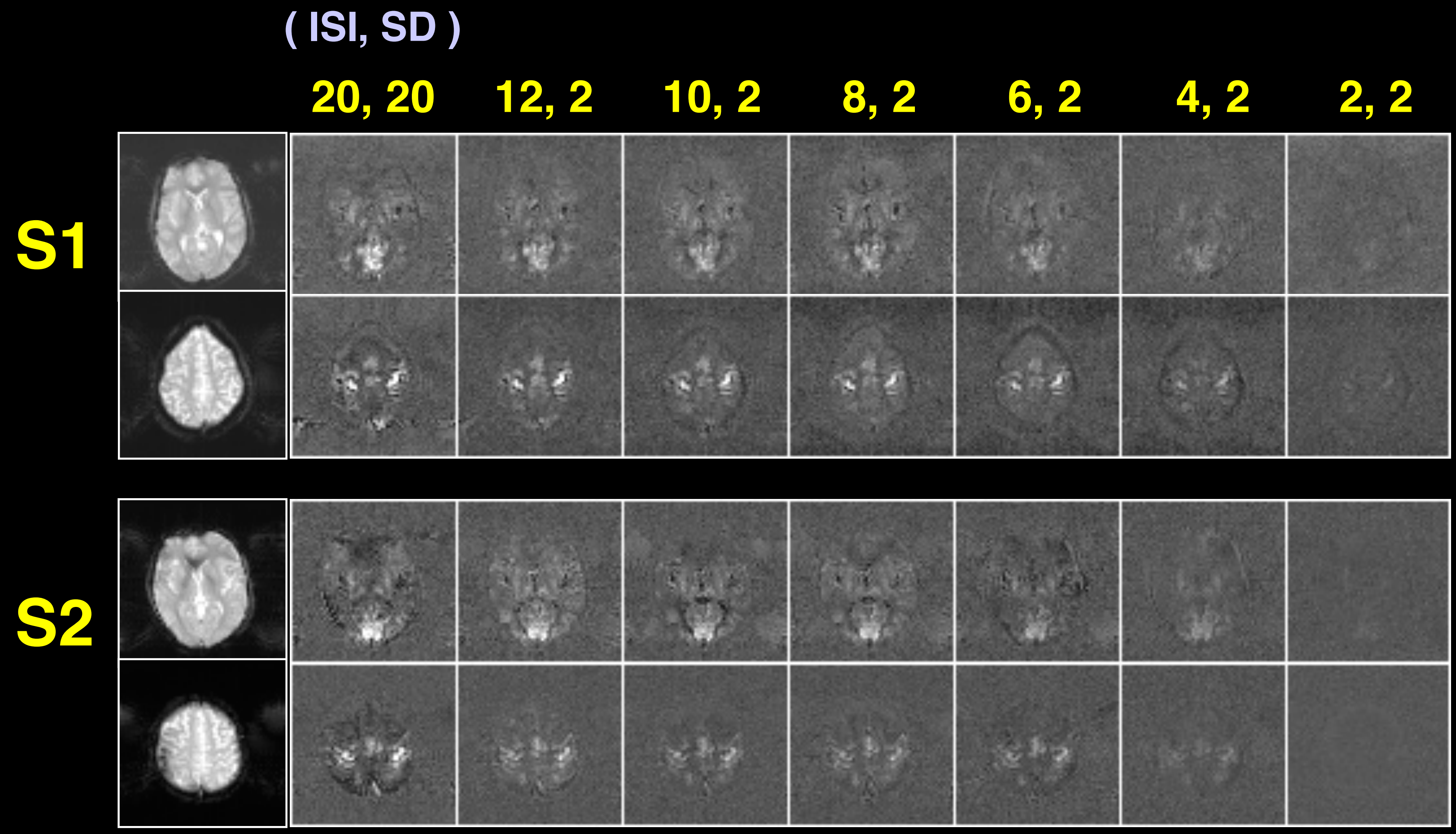


Visual Cortex



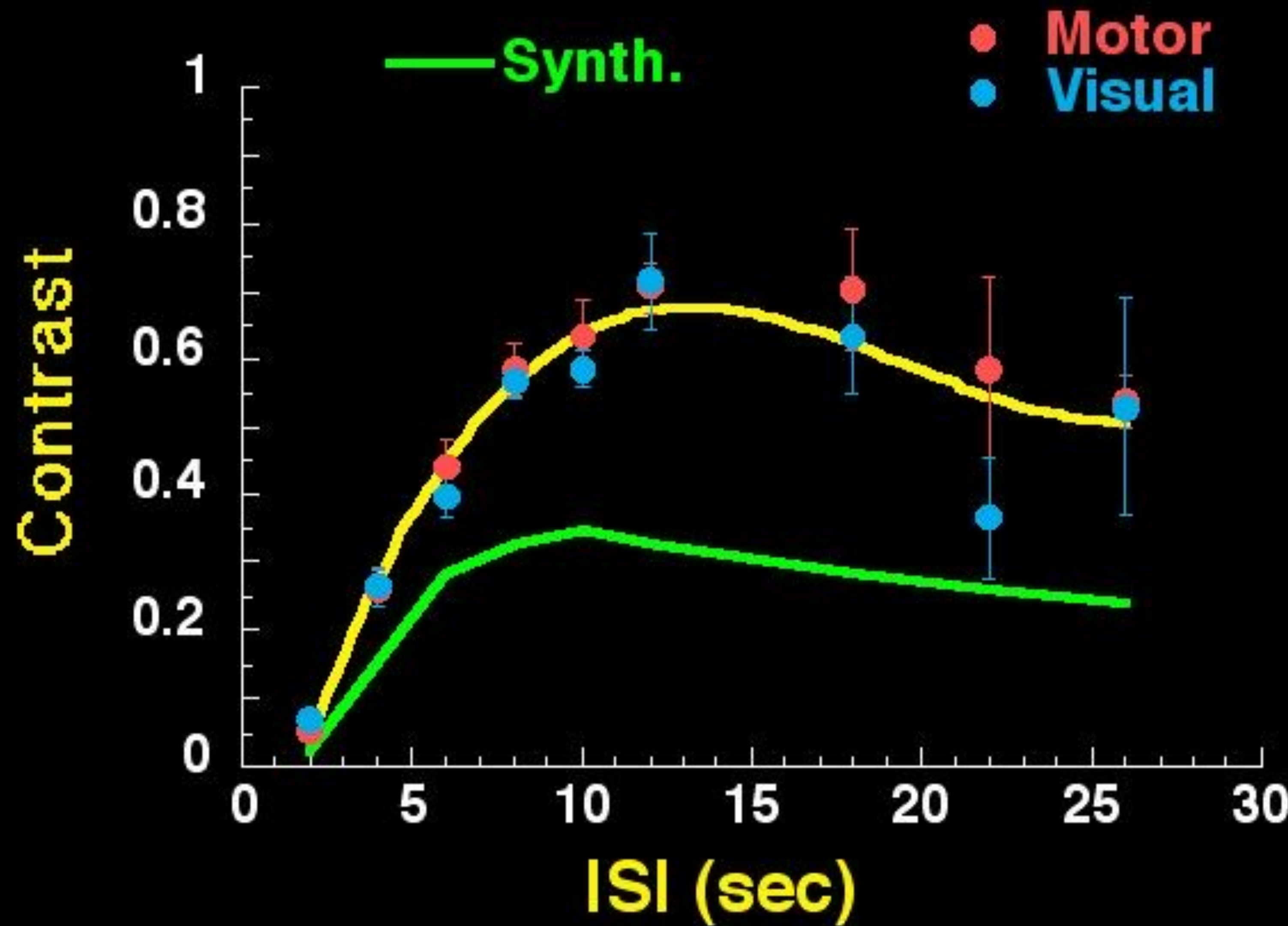
P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

Contrast to Noise Images



P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

Functional Contrast



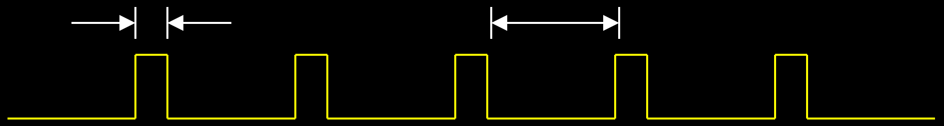
(Block design = 1)

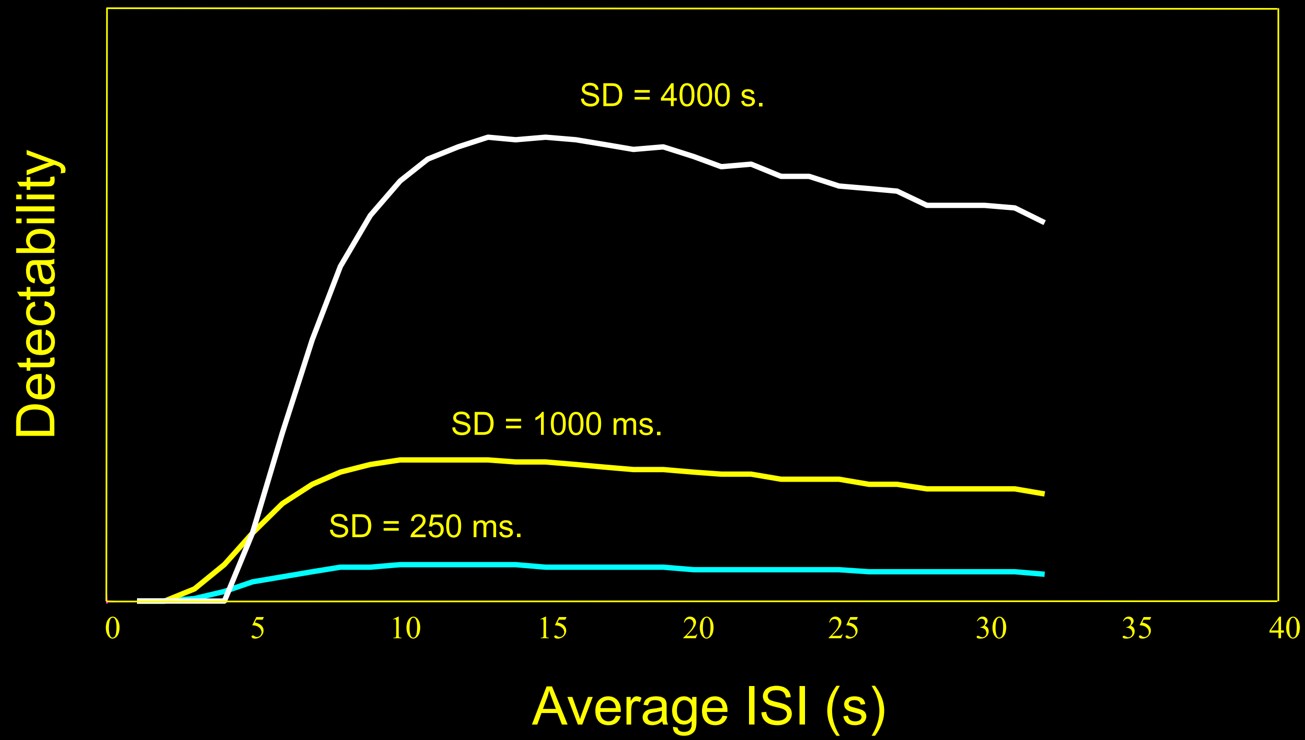
P. A. Bandettini, R. W. Cox. Functional contrast in constant interstimulus interval event - related fMRI: theory and experiment. *Magn. Reson. Med.* **43**: 540-548 (2000).

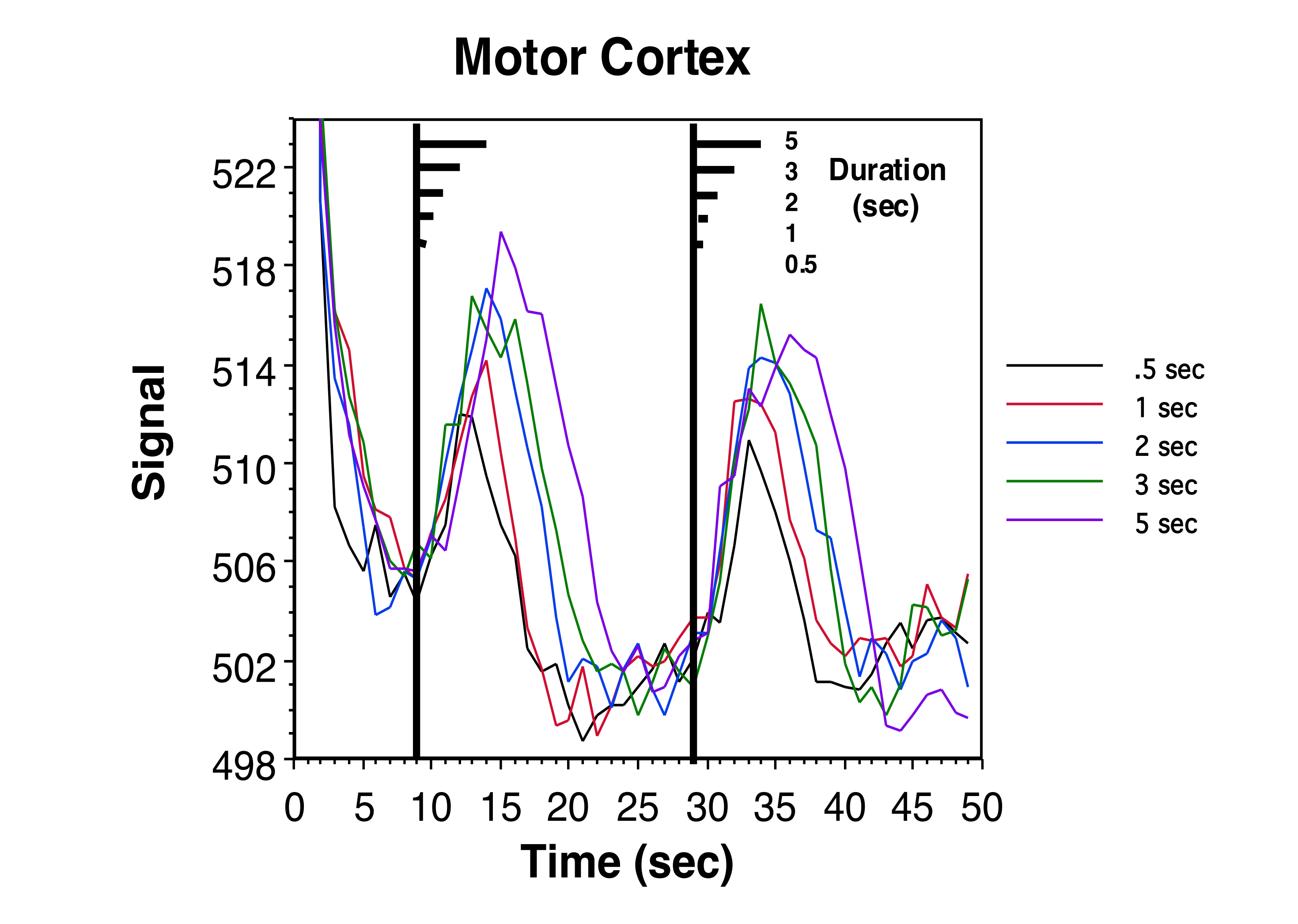
Detectability: constant ISI

SD – stimulus duration

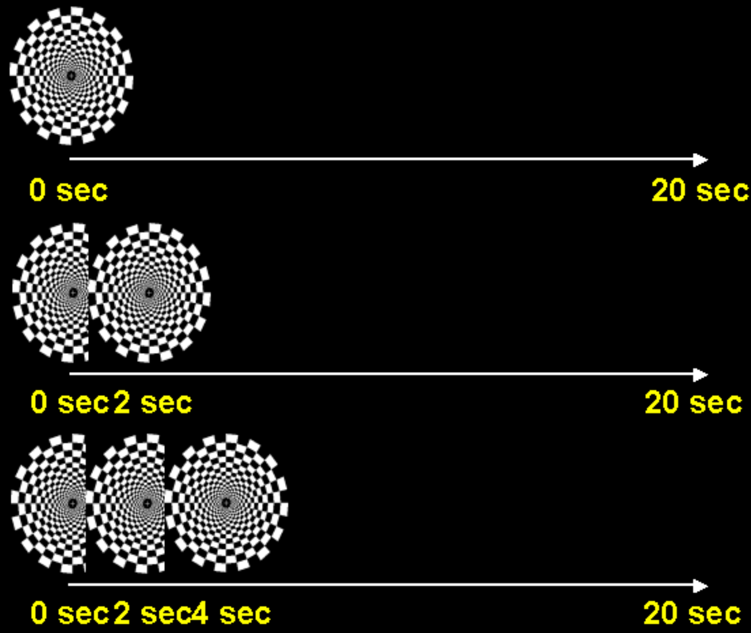
ISI – inter-stimulus interval







Bandettini, et al., The functional dynamics of blood oxygenation level contrast in the motor cortex, 12'th Proc. Soc. Magn. Reson. Med., New York, p. 1382. (1993).

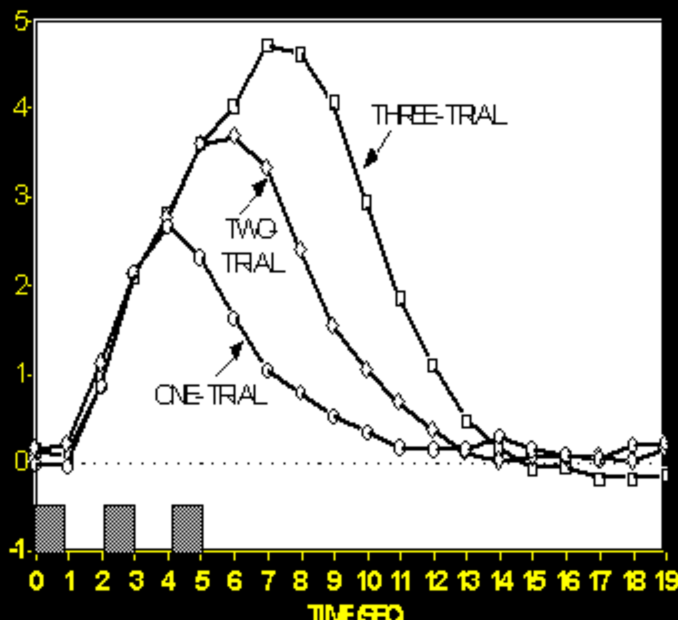


◆ Human Brain Mapping 5:329–340(1997) ◆

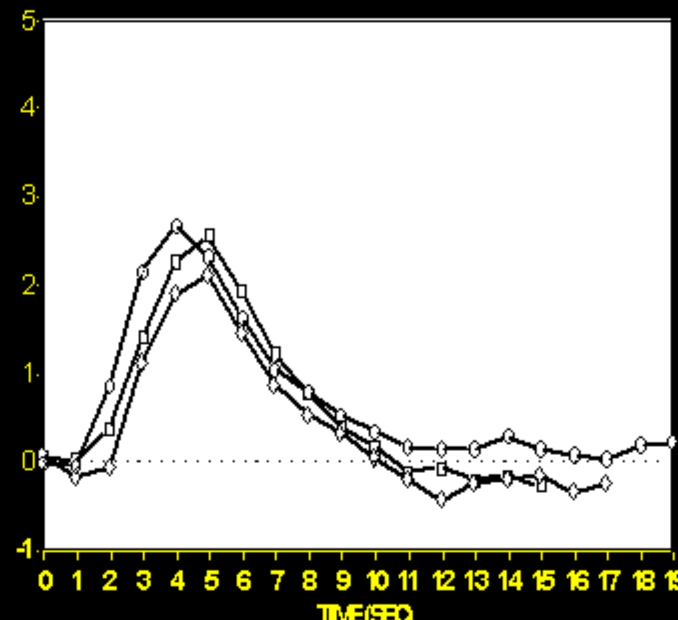
Selective Averaging of Rapidly Presented Individual Trials Using fMRI

Anders M. Dale* and Randy L. Buckner

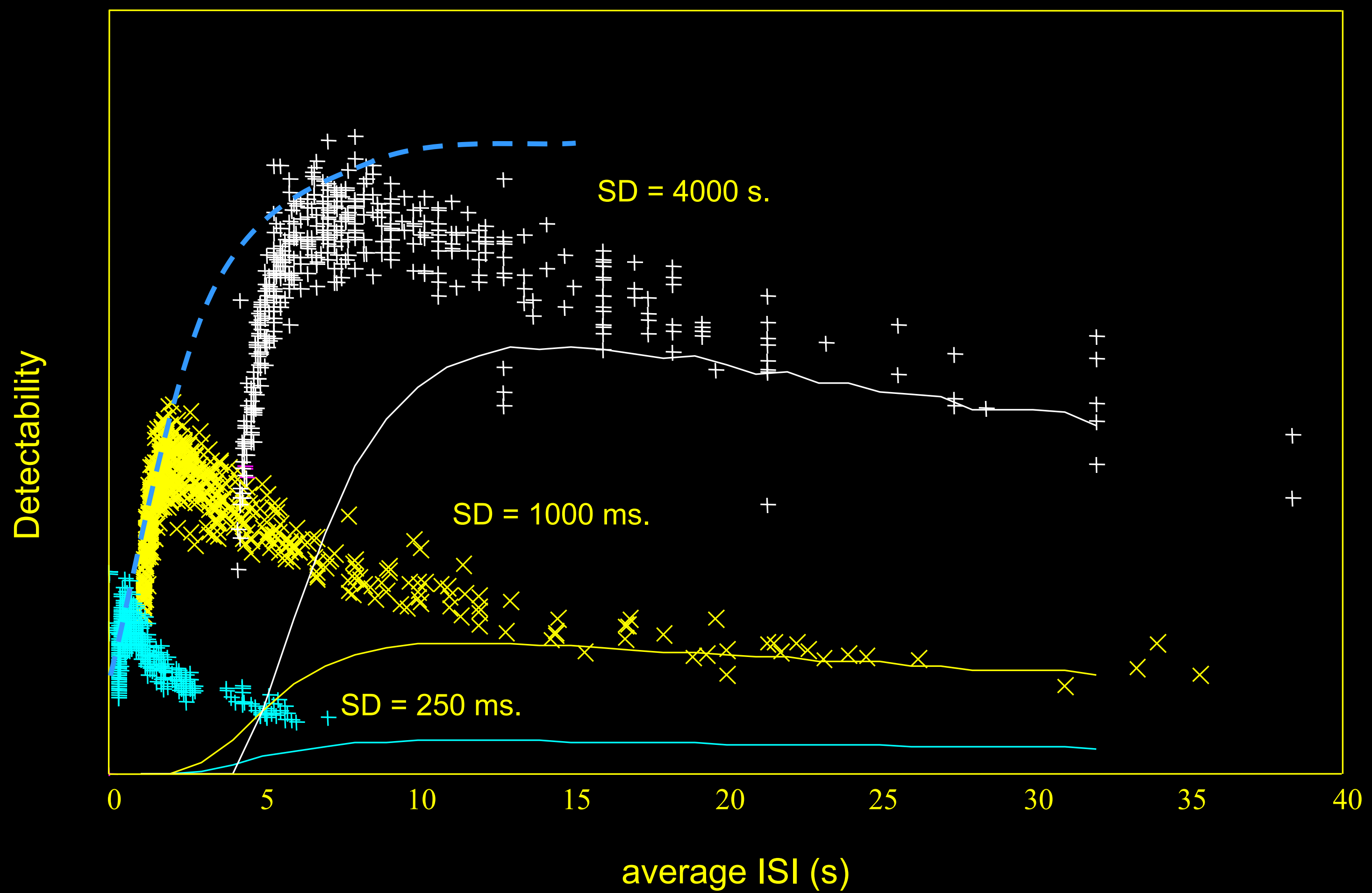
RAW DATA



ESTIMATED RESPONSES

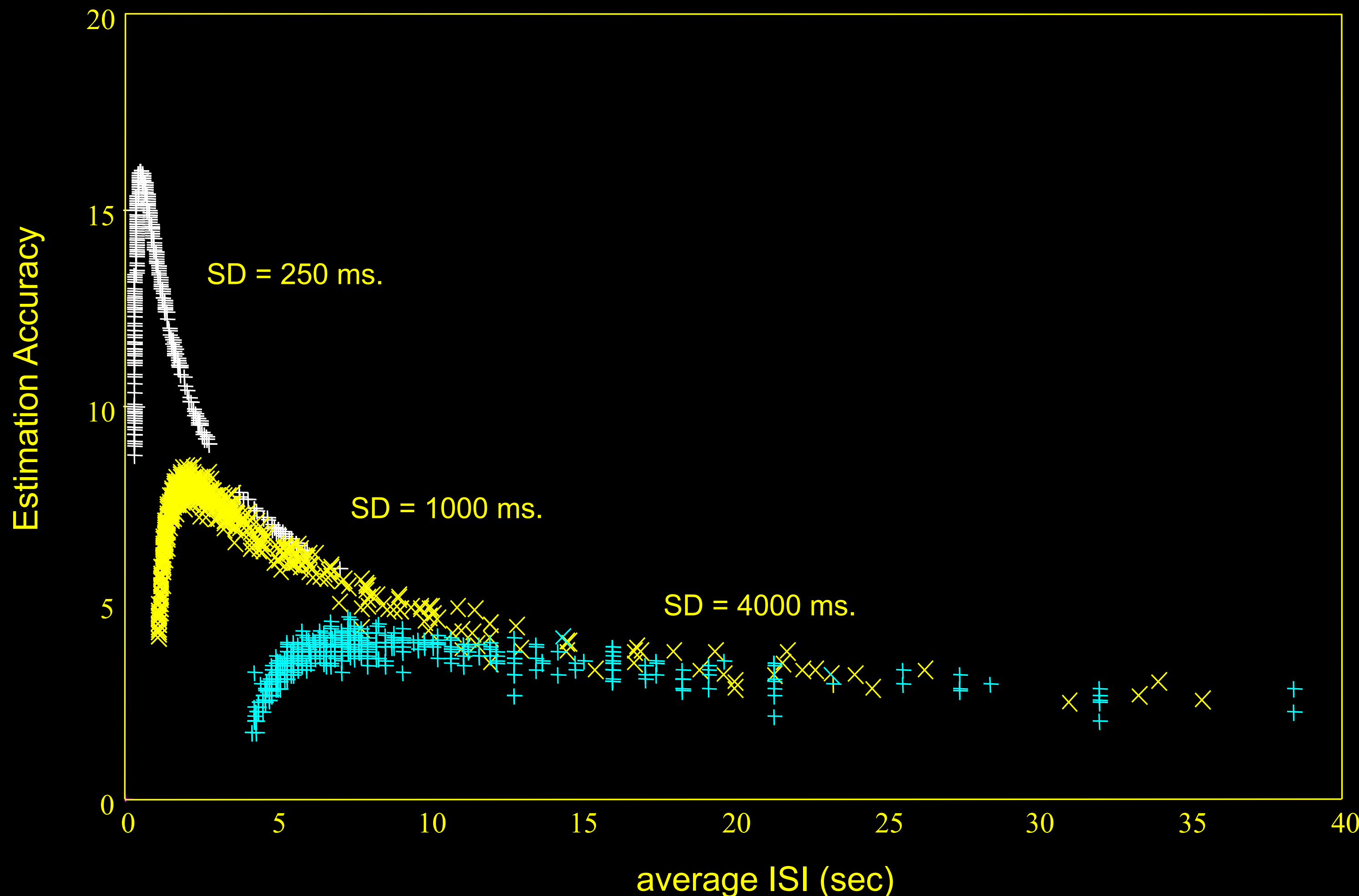


Detectability vs. Average ISI



R. M. Birn, R. W. Cox, P. A. Bandettini, Detection versus estimation in Event-Related fMRI: choosing the optimal stimulus timing. *NeuroImage* 15: 262-264, (2002).

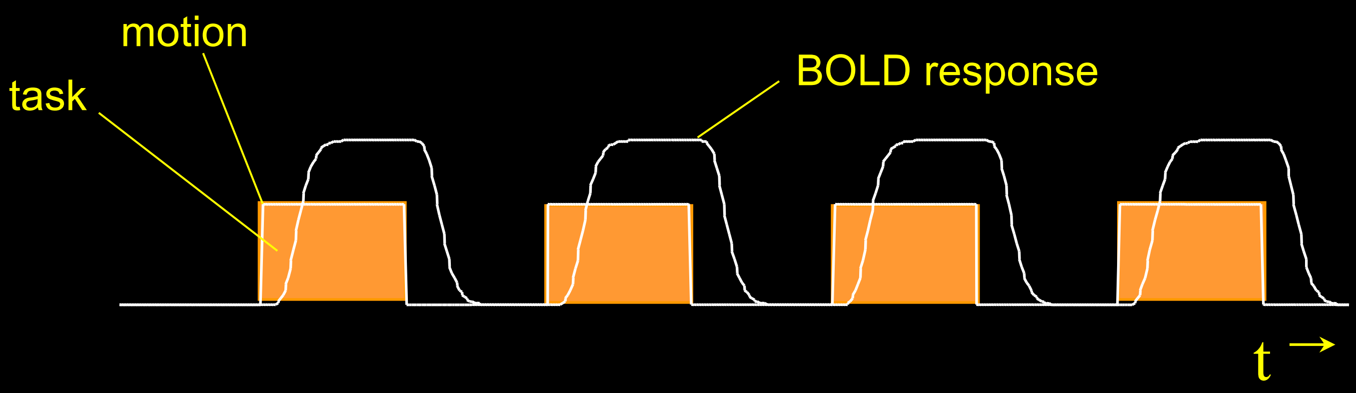
Estimation accuracy vs. average ISI



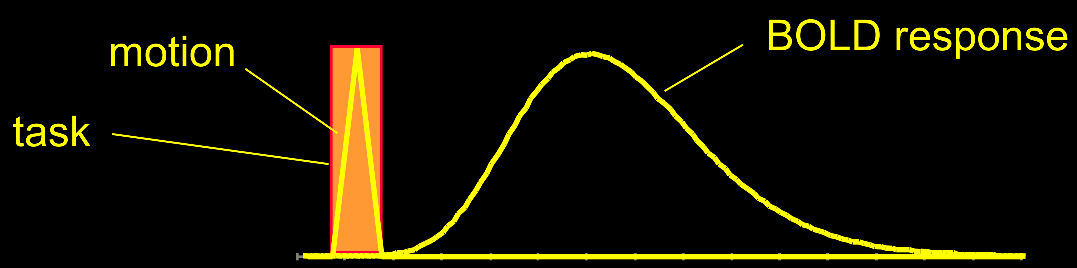
R. M. Birn, R. W. Cox, P. A. Bandettini, Detection versus estimation in Event-Related fMRI: choosing the optimal stimulus timing. *NeuroImage* 15: 262-264, (2002).

fMRI during tasks that involve brief motion

Blocked Design

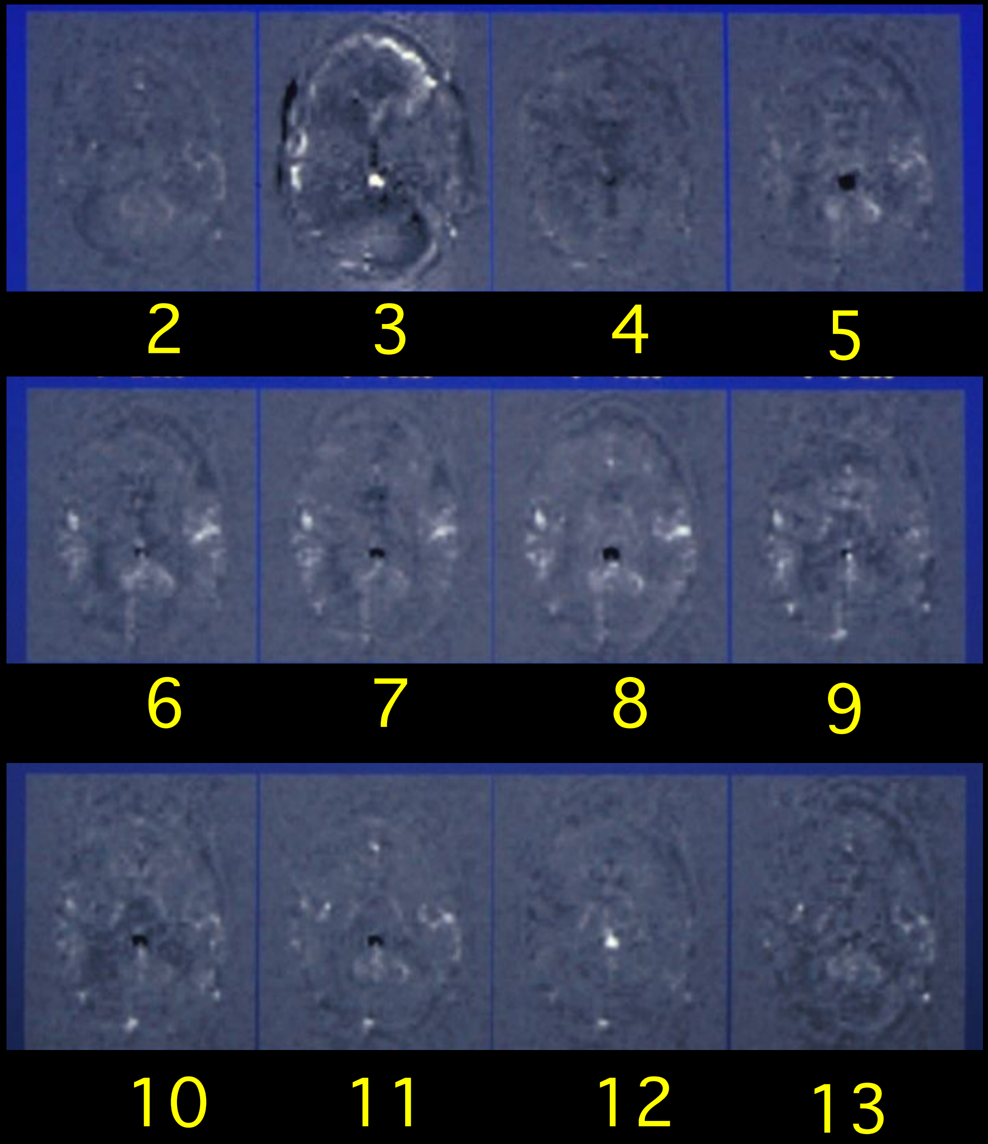


Event-Related Design



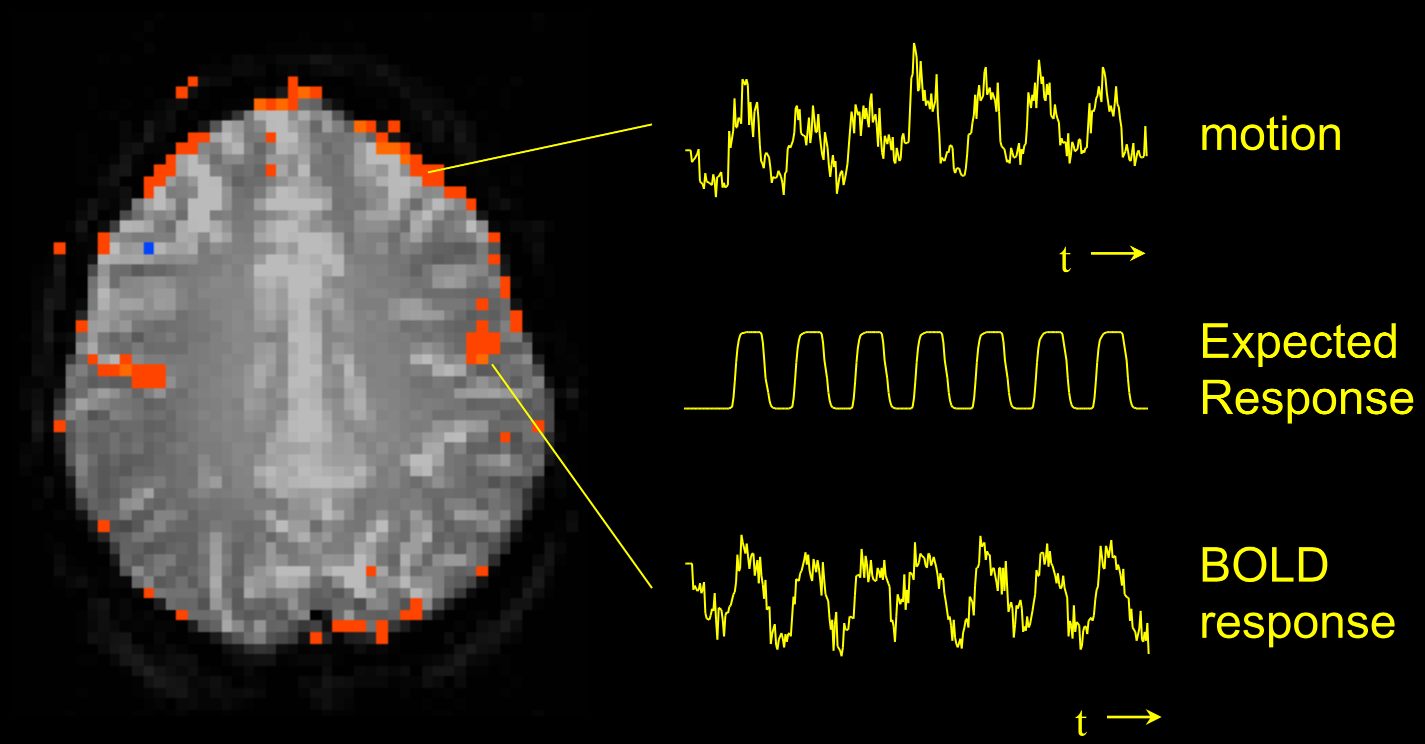
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Overt Word Production



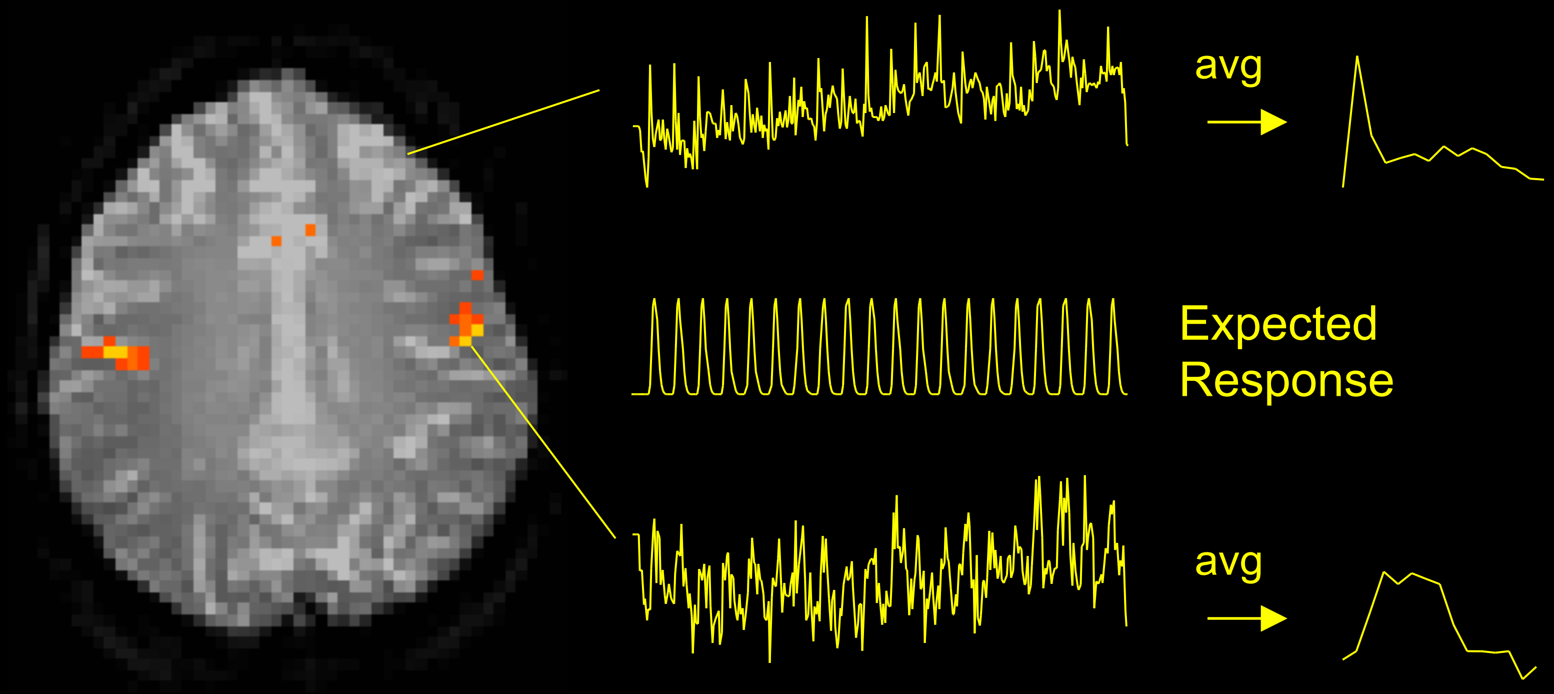
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Speaking - Blocked Trial



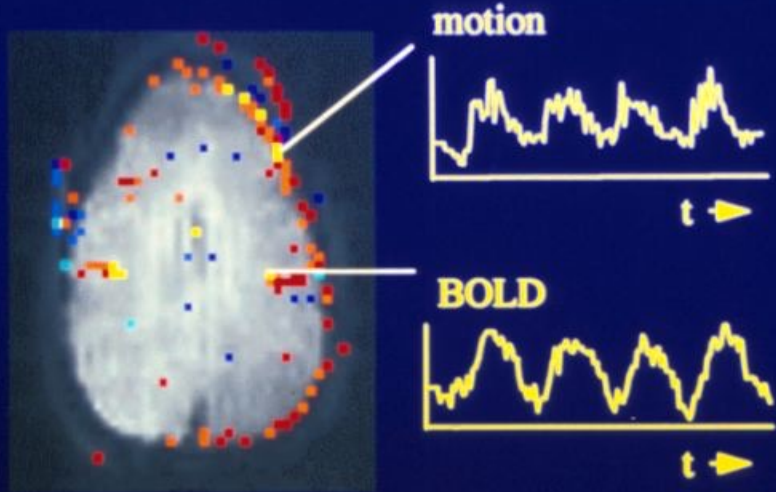
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Speaking - ER-fMRI



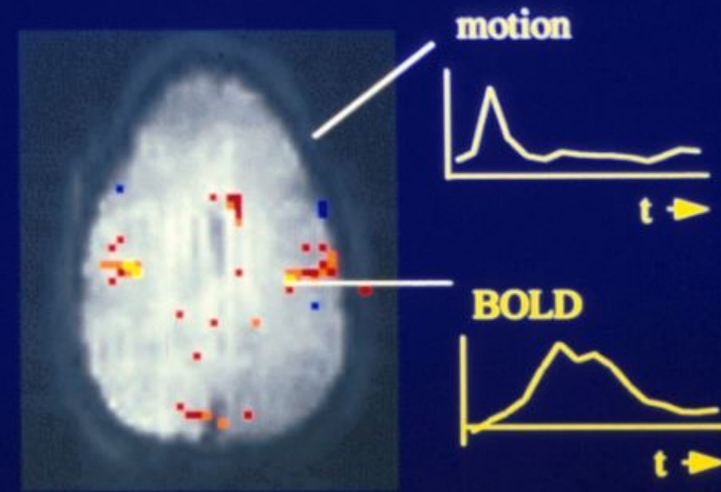
R. M. Birn, P. A. Bandettini, R. W. Cox, R. Shaker, Event - related fMRI of tasks involving brief motion. *Human Brain Mapping* 7: 106-114 (1999).

Motion-Decoupled fMRI:
Functional MRI during of overt word production



"block-trial" paradigm

Motion induced signal changes resemble functional (BOLD) signal changes

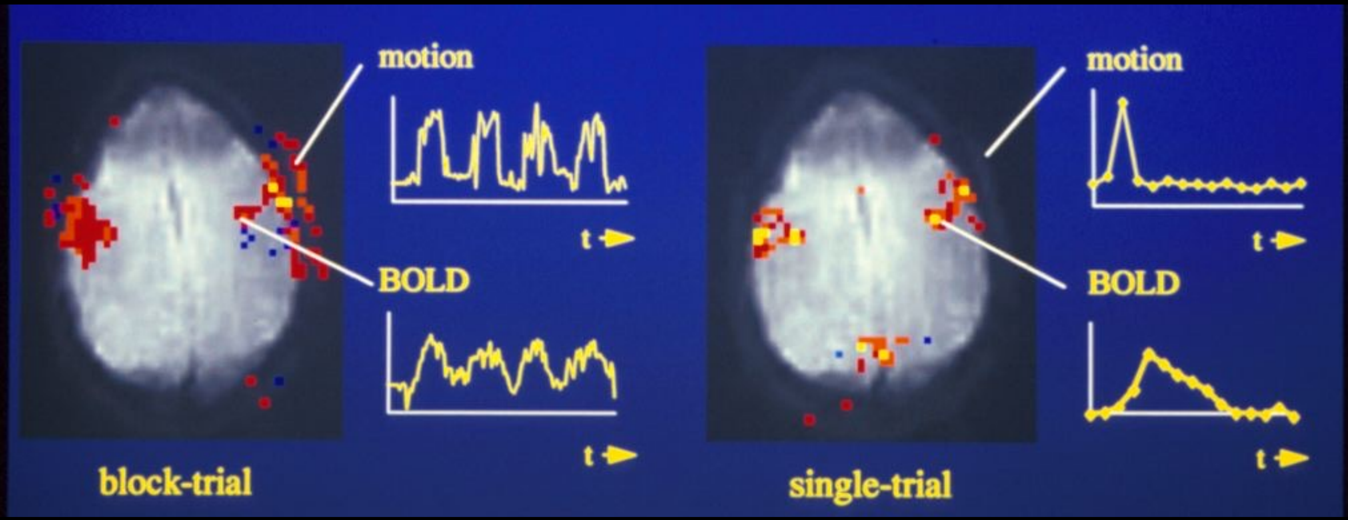


"single-trial" paradigm

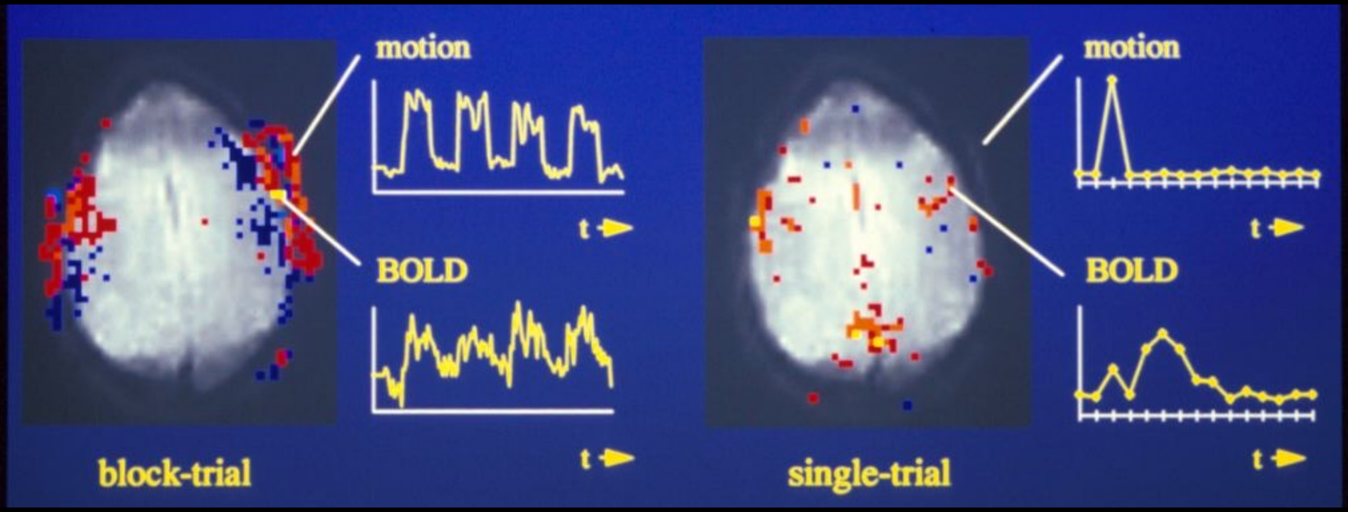
Motion induced and BOLD signal changes are separated in time

R.M. Birn, et al.

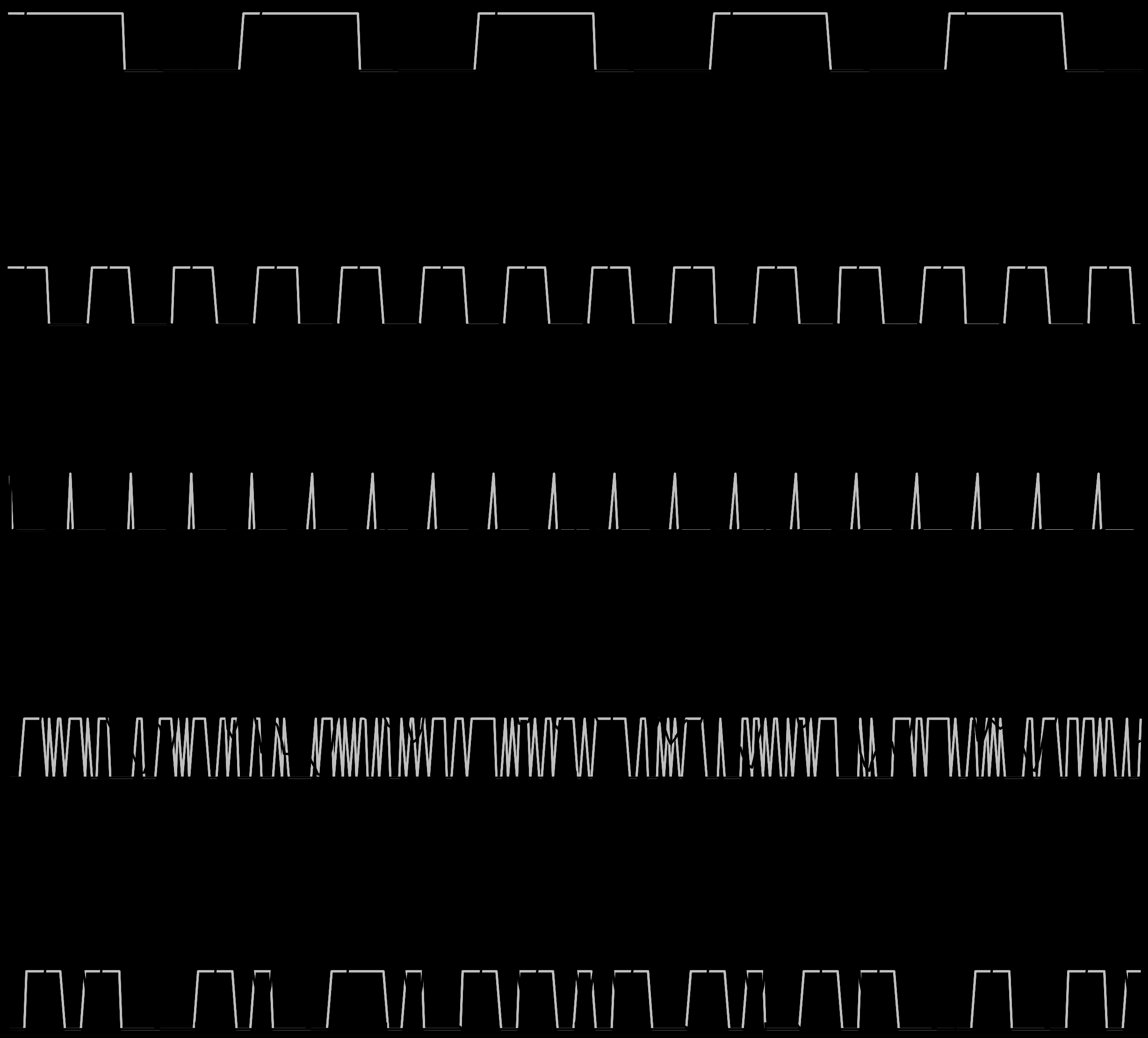
Tongue Movement

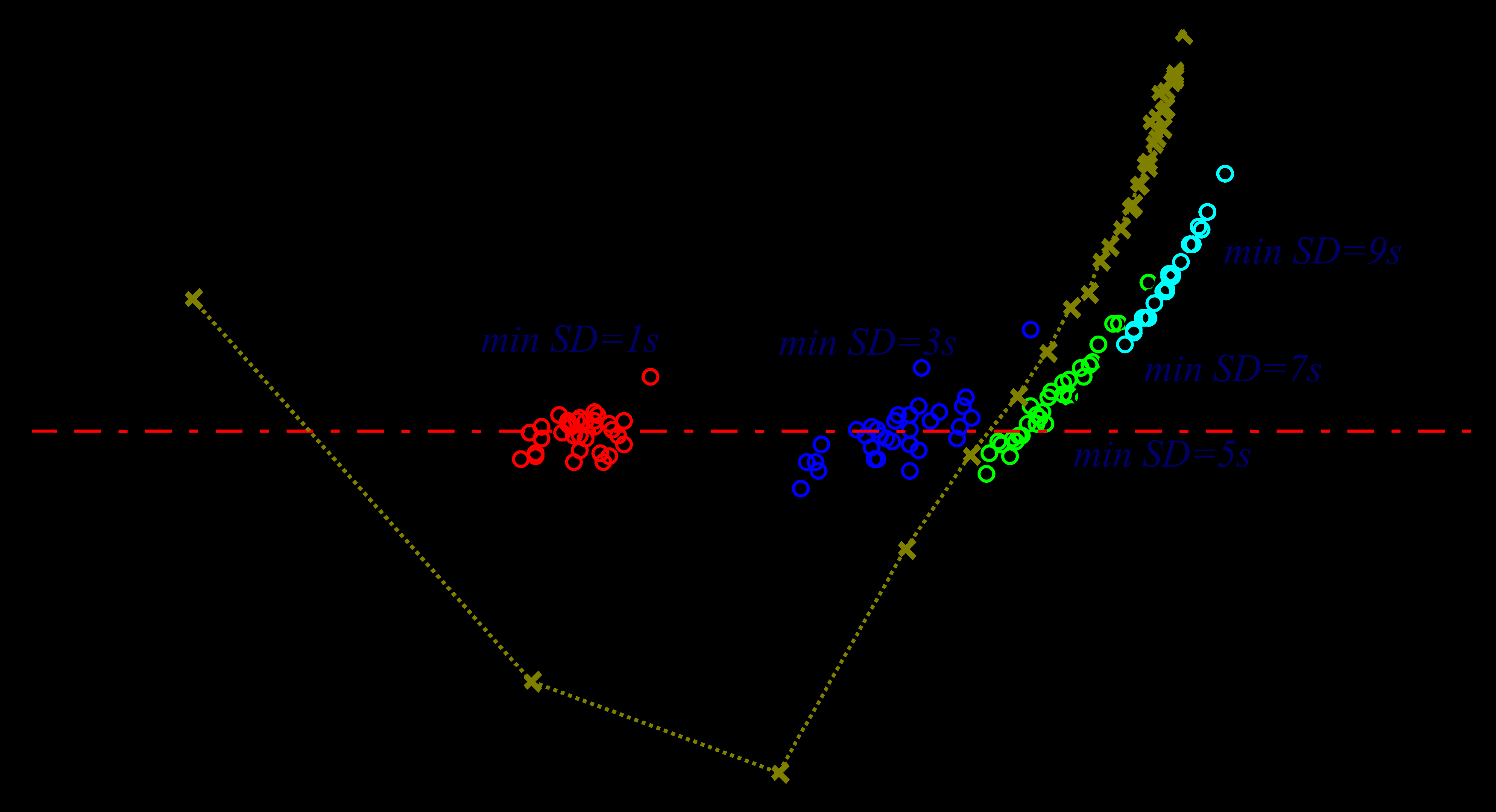


Jaw Clenching

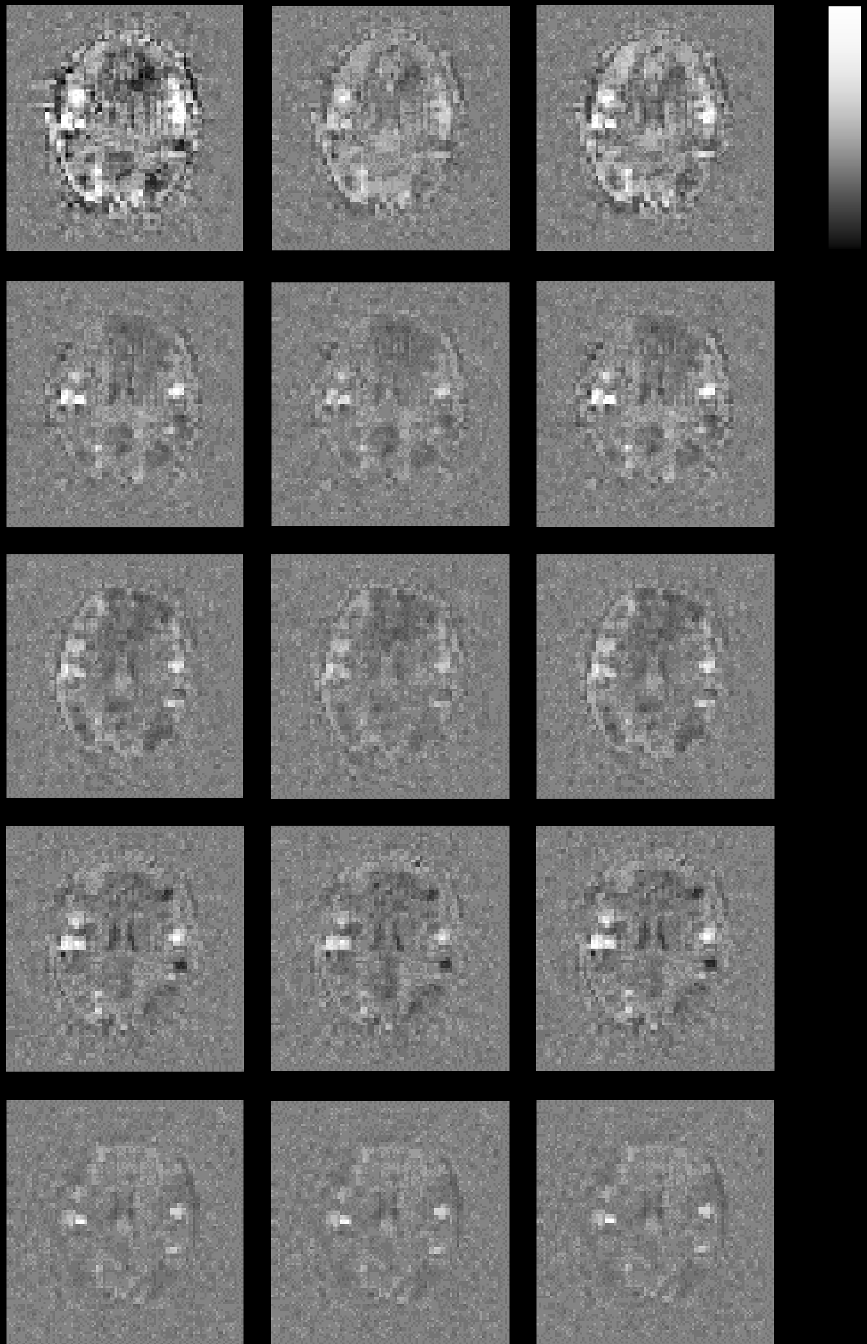


Motion-induced signal change





min SD=1s
min SD=3s
min SD=5s
min SD=7s
min SD=9s



What more information can we extract from the FMRI time series?

- Event-related developments
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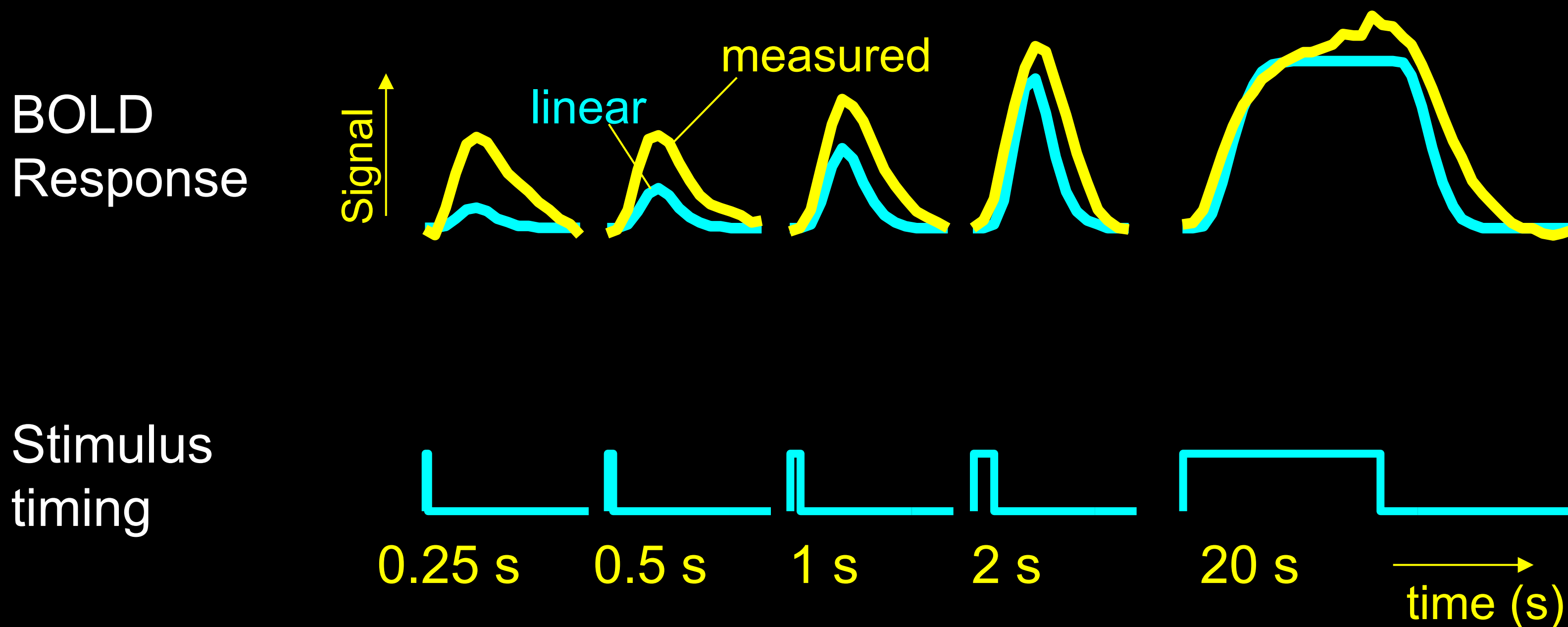
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

Dynamic Nonlinearity Assessment

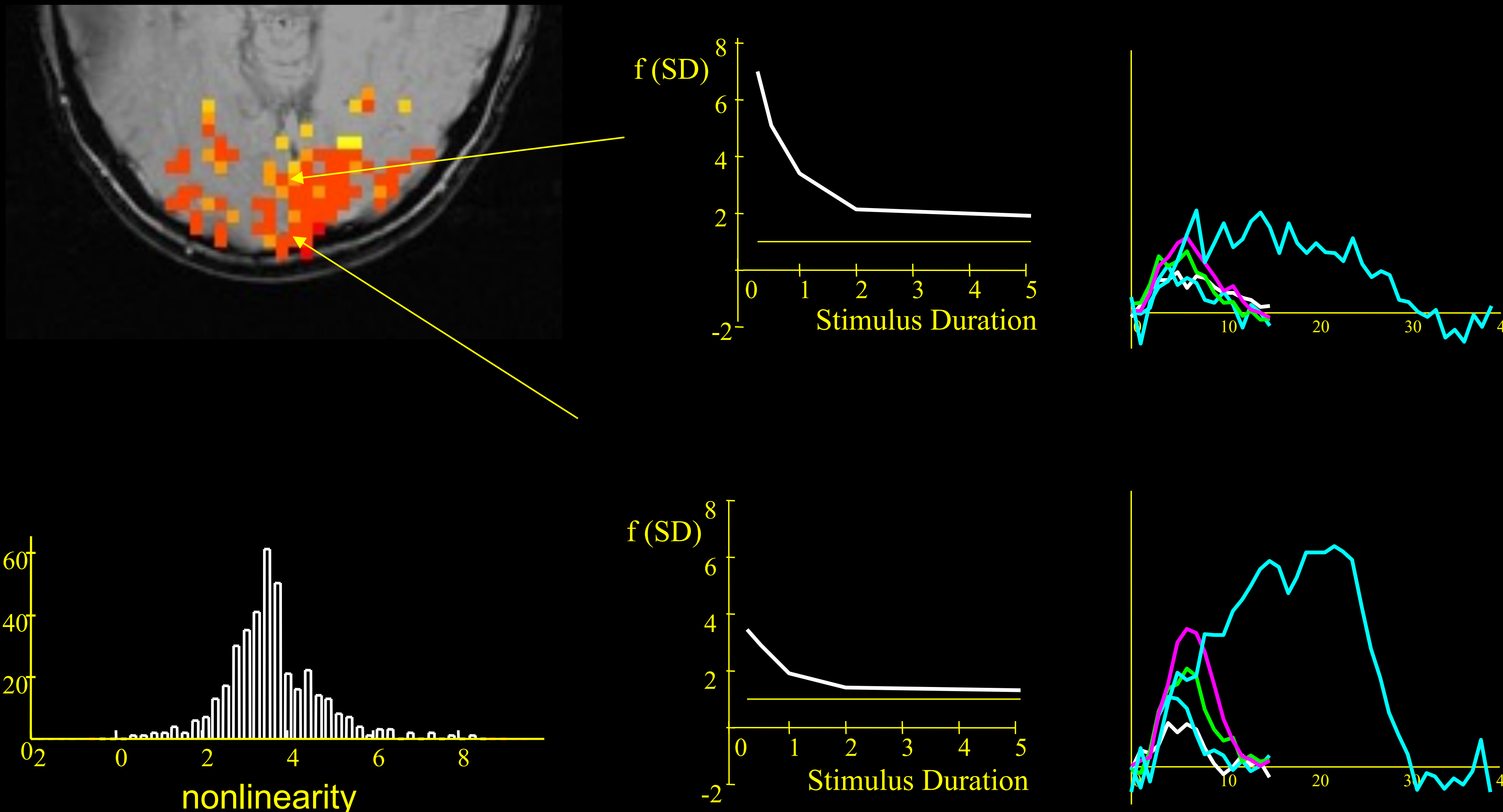
Different stimulus "ON" periods



Brief stimuli produce larger responses than expected

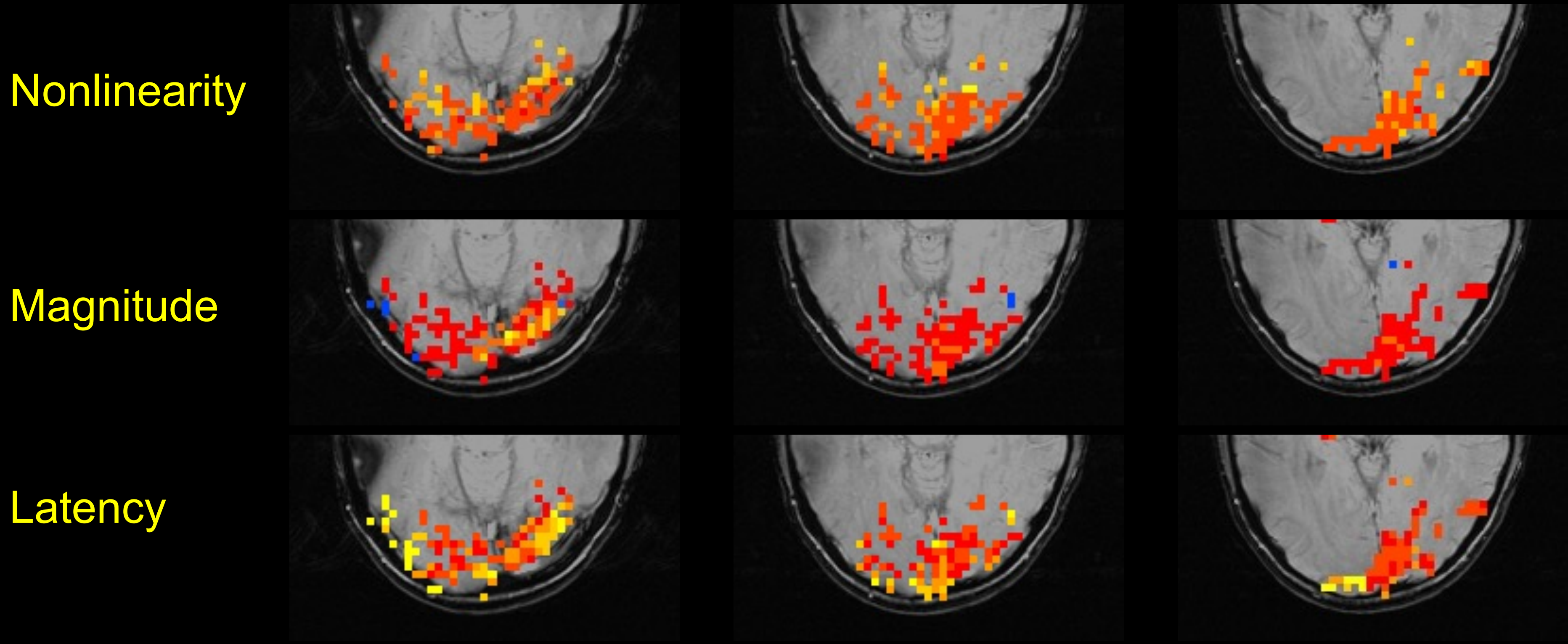
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." ***NeuroImage*****, 14: 817-826.**

Spatial Heterogeneity of BOLD Nonlinearity



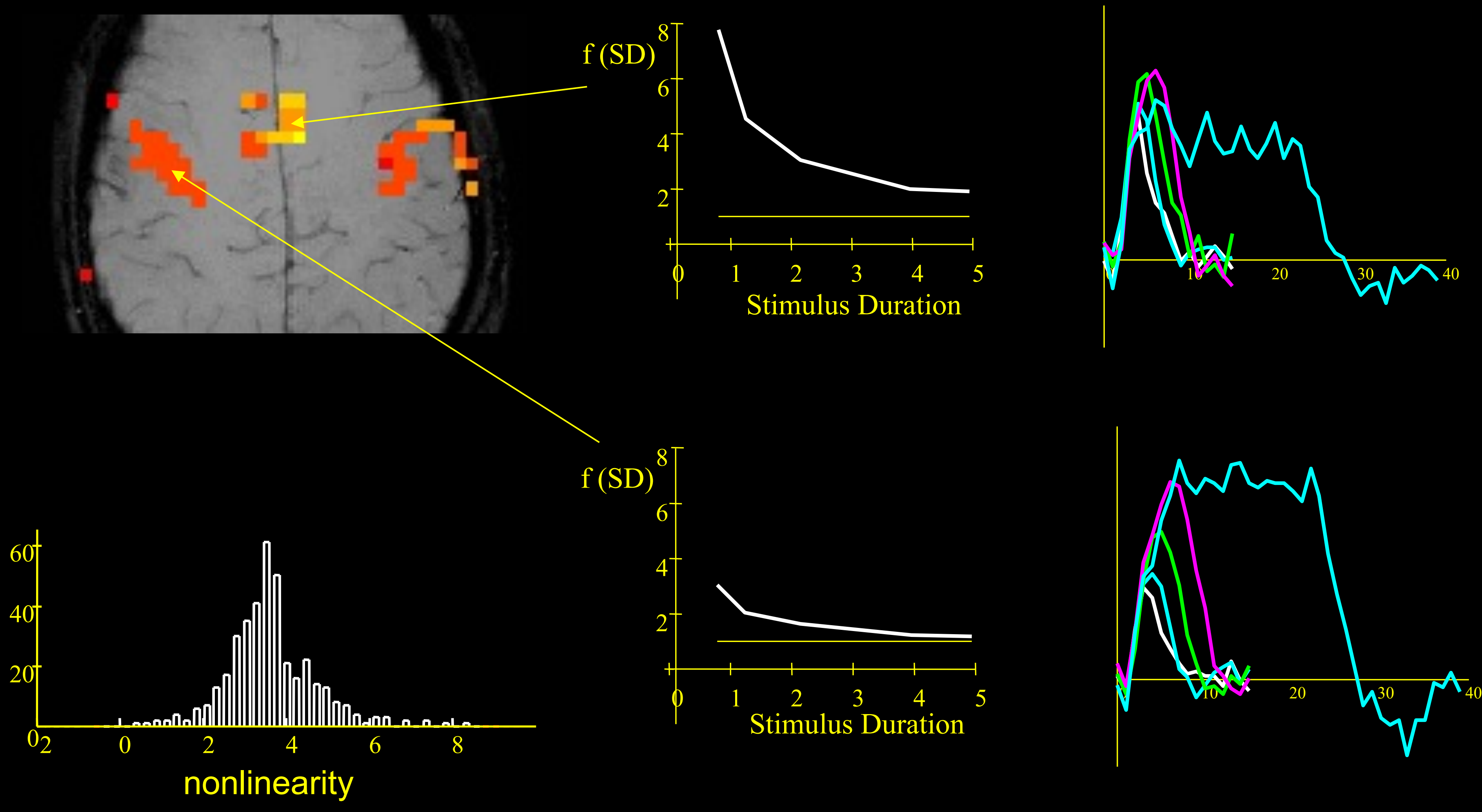
R. M. Birn, Z. Saad, P. A. Bandettini, (2001) “Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response.” *NeuroImage*, 14: 817-826.

Results – visual task



R. M. Birn, Z. Saad, P. A. Bandettini, (2001) "Spatial heterogeneity of the nonlinear dynamics in the fMRI BOLD response." *NeuroImage*, 14: 817-826.

Results – motor task

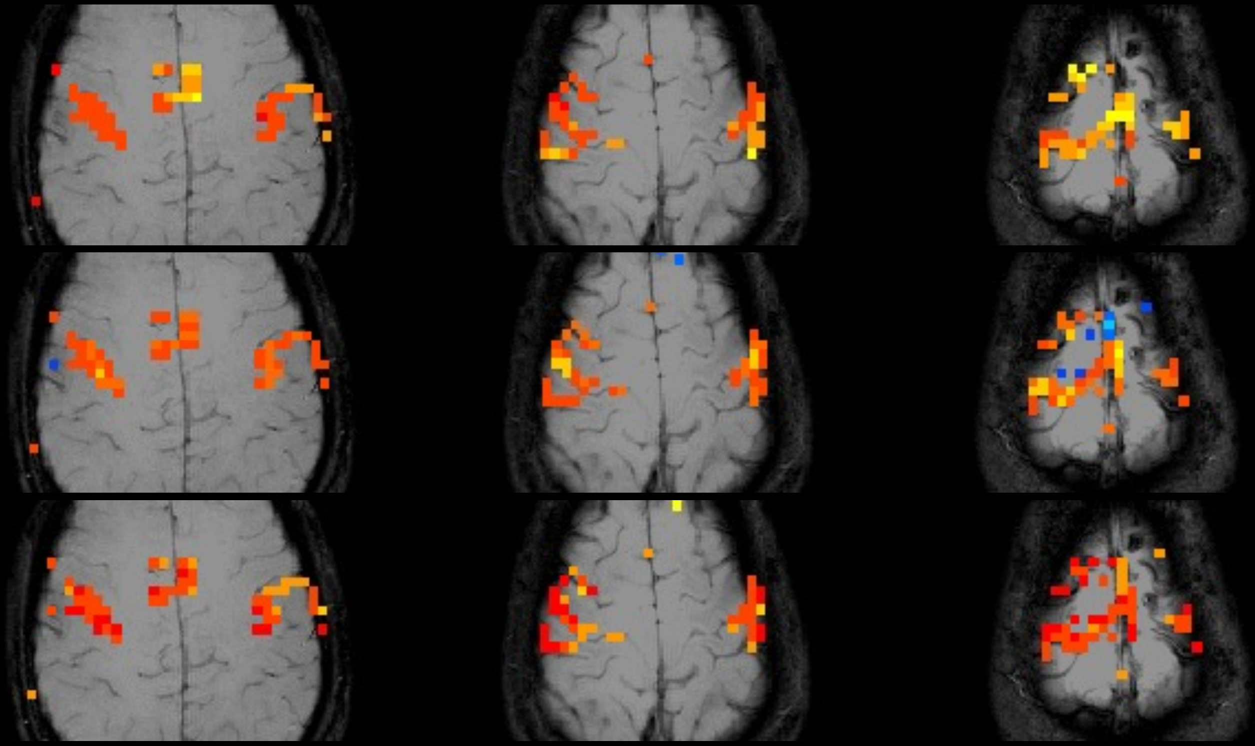


Results – motor task

Nonlinearity

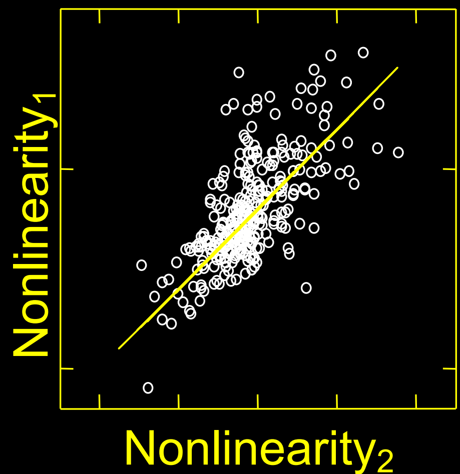
Magnitude

Latency

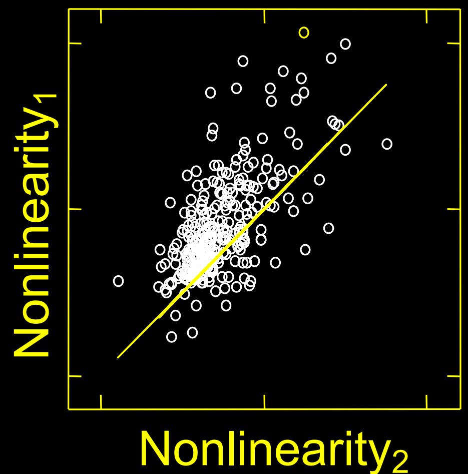


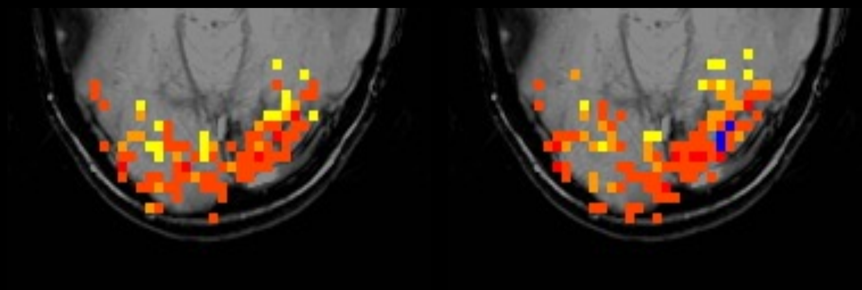
Reproducibility

Visual task

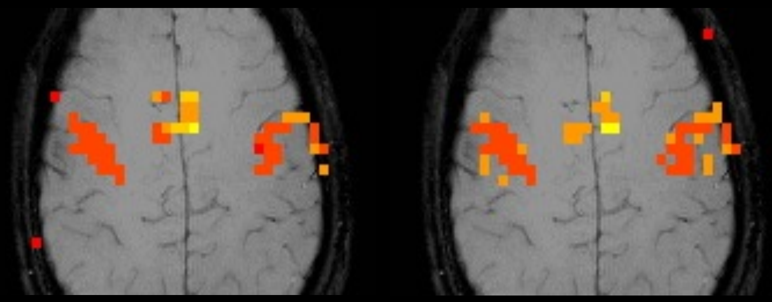


Motor task



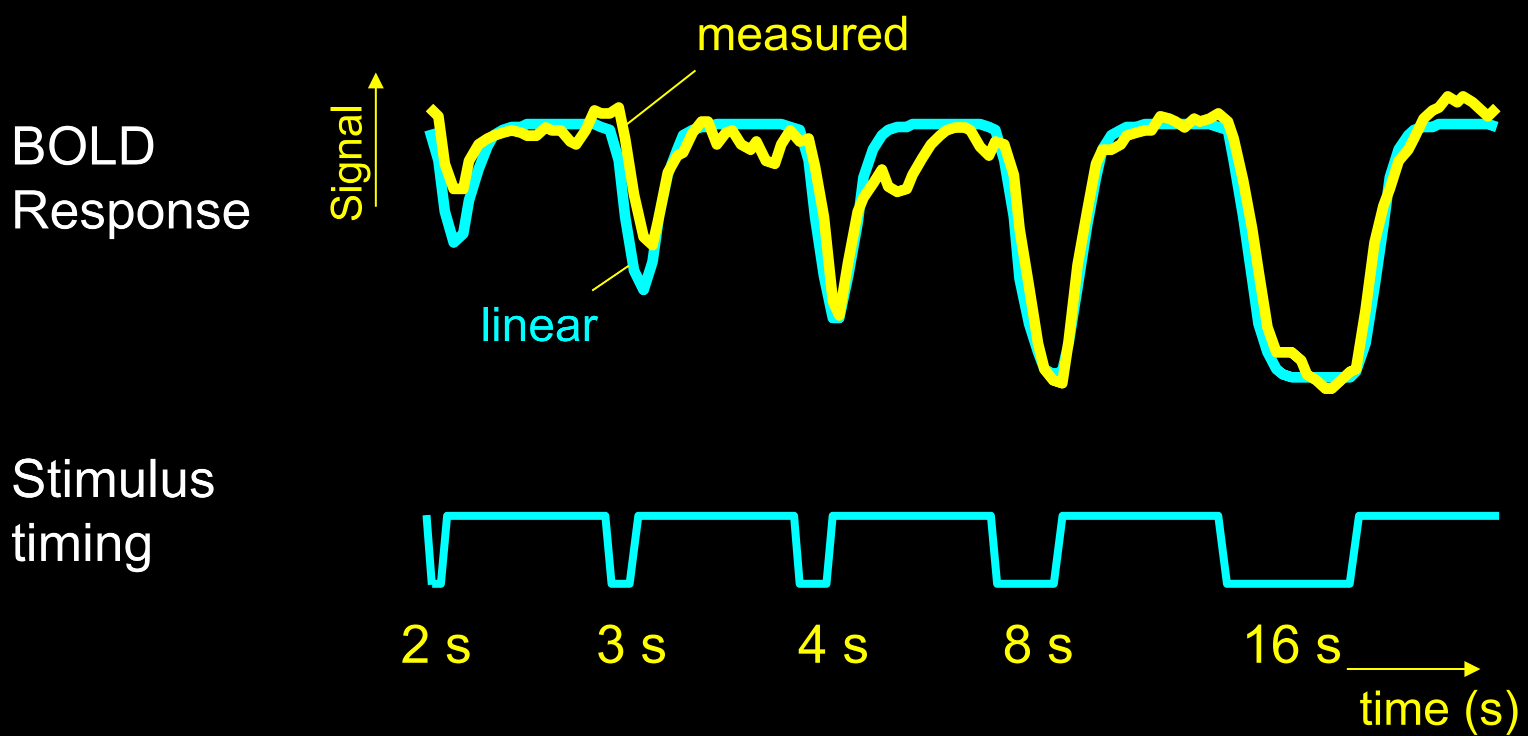


Experiment 1 Experiment 2



Experiment 1 Experiment 2

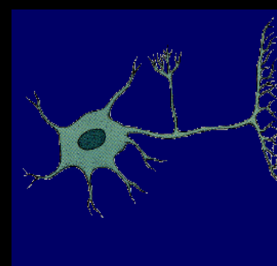
Different stimulus "ON" periods

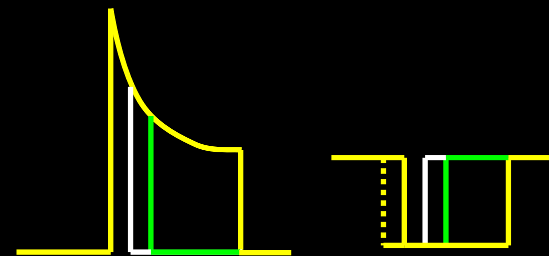


Brief stimulus OFF periods produce smaller decreases than expecte

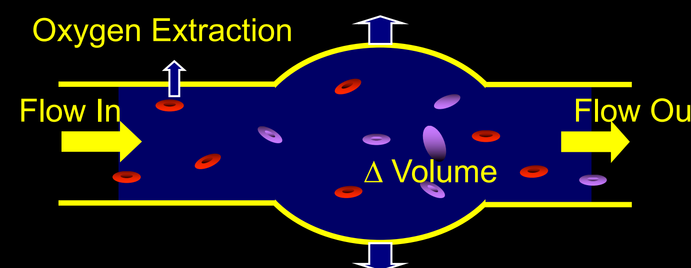
Sources of this Nonlinearity

- Neuronal



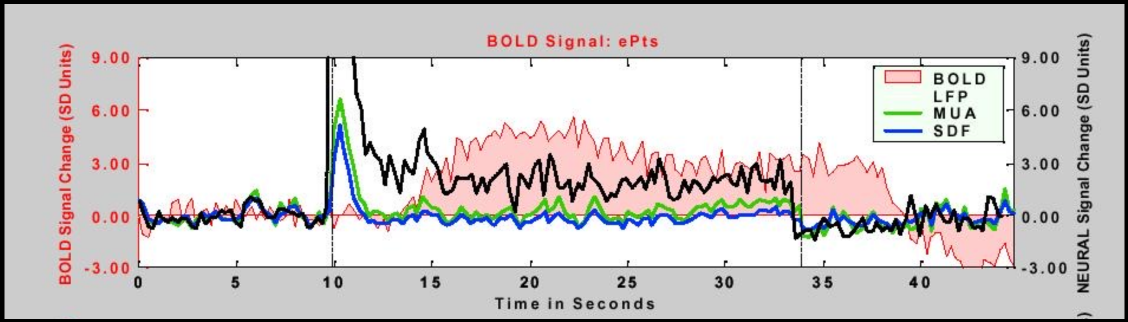


- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics

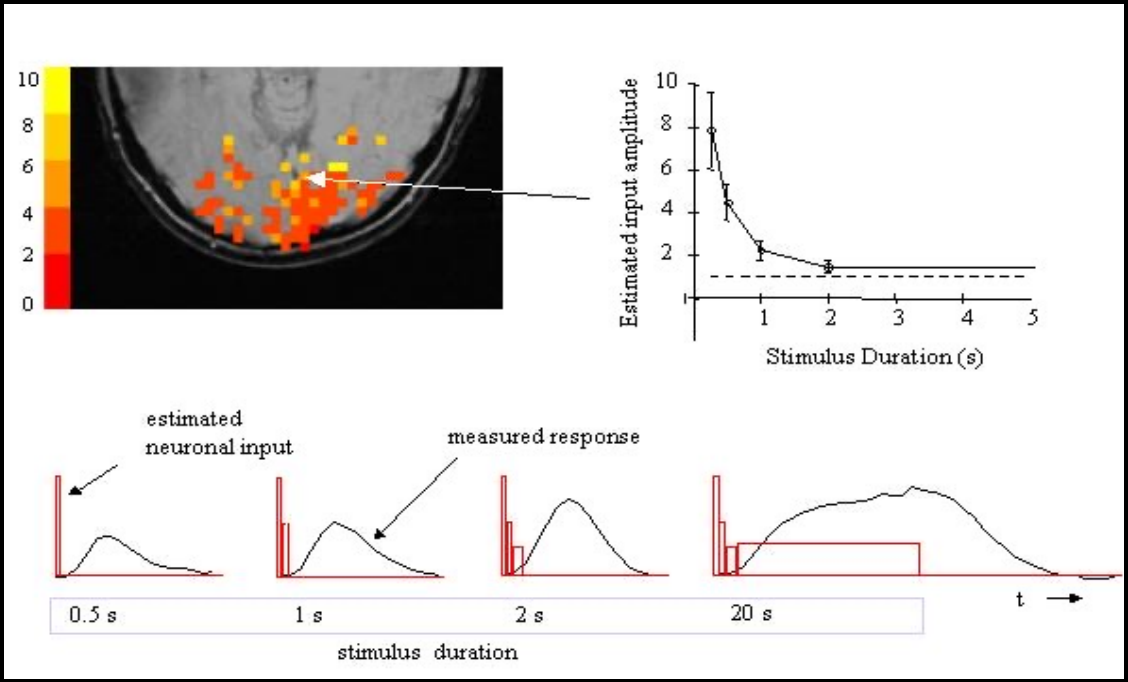


BOLD Correlation with Neuronal Activity

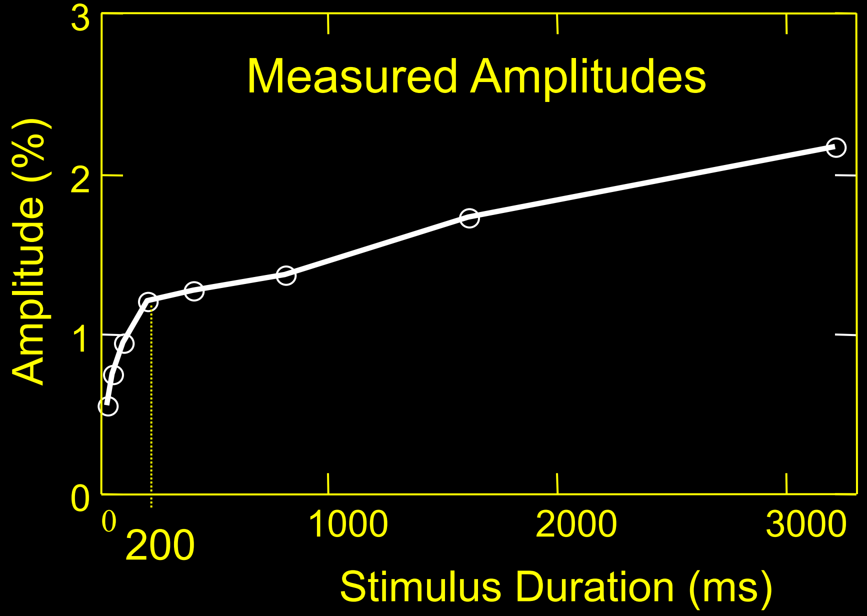
Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157.

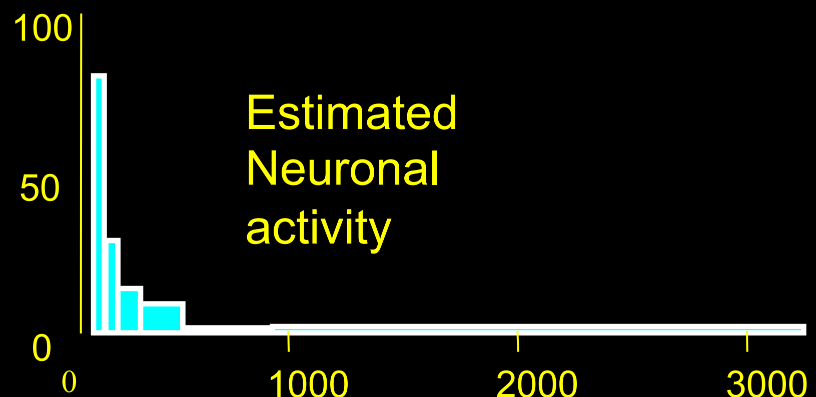


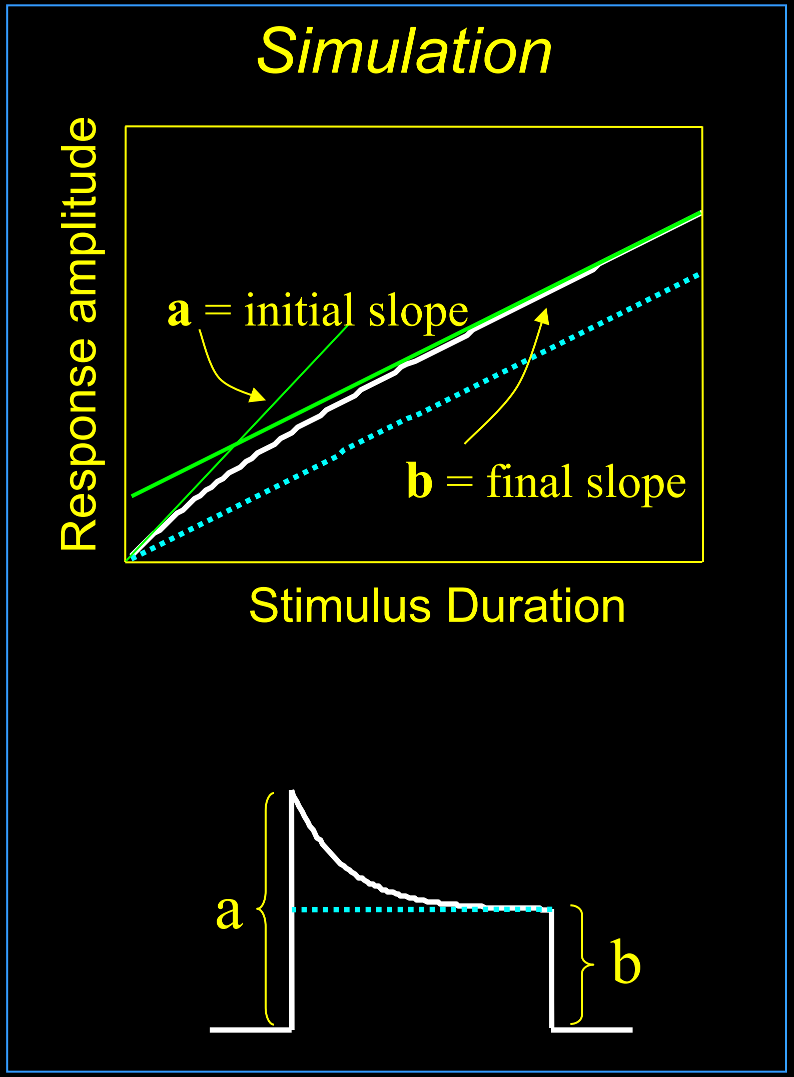
P. A. Bandettini and L. G. Ungerleider, (2001) "From neuron to BOLD: new connections." Nature Neuroscience, 4: 864-866.



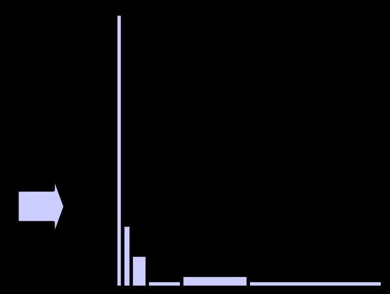
Results – constant gratings





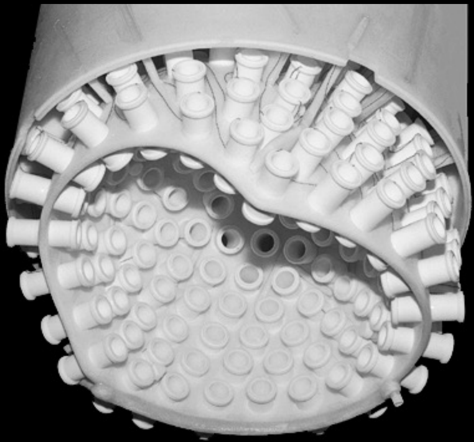


Stationary grating

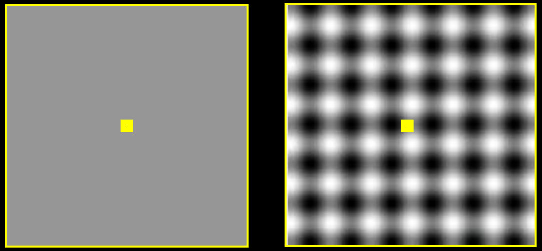


Contrast-reversing checkerboard

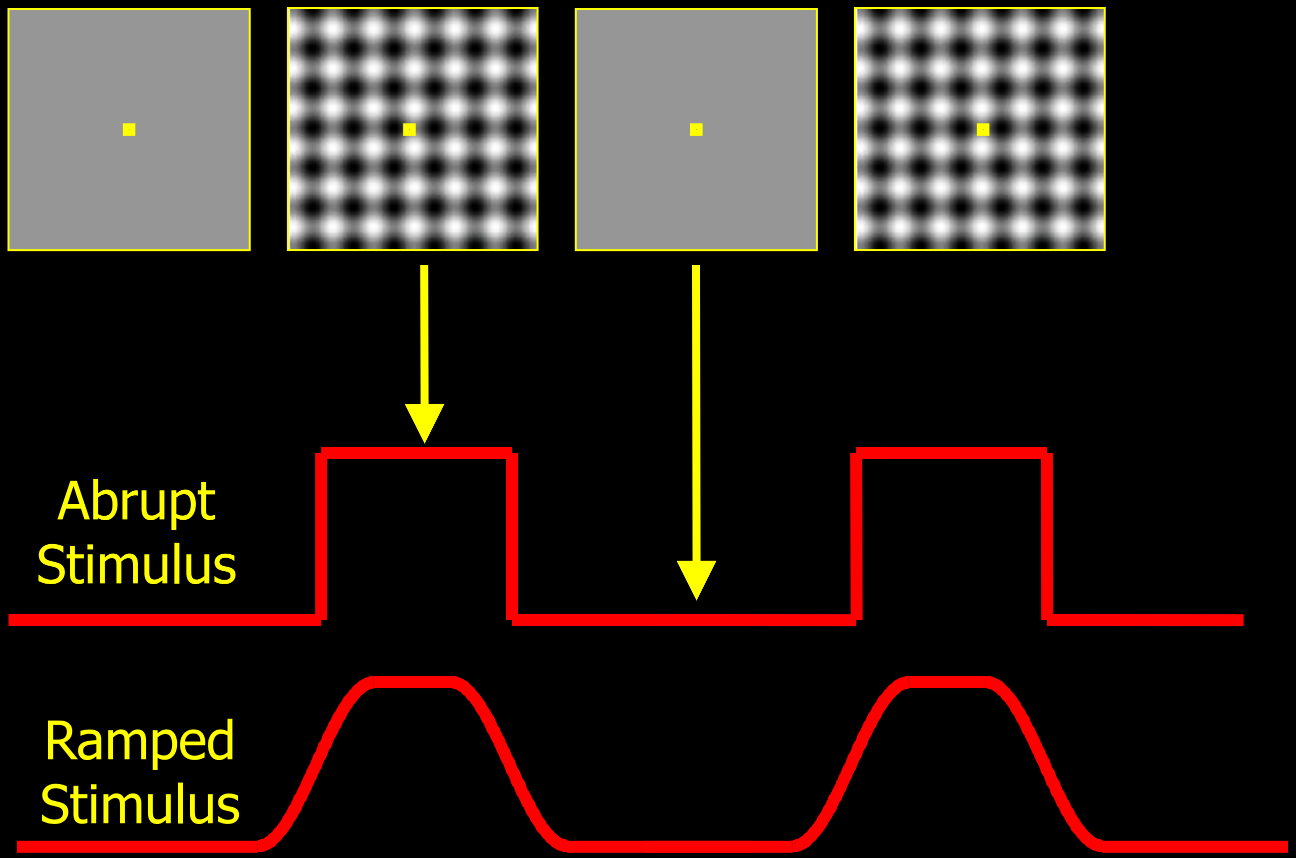
MEG and Ramped Stimulus



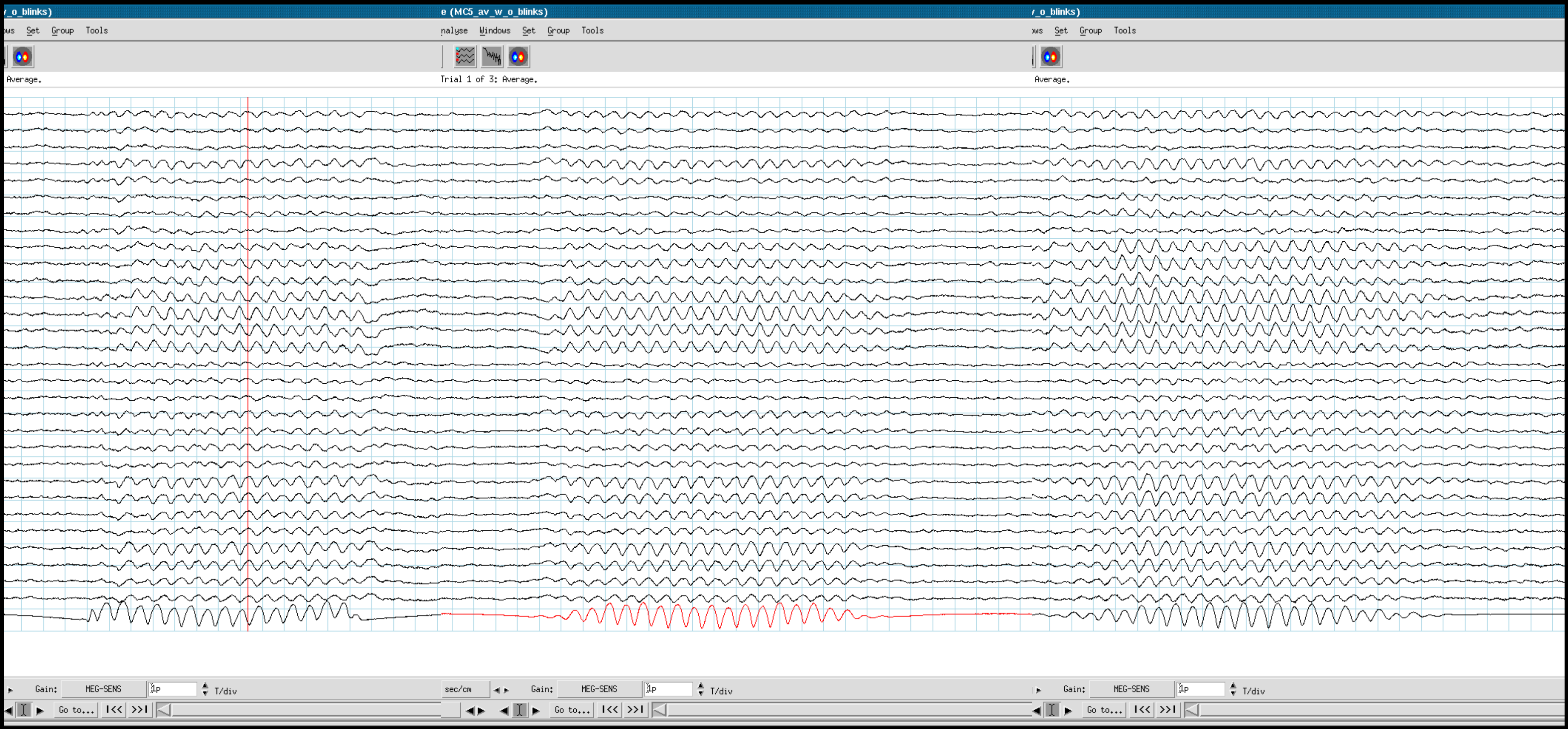
- 6 subjects
- SD: 1 or 2 seconds
- Ramp: 0, 0.5, 1 second
- 8 Hz Counterphase-modulated checkerboards
- Fixation without task
  - No blinking point
- 45 repeats
- 3 sec ISI
- 275 channels
- 600 Hz



MEG – Ramped stimuli



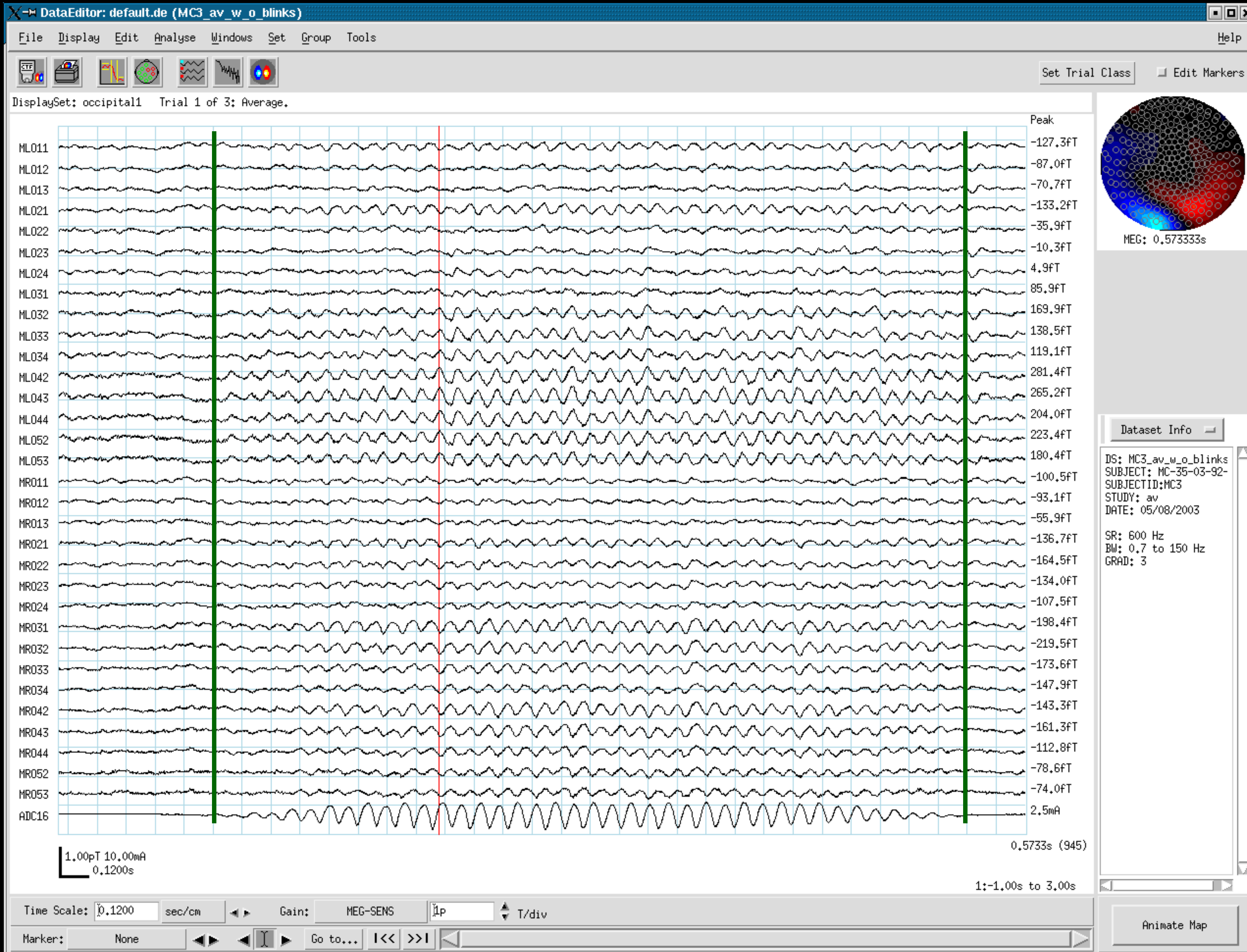
Composite – 1 second Stimulus Duration



No Ramp

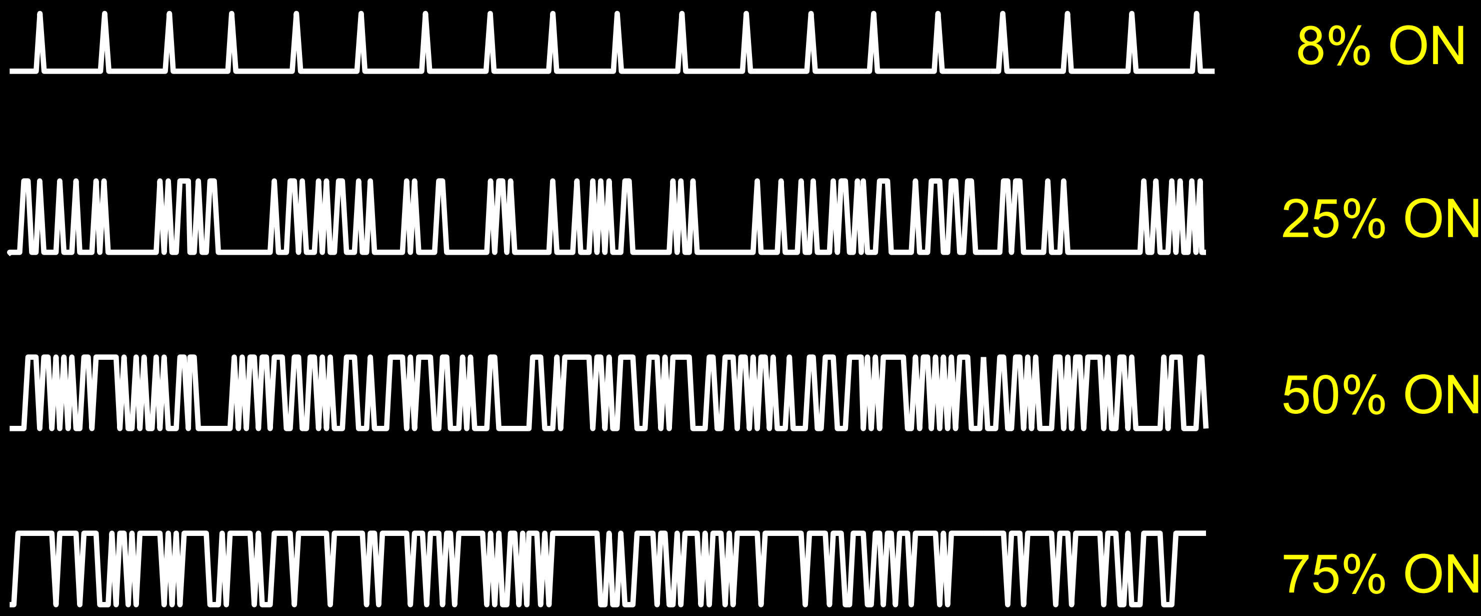
0.5 second Ramp

1 second Ramp


DataEditor: default.de (MC3_av_w_o_blinks)
File Display Edit Analyse Windows Set Group Tools Help
Set Trial Class
Edit Markers
DisplaySet: occipital1 Trial 1 of 3: Average.
Peak
ML011 -127.3fT
ML012 -87.0fT
ML013 -70.7fT
ML021 -133.2fT
ML022 -35.9fT
ML023 -10.3fT
ML024 4.9fT
ML031 85.9fT
ML032 169.9fT
ML033 138.5fT
ML034 119.1fT
ML042 281.4fT
ML043 265.2fT
ML044 204.0fT
ML052 223.4fT
ML053 180.4fT
MR011 -100.5fT
MR012 -93.1fT
MR013 -55.9fT
MR021 -136.7fT
MR022 -164.5fT
MR023 -134.0fT
MR024 -107.5fT
MR031 -198.4fT
MR032 -219.5fT
MR033 -173.6fT
MR034 -147.9fT
MR042 -143.3fT
MR043 -161.3fT
MR044 -112.8fT
MR052 -78.6fT
MR053 -74.0fT
ADC16 2.5mA
1.00pT 10.00mA
0.1200s
0.5733s (945)
1:-1.00s to 3.00s
MEG: 0.573333s
Dataset Info
DS: MC3_av_w_o_blinks
SUBJECT: MC-35-03-92-
SUBJECTID:MC3
STUDY: av
DATE: 05/08/2003
SR: 600 Hz
BW: 0.7 to 150 Hz
GRAD: 3
Time Scale: 0.1200 sec/cm
Gain: MEG-SENS 1p T/div
Marker: None
Go to...
Animate Map

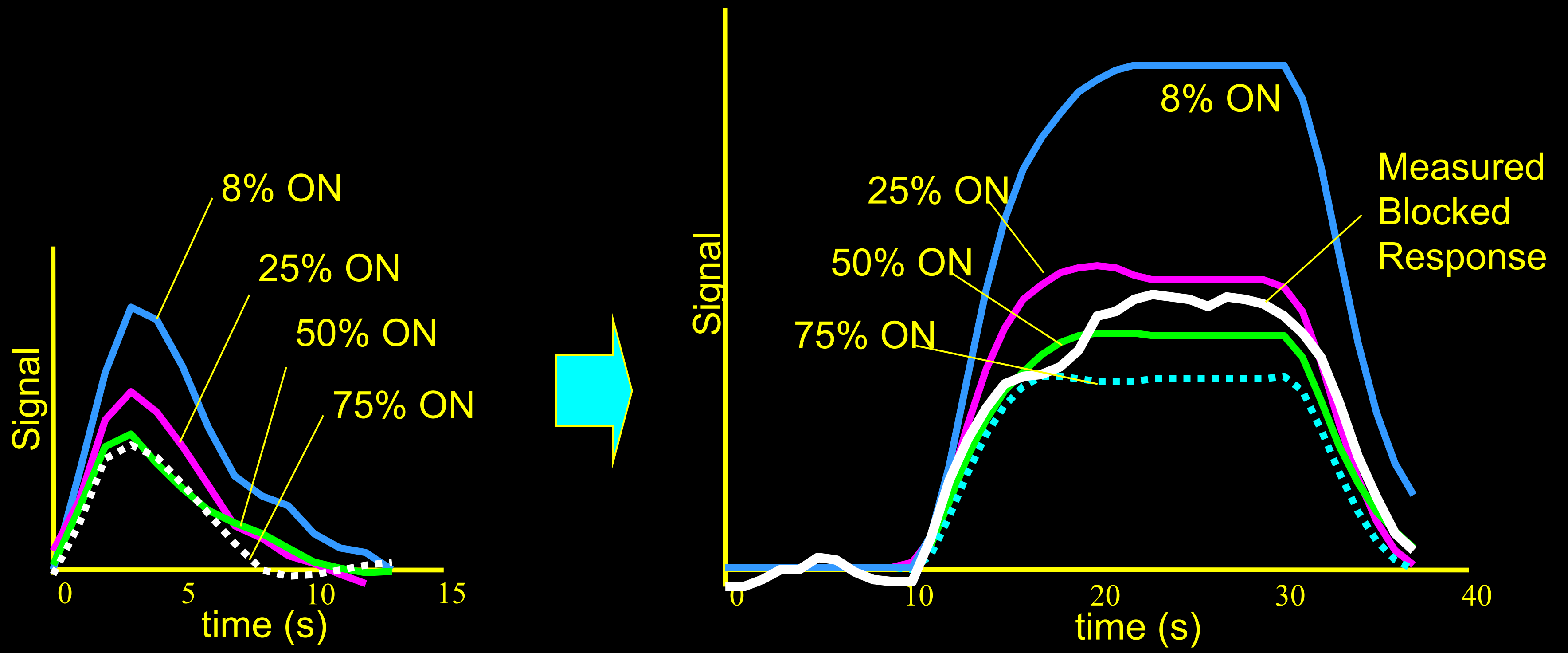
Duty cycle effect....

Rapid event-related design with varying ISI



Estimated Impulse Response

Predicted Responses to 20 s stimulation

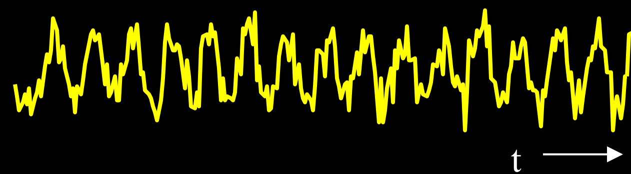


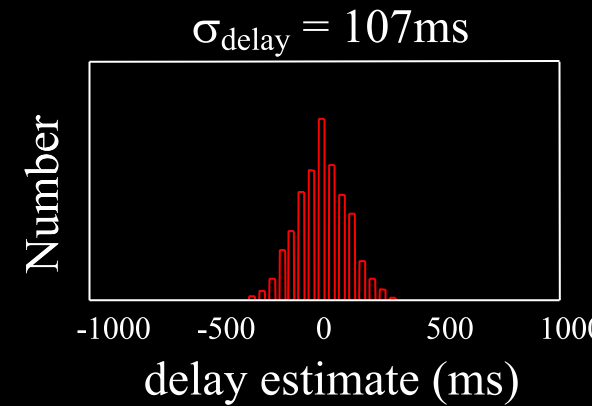
What more information can we extract from the FMRI time series?

- Event-related developments
- Linearity (Neuronal and/or Hemodynamic?)
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

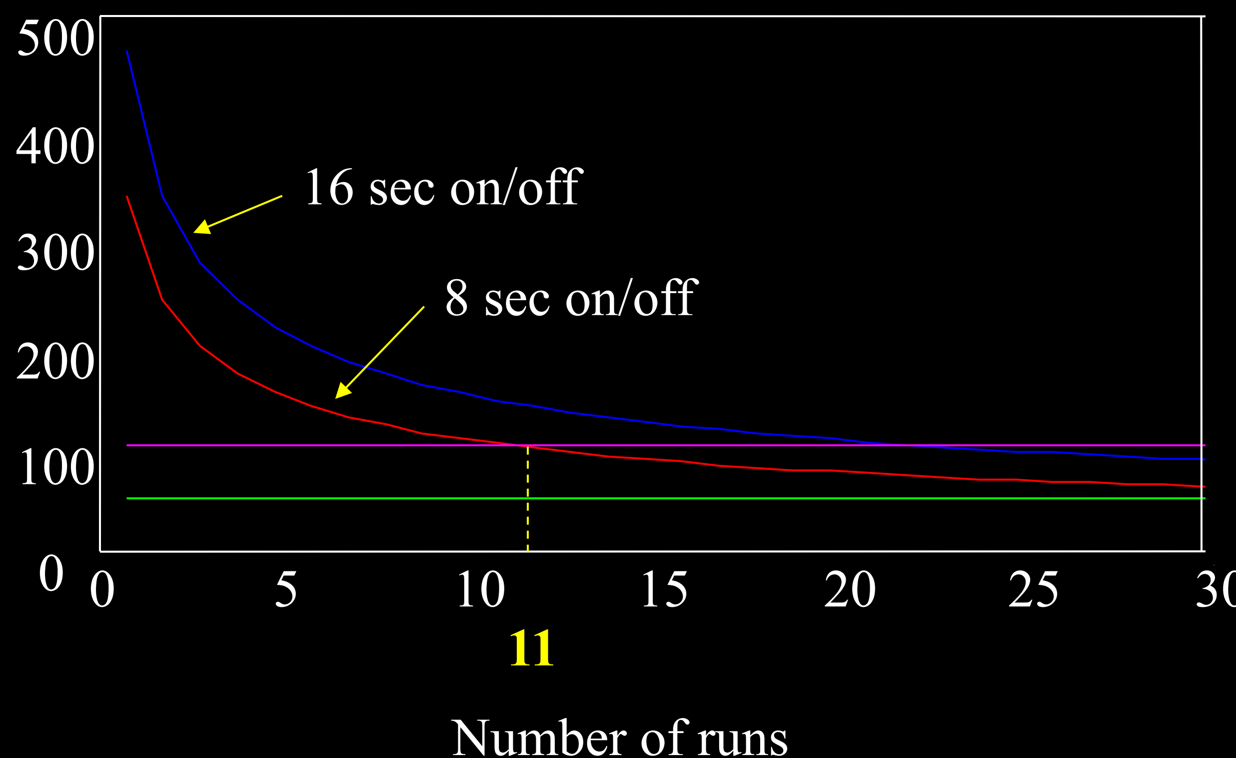
1 run:

1% Noise
4% BOLD
256 time pts /run
1 second TR





Smallest latency
Variation Detectable
(ms) ($p < 0.001$)

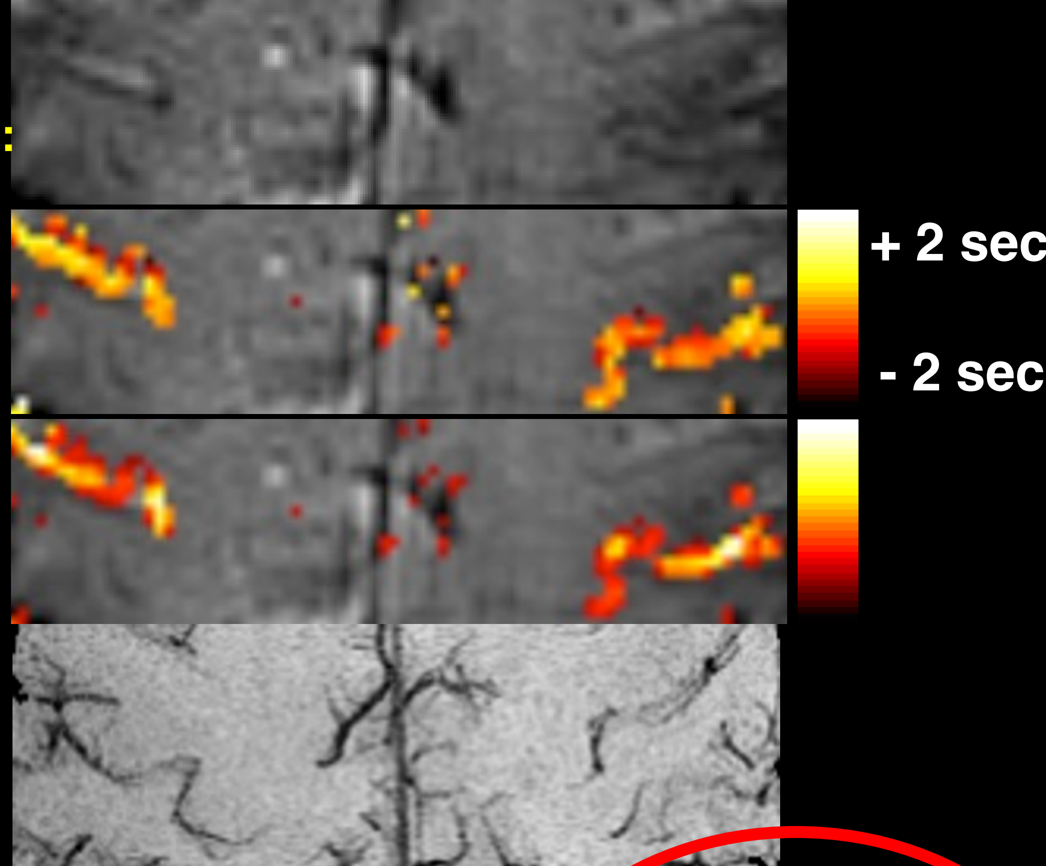


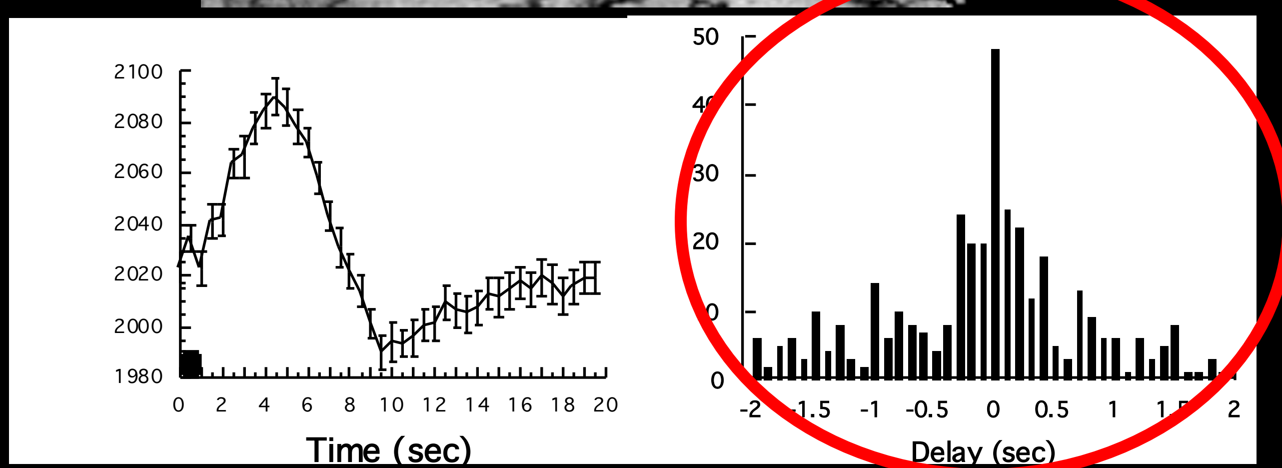
The major obstacle in BOLD contrast temporal resolution:

Latency

Magnitude

Venogram

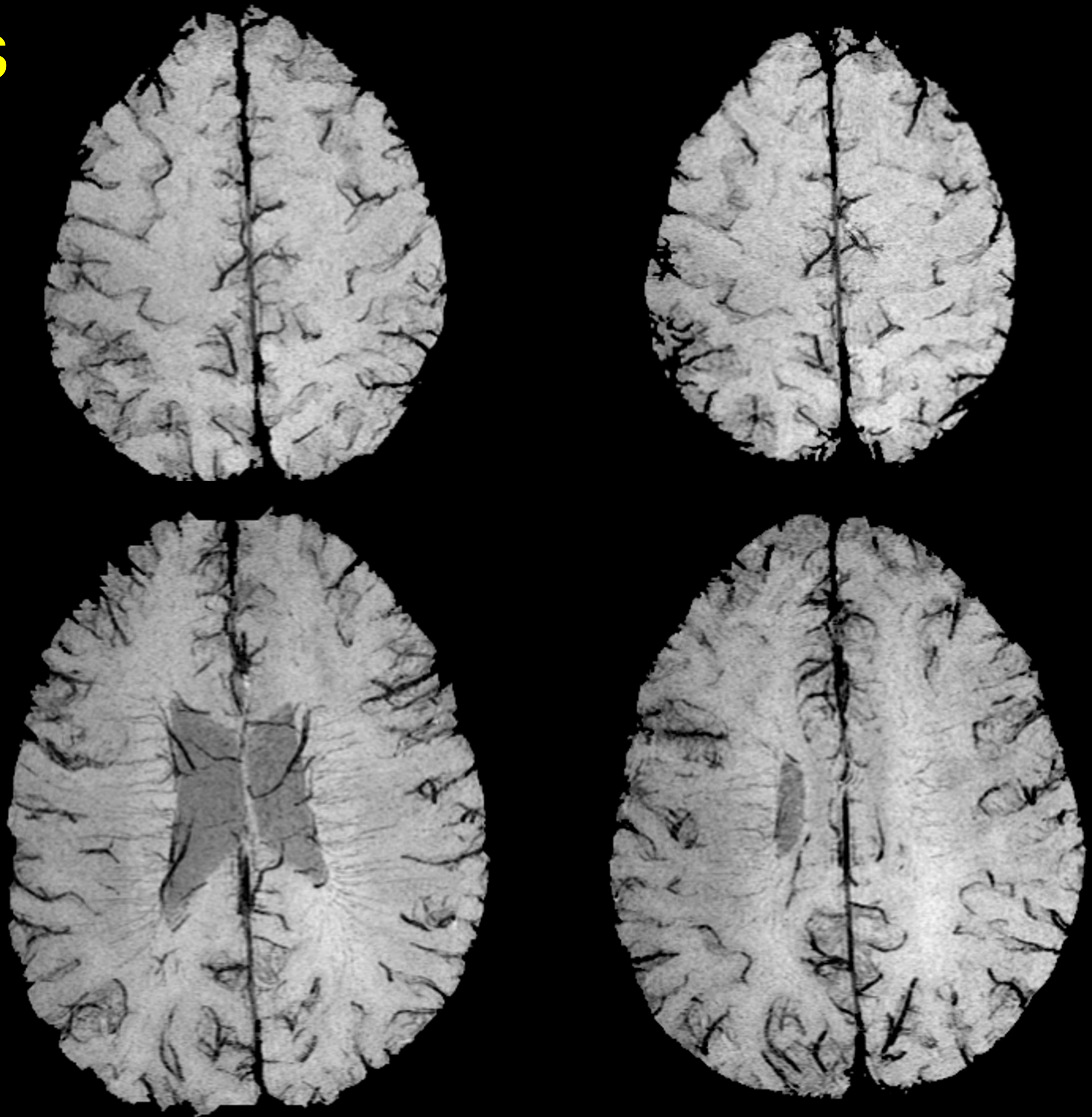


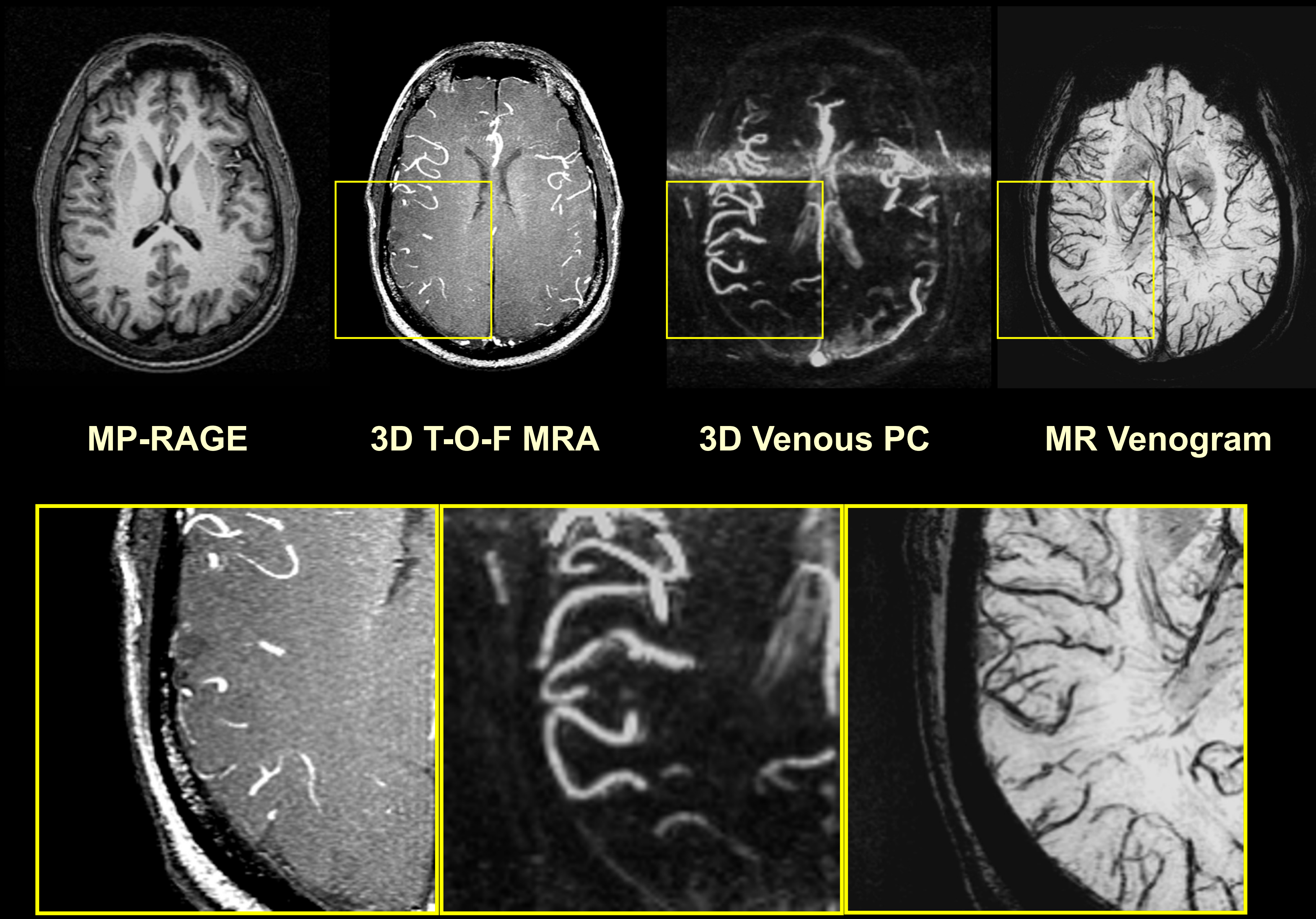


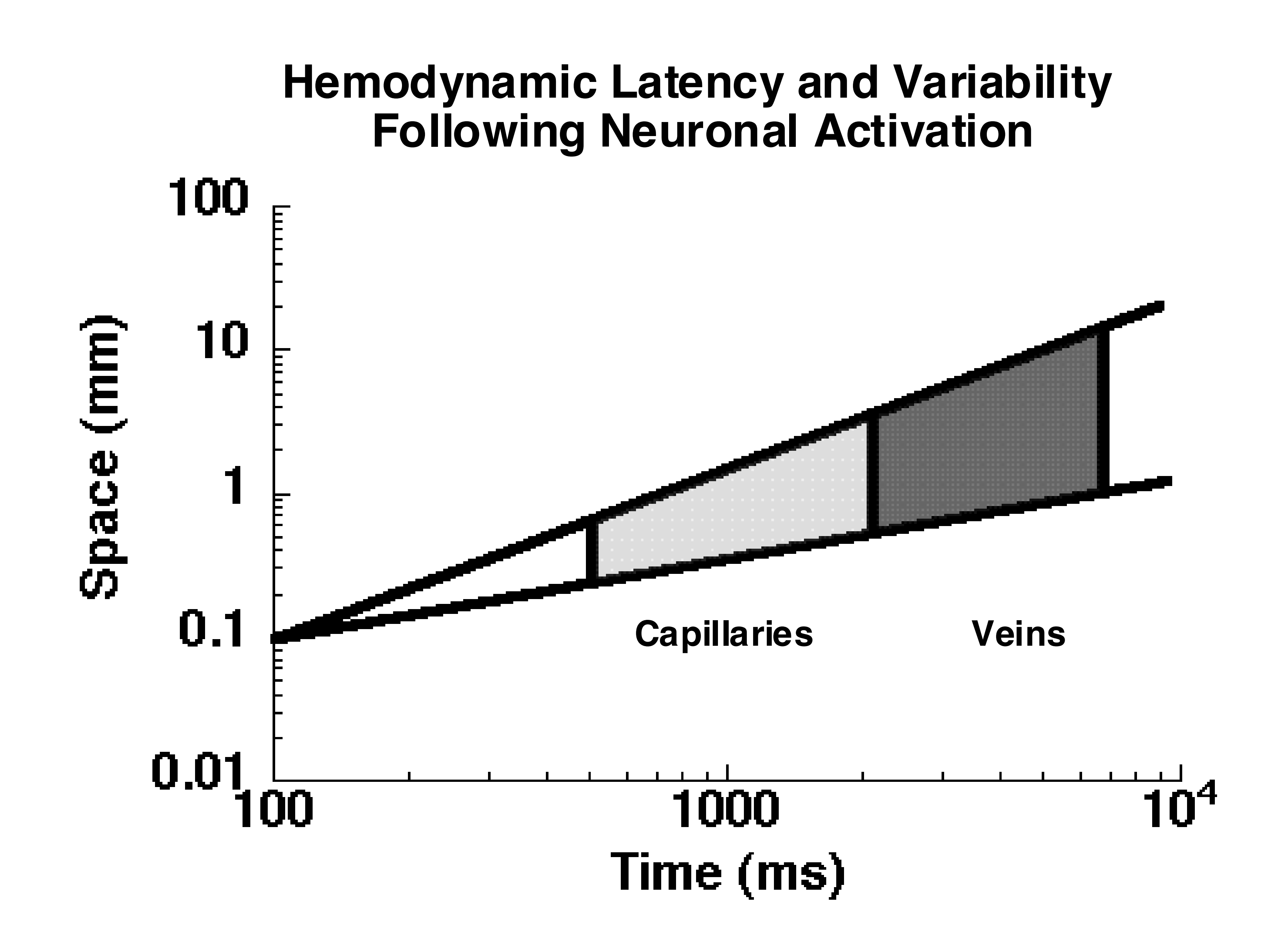
P. A. Bandettini, The temporal resolution of Functional MRI *in* "Functional MRI" (C. Moonen, and P. Bandettini., Eds.), p. 205-220, Springer - Verlag,. 1999.

A tangent into venograms

(3 Tesla)




MP-RAGE
3D T-O-F MRA
3D Venous PC
MR Venogram

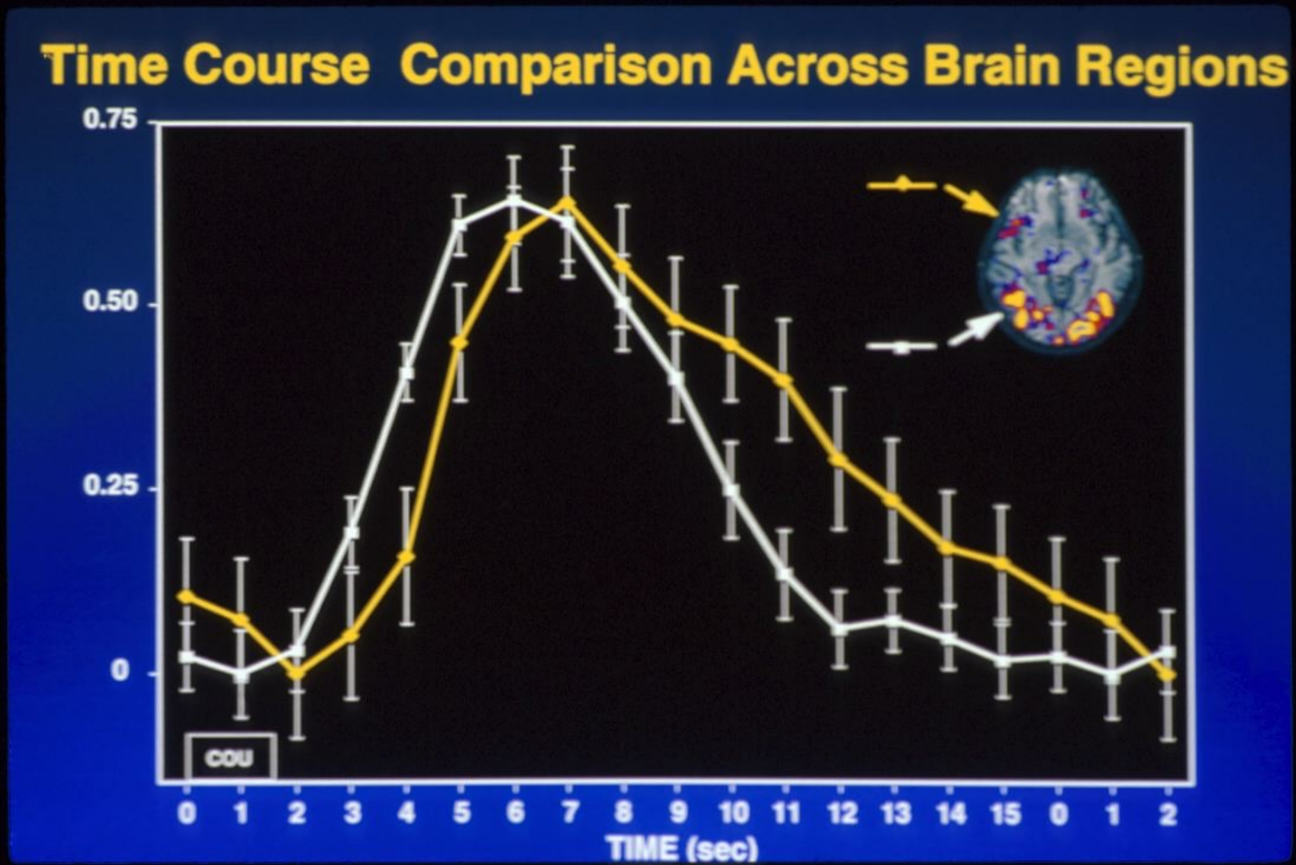

Hemodynamic Latency and Variability
Following Neuronal Activation
Space (mm)
100
10
1
0.1
0.01
Capillaries
Veins
100
1000
10^4
Time (ms)

Proc. Natl. Acad. Sci. USA
Vol. 93, pp. 14878–14883, December 1996
Neurobiology

Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging

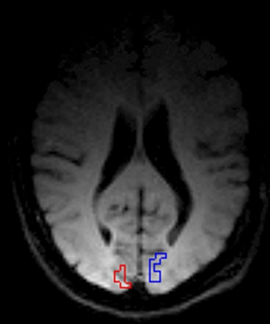
(neuroimaging/single trial/language/prefrontal)

RANDY L. BUCKNER†‡§¶, PETER A. BANDETTINI†‡, KATHLEEN M. O'CRAVEN†‖, ROBERT L. SAVOY†‖,
STEVEN E. PETERSEN**††, MARCUS E. RAICHLE§**††, AND BRUCE R. ROSEN†‡

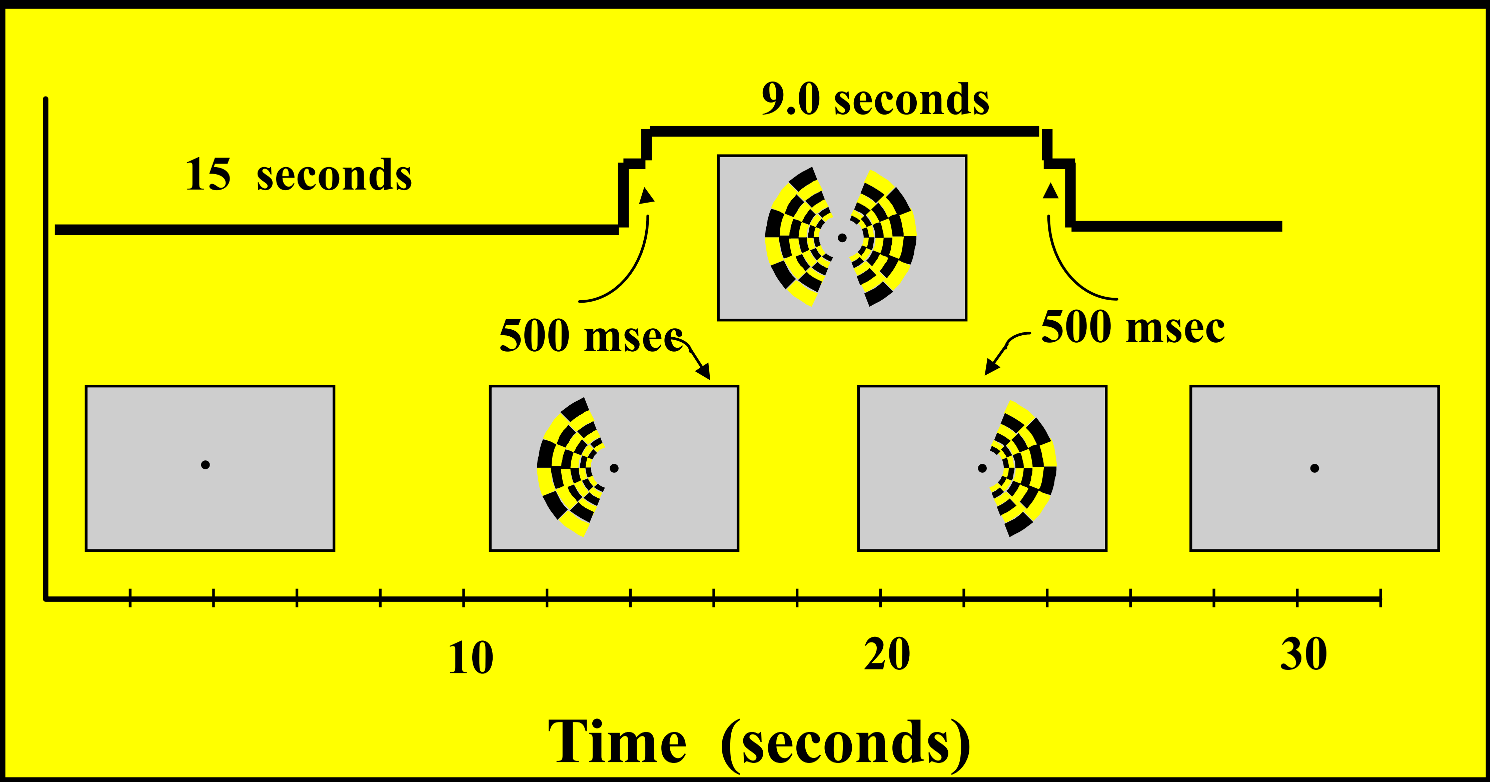


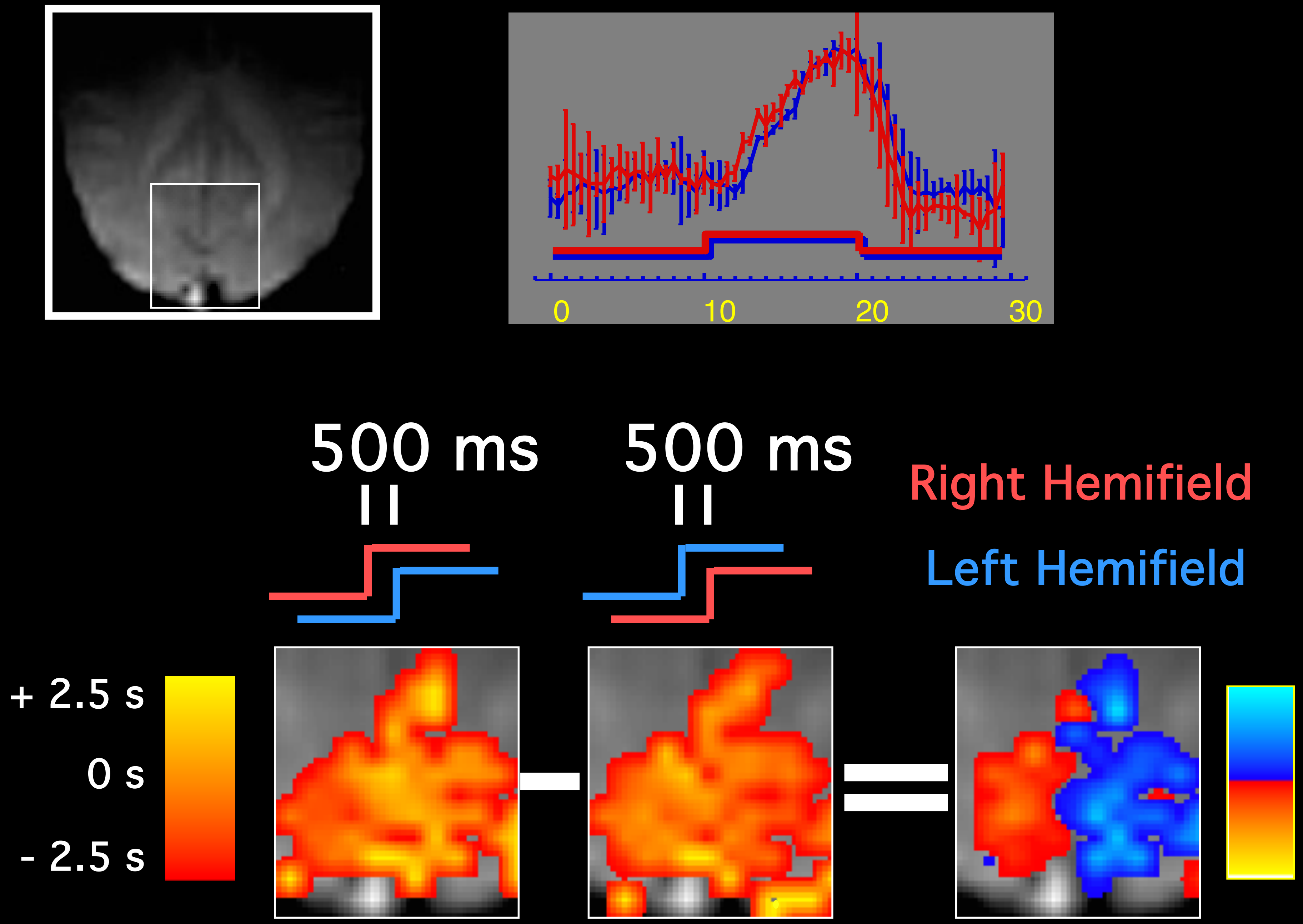
Hemi-Field Experiment

Right
Hemisphere



Left
Hemisphere





0
10
20
30
500 ms
500 ms
Right Hemifield
Left Hemifield
+ 2.5 s
0 s
- 2.5 s

Cognitive Neuroscience Application:

Understanding neural system dynamics through task modulation and measurement of functional MRI amplitude, latency, and width

PNAS

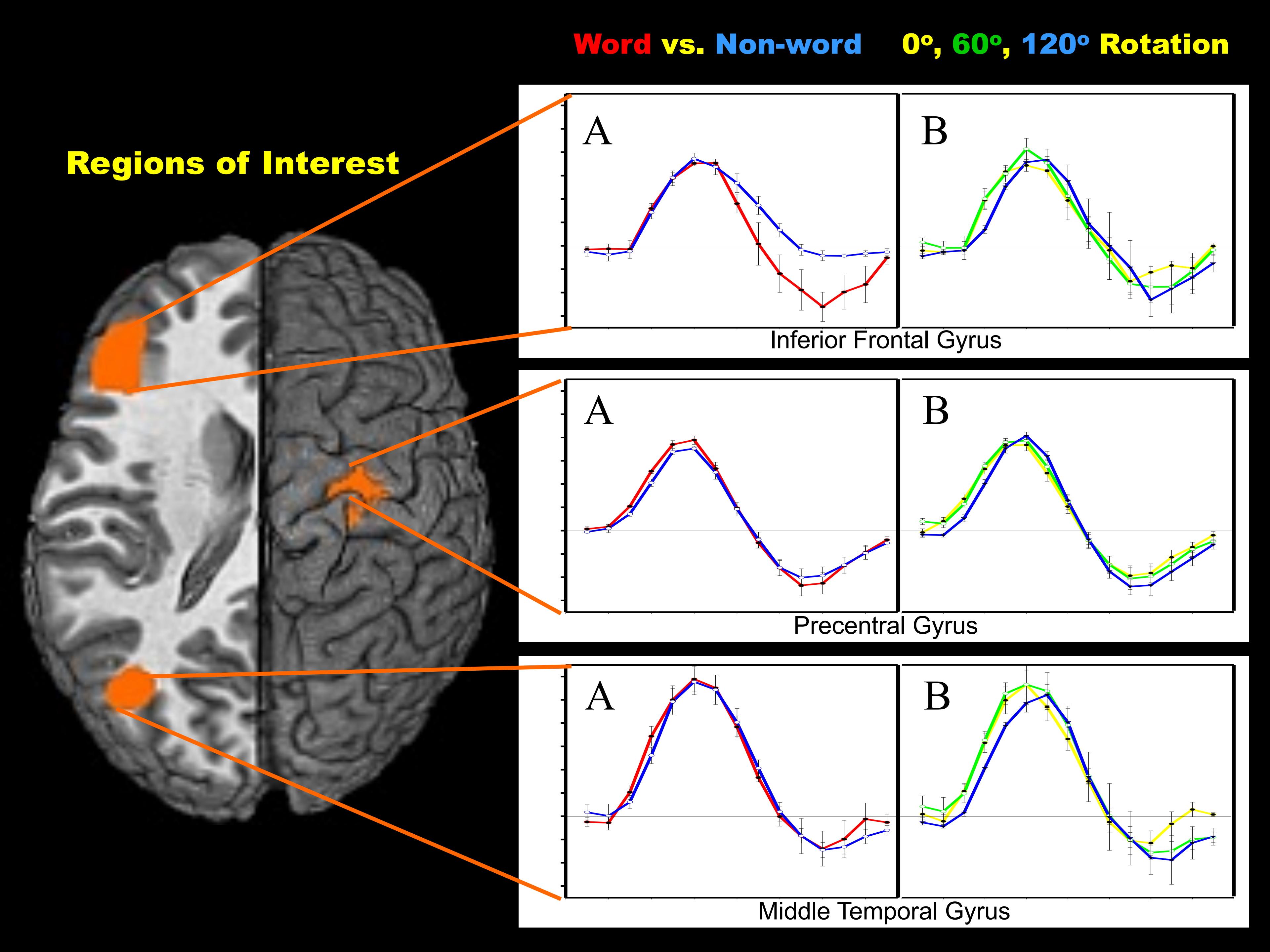
P. S. F. Bellgowan*†, Z. S. Saad‡, and P. A. Bandettini*

*Laboratory of Brain and Cognition and ‡Scientific and Statistical Computing Core, National Institute of Mental Health, Bethesda, MD 20892

Communicated by Leslie G. Ungerleider, National Institutes of Health, Bethesda, MD, December 19, 2002 (received for review October 31, 2002)

Lexical Delay

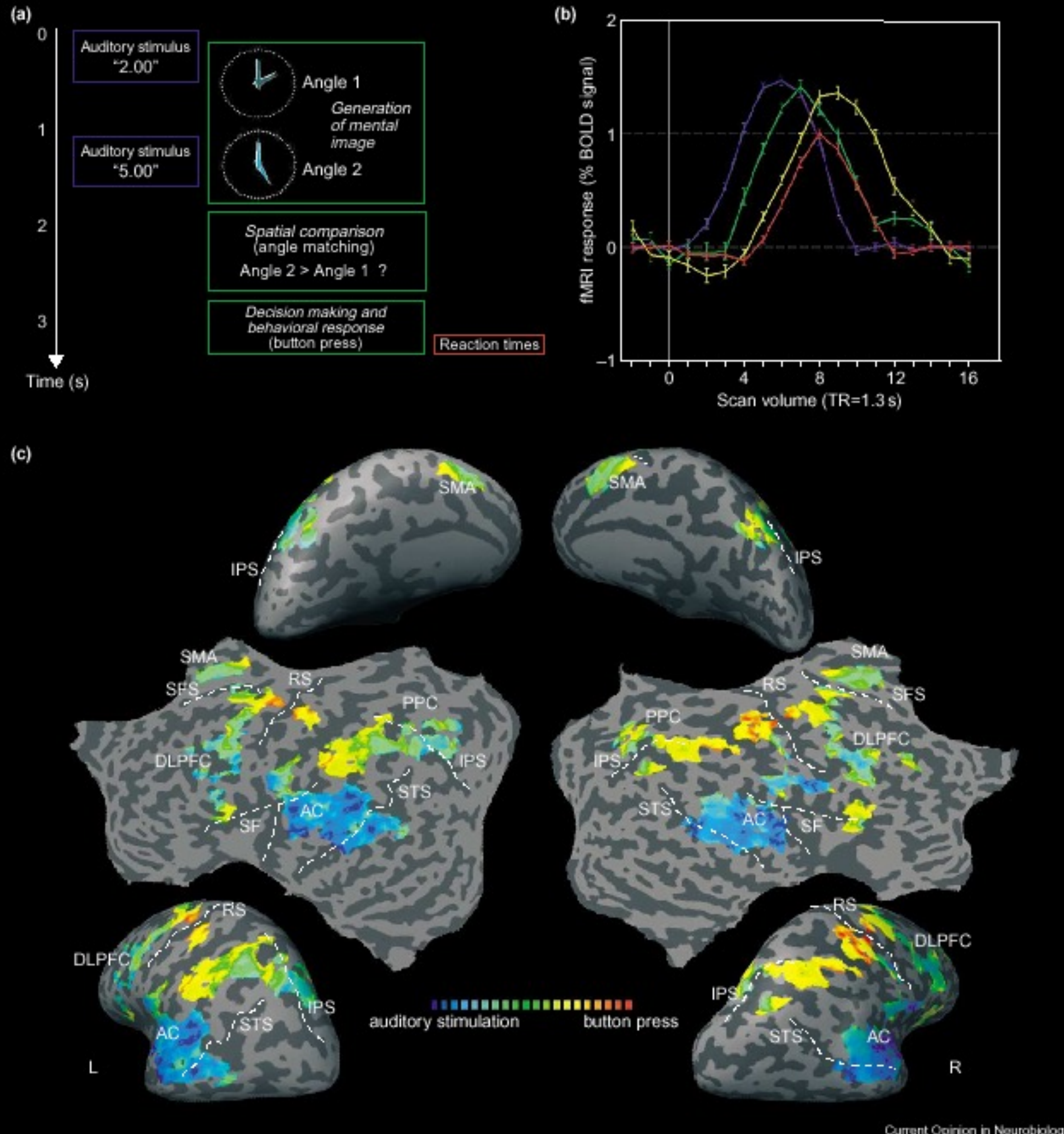
Rotational Delay	Words	Non-Words	Mean Reaction Time
0^0	smudge	dierts	823 ms
60^0	frolic	cuhlos	891 ms
120^0	slouch	gedmus	1446 ms
Mean Reaction Time	986 ms	1219 ms	



Word vs. Non-word
0º, 60º, 120º Rotation
Regions of Interest
A
B
Inferior Frontal Gyrus
A
B
Precentral Gyrus
A
B
Middle Temporal Gyrus

No calibration

Formisano, E. and R. Goebel, *Tracking cognitive processes with functional MRI mental chronometry.* Current Opinion in Neurobiology, 2003. **13**: p. 174-181.

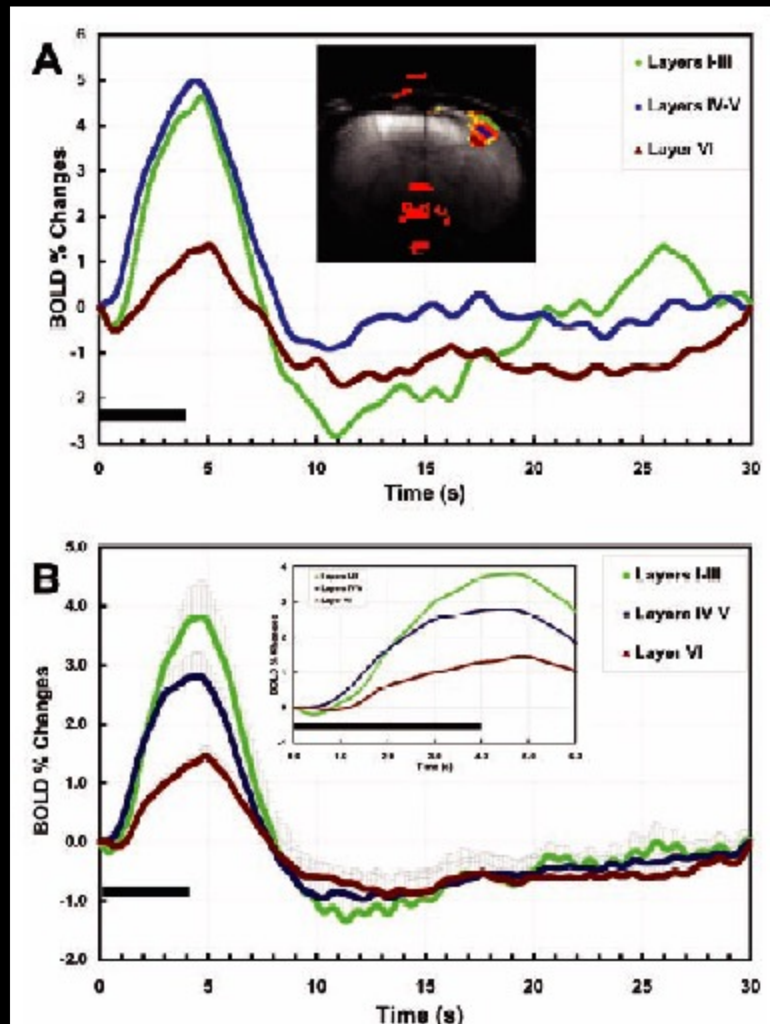


Laminar specificity of functional MRI onset times during somatosensory stimulation in rat

Afonso C. Silva* and Alan P. Koretsky

Laboratory of Functional and Molecular Imaging, National Institute of Neurological Disorders and Stroke, Bethesda, MD 20892

15182–15187 | PNAS | November 12, 2002 | vol. 99 | no. 23



No calibration

11.7 T

What more information can we extract from the FMRI time series?

- Event-related developments
- Linearity (Neuronal and/or Hemodynamic?)
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

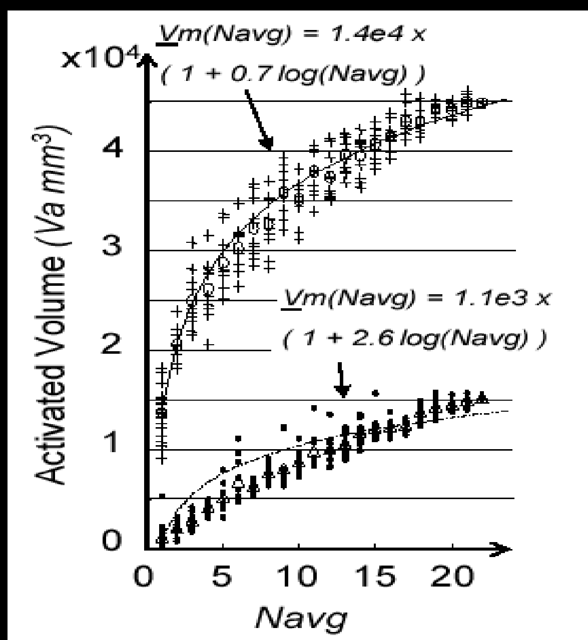
The spatial extent of the BOLD response

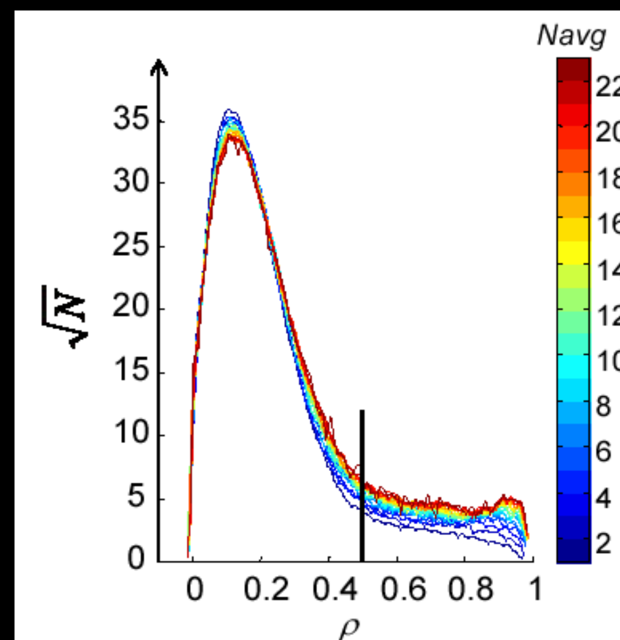
Ziad S. Saad,[a,b,*] Kristina M. Ropella,[b] Edgar A. DeYoe,[c] and Peter A. Bandettini[a]

[a] Laboratory of Brain and Cognition, National Institute of Mental Health, NIH, Bethesda, MD 20892-1148, USA
[b] Department of Biomedical Engineering Marquette University, Milwaukee, WI 53233, USA
[c] Department of Cell Biology, Neurobiology and Anatomy, Medical College of Wisconsin, Milwaukee, WI 53226, USA

Received 16 August 2002; revised 29 October 2002; accepted 21 November 2002

NeuroImage, **19:** 132-144, (2003).





Maximizing Signal

- Higher Bo Field
  - Linear or greater increase in S/N
  - Tradeoff in susceptibility artifacts
- Radio frequency Coils
  - Smaller the coil the higher the S/N
  - Tradeoff in coverage
- Choice of repetition time (TR)
  - Faster is better (more data points to average)
  - Tradeoff in coverage (10 slices/sec)
    - *min TR = (time/slice) x number of slices in volume*
  - Diminishing returns because of noise correlation
- Voxel volume
  - Linear relationship between S/N and voxel volume
  - Larger voxels increase partial volume averaging -> reduction of functional signal
- Averaging
  - Increase in sensitivity by sqrt(N)
  - System and subject instabilities increase with longer time

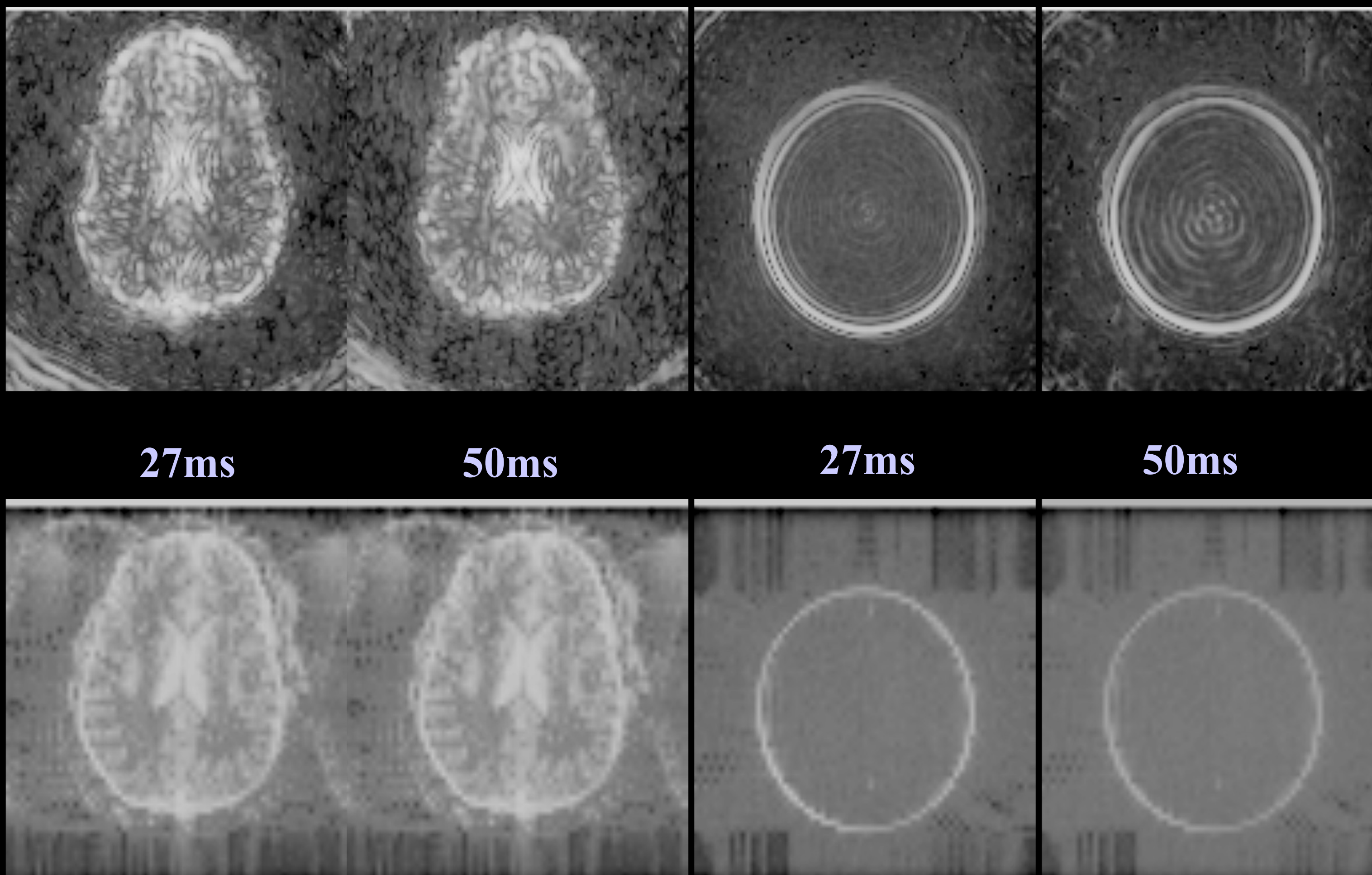
Temporal vs. Spatial SNR- 3T

26ms 49ms 26ms 49ms

27ms 50ms 27ms 50ms

SPIRAL

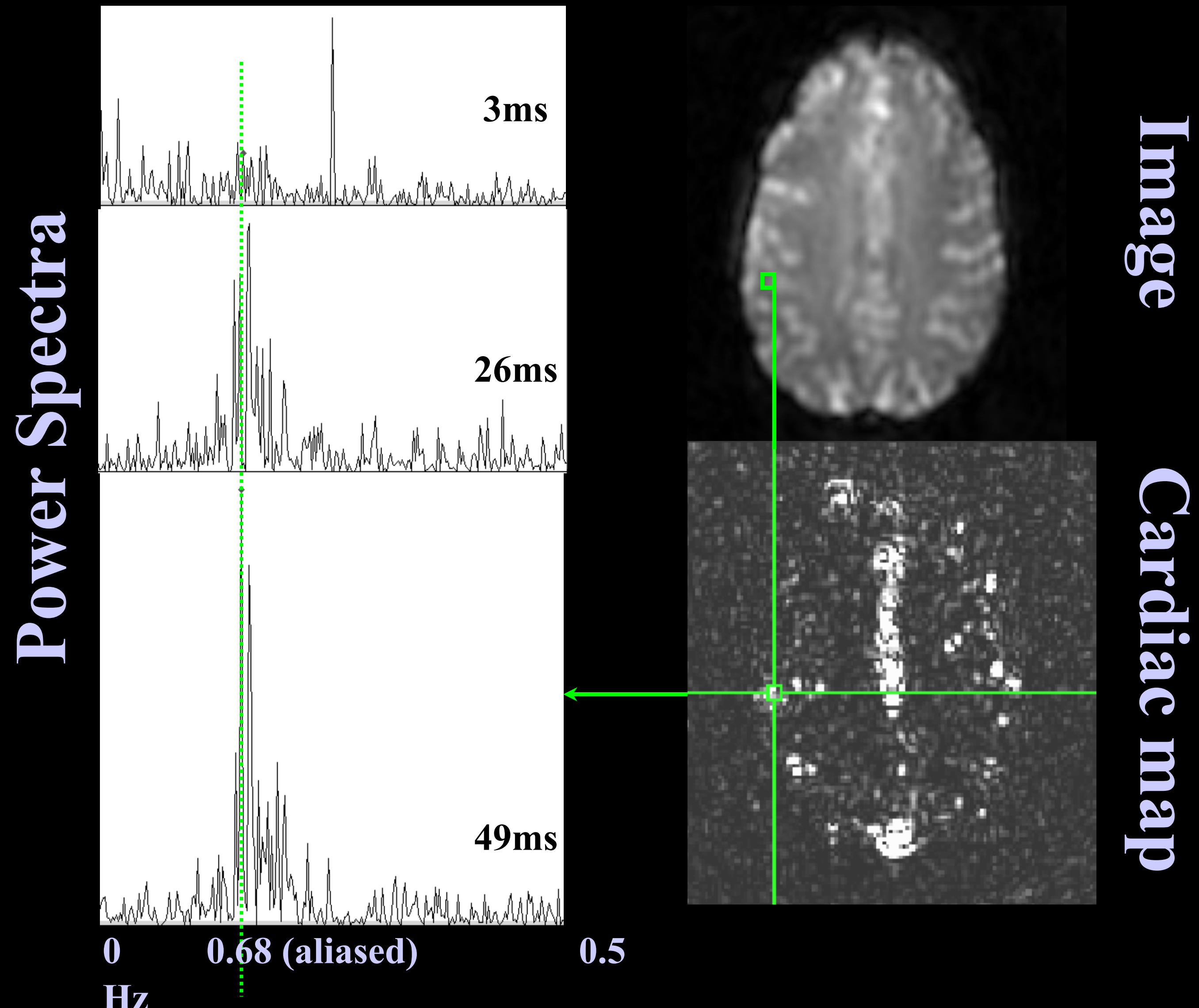
EPI

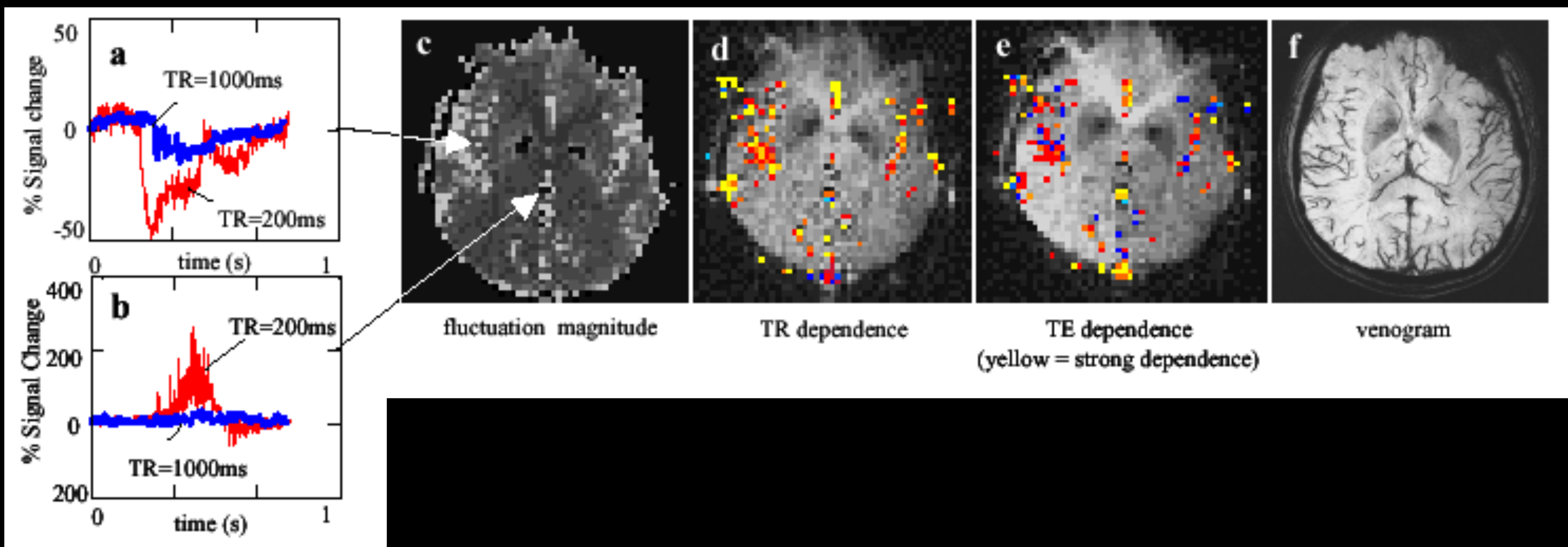


Physiologic Fluctuations

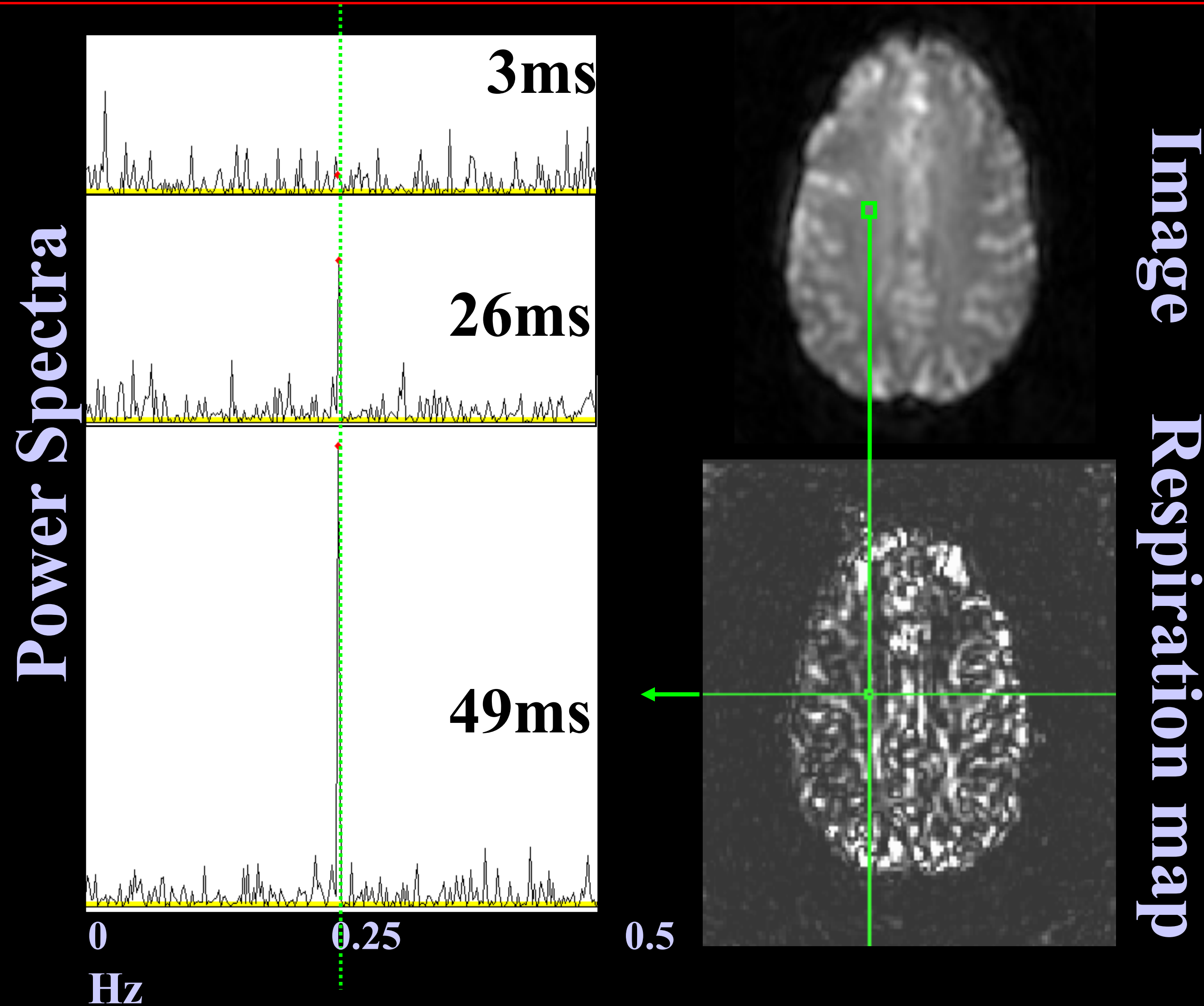
Cardiac	0.6 to 1.2 Hz
Respiratory	0.1 to 0.2 Hz
Low Frequency	0.0 to 0.1 Hz

0.68 Hz Cardiac rate at 3T




a
TR=1000ms
TR=200ms
50
0
-50
% Signal change
0
time (s)
1
b
TR=200ms
TR=1000ms
400
200
0
200
% Signal Change
0
time (s)
1
c
d
e
f
fluctuation magnitude
TR dependence
TE dependence
(yellow = strong dependence)
venogram

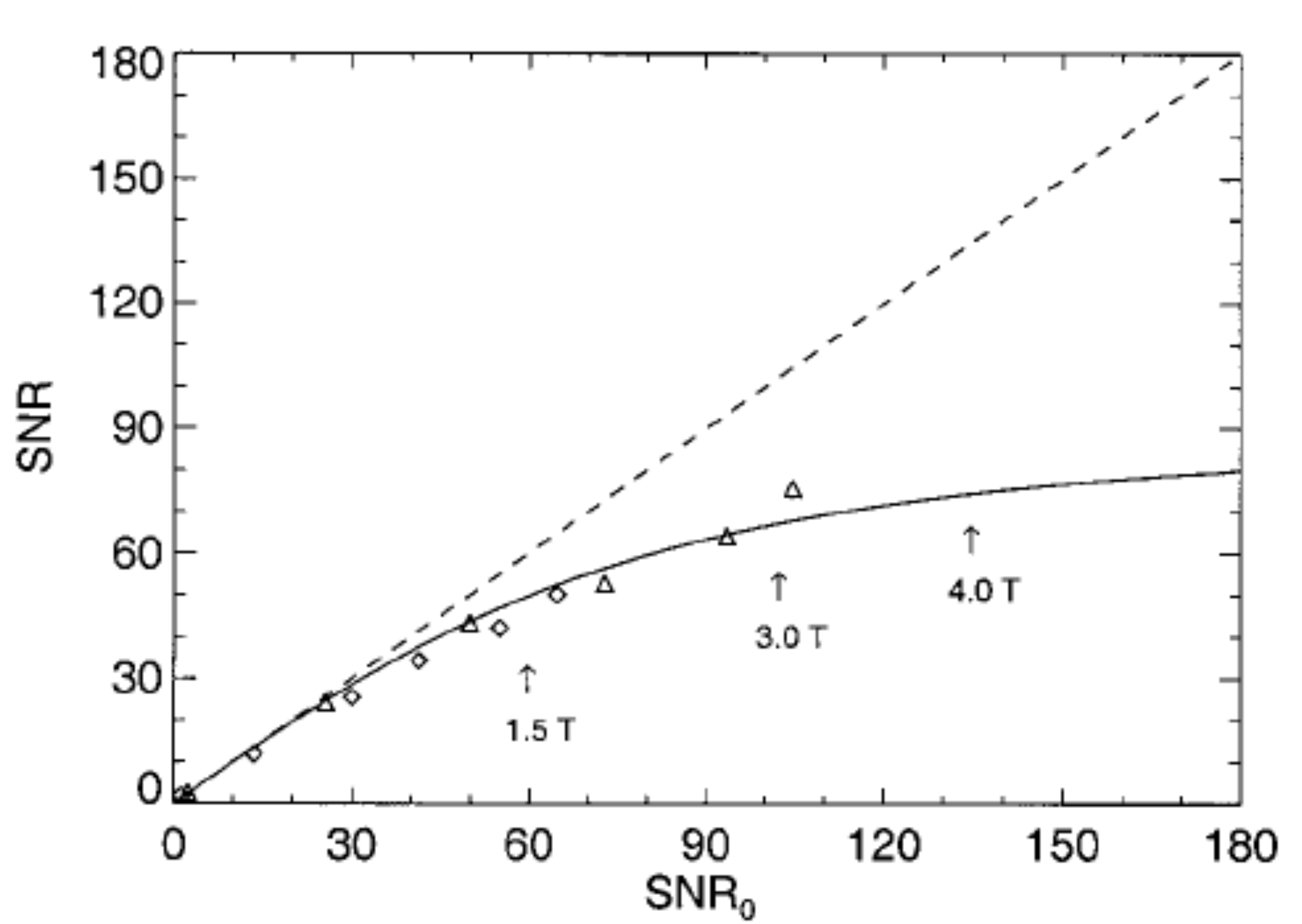
0.25 Hz Breathing at 3T



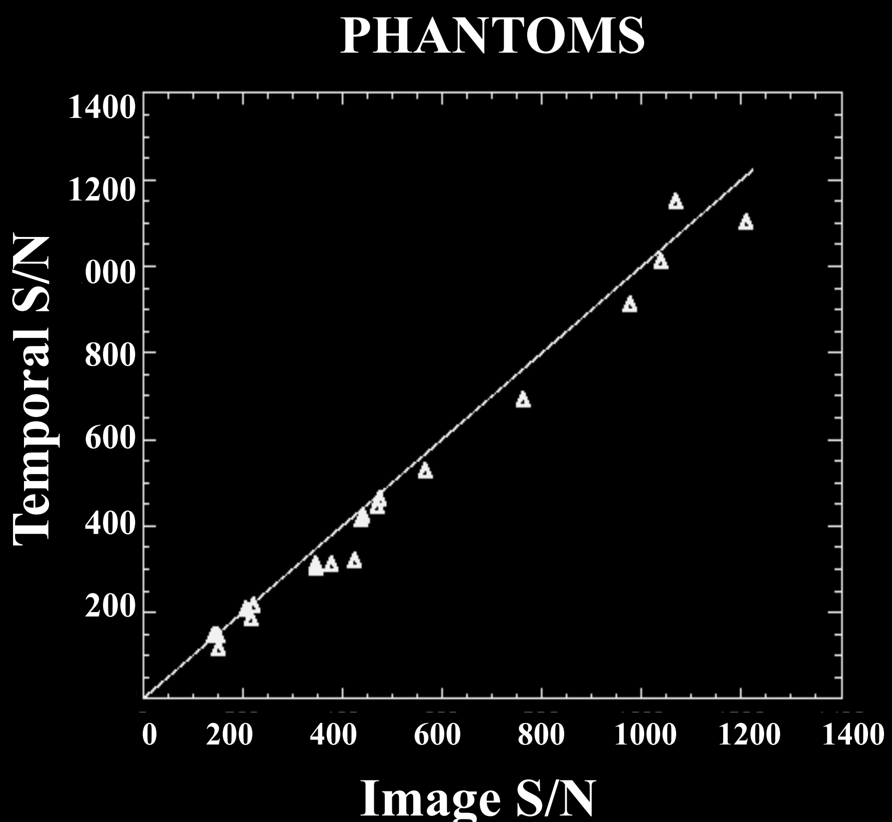
Magnetic Resonance in Medicine 45:595–604 (2001)

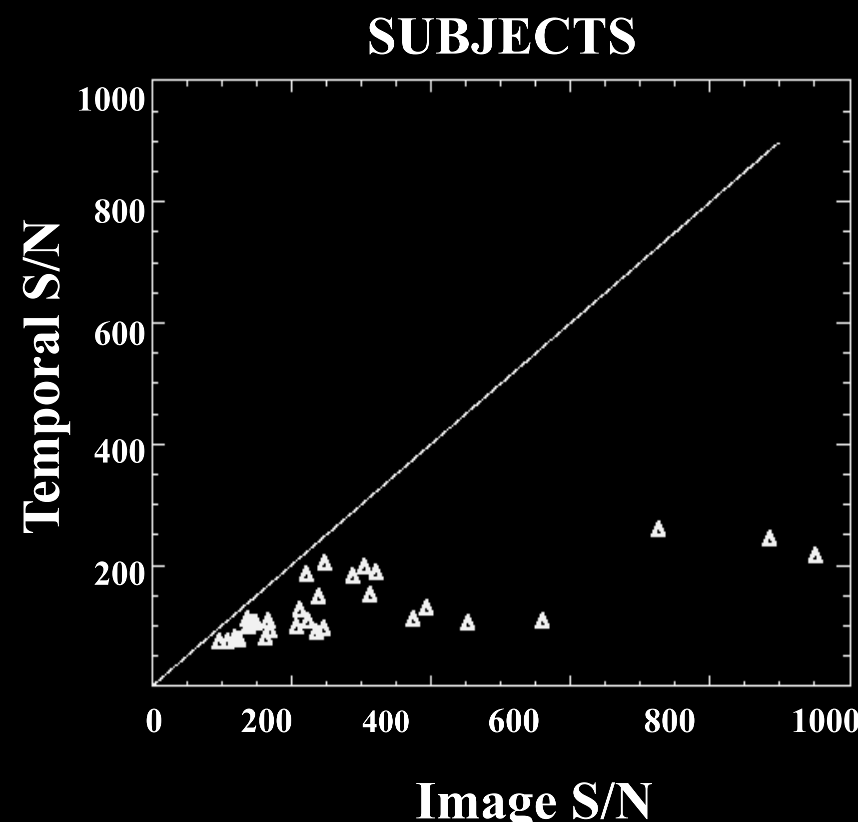
Neuroimaging at 1.5 T and 3.0 T: Comparison of Oxygenation-Sensitive Magnetic Resonance Imaging

Gunnar Krüger,* Andreas Kastrup, and Gary H. Glover



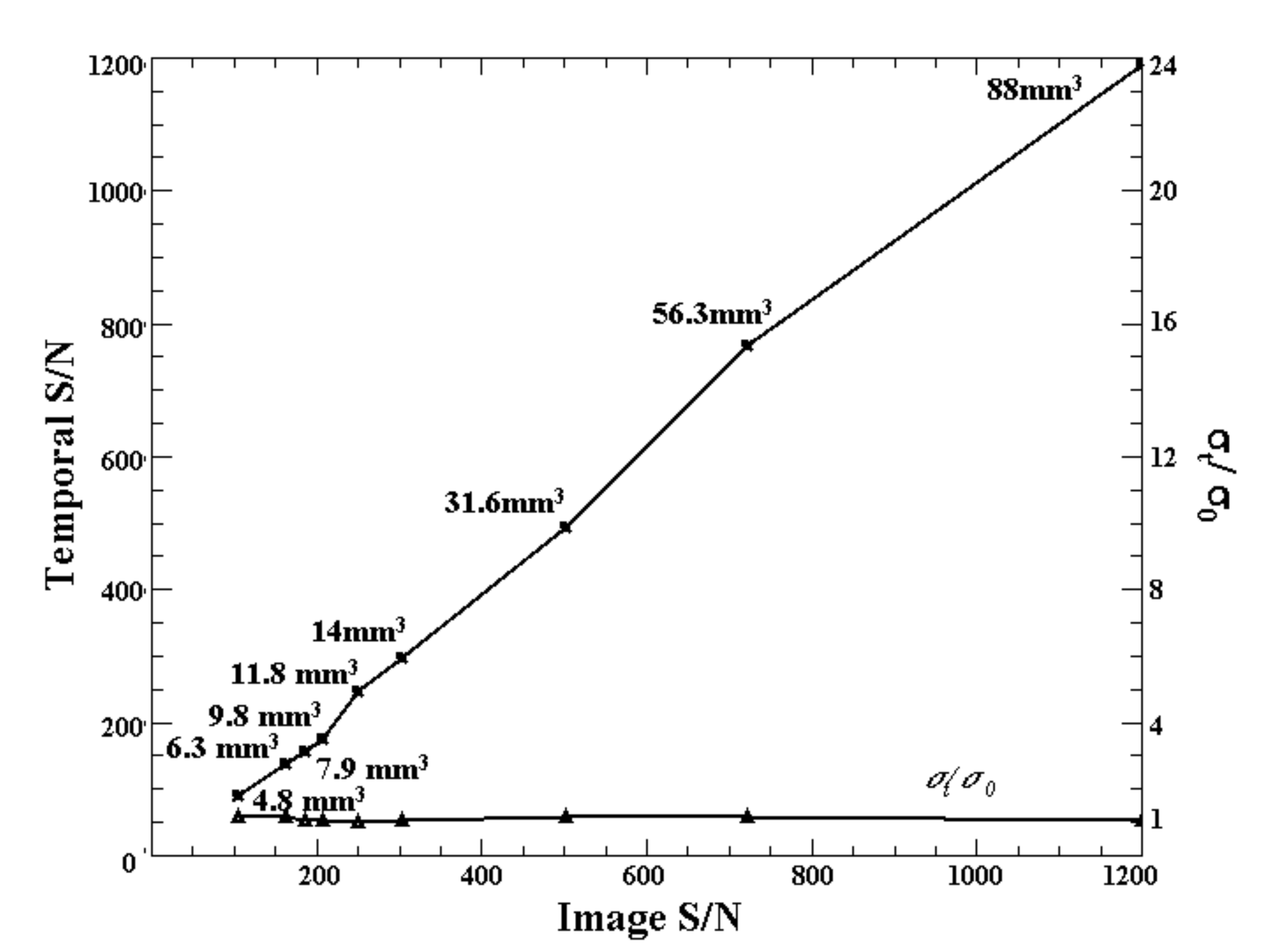
Temporal S/N vs. Image S/N





N. Petridou

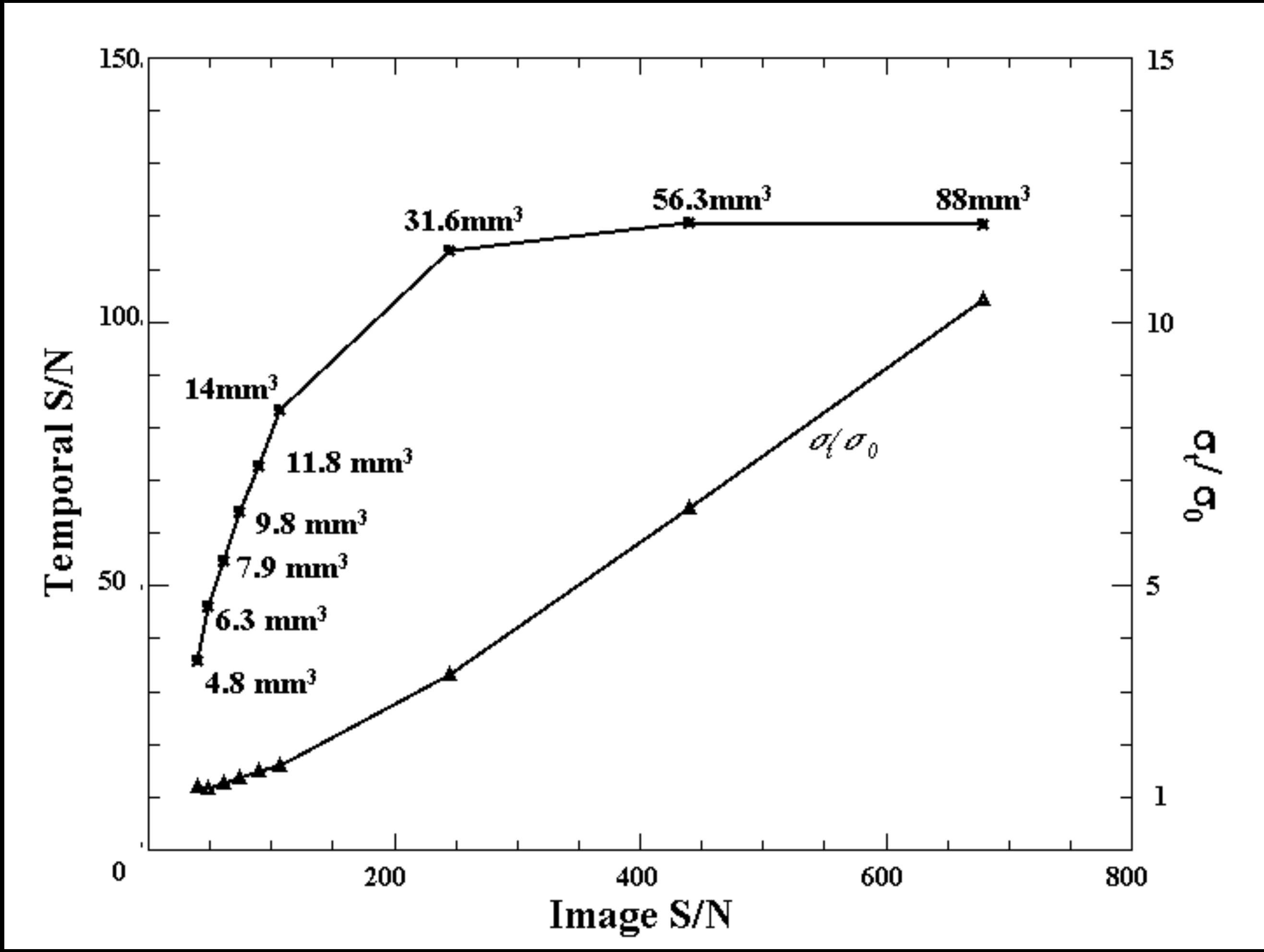
Temporal vs. Image S/N
Optimal Resolution Study



Phantom data

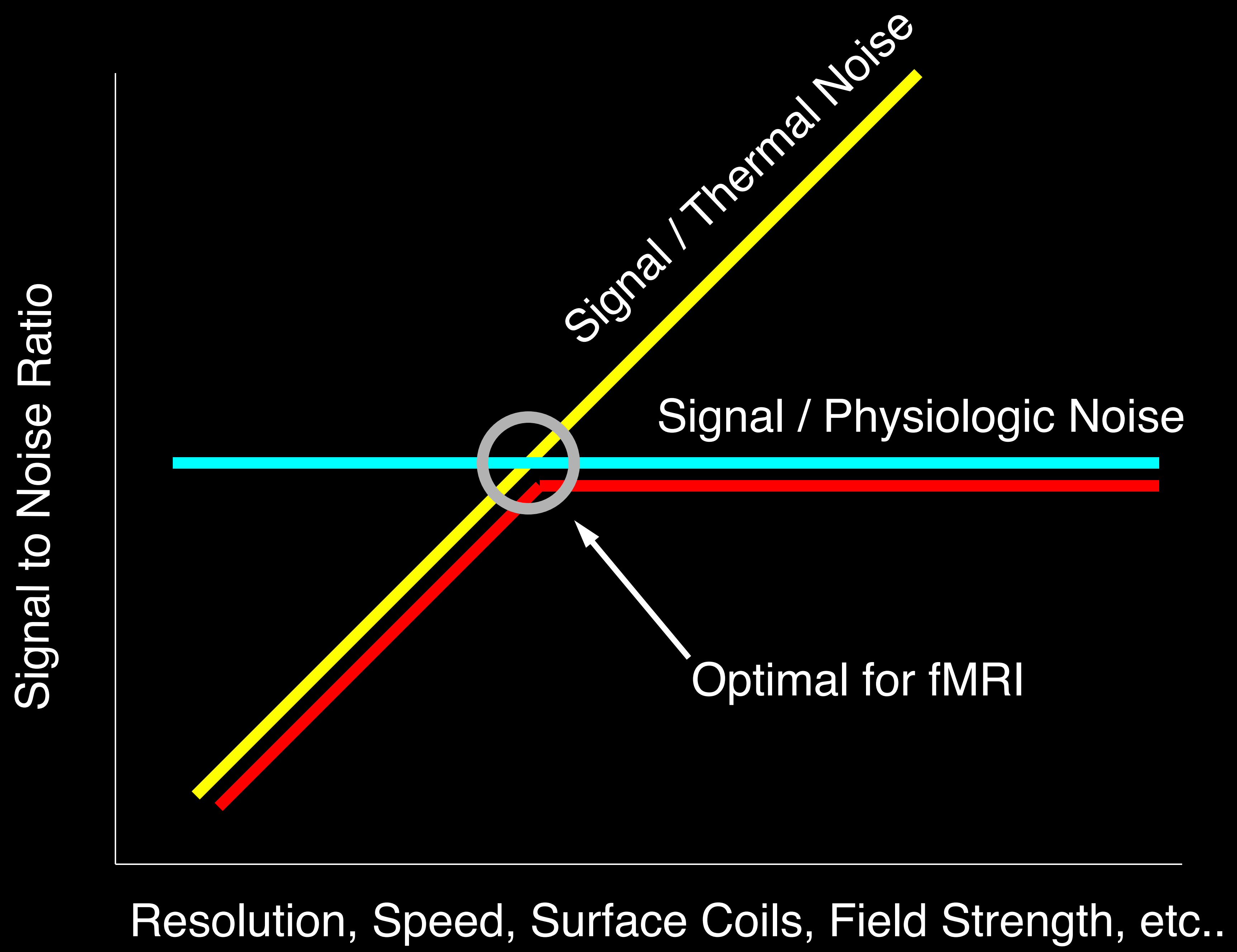
Petridou et al

Temporal vs. Image S/N
Optimal Resolution Study



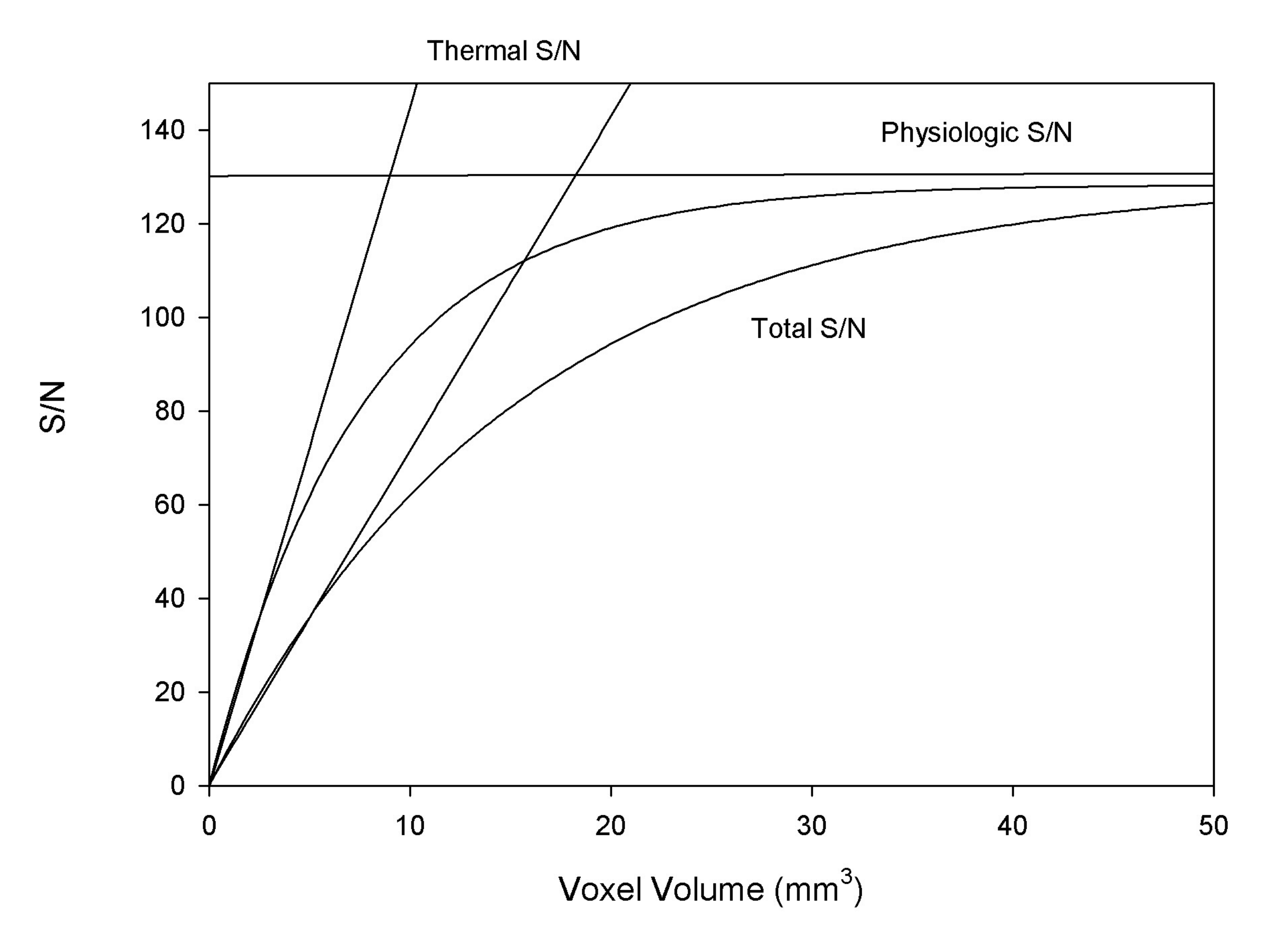
Human data

Petridou et al



Signal / Thermal Noise
Signal / Physiologic Noise
Optimal for fMRI
Signal to Noise Ratio
Resolution, Speed, Surface Coils, Field Strength, etc..

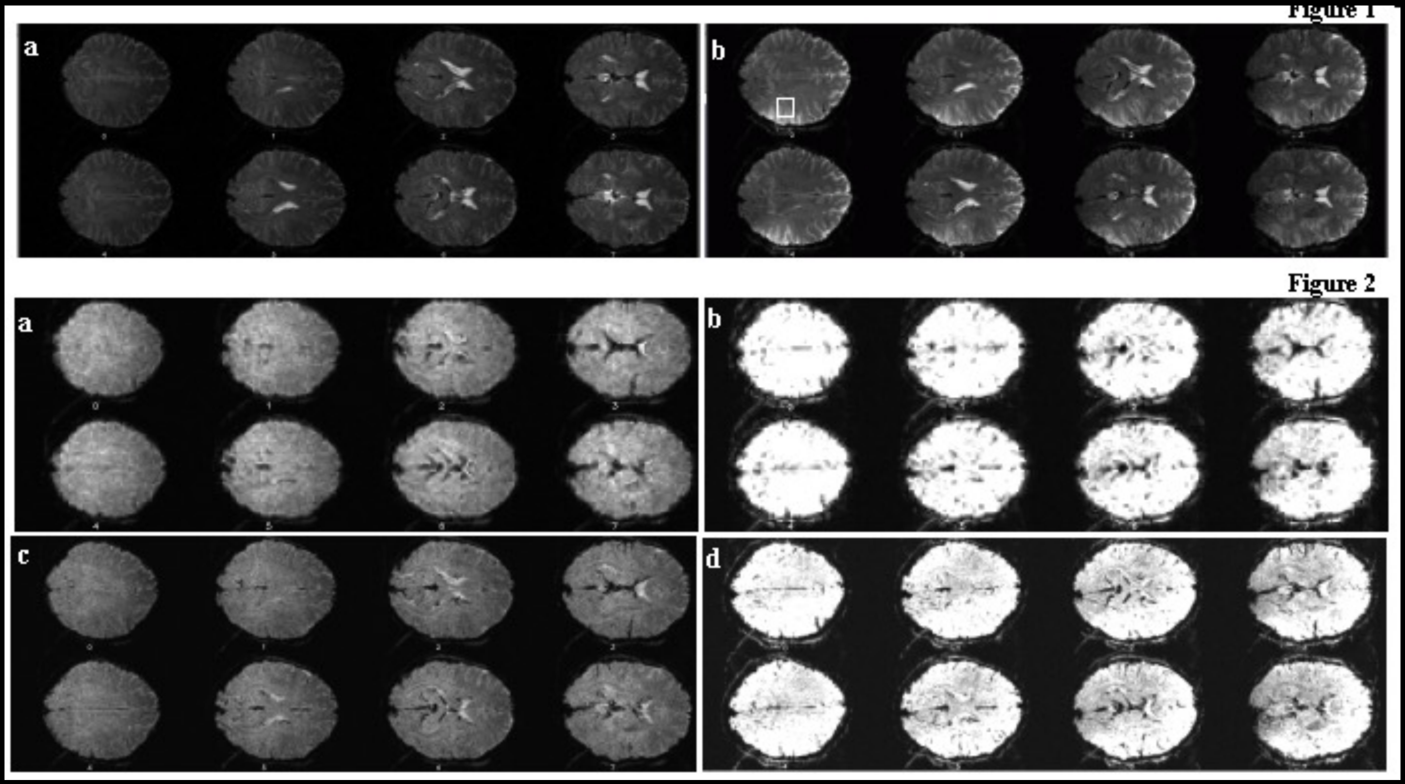
Doubling Sensitivity with RF coils



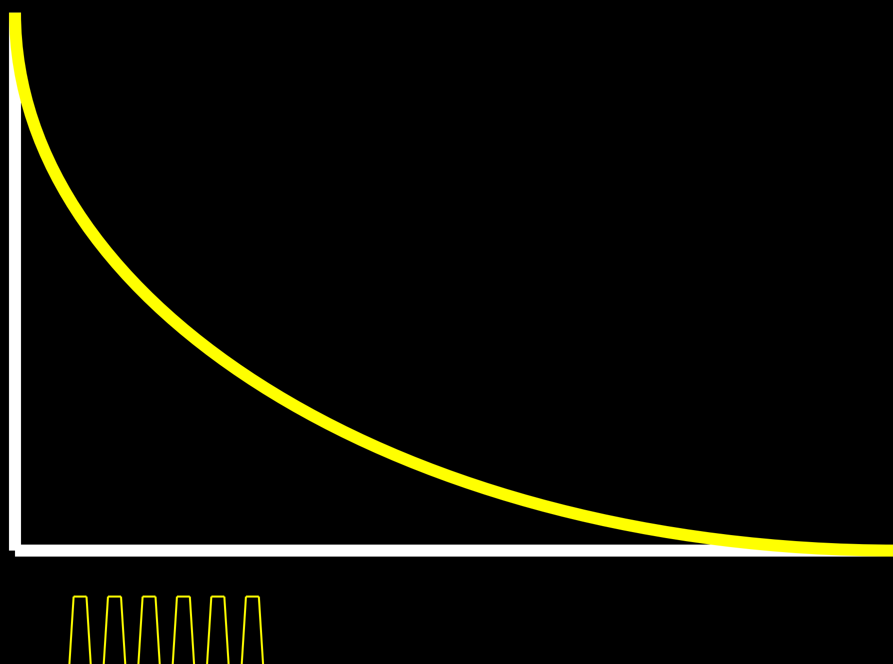
Single shot full k-space echo-planar-imaging with an eight-channel phase array coil at 3T.

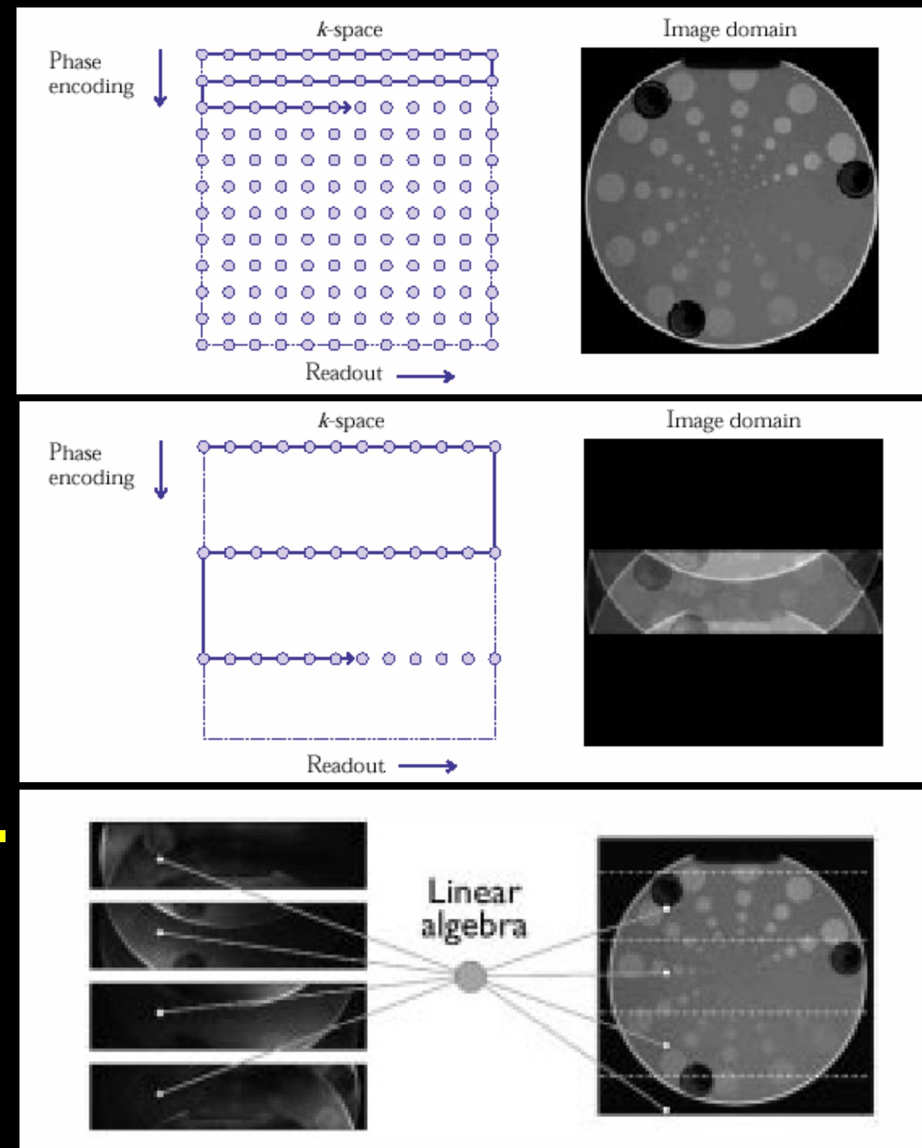
Jerzy Bodurka[1], Peter van Gelderen[2], Patrick Ledden[3], Peter Bandettini[1], Jeff Duyn[2]
[1]Functional MRI Facility NIMH/NIH, [2]Advance MRI NINDS/NIH, [3]Nova Medical Inc.

Quadrature Head Coil | 8 Channel Array



SENSE Imaging





≈ 5 to 30 ms

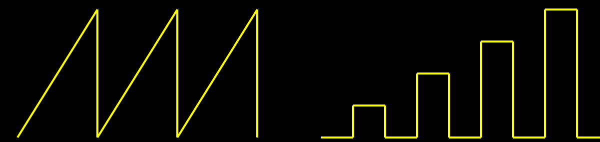
Pruessmann, et al.

What more information can we extract from the FMRI time series?

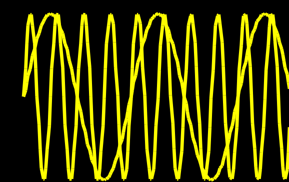
- Event-related developments
- Linearity (Neuronal and/or Hemodynamic?)
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

Neuronal Activation Input Strategies

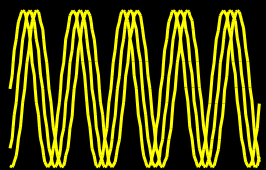
1. Block Design
2. Parametric Design



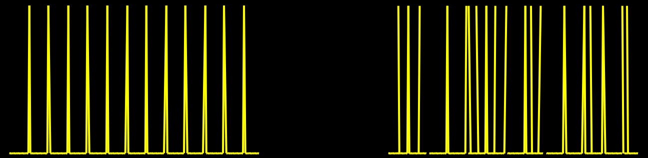
3. Frequency Encoding



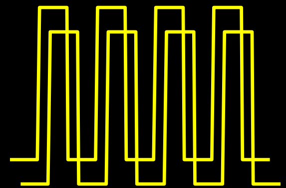
4. Phase Encoding



5. Event Related



6. Orthogonal Design



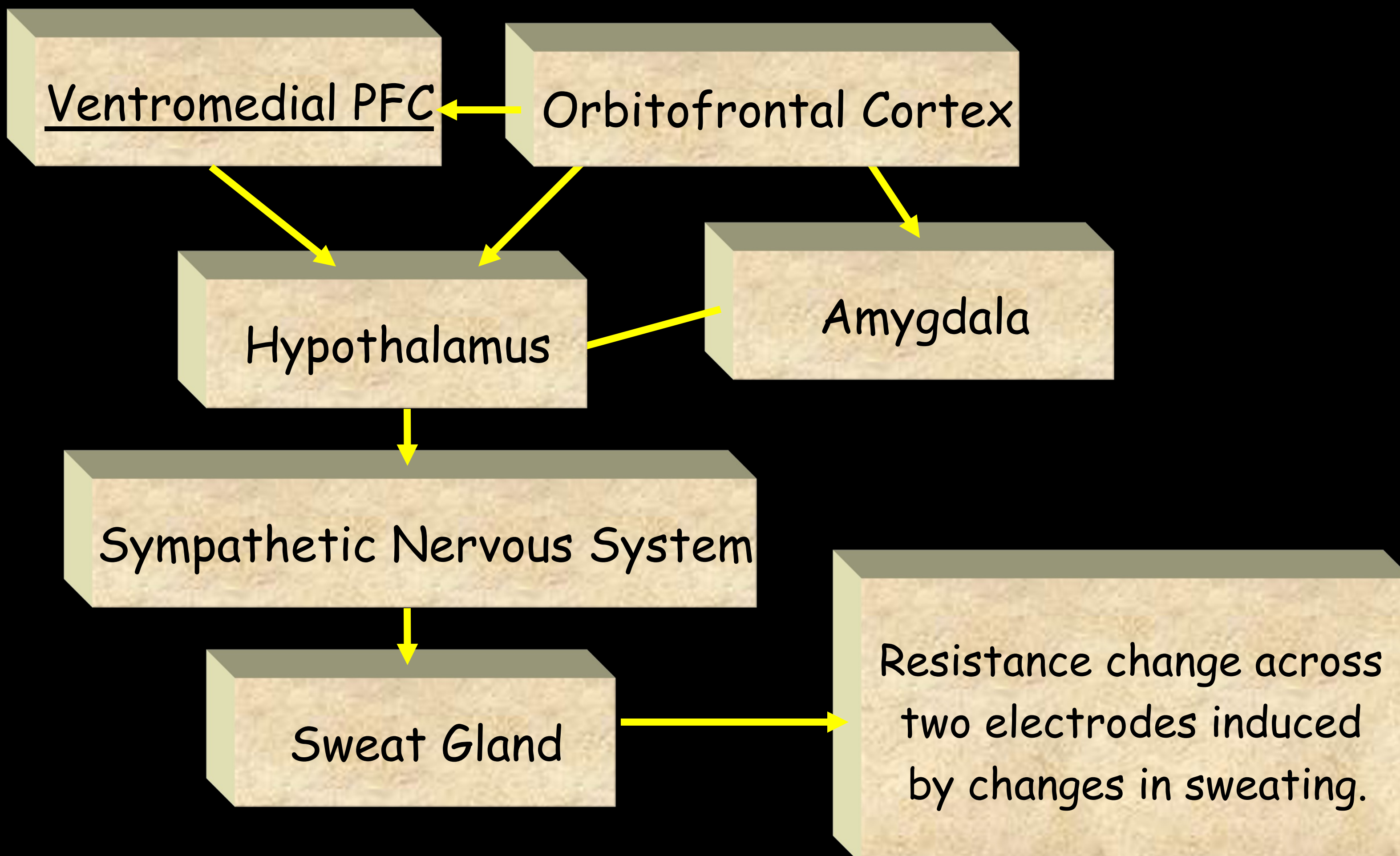
7. Free Behavior Design

Free Behavior Design

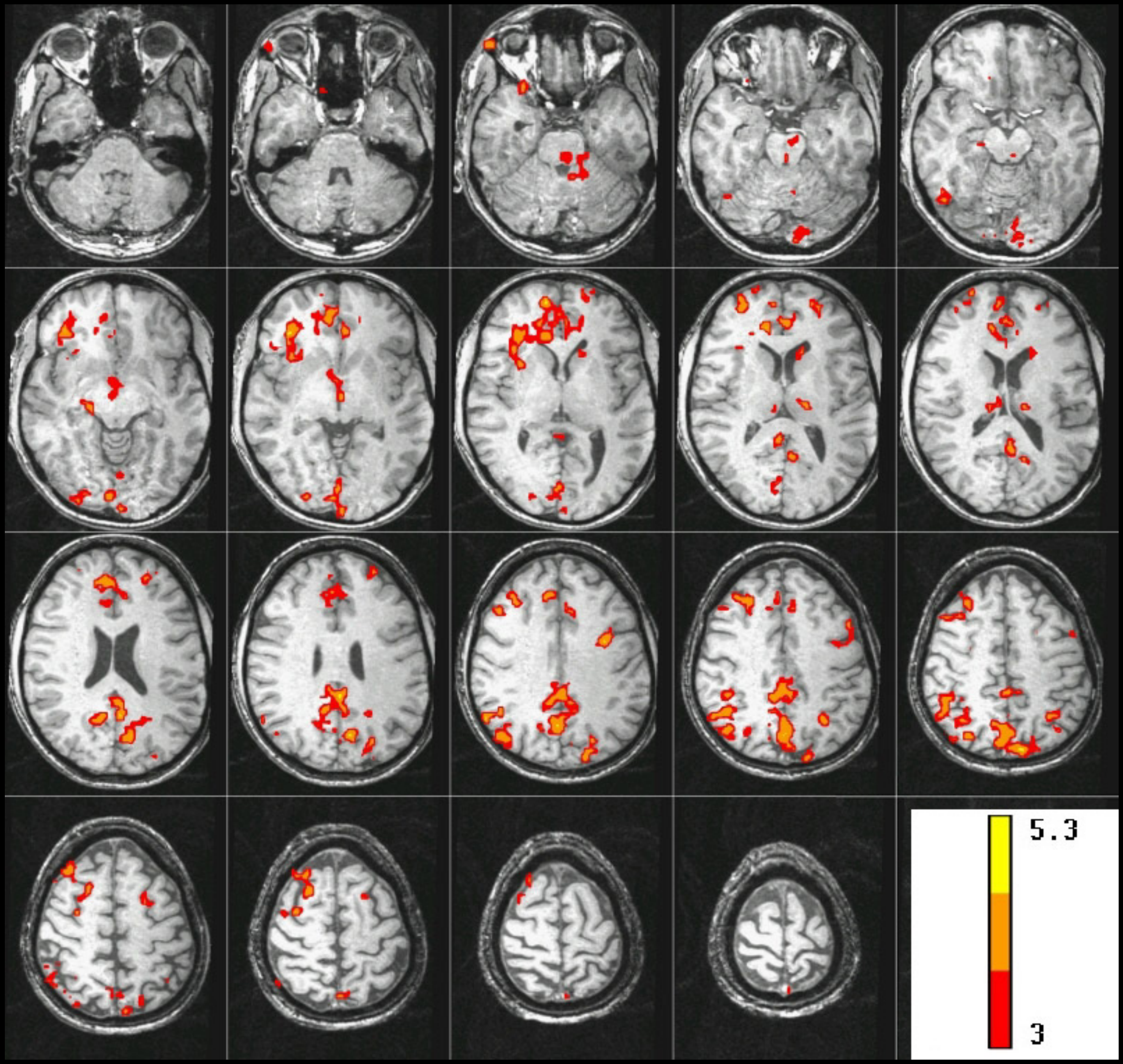
Use a continuous measure as a reference function:

- Task performance
- Skin Conductance
- Heart, respiration rate..
- Eye position
- EEG

The Skin Conductance Response (SCR)



Brain activity correlated with SCR during “Rest”



J. C. Patterson II, L. G. Ungerleider, and P. A Bandettini, Task - independent functional brain activity correlation with skin conductance changes: an fMRI study. *NeuroImage 17: 1787-1806, (2002).*

Simultaneous EEG and fMRI of the alpha rhythm

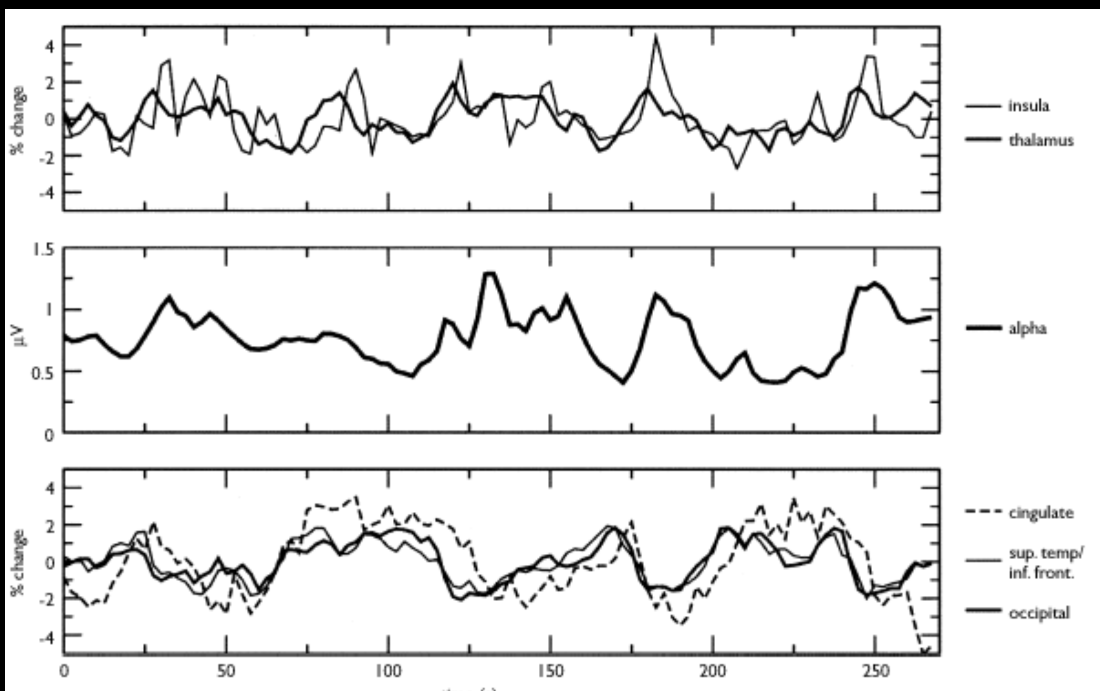
Robin I. Goldman,[2,CA] John M. Stern,[1] Jerome Engel Jr[1] and Mark S. Cohen

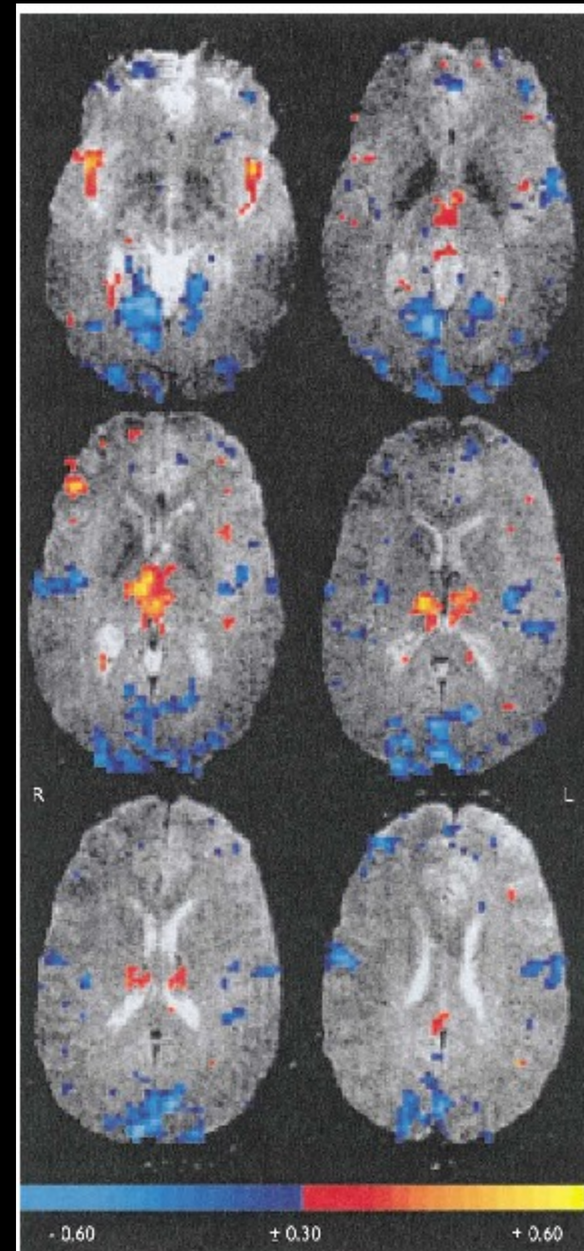
Ahmanson-Lovelace Brain Mapping Center, UCLA, 660 Charles Young Drive South, Los Angeles, CA 90095; [1]Department of Neurology, UCLA School of Medicine, Los Angeles, CA; [2]Hatch Center for MR Research, Columbia University, HSD, 710 W. 168th St., NIB-1, Mailbox 48, NY, NY 10032, USA

[CA,2]Corresponding Author and Address: rg2146@columbia.edu

Received 28 October 2002; accepted 30 October 2002

DOI: 10.1097/01.wnr.0000047685.08940.d0





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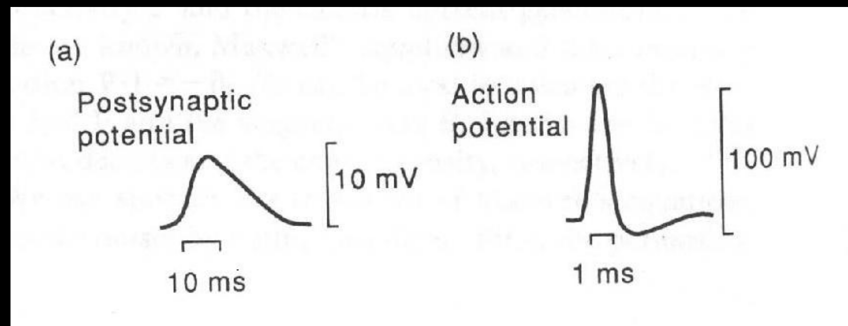
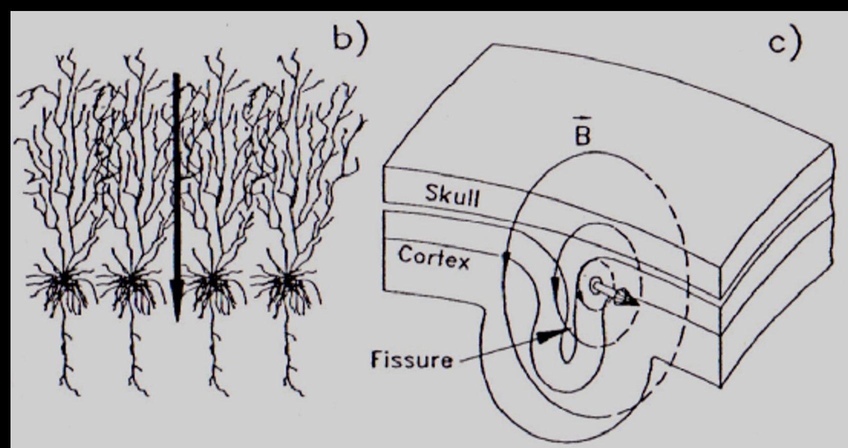
- Hemodynamic Latency
- Sensitivity and “Noise”
- Design and analysis innovations
- Neuronal current imaging

Primary People Involved

Jerzy Bodurka
Natalia Petridou
Frank Ye
Rasmus Birn

The Basic Idea...





100 fT at on surface of skull

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

Derivation of B field generated in an MRI voxel by a current dipole

Single dendritic tree having a diameter d, and length L behaves like a conductor with conductivity σ. Resistance is R=V/I, where $R=4L/(\pi d^2 \sigma)$. From Biot-Savart:

$$B = \frac{\mu_0}{4\pi}\frac{Q}{r^2} = \frac{\mu_0}{16}\frac{d^2 \sigma V}{r^2}$$

by substituting d = 4μm, $\sigma \approx 0.25\ \Omega^{-1}\ m^{-1}$, V = 10mV and

r = 4cm (measurement distance when using MEG) the resulting value is: **B≈0.002 fT**

Because **B_{MEG}=100fT** is measured by MEG on the scalp, (0.002 fT x 50,000 = 100 fT), must coherently act to generate such field. These bundles of neurons produce, within a typical voxel, 1 mm x 1 mm x 1 mm, a field of order:

$$B_{MRI} = B_{MEG}\left(\frac{r_{MEG}}{r_{MRI}}\right)^2 = B_{MEG}\left(\frac{4\ cm}{0.1\ cm}\right)^2 = 1600\ B_{MEG}$$

$B_{MRI} \approx 0.2$nT

J. Bodurka, P. A. Bandettini. *Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes.* **Magn. Reson. Med. 47: 1052-1058, (2002).**

Some background...

G. C. Scott, M. L. Joy, R. L. Armstrong, R. M. Henkelman, *RF current density imaging homogeneous media.* **Magn. Reson. Med. 28: 186-201, (1992).**

M. Singh, *Sensitivity of MR phase shift to detect evoked neuromagnetic fields inside the head.* **IEEE Transactions on Nuclear Science. 41: 349-351, (1994).**

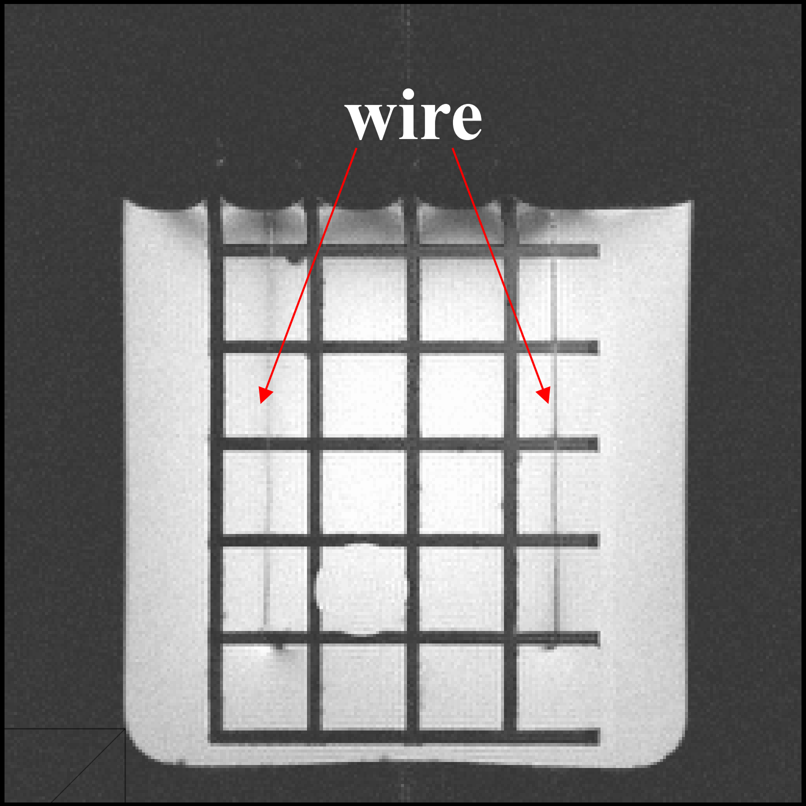
H. Kamei, J, Iramina, K. Yoshikawa, S. Ueno, *Neuronal current distribution imaging using MR.* **IEEE Trans. On Magnetics, 35: 4109-4111, (1999)**

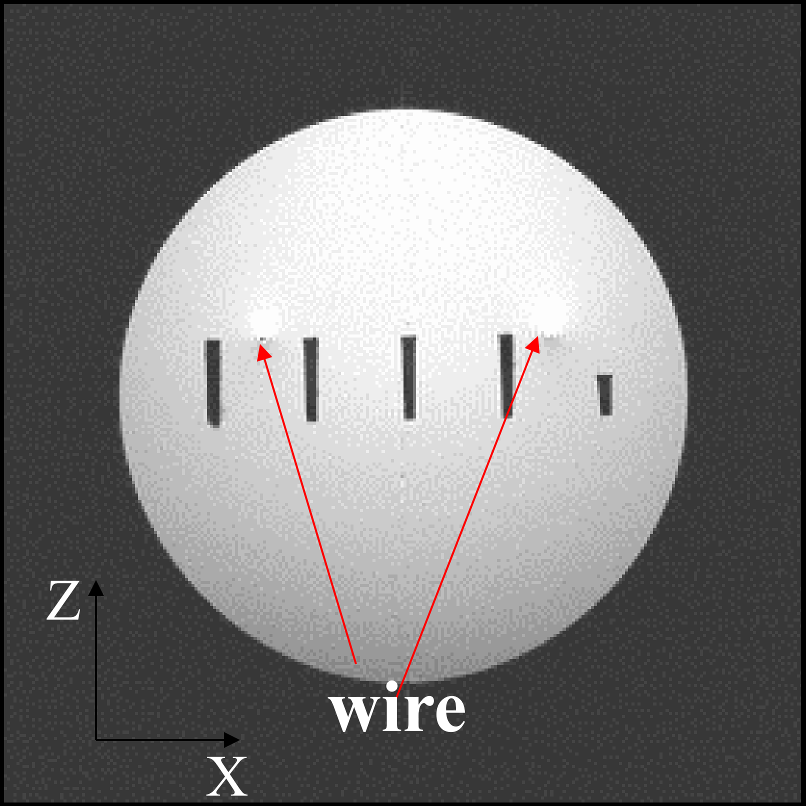
J. Bodurka, P. A. Bandettini. *Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes.* **Magn. Reson. Med. 47: 1052-1058, (2002).**

D. Konn, P. Gowland, R. Bowtell, *MRI detection of weak magnetic fields due to an extended current dipole in a conducting sphere: a model for direct detection of neuronal currents in the brain.* **Magn. Reson. Med. 50: 40-49, (2003).**

J. Xiong, P. T. Fox, J.-H. Gao, *Direct MRI Mapping of neuronal activity.* **Human Brain Mapping, 20: 41-49, (2003)**

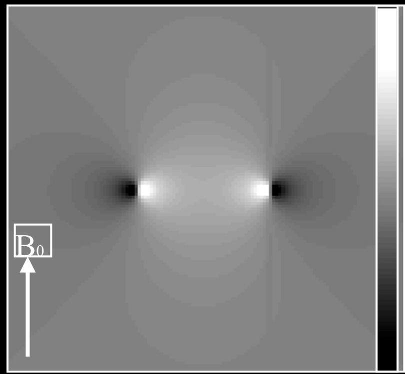
Current Phantom Experiment



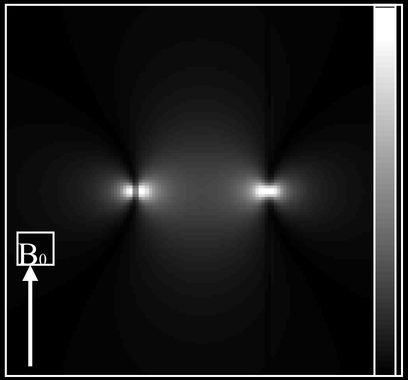


Simulation

calculated $B_c \parallel B_0$



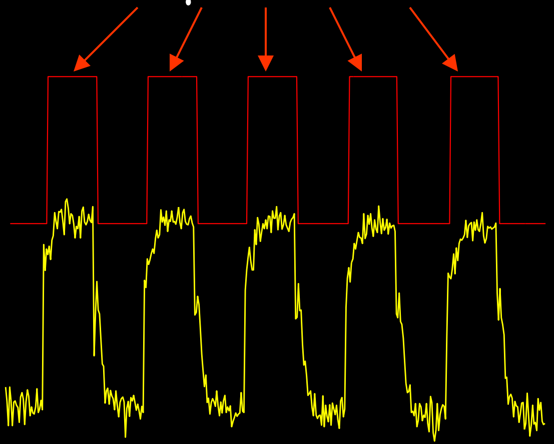
calculated $|\Delta B_c| \parallel B_0$



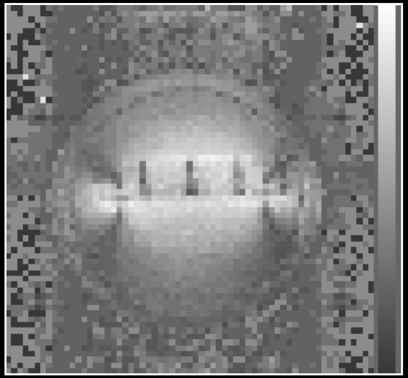
Measurement

$\Delta\phi \cong 20^0$

Correlation image

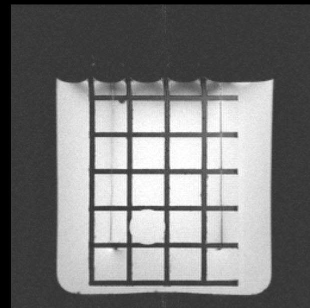


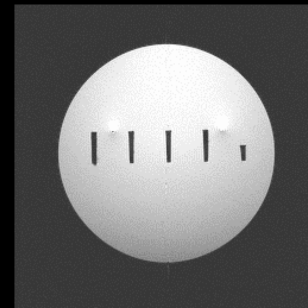
Single shot GE EPI

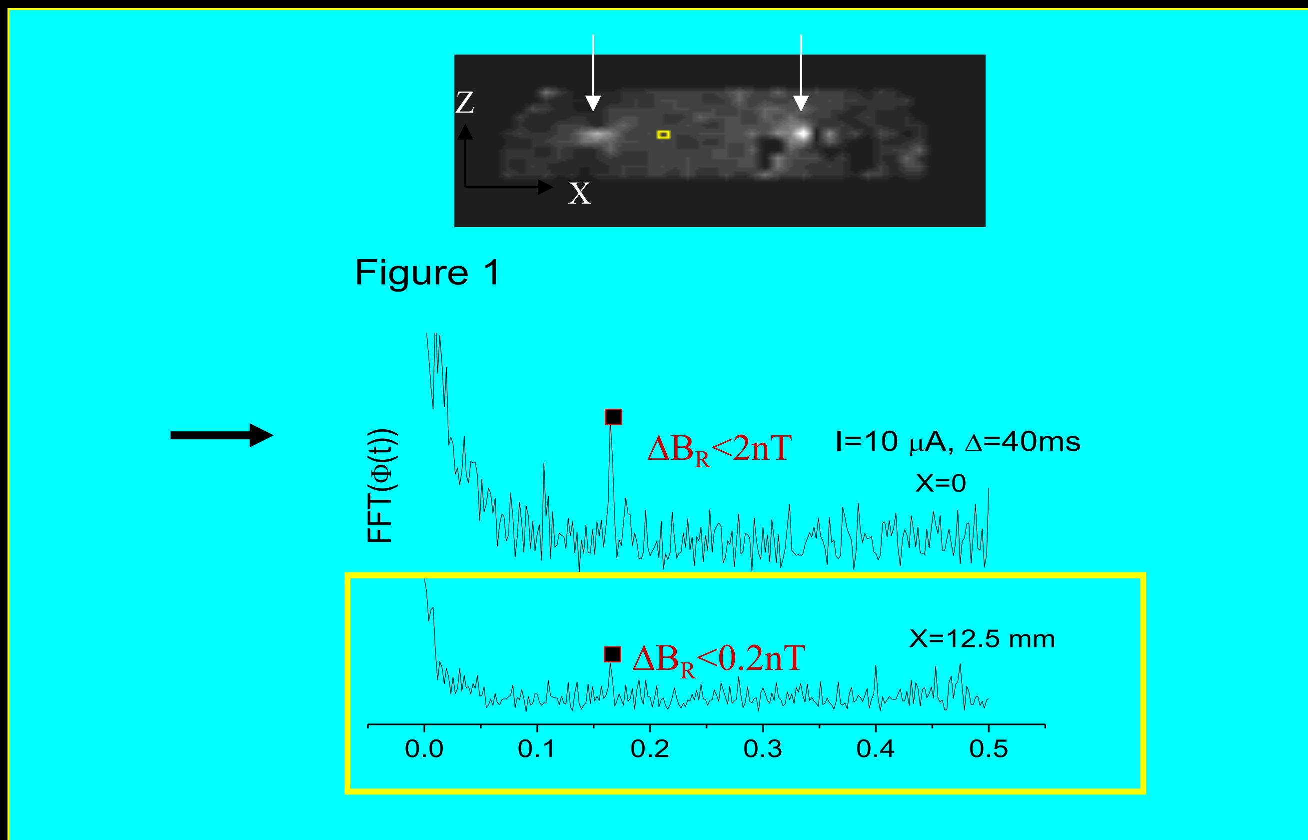


Spectral image

J. Bodurka, P. A. Bandettini. Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes, Magn. Reson. Med. 47: 1052-1058, (2002).

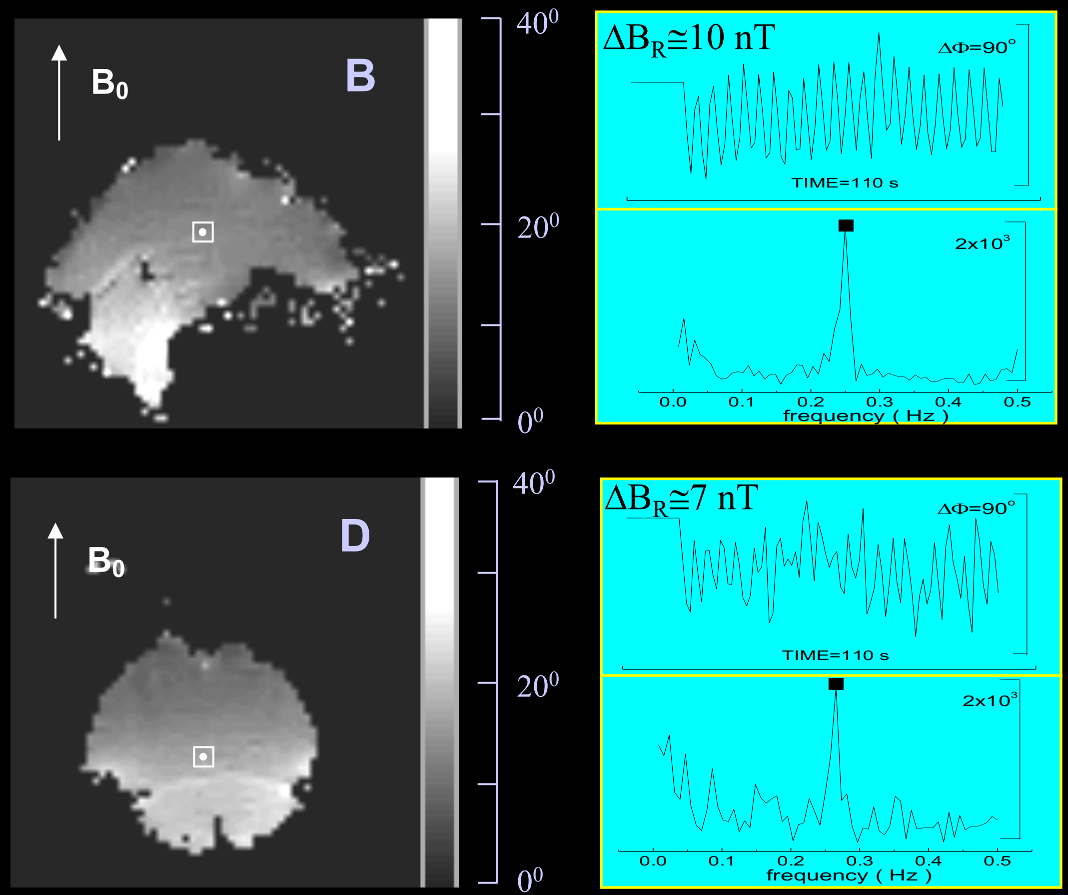




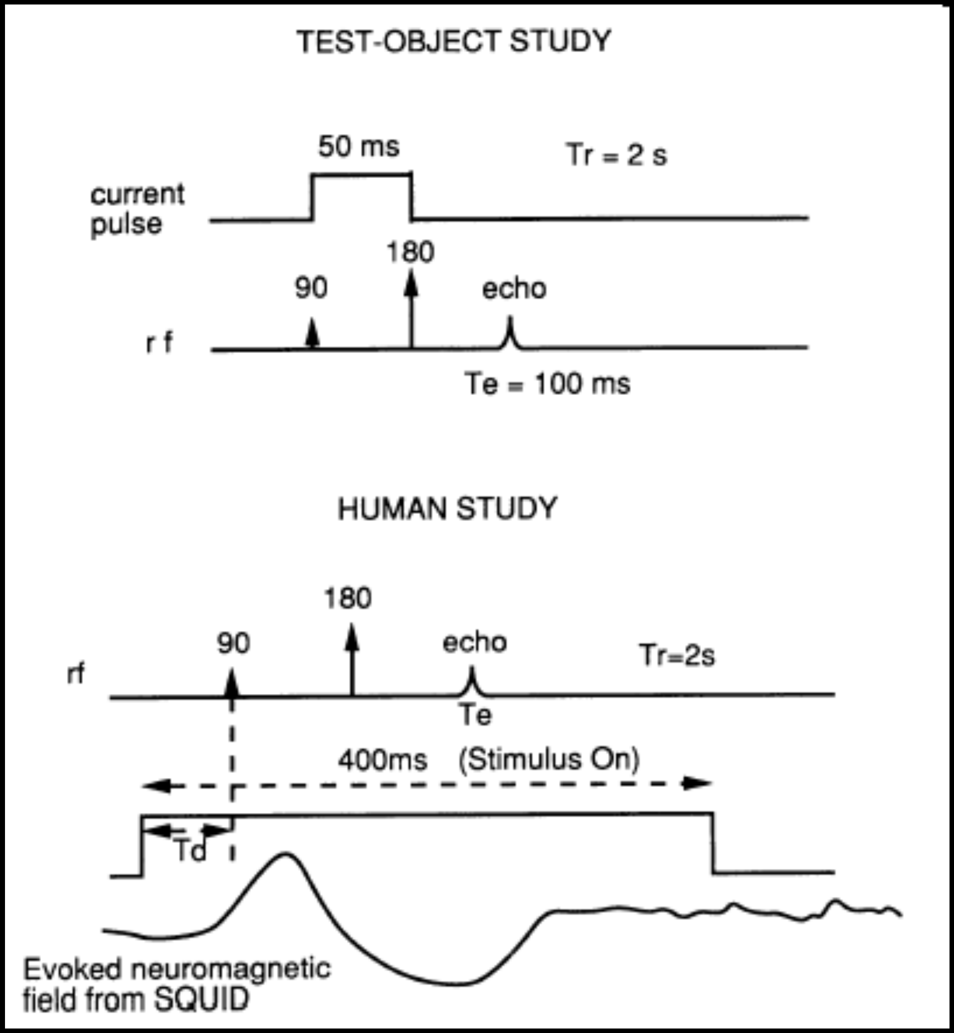


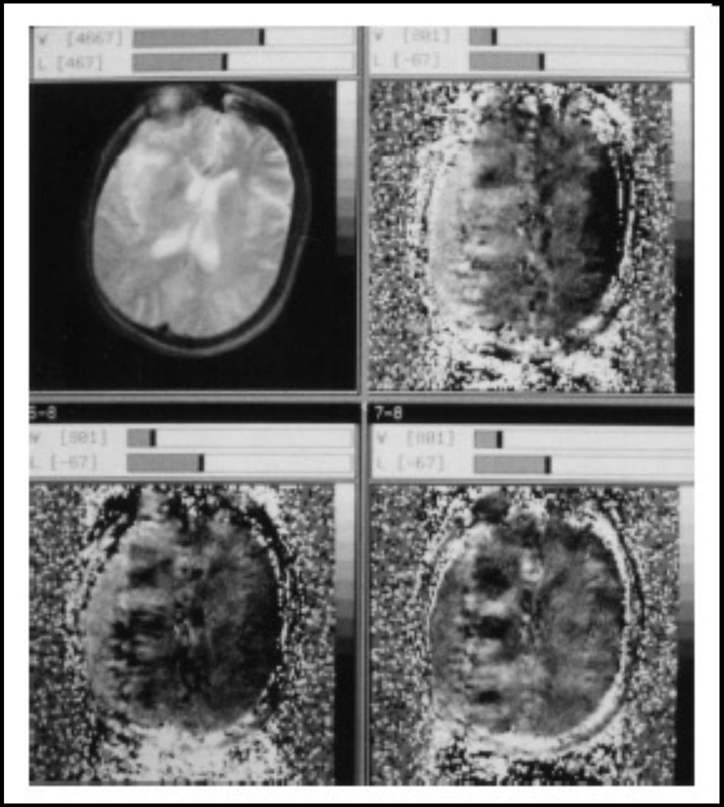
J. Bodurka, P. A. Bandettini. Toward direct mapping of neuronal activity: MRI detection of ultra weak transient magnetic field changes, Magn. Reson. Med. 47: 1052-1058, (2002).

Human Respiration



The use of spin-echo to “tune” to transients..

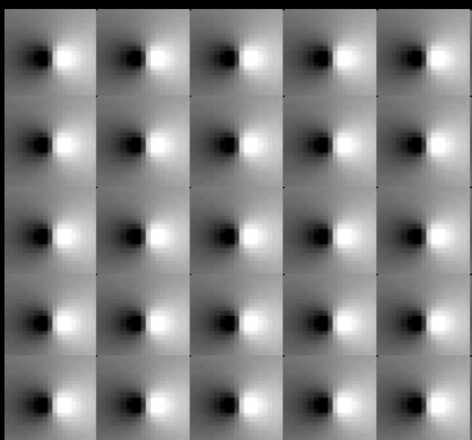


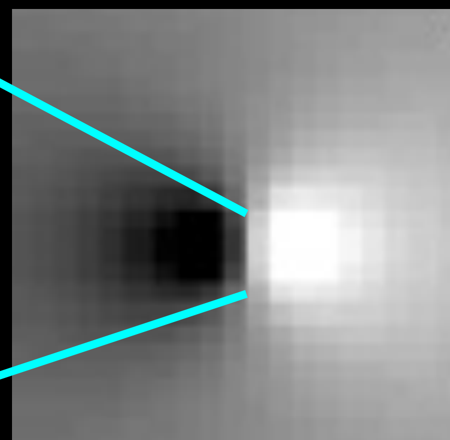


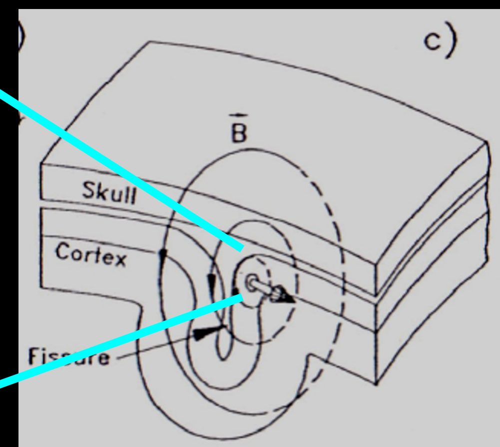
M. Singh, *Sensitivity of MR phase shift to detect evoked neuromagnetic fields inside the head.*

IEEE Transactions on Nuclear Science. 41: 349-351, (1994).

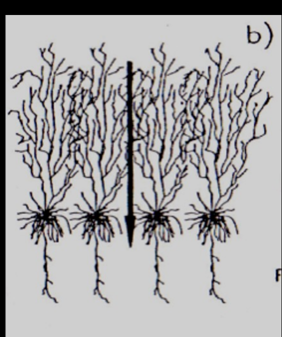
Phase vs. Magnitude...



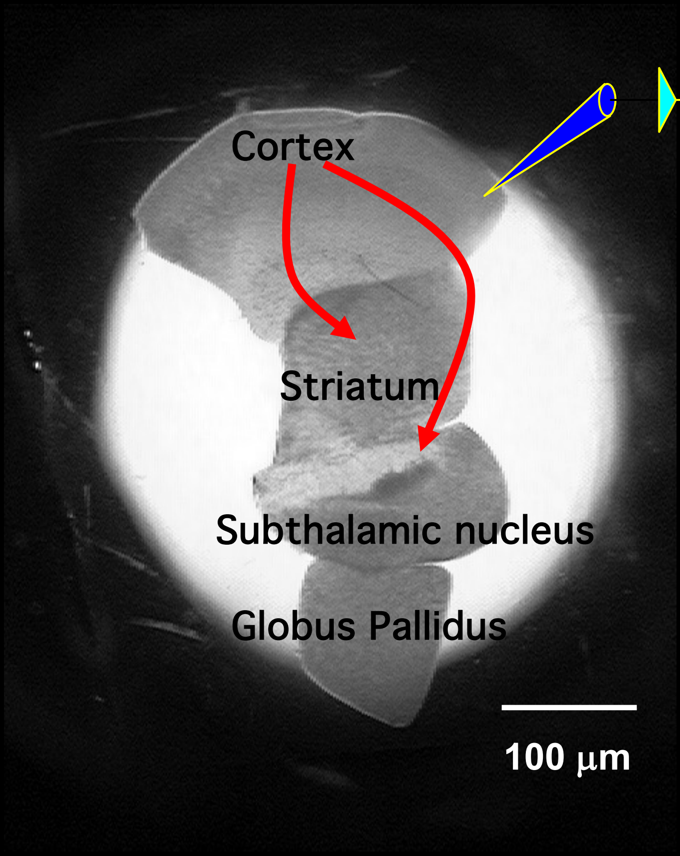




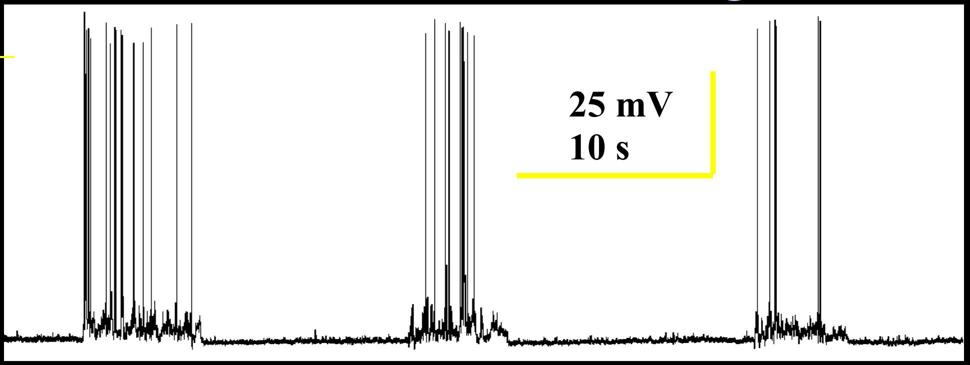
0.1 to 0.3 Deg.



in vitro model



Patch electrode recording



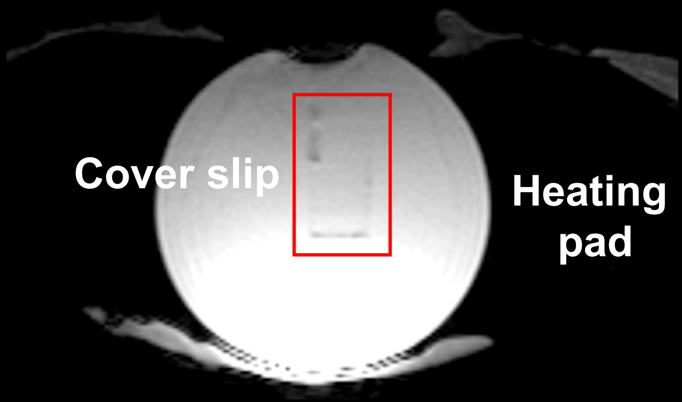
•coronal sections of newborn-rat brains ; in-plane:~1mm^2, thickness: ~60-100 μm

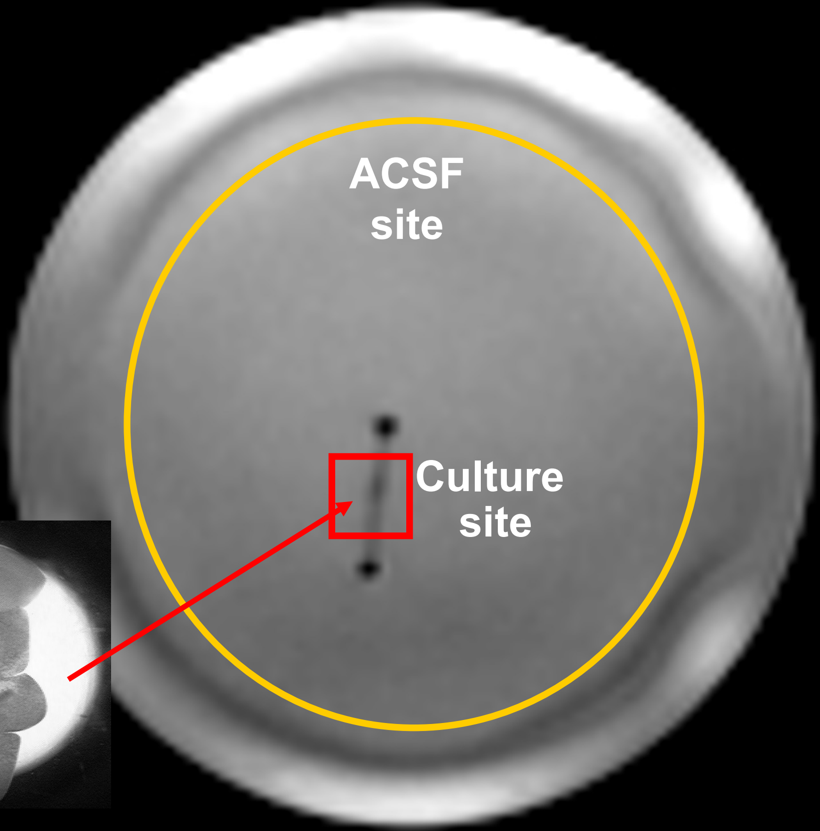
Neuronal Population: 10,000-50,000

- Spontaneous synchronized activity ; current: ~ 180nA-2μA, ΔB: ~ 60pT-0.5nT

Plenz, D. and S.T. Kital. Nature, 1999. **400**: p. 677-682.

methods - *imaging*





Imaging

- 3T, Surface coil receive
- FSE structural images (256x256)
- SE EPI single shot, TE: 60ms, TR:1s, flip angle: 90^0,

  FOV: 18cm, matrix: 64x64, 4 slices (3mm)

methods - *imaging*

Six Experiments

two conditions per experiment

<u>Active</u>

600 images

neuronal activity present

<u>Inactive</u>

600 images

neuronal activity terminated

via TTX administration

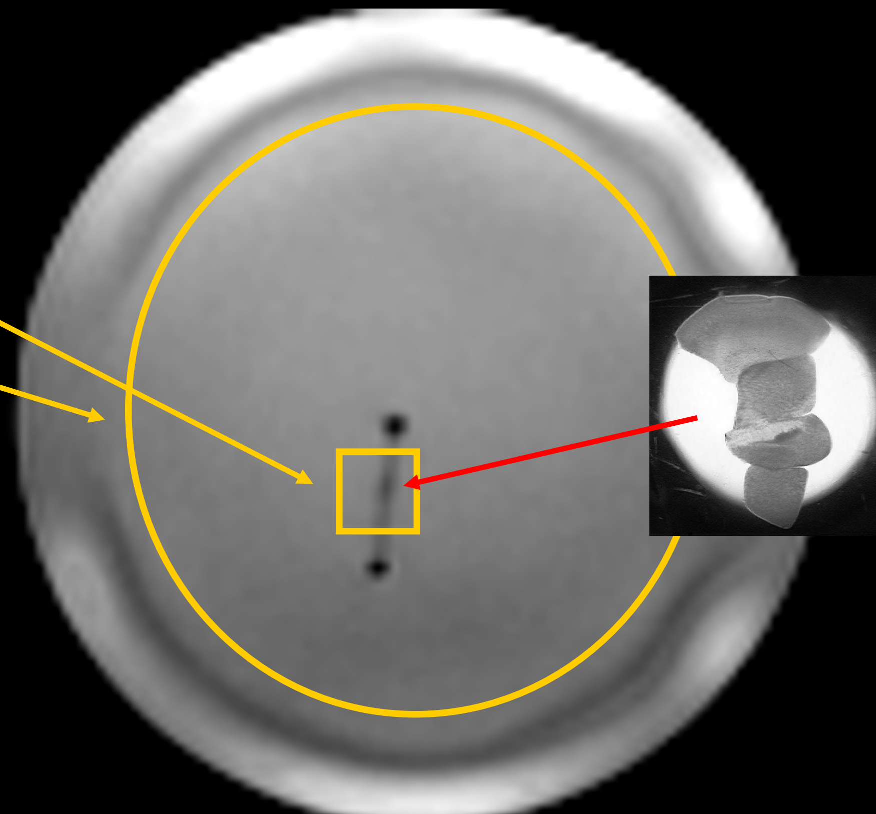
methods - *analysis*

Phase images

- Spectrum for each voxel
- Two voxel groups (all slices)

Culture (~9 voxels)

CSF (~420 voxels)



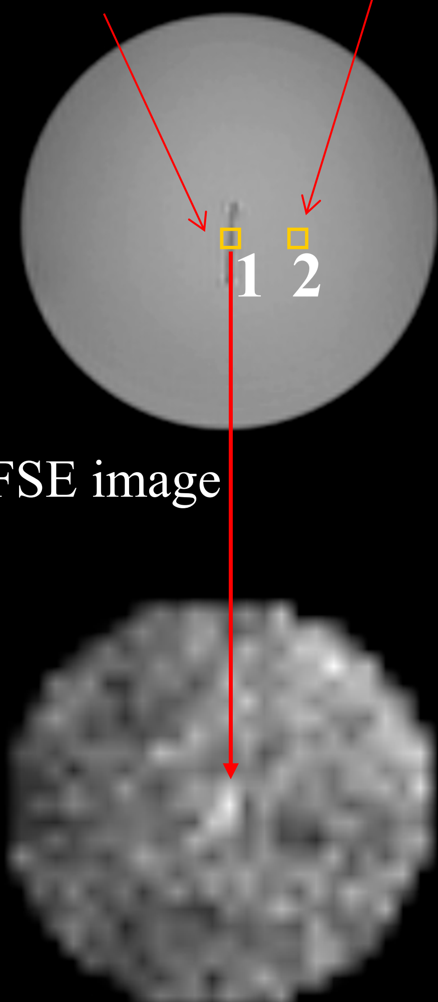
Principal Component Analysis

of the Spectrum

per group

results

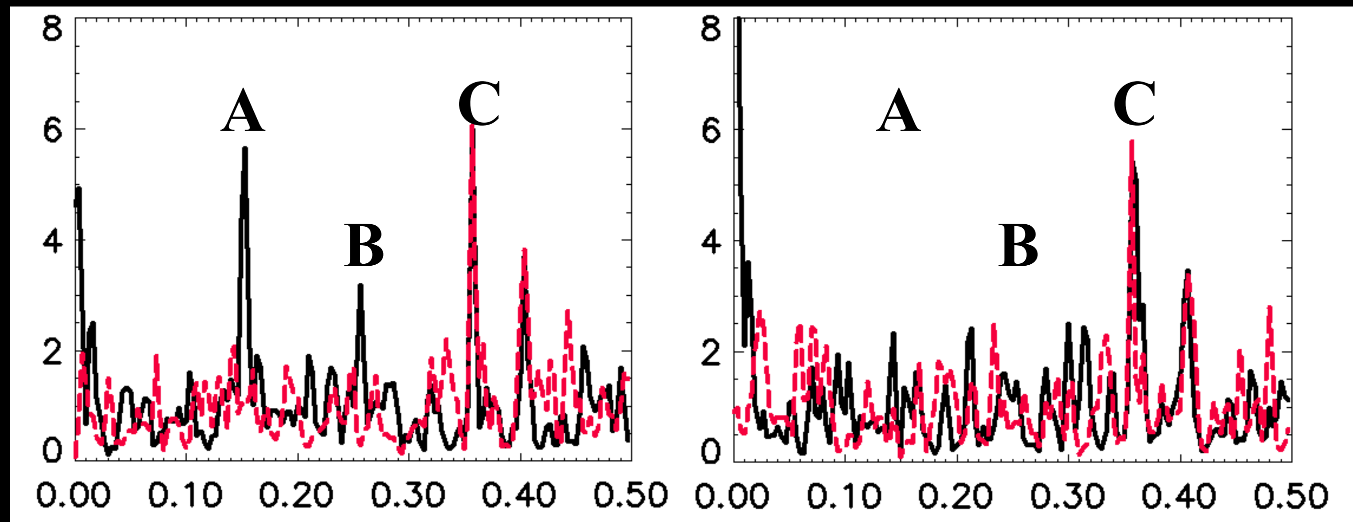
Culture CSF



FSE image

0.15Hz map

1: culture *2: CSF*



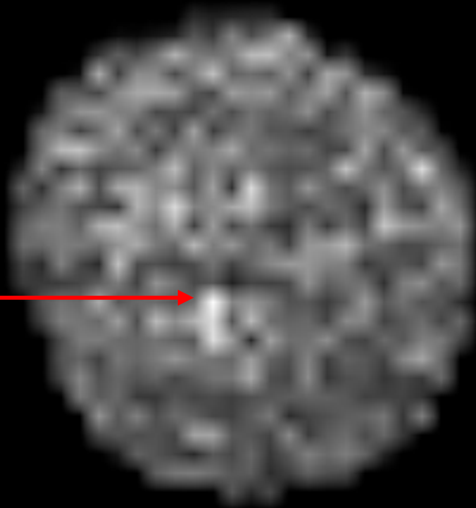
Active condition: black line
Inactive condition: red line

A: 0.15 Hz activity, on/off frequency
B: activity
C: scanner noise (cooling-pump)

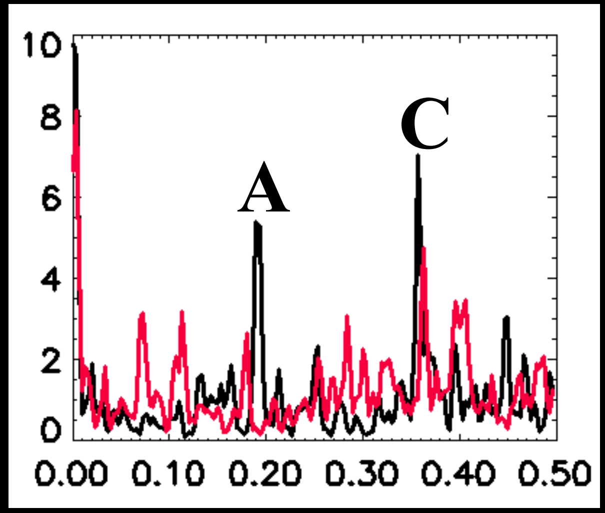
results

Echo Planar Image

0.19Hz map



Culture



A: 0.19 Hz activity
C: scanner cooling-pump

Active condition: black line
Inactive condition: red line

Strategies for Detection

- Time shifted sampling
- Under sampling

Time shifted sampling

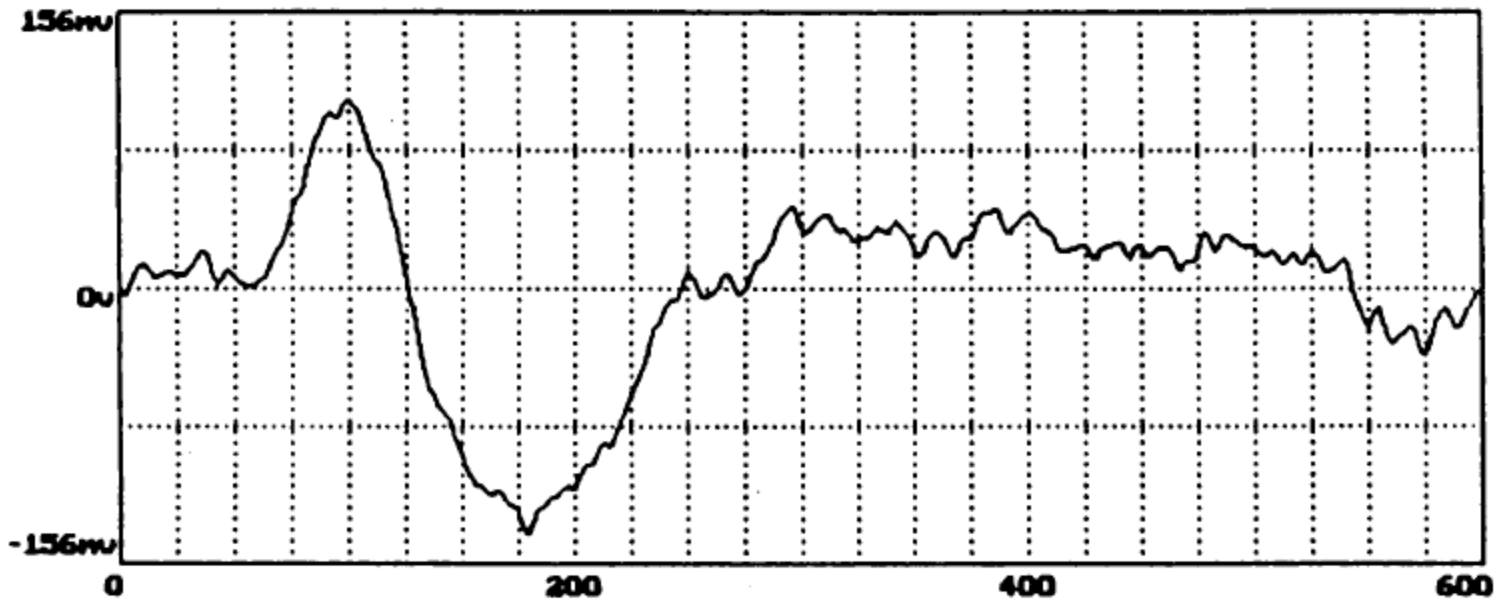
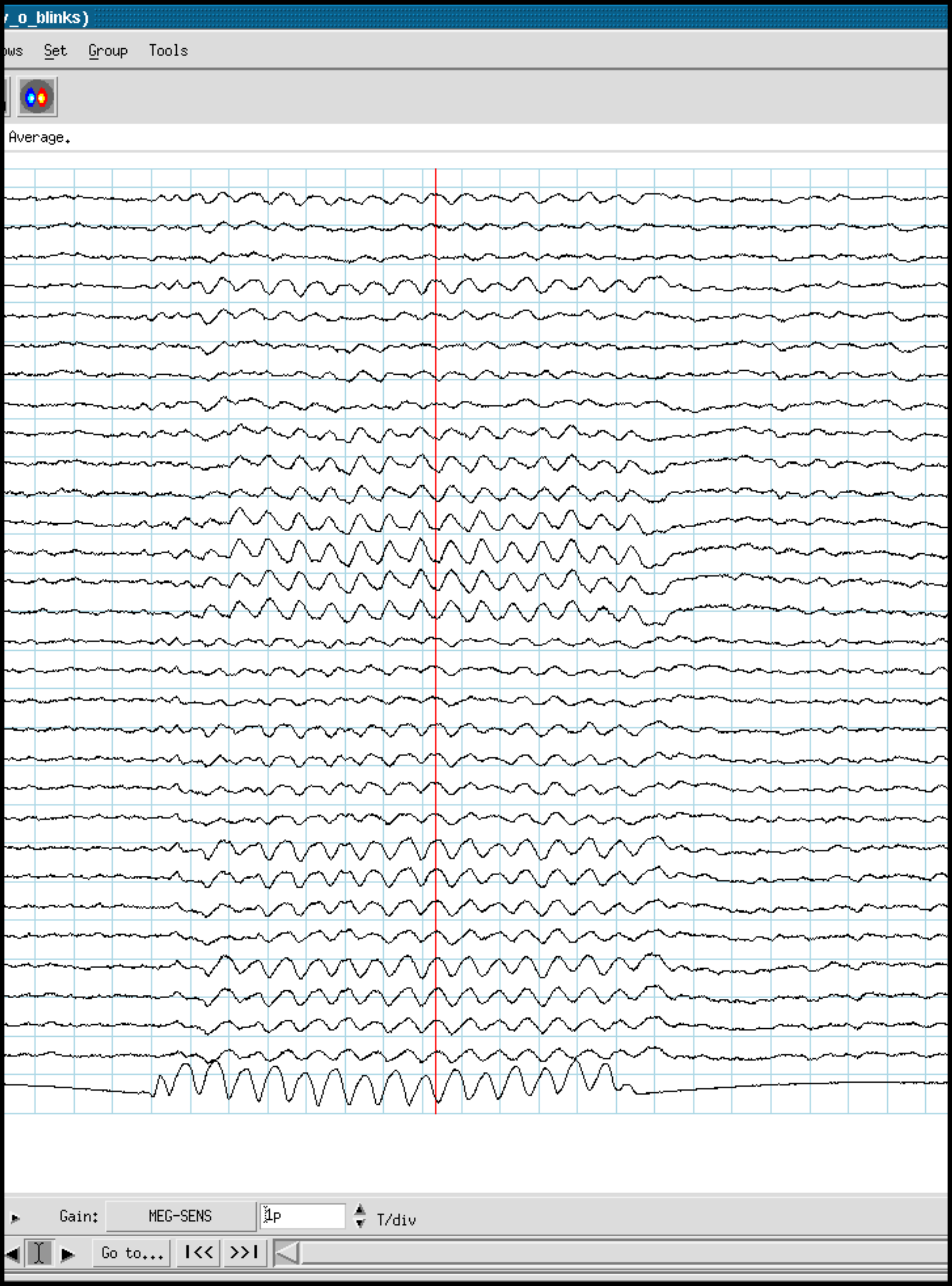


Fig. 4. A typical neuromagnetic field measurement normal to the head in response to auditory stimulation. A 50 ms wide prominent peak is seen at about 100 ms post-stimulus, followed by a wider, polarity reversed peak at about 200 ms.

M. Singh, *Sensitivity of MR phase shift to detect evoked neuromagnetic fields inside the head.* **IEEE Transactions on Nuclear Science. 41: 349-351, (1994).**

Undersampling

8 Hz alternating checkerboard

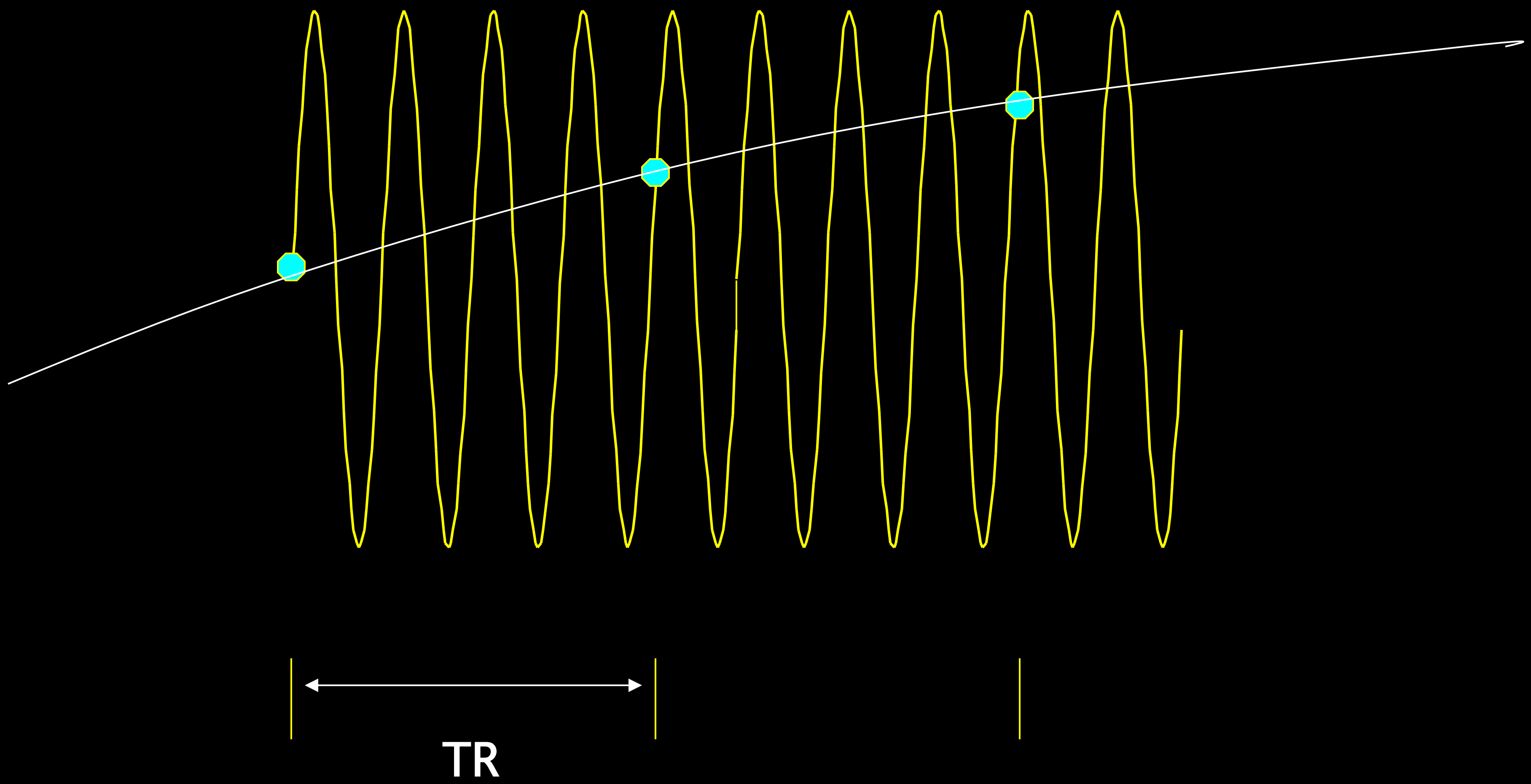


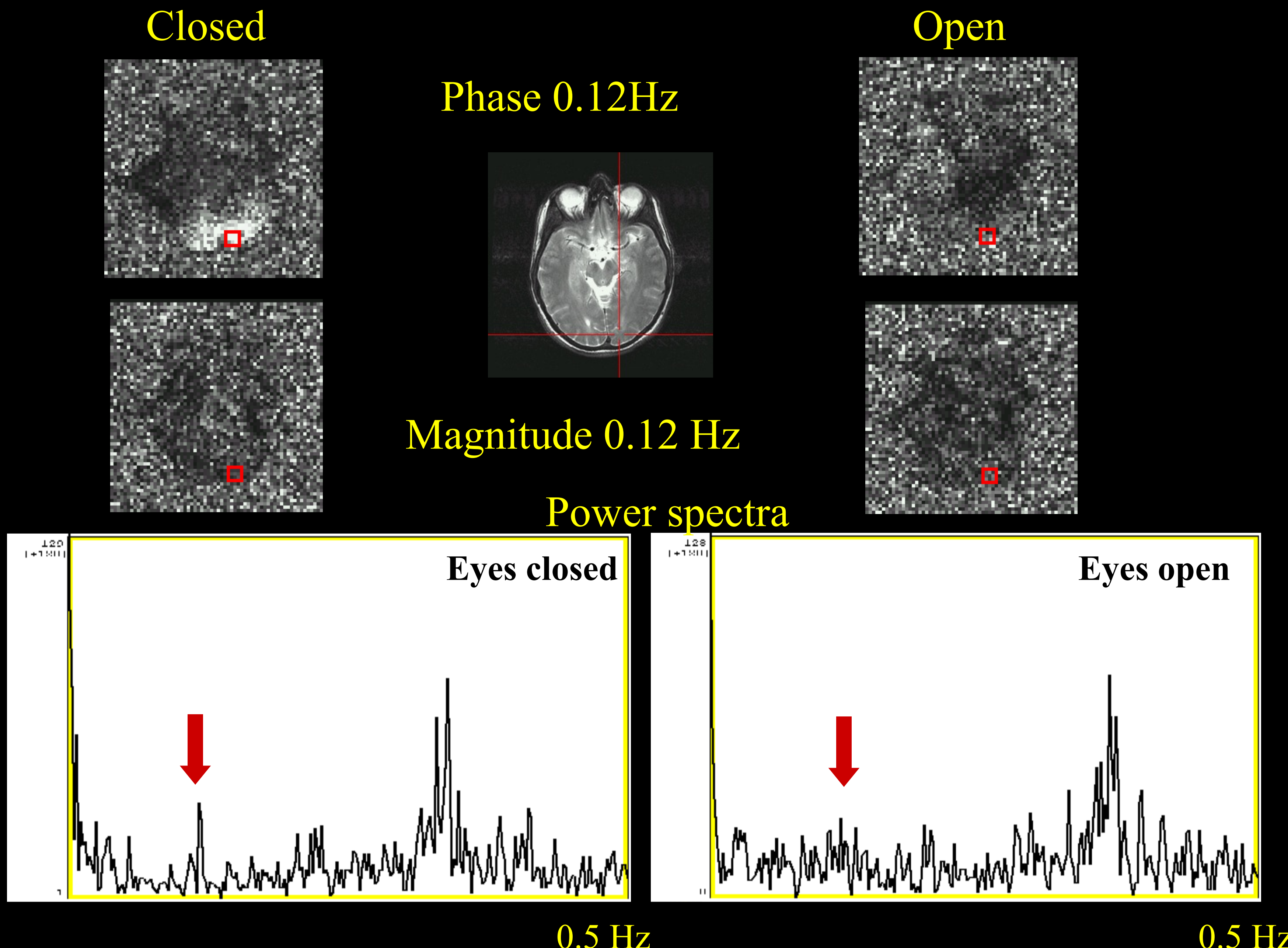
MEG

Photodiode

Undersampling

Alternating Checkerboard Frequency




Closed
Open
Phase 0.12Hz
Magnitude 0.12 Hz
Power spectra
Eyes closed
Eyes open
0.5 Hz
0.5 Hz

Caution, Despair, Hope...

- Need to rule out BOLD or other mechanisms

- Noise is larger than effect
- MR sampling rate is slow

- Neuronal activation timing is variable and unspecified
- Models describing spatial distribution and locally induced magnetic fields remain relatively uncharacterized...therefore could be off by up to an order of magnitude.

- Well characterized stimuli
- "Transient-tuned" pulse sequences (spin-echo, multi-echo)
- Sensitivity and/or resolution improvements
- Simultaneous electrophysiology – animal models?
- Synchronization improvements.

FIM Unit & FMRI Core Facility

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Jerzy Bodurka
Frank Ye
Wen-Ming Luh

Computer Specialist:
Adam Thomas

Post Docs:
Rasmus Birn
Hauke Heekeren
David Knight
Anthony Boemio
Niko Kriegeskorte
Patrick Bellgowan
Ziad Saad

Graduate Student:
Natalia Petridou

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Ilana Levy
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August Tuan
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Marta Maieron
Guosheng Ding

Clinical Fellow:
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Psychologist:
Julie Frost

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Julia Choi
Thomas Gallo
Jenna Gelfand
Hannah Chang
Courtney Kemps
Douglass Ruff
Carla Wettig
Kang-Xing Jin

Program Assistant:
Kay Kuhns

Scanning Technologists:
Karen Bove-Bettis
Paula Rowser
Alda Ottley