Spatial, Temporal, and Interpretative Limits of fMRI

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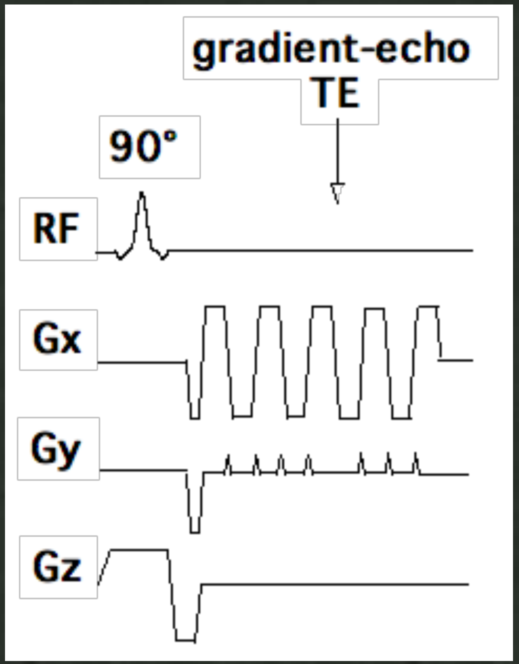
1991

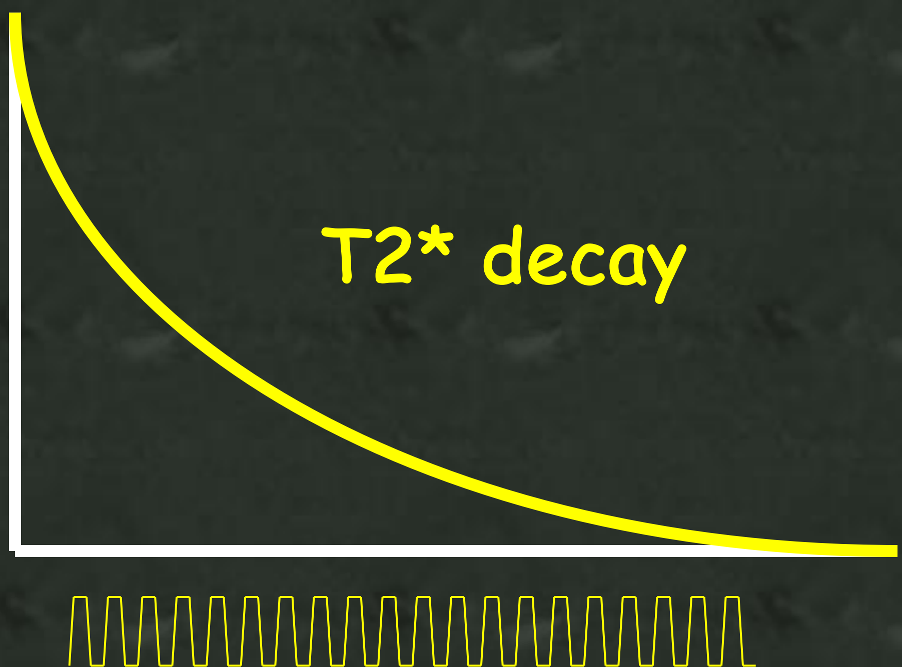
What really limits fMRI ?

- Imaging Methodology
- Hemodynamic Response Function

We can typically image faster and at higher resolution than the functional resolution that is determined by the hemodynamic response function.

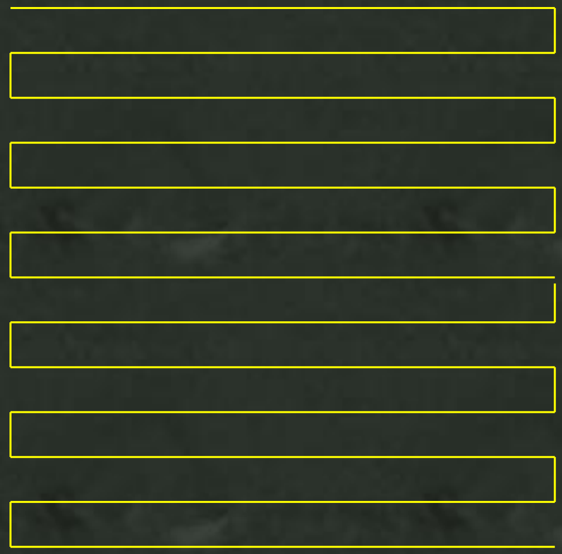
Single Shot Echo Planar Imaging (EPI)





EPI Readout Window

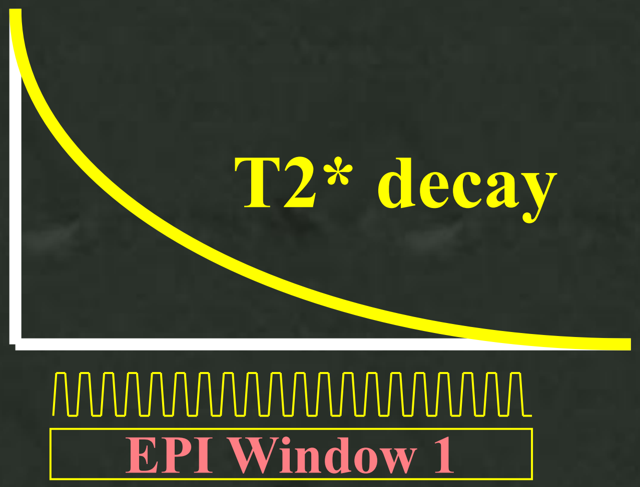
≈ 20 to 40 ms

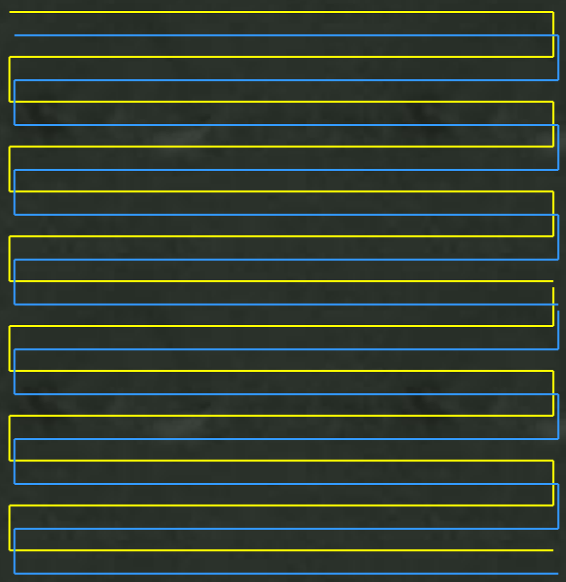


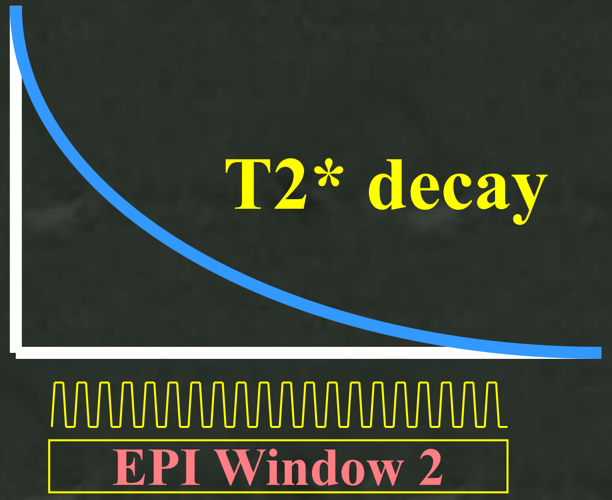
How might we improve things?

- Multi-shot imaging
- Partial k-space imaging
- RF coils
- SENSE imaging
- Higher field strength

Multi-shot imaging



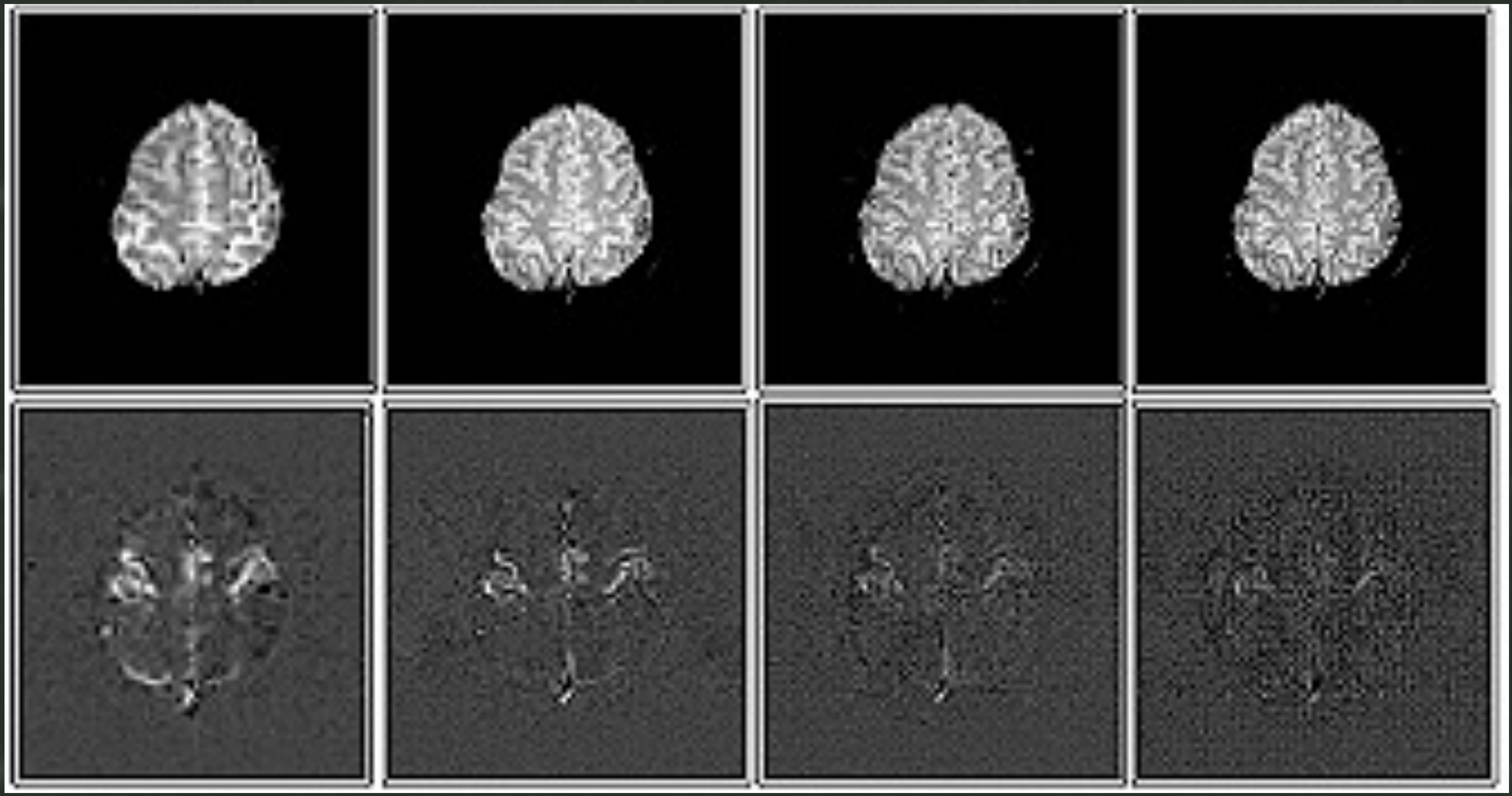




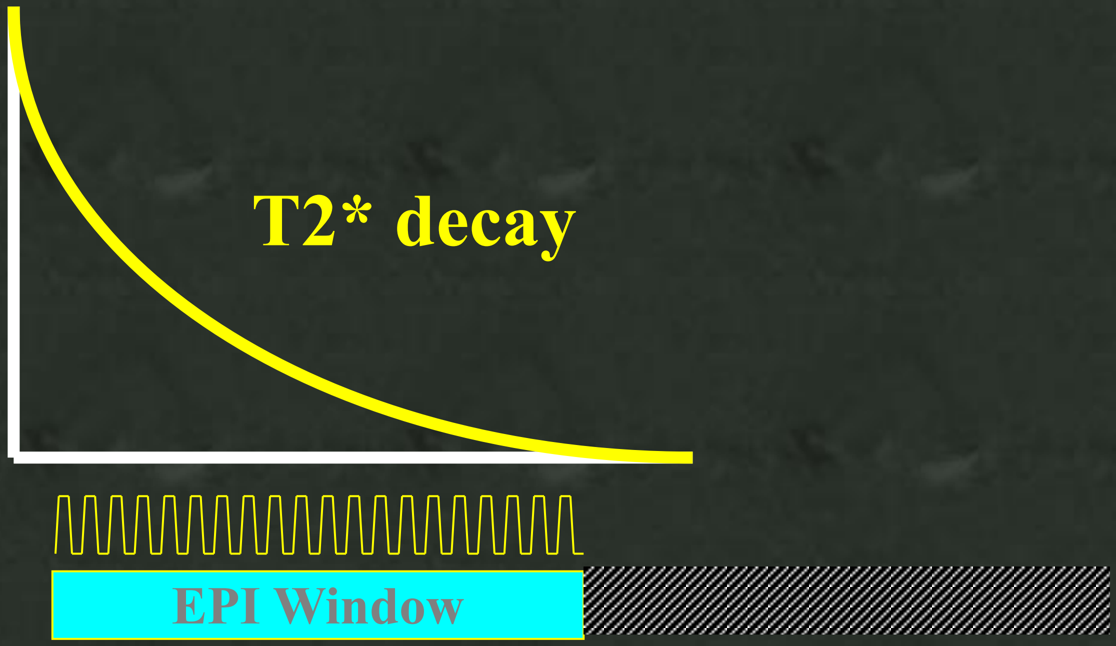
- Requires navigator pulses
- Temporal resolution and stability tradeoff

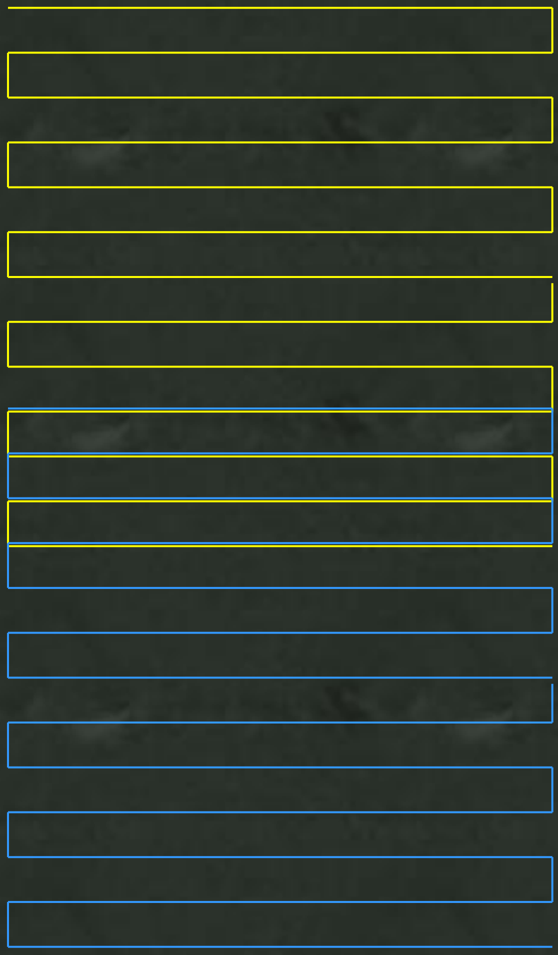
Multi-shot imaging

Excitations	1	2	4	8
Matrix Size	64 x 64	128 x 128	256 x 128	256 x 256



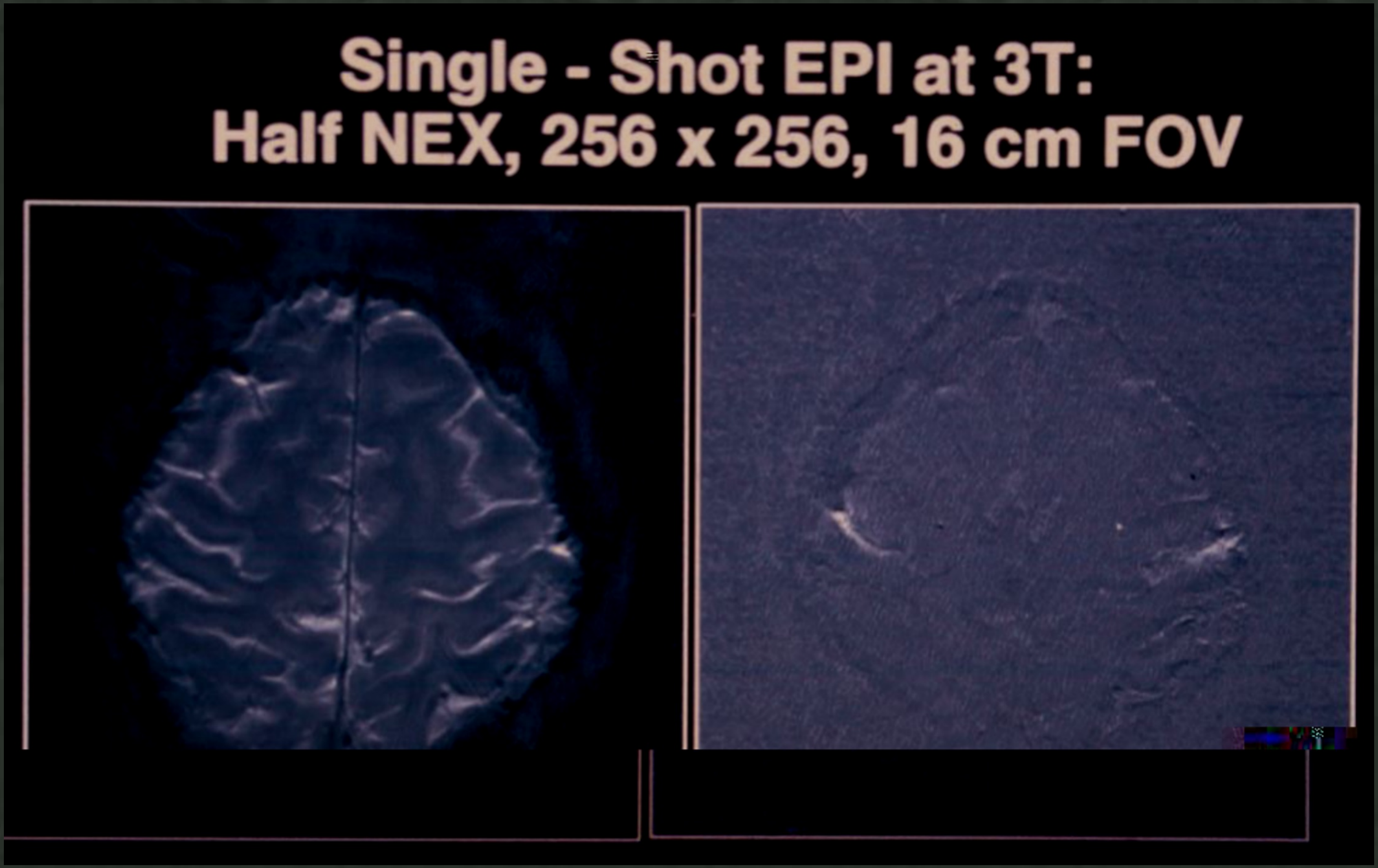
Partial k-space imaging





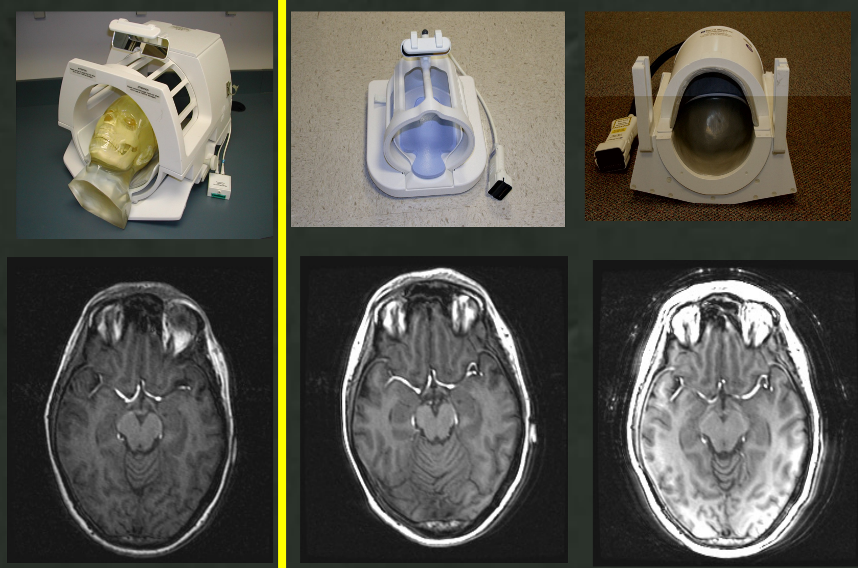
- More warping
- Lower image SNR
- Improvement in one dimension

Partial k-space imaging



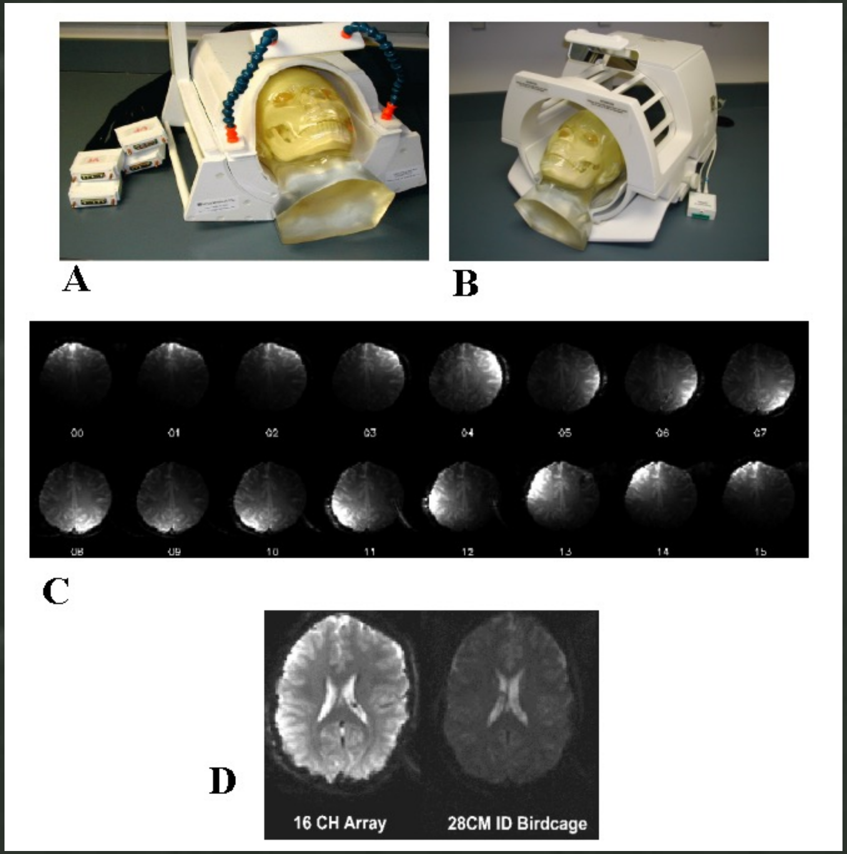
RF coils

8 channel parallel receiver coil



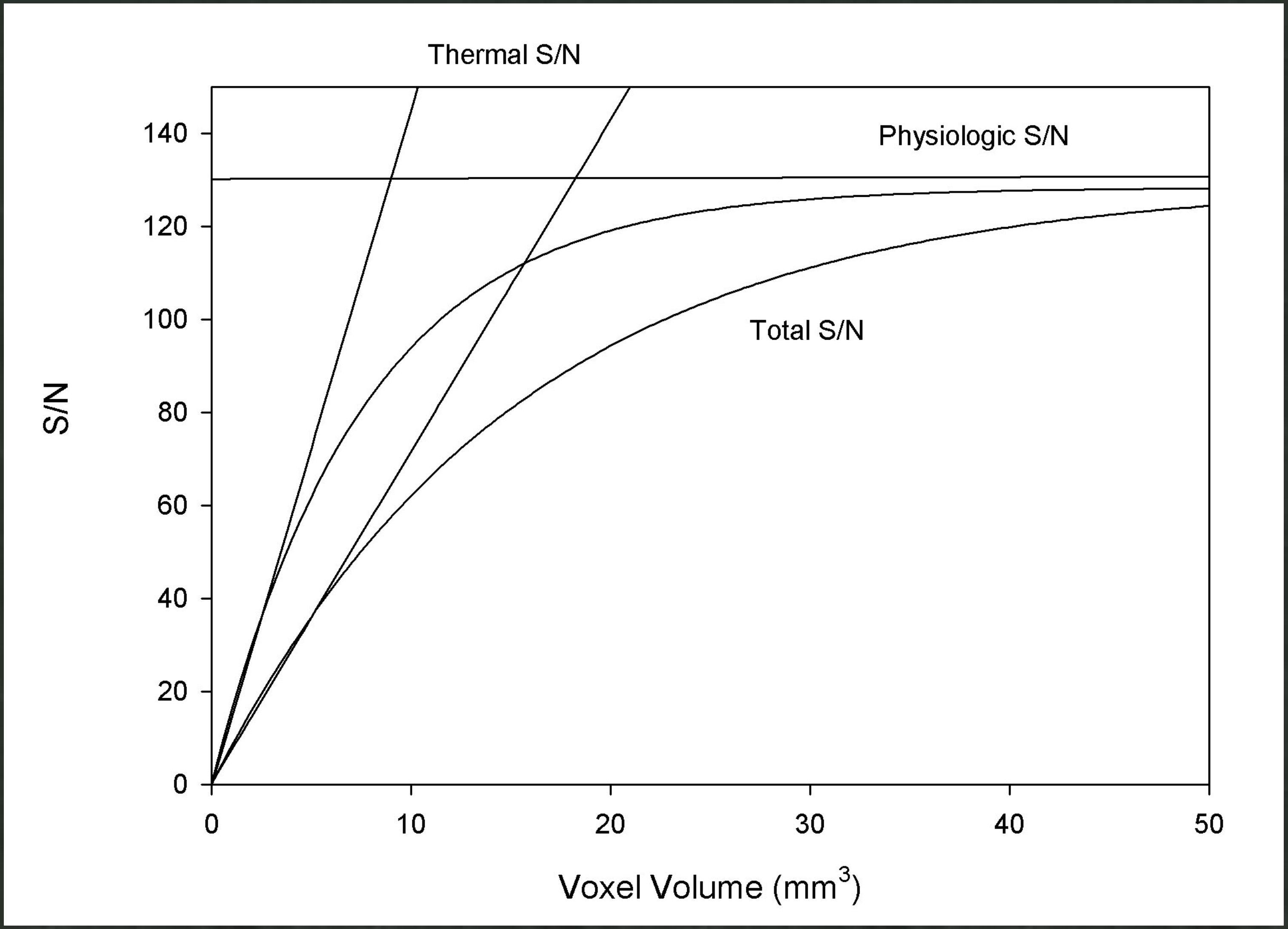
GE birdcage   GE 8 channel coil   Nova 8 channel coil

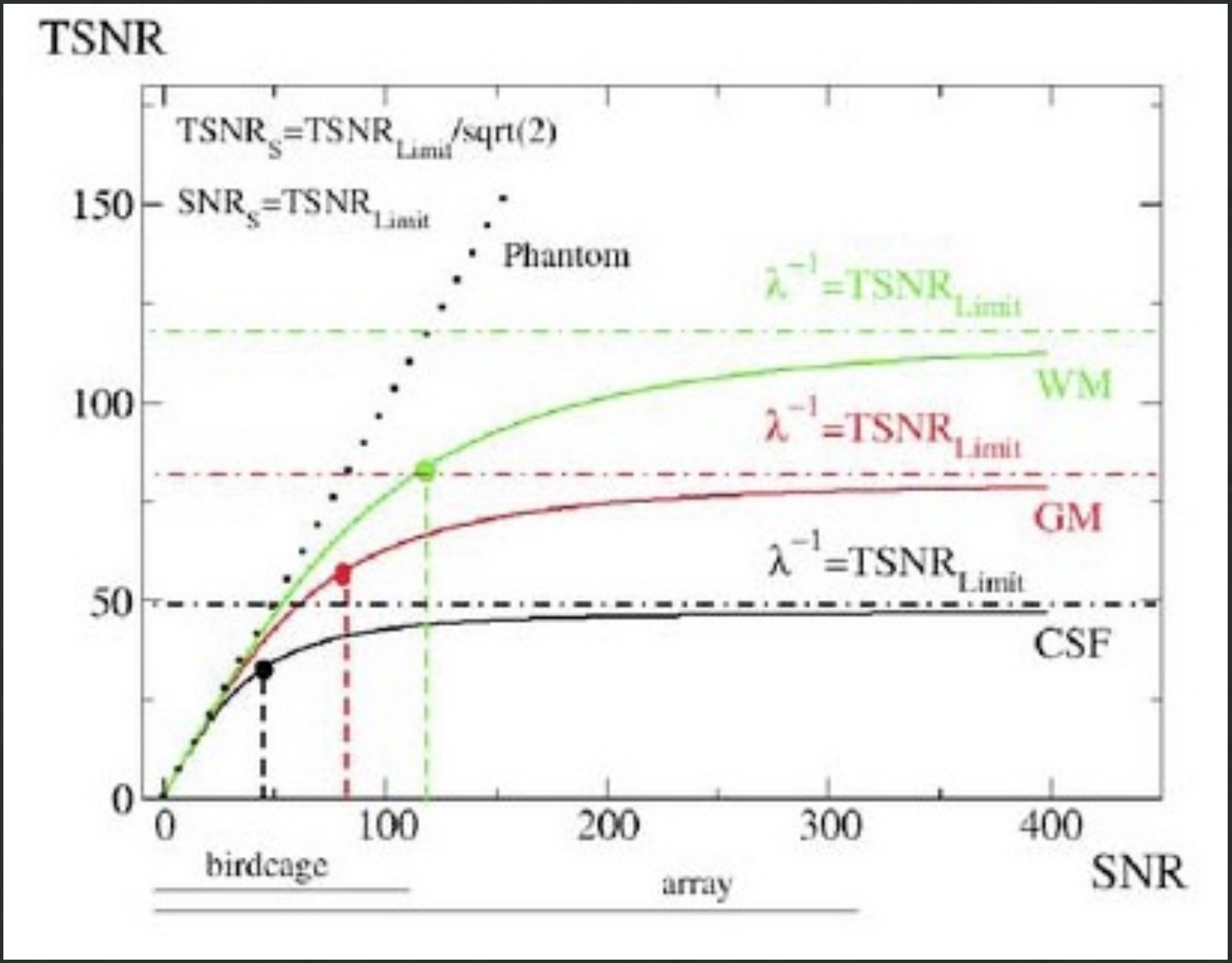
16 channel parallel receiver coil



J. Bodurka, et al, MRM 51 (2004) 165-171.

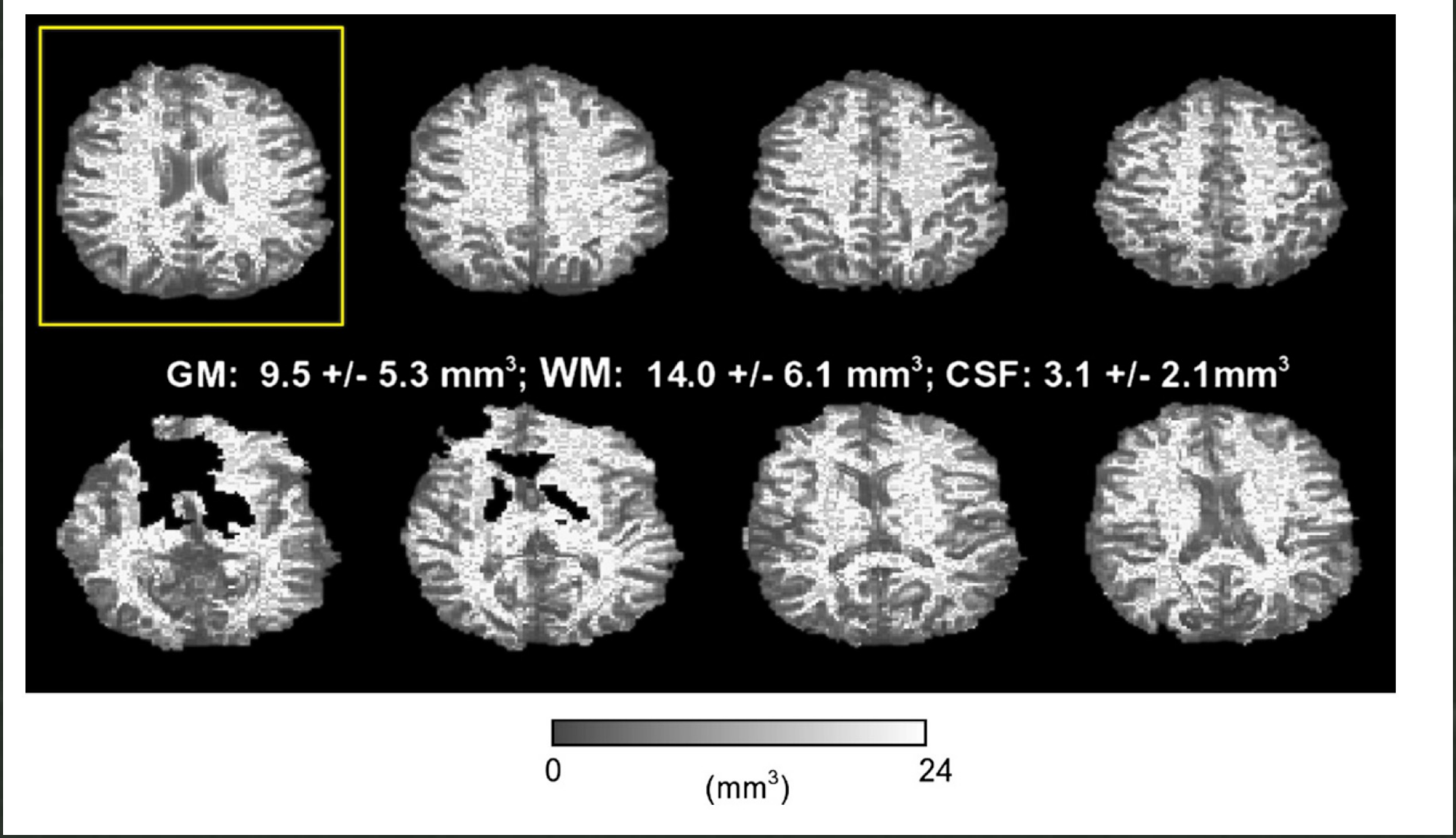
Simulated gains in TNSR with doubling sensitivity





J. Bodurka, F. Ye, N Petridou, P. A. Bandettini, Mapping the MRI voxel volume in which thermal noise matches physiological noise – implications for fMRI. *NeuroImage,* 34, 542-549 (2007)

Finding the "Suggested resolution"



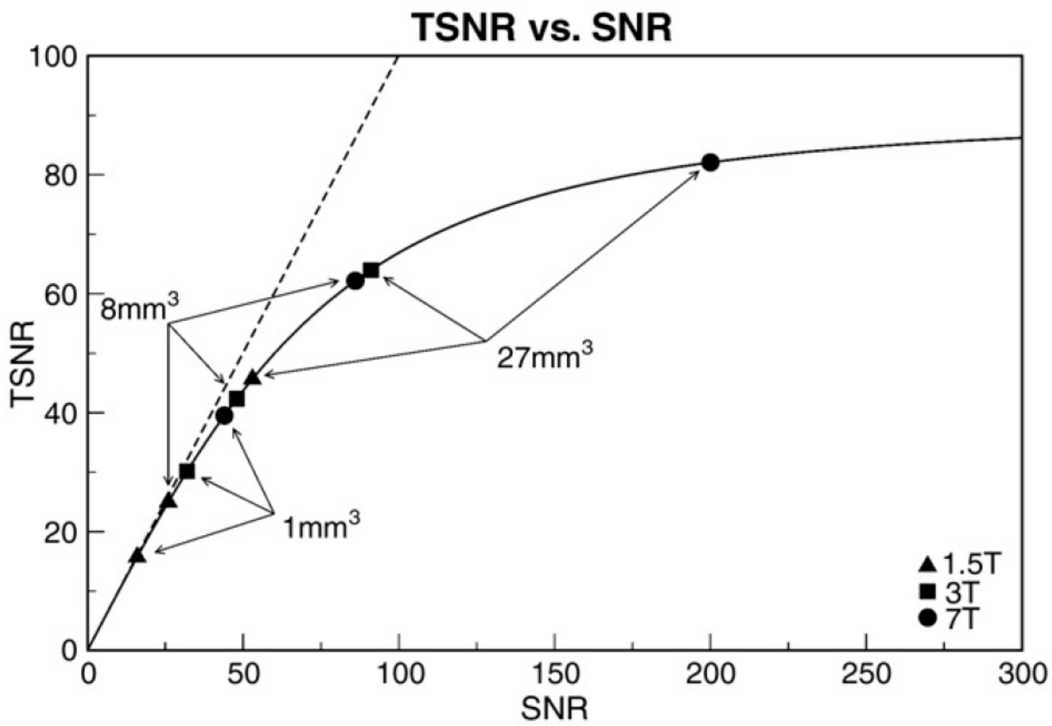
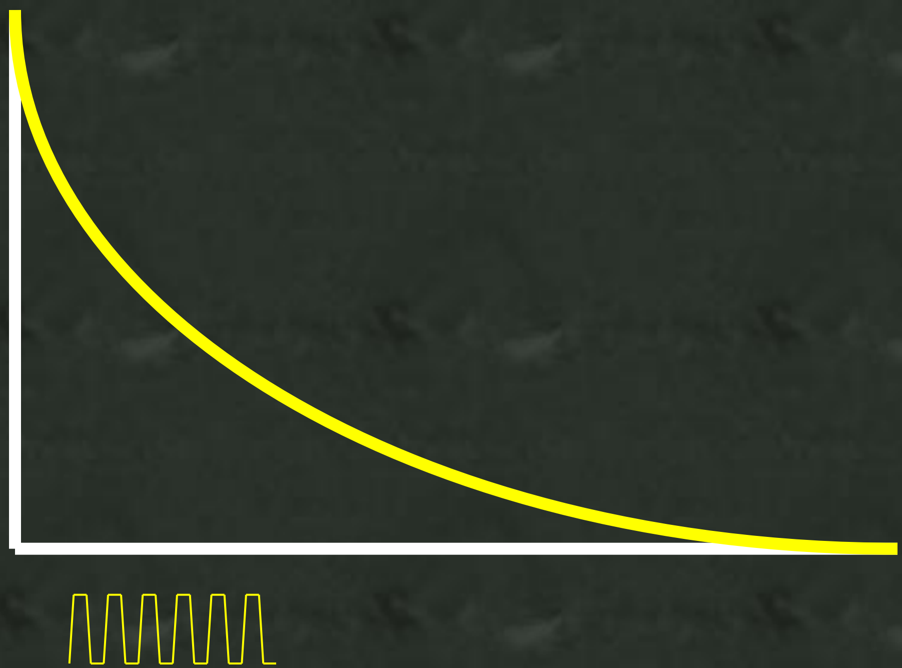
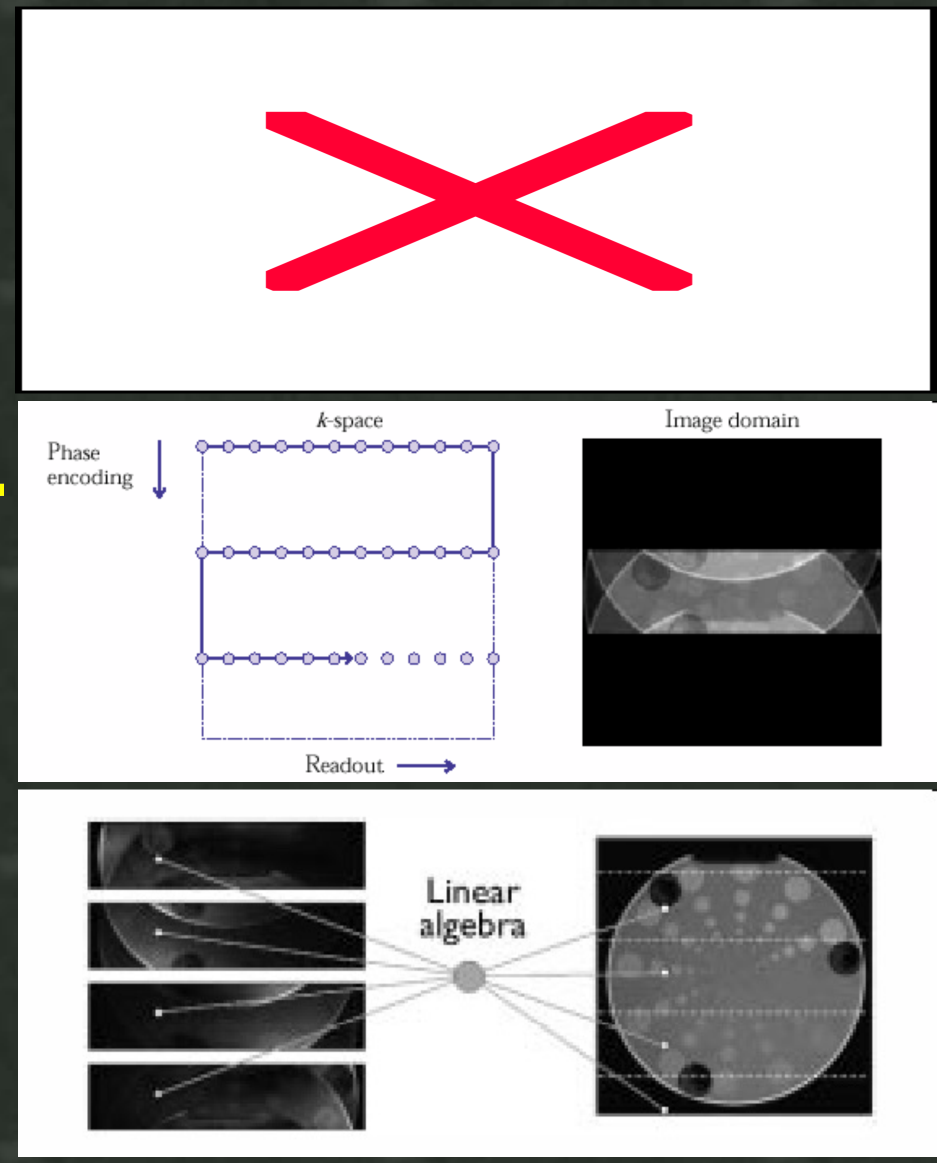


Fig. 1. A schematic of the relationship between TSNR and SNR in gray matter is shown. The dashed line represents this relationship in the absence of physiological noise. In vivo, gains in TSNR are limited by physiological noise as SNR is increased and this relationship is displayed with the solid line. For gray matter, the TSNR limit is approximately 87 (Bodurka et al., 2005). Using values derived from those reported by Triantafyllou et al. (2005), estimates of SNR for 1.5 T, 3 T and 7 T scanners equipped with standard head coils are shown for voxel sizes of $1 \times 1 \times 1\ mm^3 = 1\ mm^3$, $2 \times 2 \times 2\ mm^3 = 8\ mm^3$ and $3 \times 3 \times 3\ mm^3 = 27\ mm^3$.

SENSE Imaging



≈ 5 to 30 ms



Pruessmann, et al.

- Gain in resolution per window width

If shorter readout window is used:

- Small gain in #slices per TR
- Reduced distortions

- Reduced Image SNR

SENSE Imaging

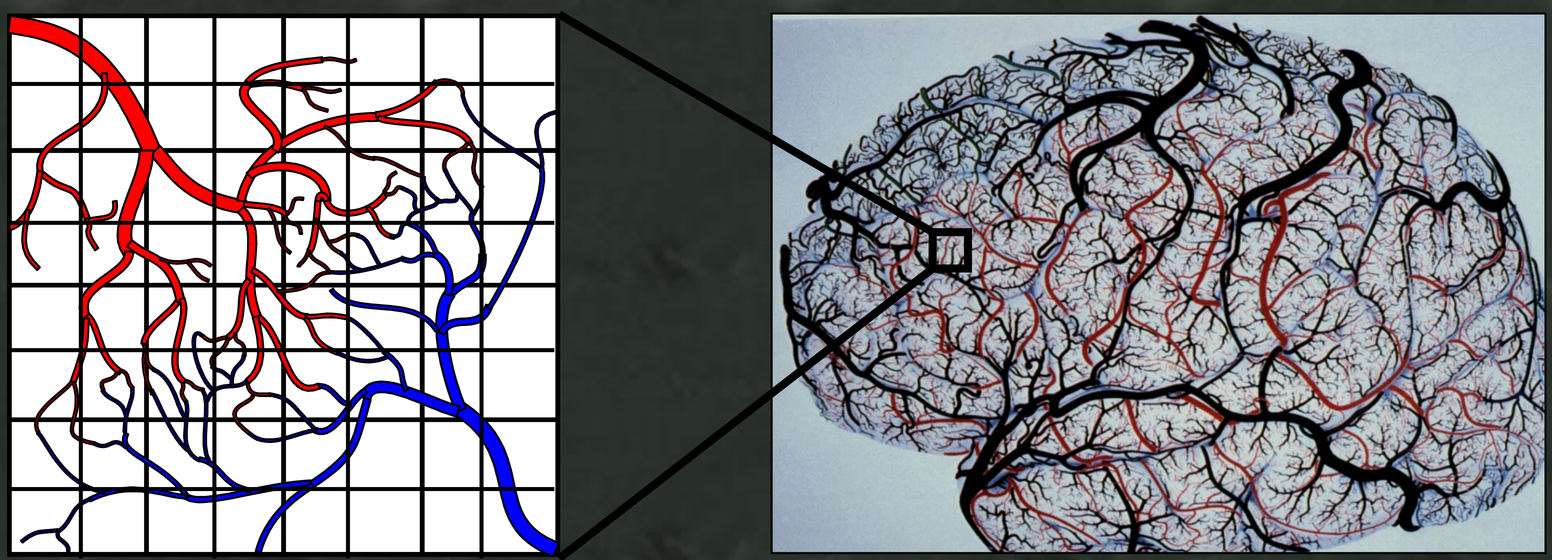
3T single-shot SENSE EPI using 16 channels: 1.25x1.25x2mm

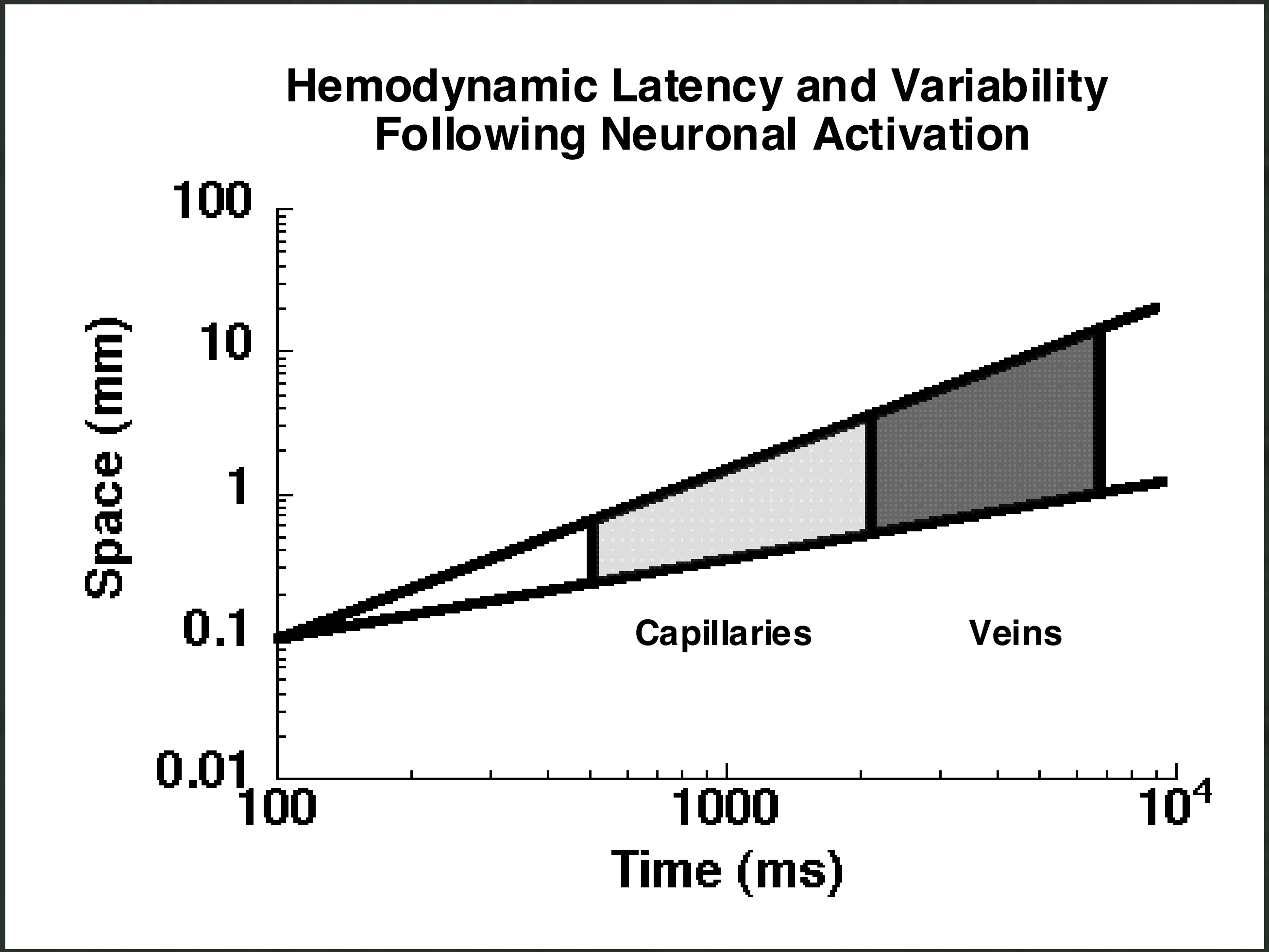
Bodurka et al.

The Hemodynamic Response Function

Neuronal Activation → ? → Hemodynamics → ? → Measured Signal

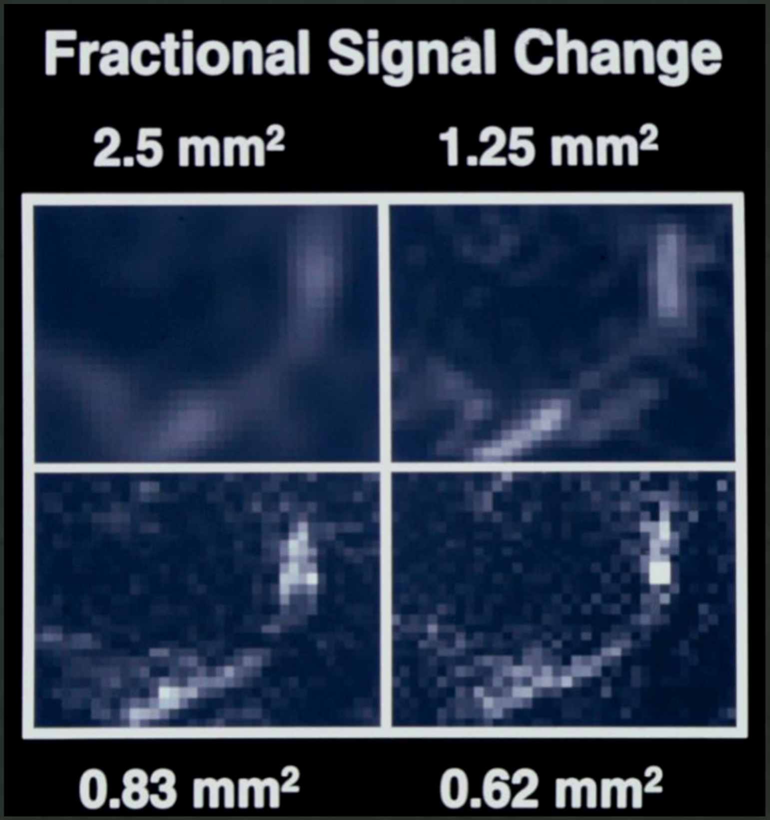
Noise → ? → Measured Signal

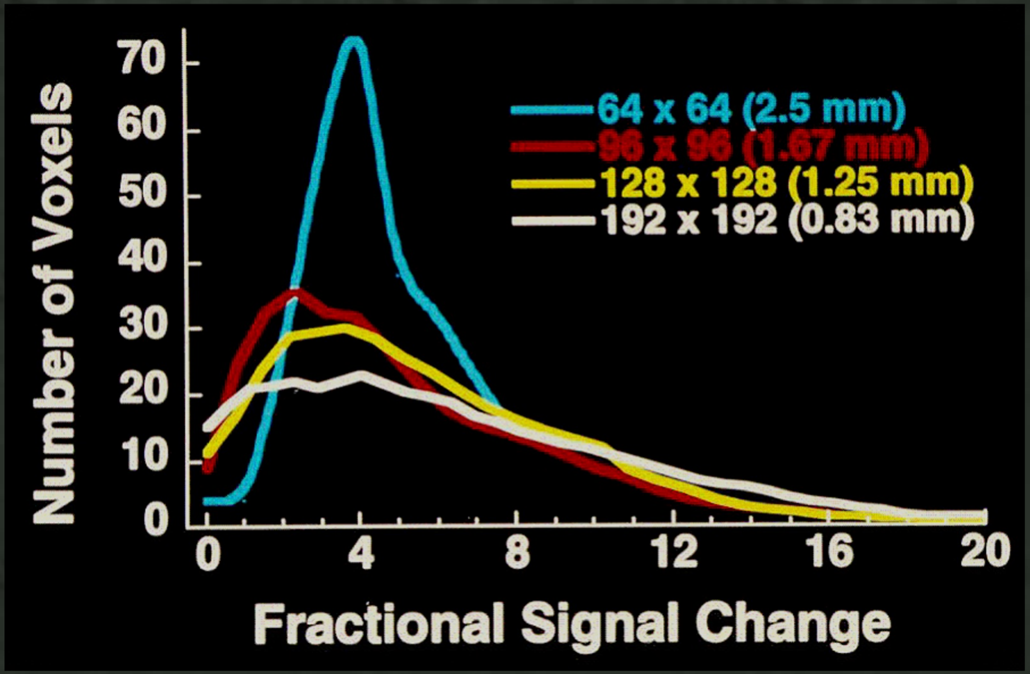




Hemodynamic Latency and Variability
Following Neuronal Activation
100
10
1
0.1
0.01
Space (mm)
Capillaries
Veins
100
1000
10^4
Time (ms)

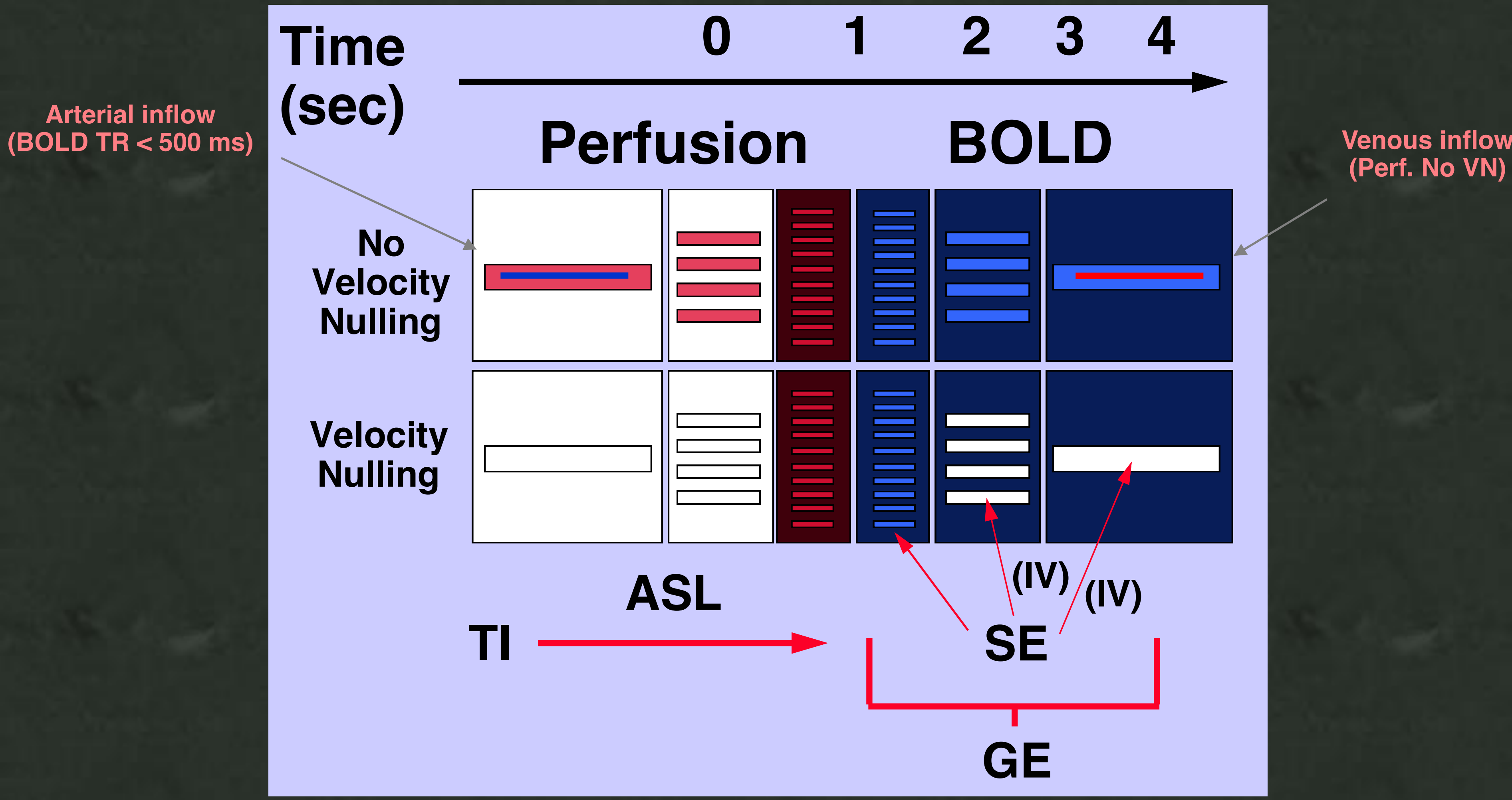
The effect of increasing spatial resolution





Large vessel effects tend to be amplified…

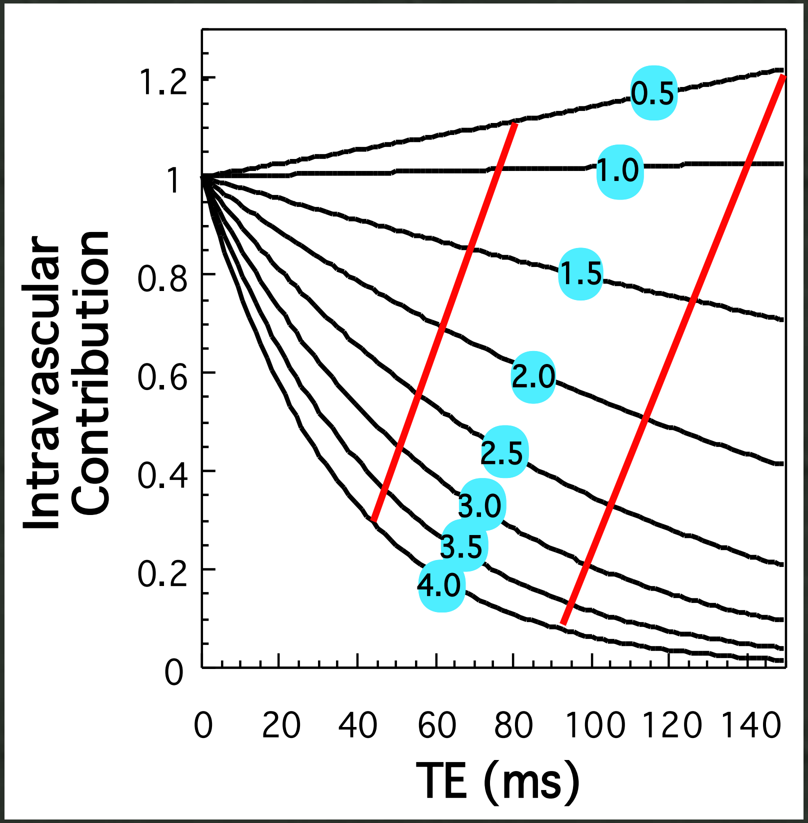
Hemodynamic Specificity



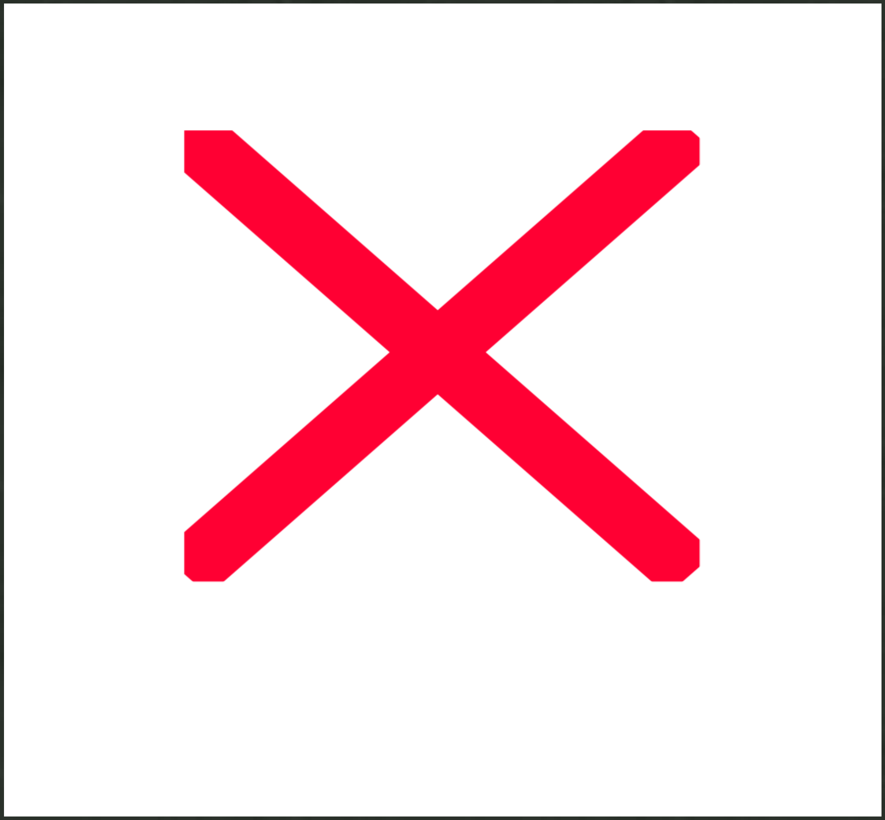
Some pulse sequence strategies..

Field strength dependence of intravascular effects

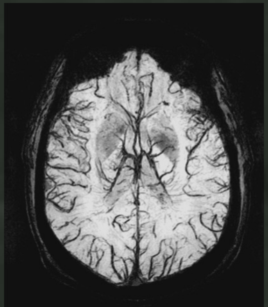
Spin-echo, %HbO_2 = 60



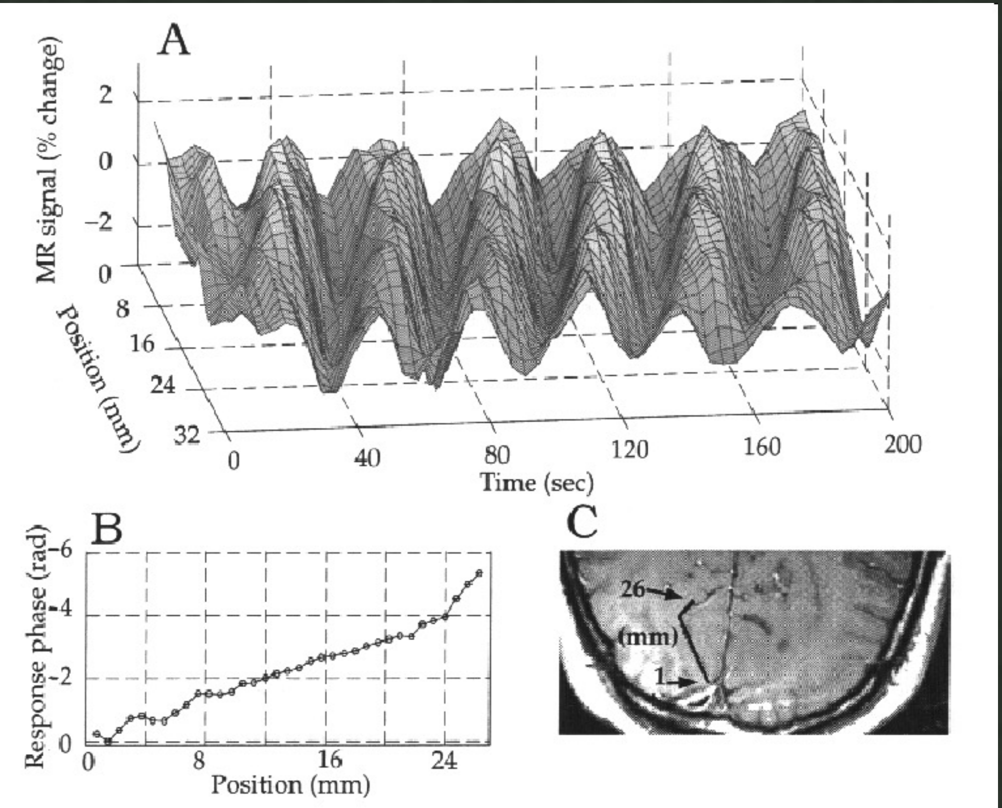
Gradient-echo, %HbO_2 = 60



Source of contrast in venograms..



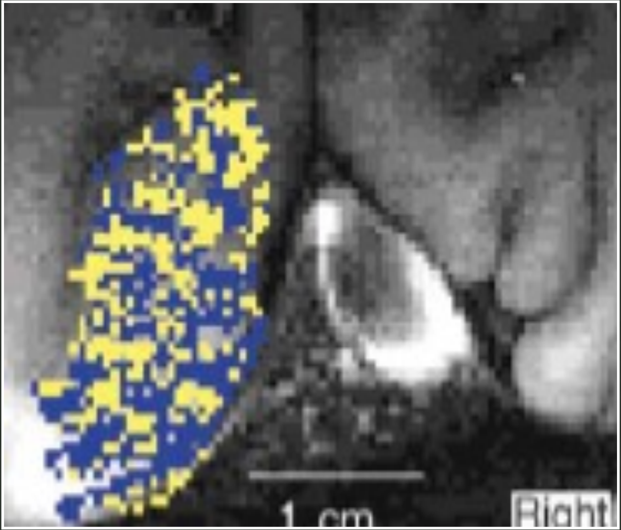
PSF FWHM = 3.5mm



S.A. Engel, et al. Investigative Ophthalmology & Visual Science 35 (1994) 1977-1977.

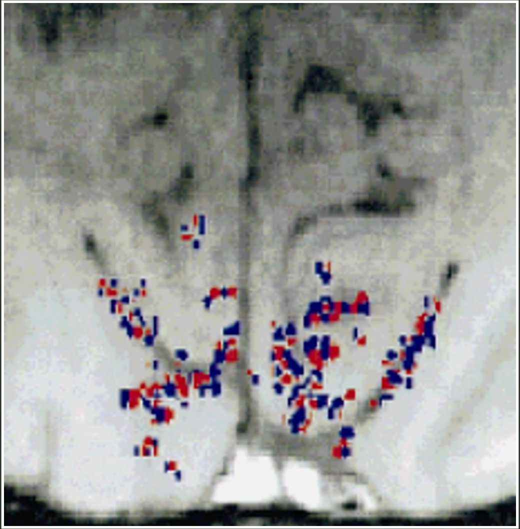
Detailed structure is extractable

0.47 x 0.47 in plane resolution



Cheng, et al. (2001) Neuron,32:359-374

0.54 x 0.54 in plane resolution

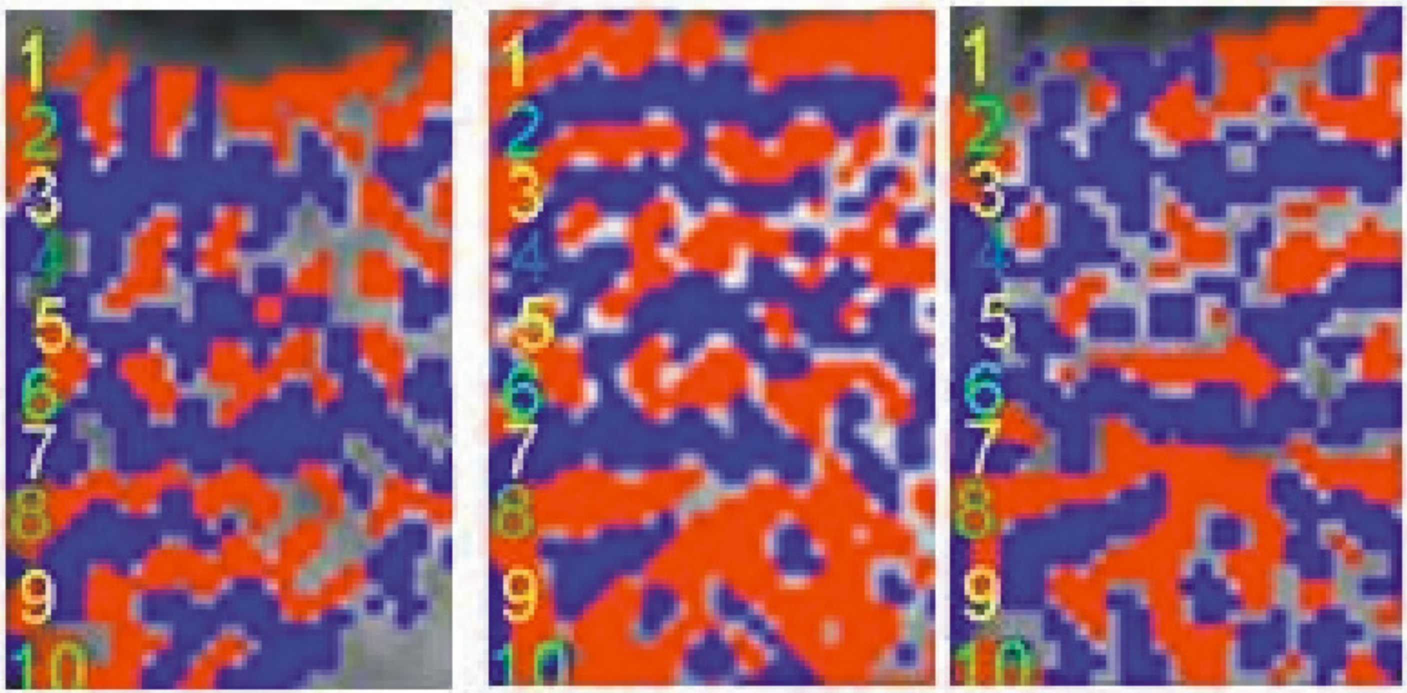


Menon et al, (1999) MRM 41 (2): 230-235

Multi-shot with navigator pulse

HSE-BOLD demonstration of ocular dominance columns

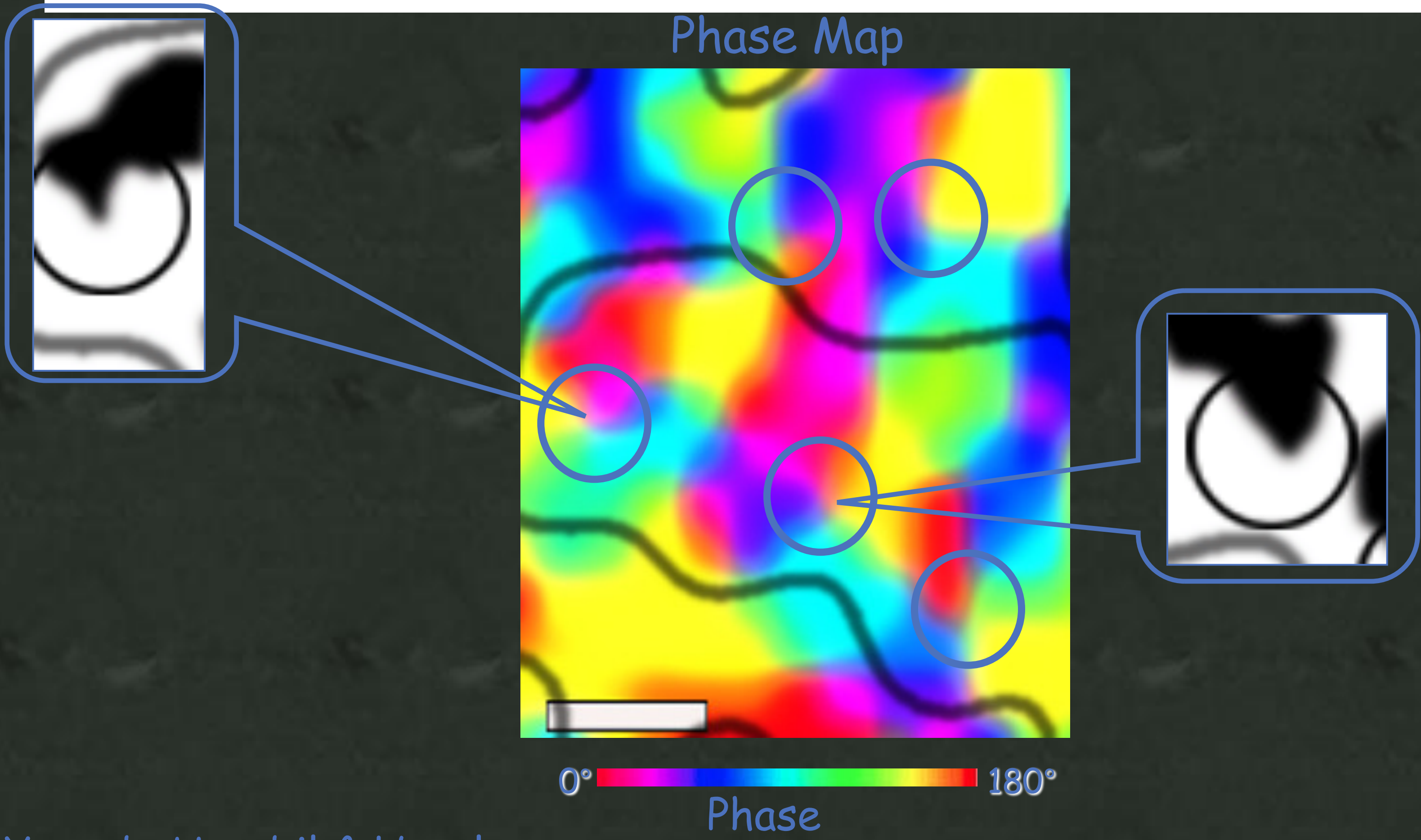
human, 7T, 0.5×0.5×3 mm^3



day 1 **day 2** **day 3**

Yacoub et al: differential maps contrasting stimulation of the left and right eye

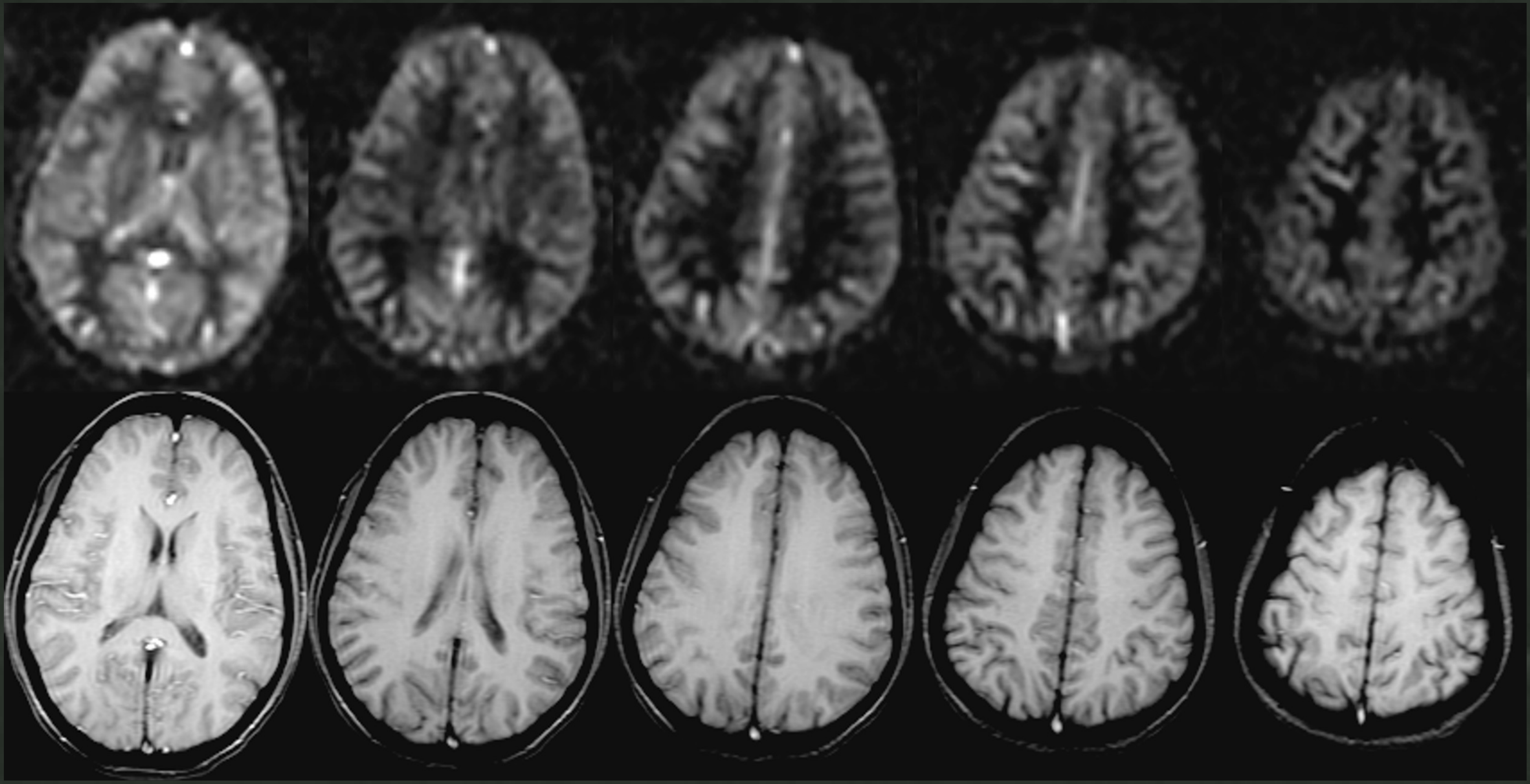
Orientation Columns in Human V1 as Revealed by fMRI at 7T



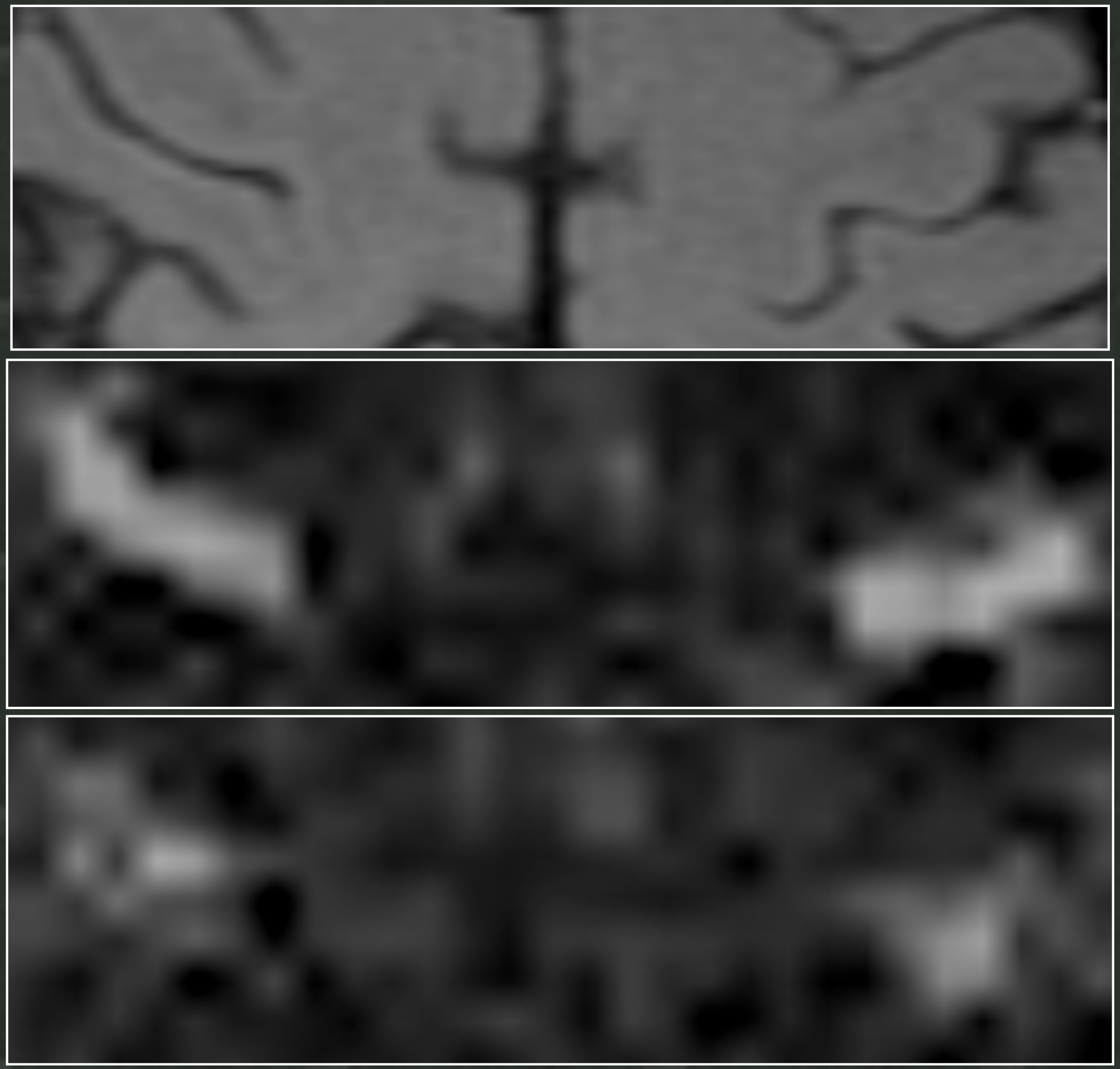
Yacoub, Ugurbil & Harel
University of Minnesota / CMRR
HBM 2006

Scalebar = 0.5 mm

Perfusion (ASL)



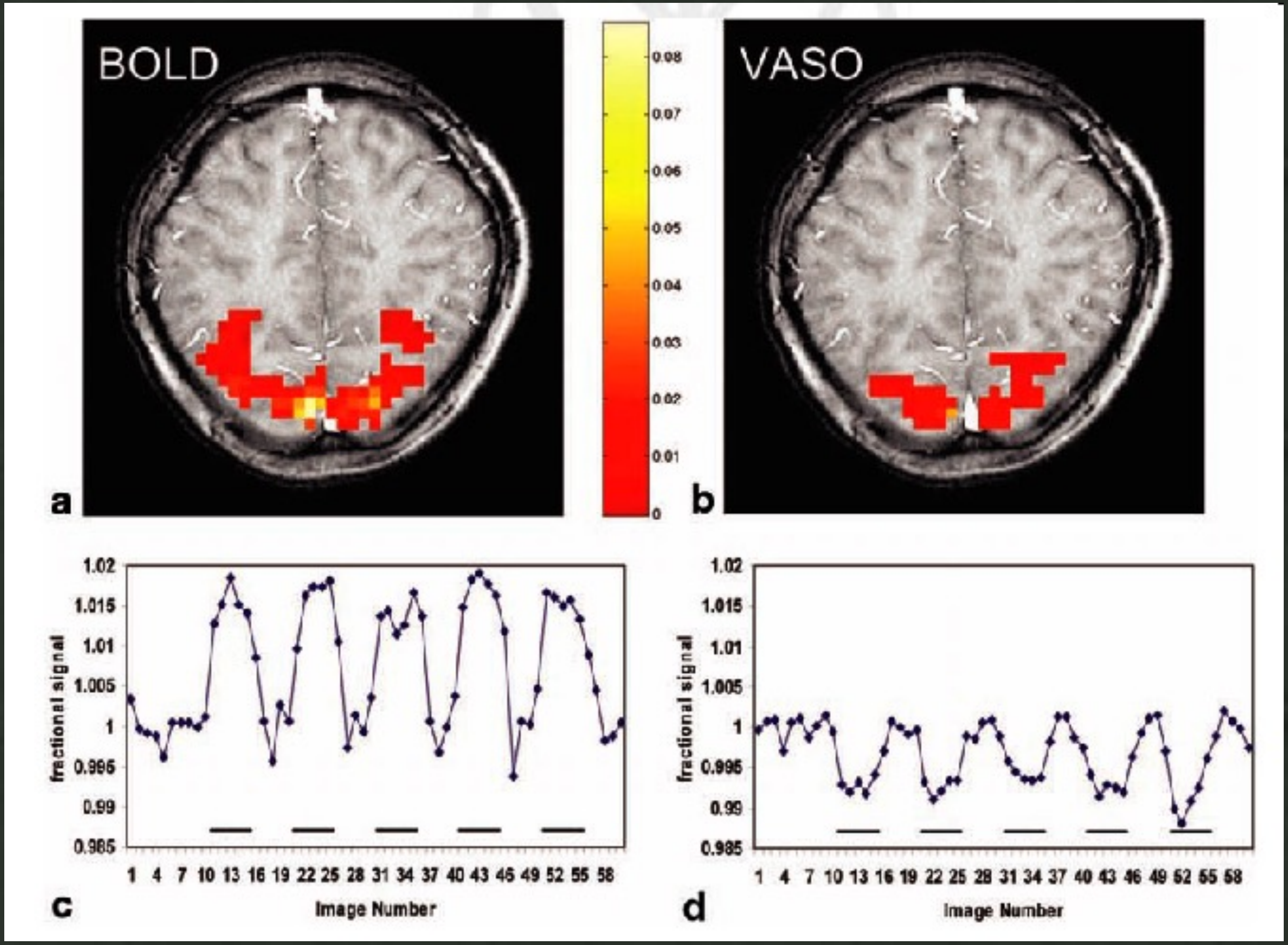
Simultaneous BOLD and Perfusion



BOLD

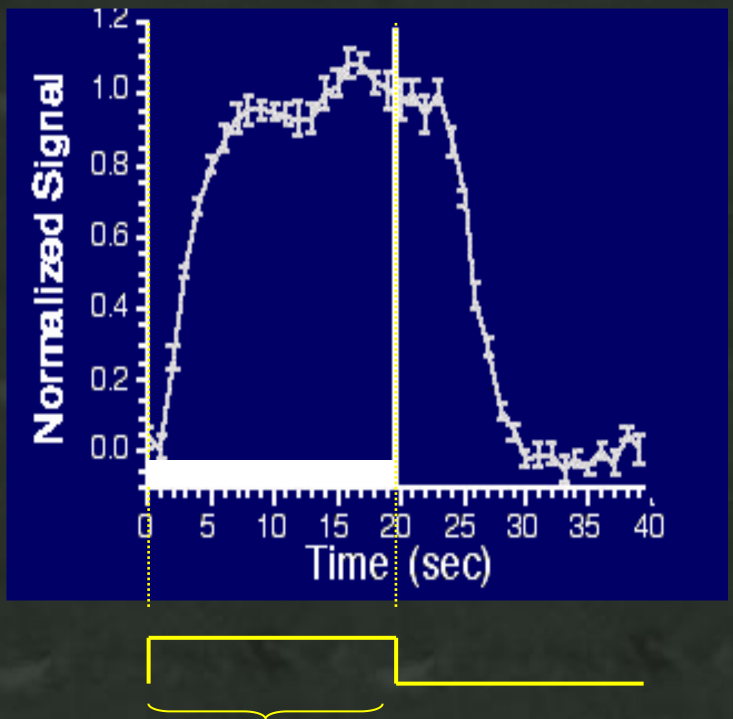
Perfusion

Is Vascular Space Occupancy Imaging (VASO) more specific?

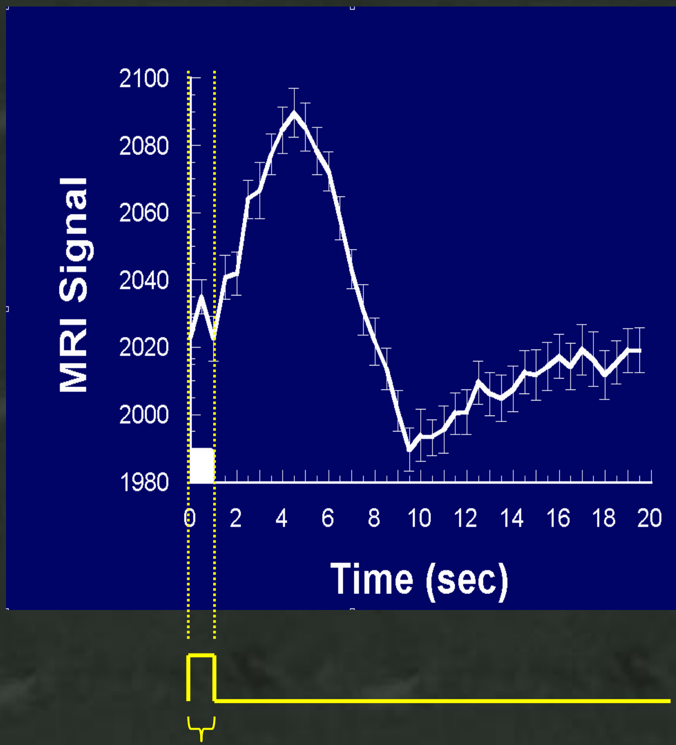


Lu et al, MRM 50 (2): 263-274 (2003)

Temporal resolution

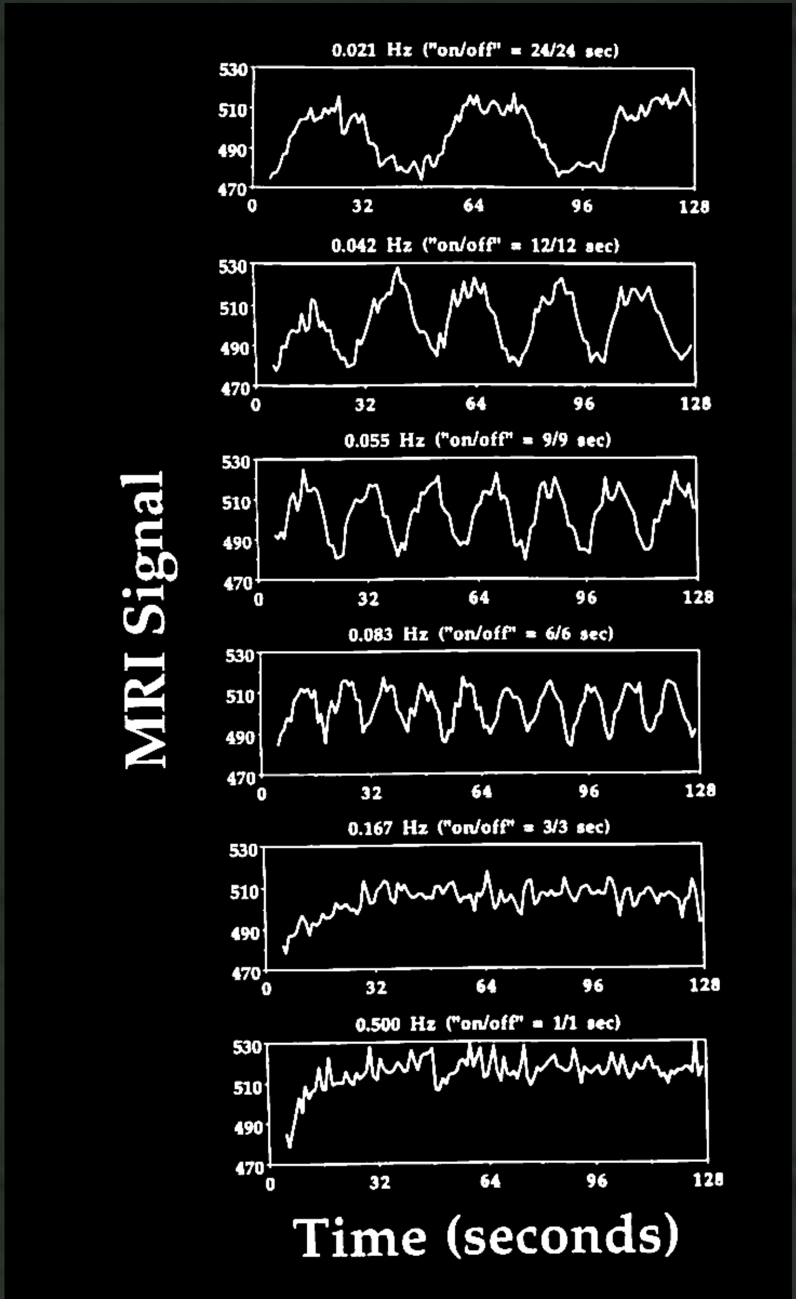


task

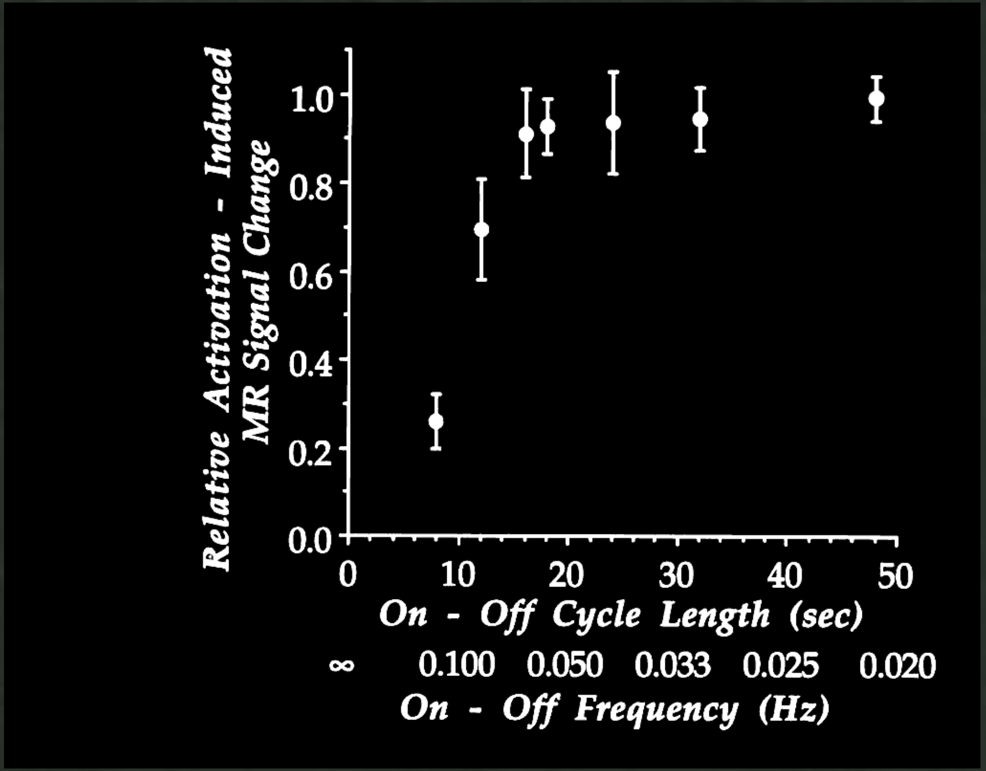


task

Temporal Resolution



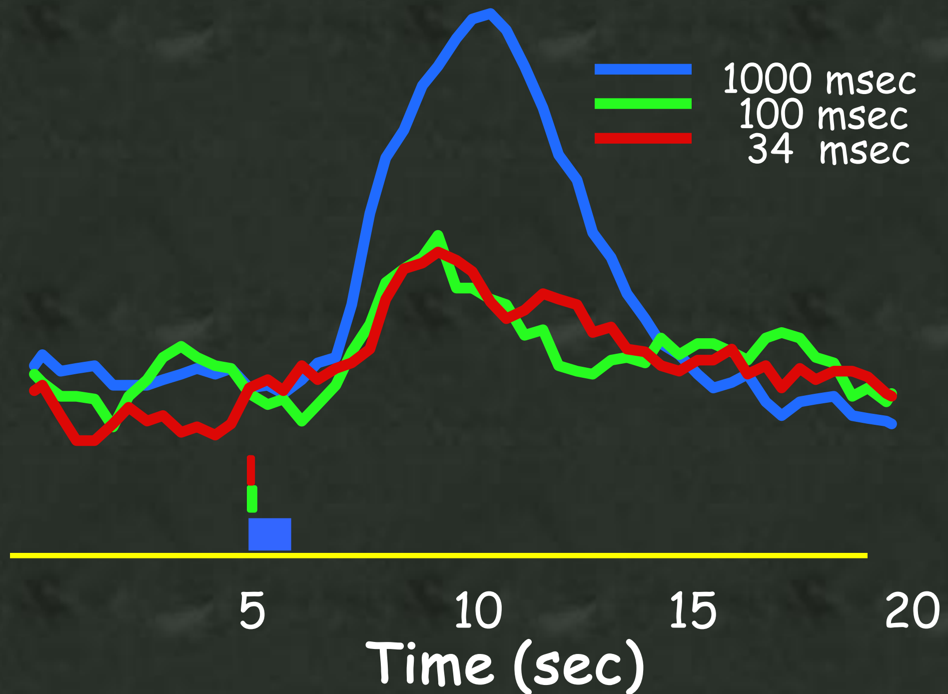
How rapidly can one switch on and off?



P. A. Bandettini,, Functional MRI using the BOLD approach: dynamic characteristics and data analysis methods, in "Diffusion and Perfusion: Magnetic Resonance Imaging" (D. L. Bihan, Ed.), p.351-362, Raven Press, New York, 1995.

Temporal Resolution

How brief of a stimulus can one give?



R. L. Savoy, et al., Pushing the temporal resolution of fMRI: studies of very brief visual stimuli, onset variability and asynchrony, and stimulus-correlated changes in noise, 3'rd Proc. Soc. Magn. Reson., Nice, p. 450. (1995).

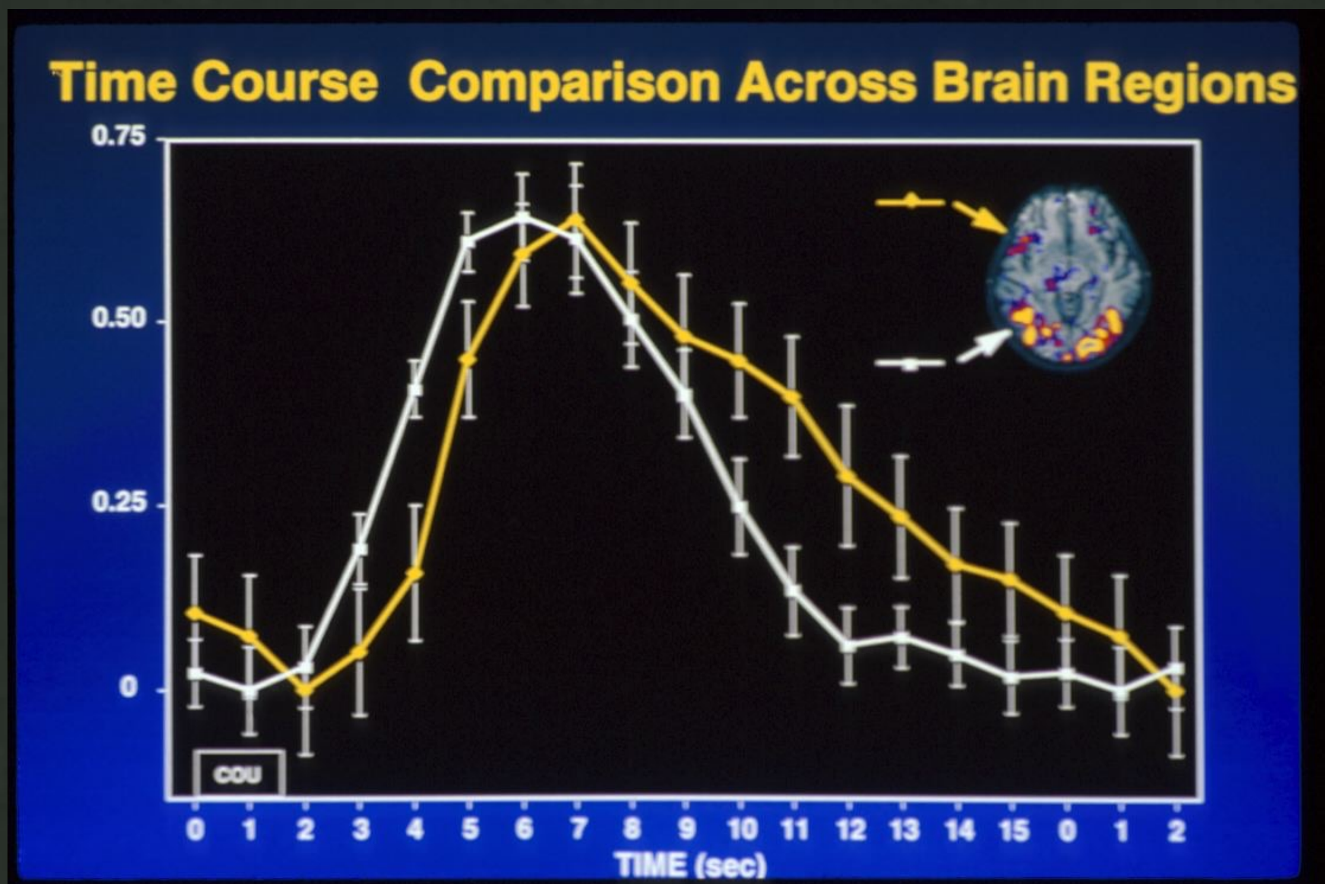
Temporal Resolution

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

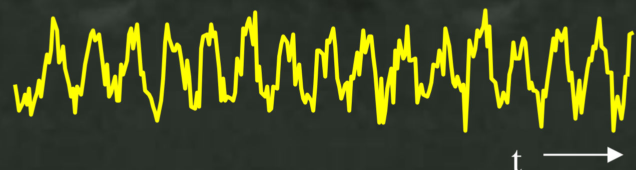
(neuroimaging/single trial/language/prefrontal)

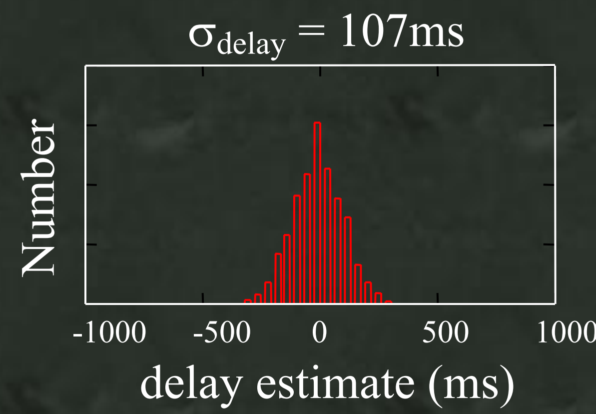
RANDY L. BUCKNER[†‡§¶], PETER A. BANDETTINI[†‡], KATHLEEN M. O'CRAVEN[†‖], ROBERT L. SAVOY[†‖], STEVEN E. PETERSEN[**††], MARCUS E. RAICHLE[§**††], AND BRUCE R. ROSEN[†‡]



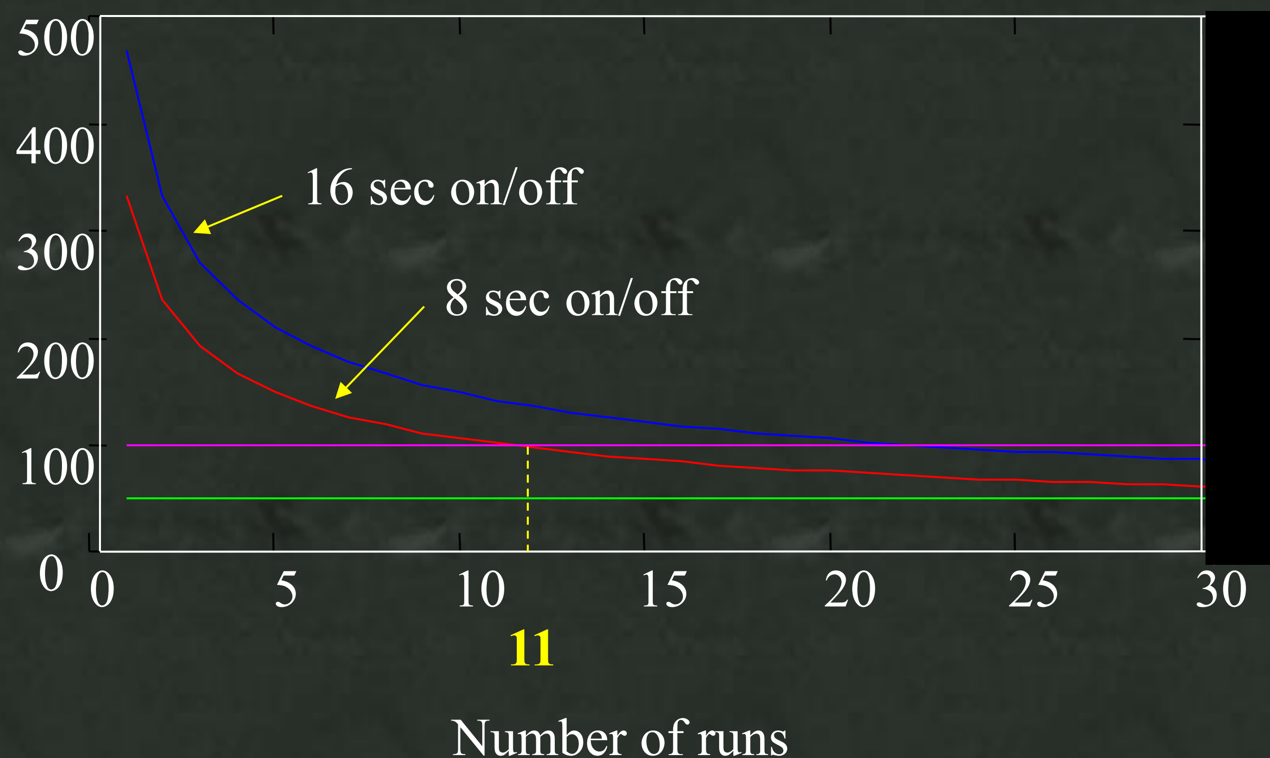
1% Noise
4% BOLD
256 time pts /run
1 second TR

1 run:

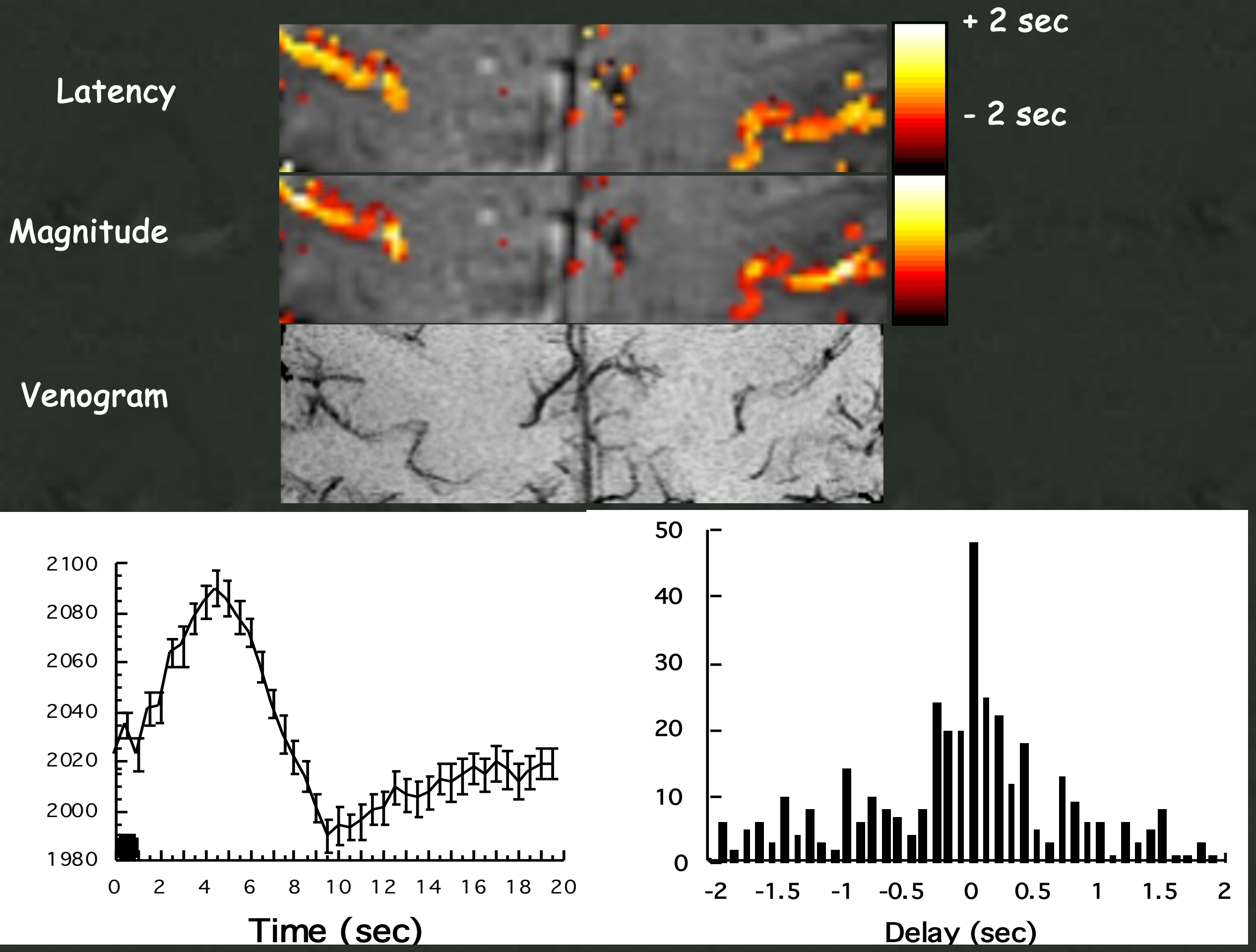




Smallest latency Variation Detectable (ms) ($p < 0.001$)



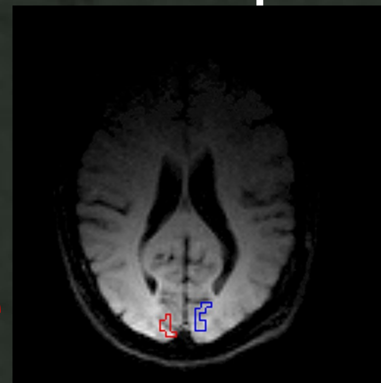
Latency Variation...



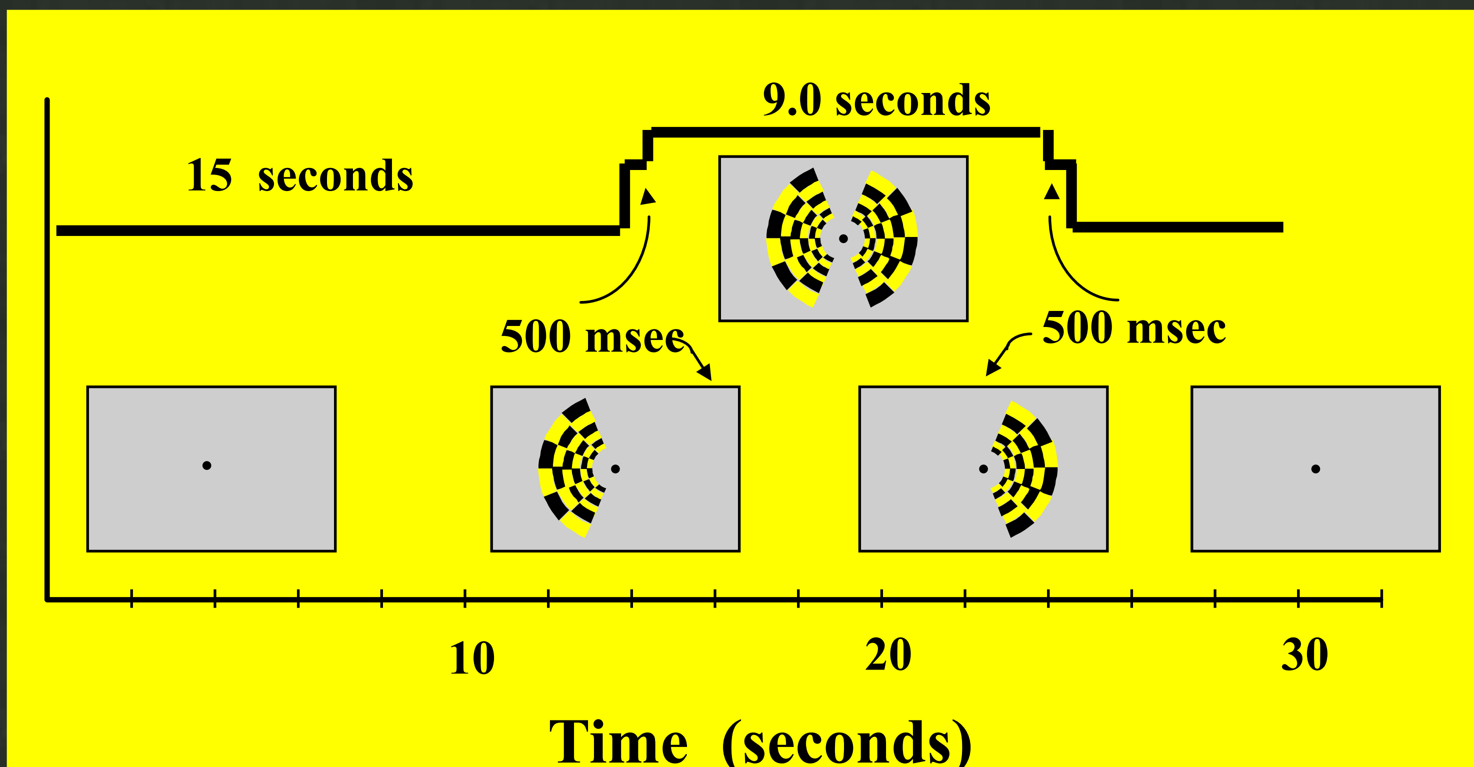
P. A. Bandettini, (1999) "Functional MRI" 205-220.

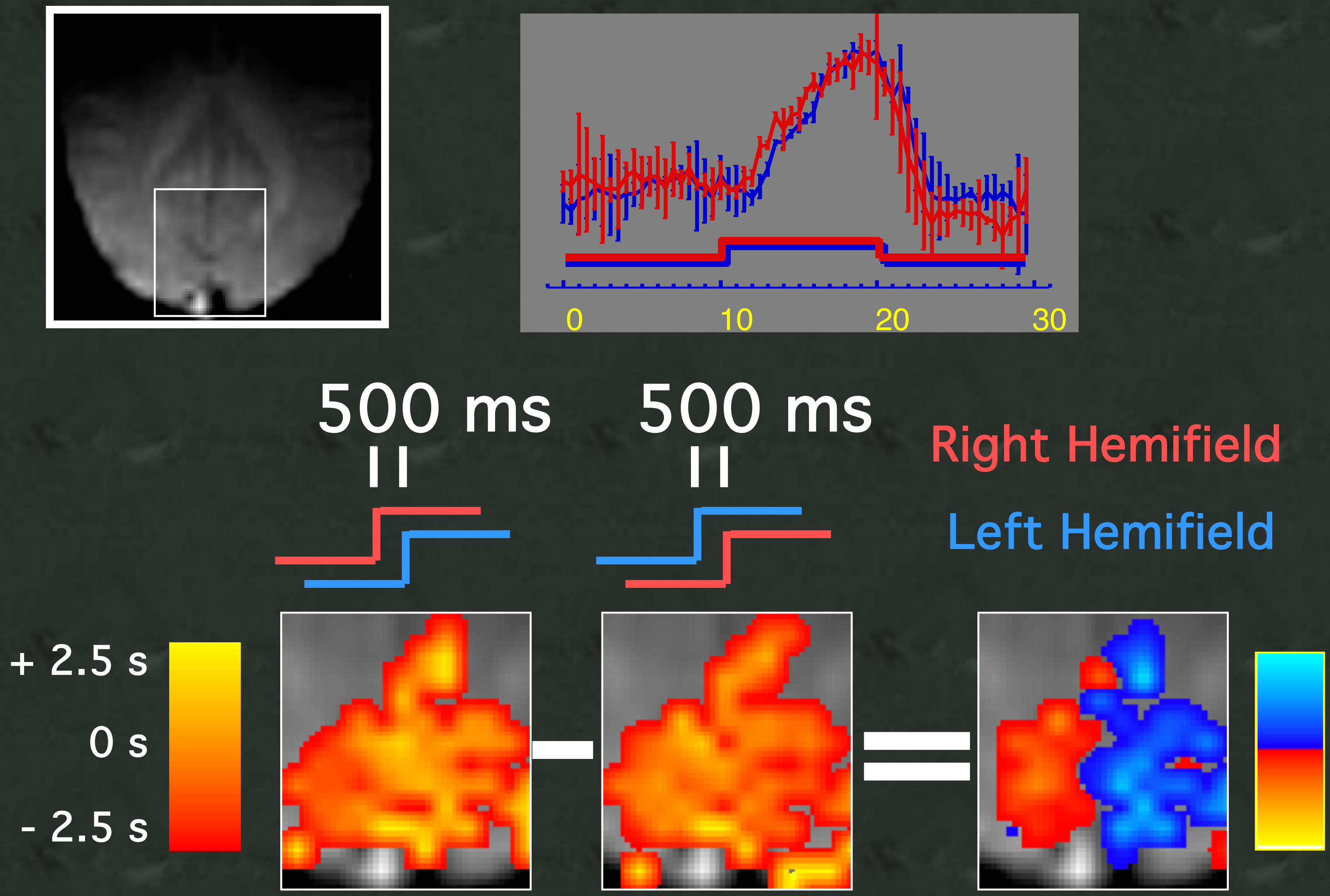
Hemi-Field Experiment

Right Hemisphere



Left Hemisphere



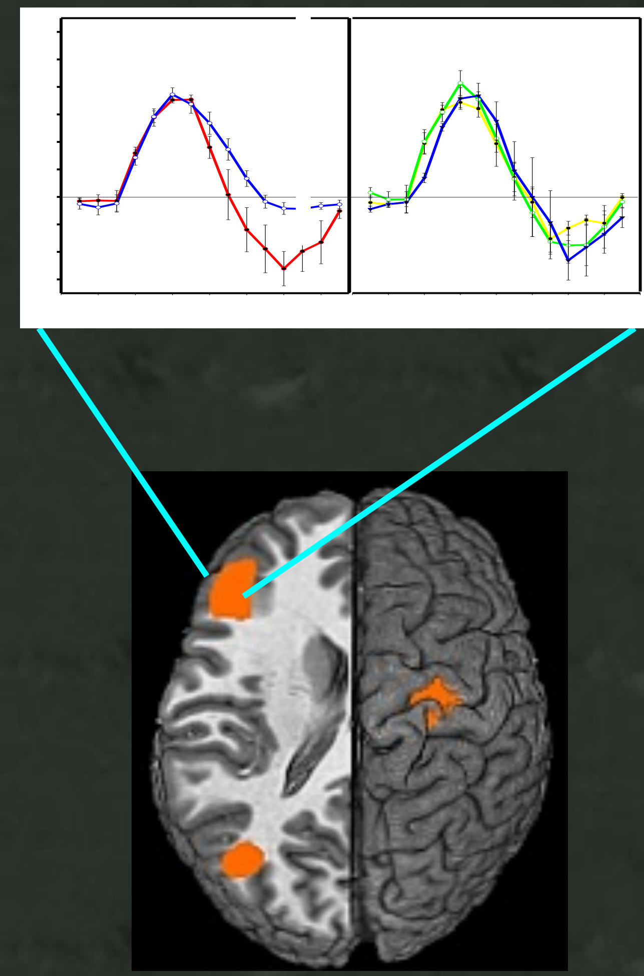

0
10
20
30
500 ms
500 ms
Right Hemifield
Left Hemifield
+ 2.5 s
0 s
- 2.5 s

Task timing modulation

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

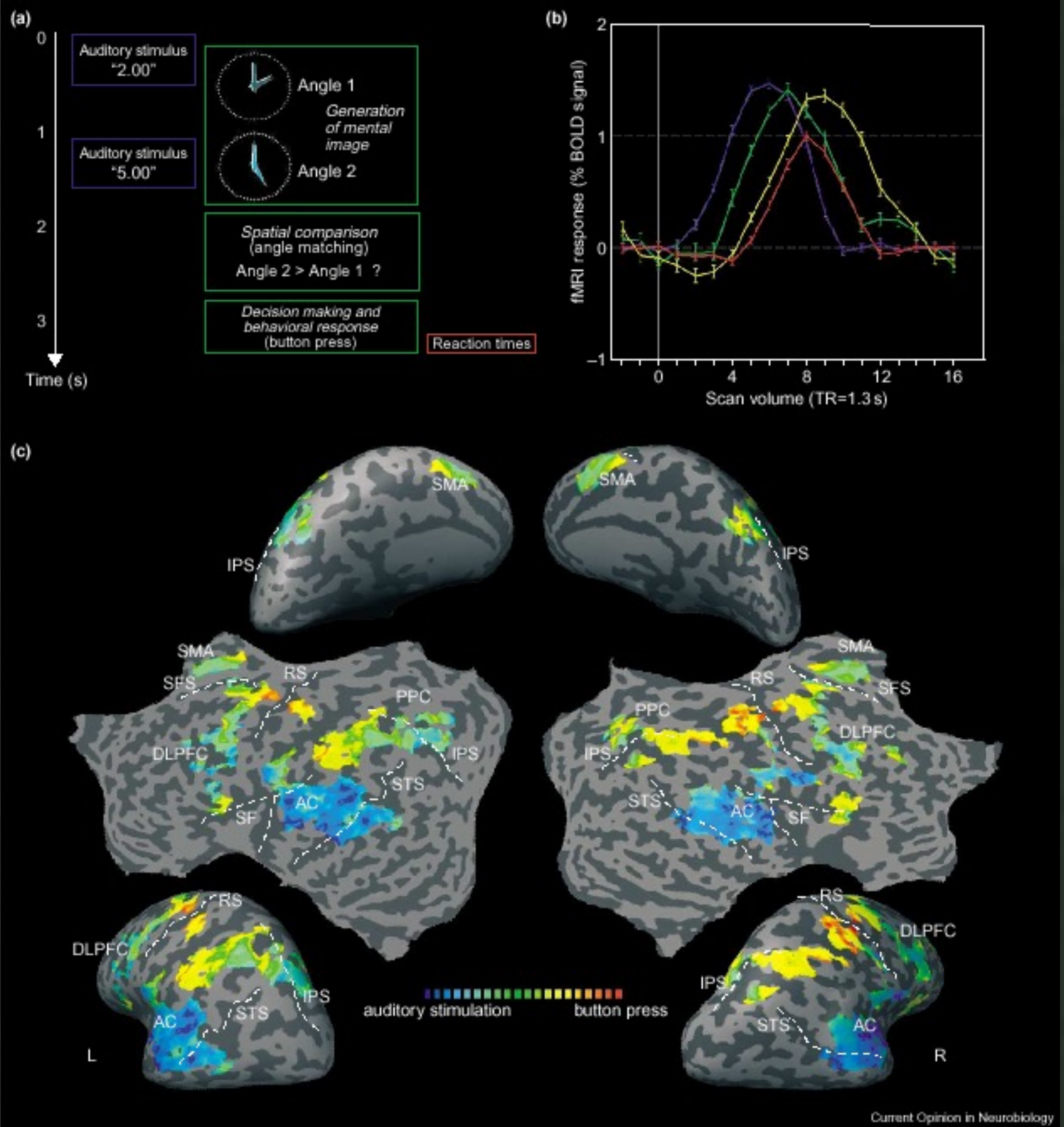
Word vs. Non-word

0°, 60°, 120° Rotation



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

No calibration



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

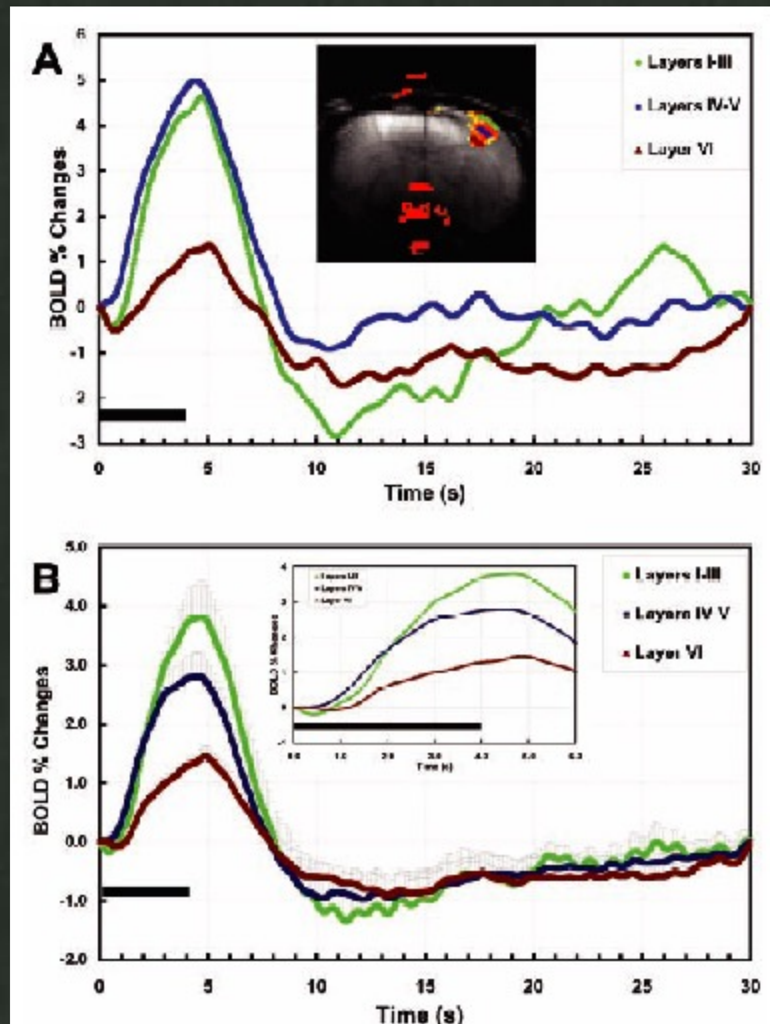
Laminar specificity of functional MRI onset times during somatosensory stimulation in rat

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



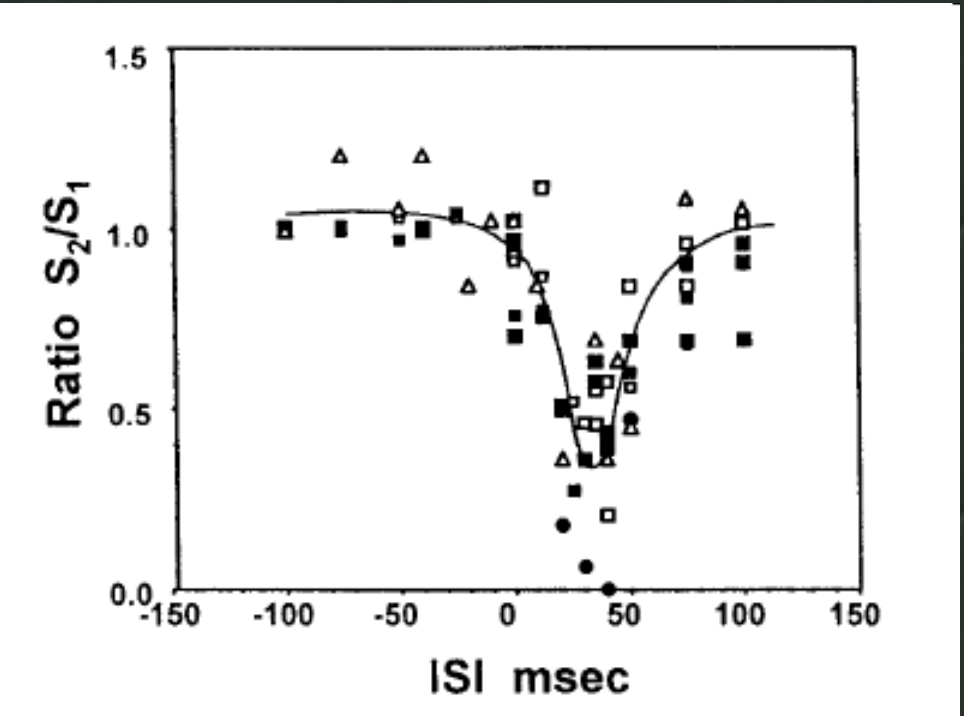
11.7 T

Temporal resolution factors	Values for each factor
Fastest image acquisition rate	≈64 images/s
Minimum time for signal to significantly deviate from baseline	≈3 s
Fastest on-off rate in which amplitude-is not compromised	≈8 s on, 8 s off
Fastest on-off rate in which hemodynamic response keeps up	≈2 s on, 2 s off
Minimum activation duration	≈30 ms (no limit determined yet, but the response behaves similarly below 500 ms)
Standard deviation of baseline signal	≈1% (less if physiological fluctuations and system instabilities are filtered out)
Standard deviation of onset time estimation	≈450 ms
Standard deviation of return to baseline time estimation	≈1250 ms
Standard deviation of entire on-off response time estimation	≈650 ms
Range of latencies over space	± 2.5 s

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

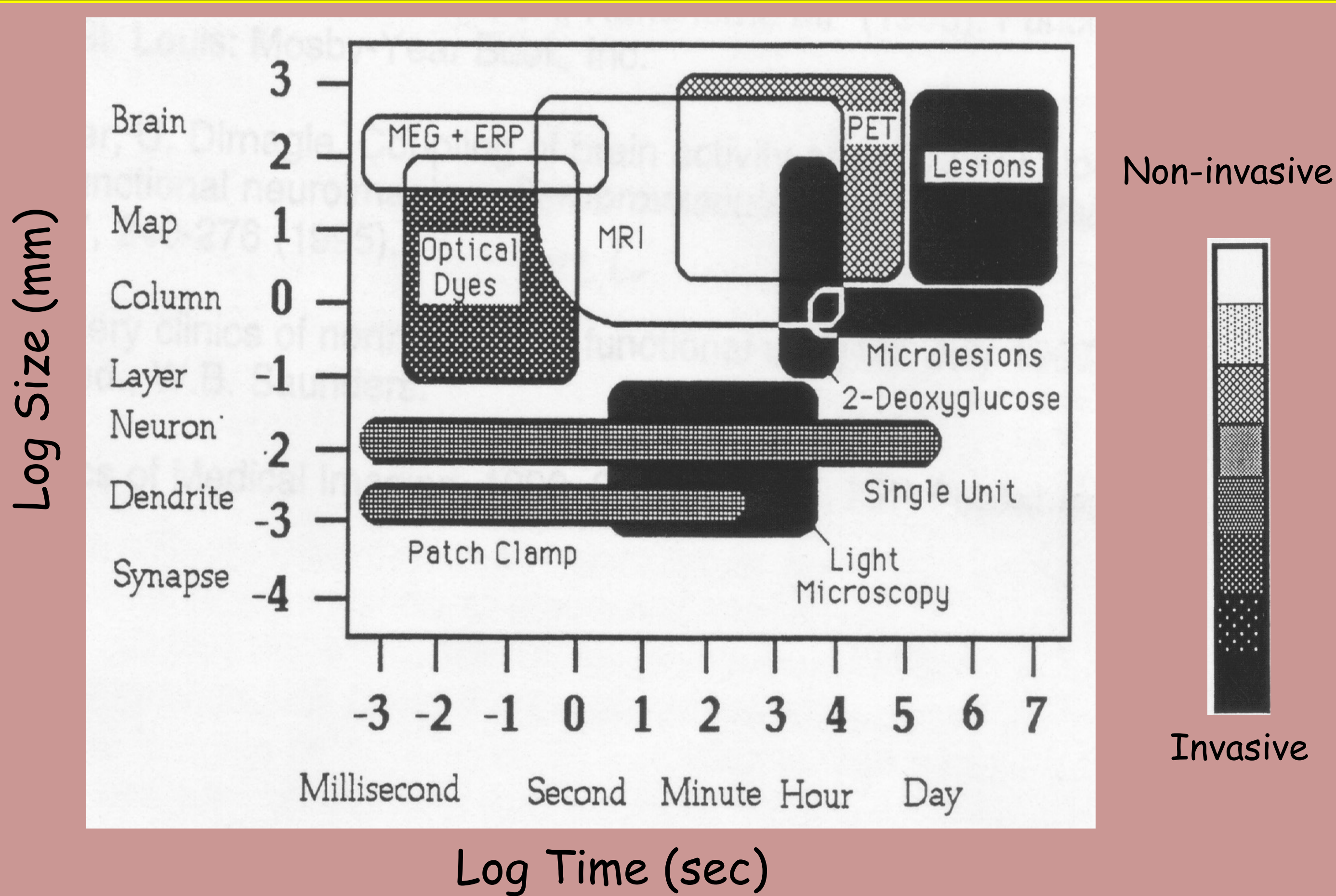
An approach to probe some neural systems interaction by functional MRI at neural time scale down to milliseconds

Seiji Ogawa[†‡], Tso-Ming Lee[†], Ray Stepnoski[†], Wei Chen[§], Xiao-Hong Zhu[§], and Kamil Ugurbil[§]



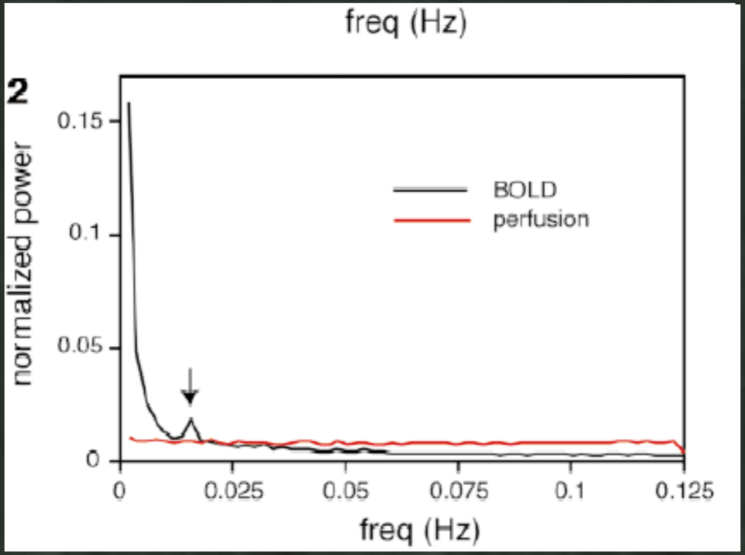
11026–11031 PNAS **September 26, 2000** vol. 97 no. 20

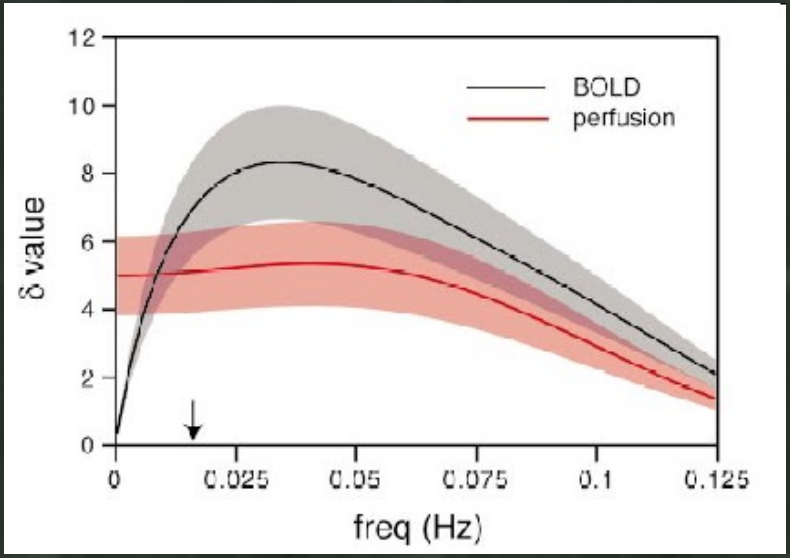
Functional Neuroimaging Techniques



Slow Limits…

Perfusion is better than BOLD for slow "state change" comparisons..

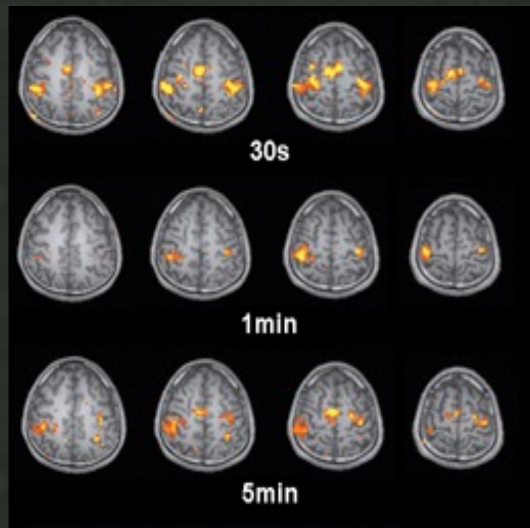




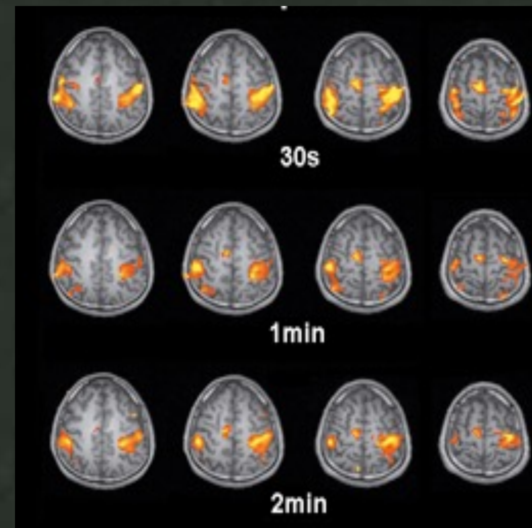
GK Aguirre et al, (2002) NeuroImage 15 (3): 488-500

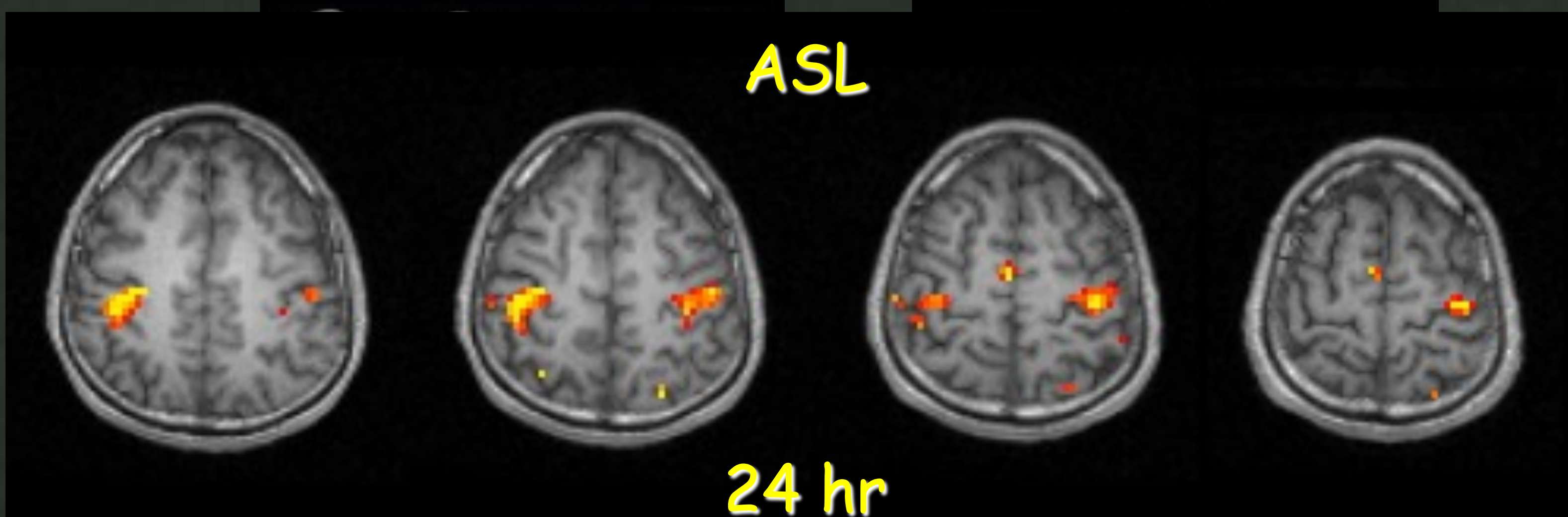
Perfusion vs. BOLD: Low Task Frequency

Perfusion

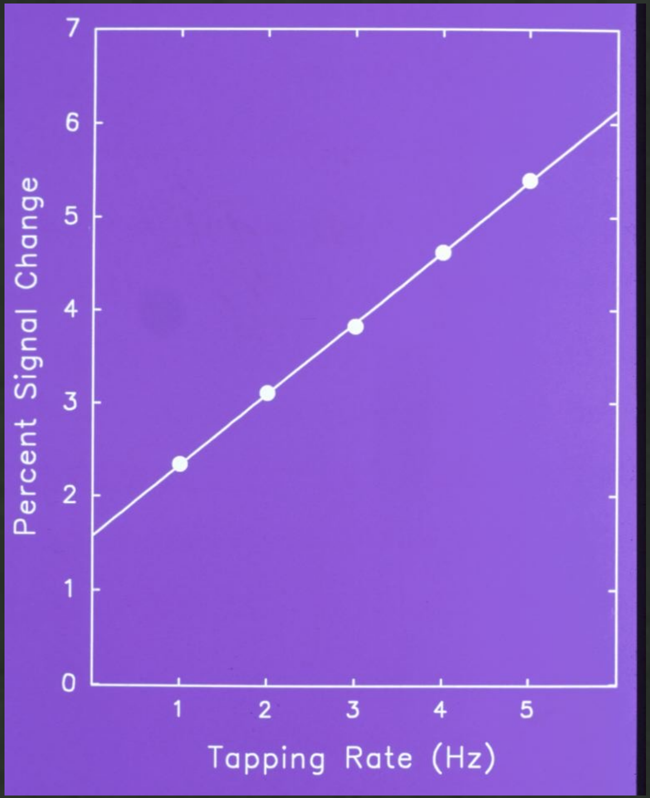


BOLD

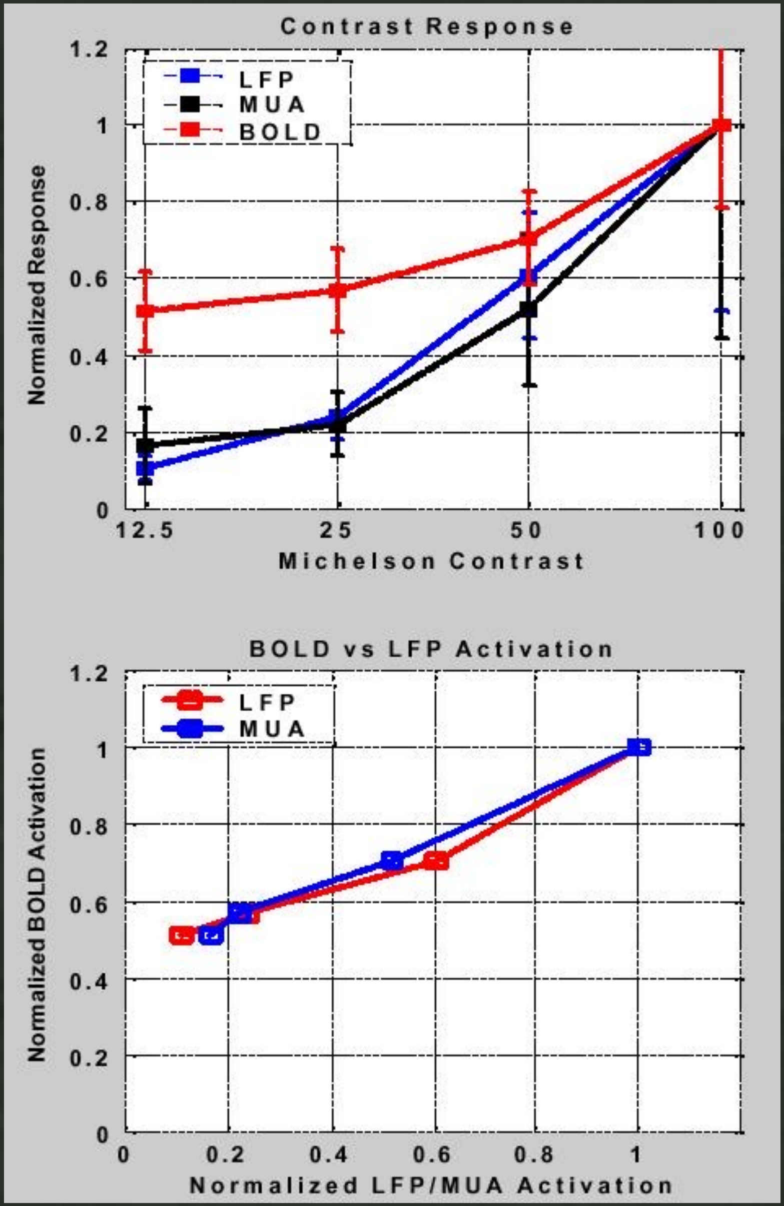




Wang et al., 2002

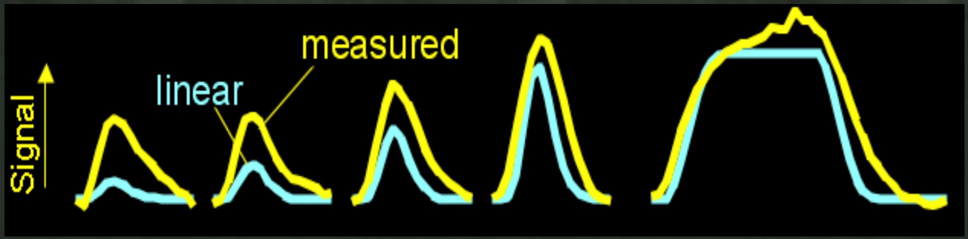


S. M. Rao et al, (1996) "Relationship between finger movement rate and functional magnetic resonance signal change in human primary motor cortex." *J. Cereb. Blood Flow and Met.* 16, 1250-1254.

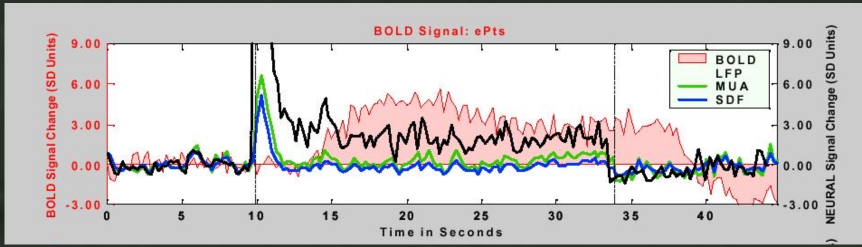


Logothetis et al. (2001) "Neurophysiological investigation of the basis of the fMRI signal" Nature, 412, 150-157

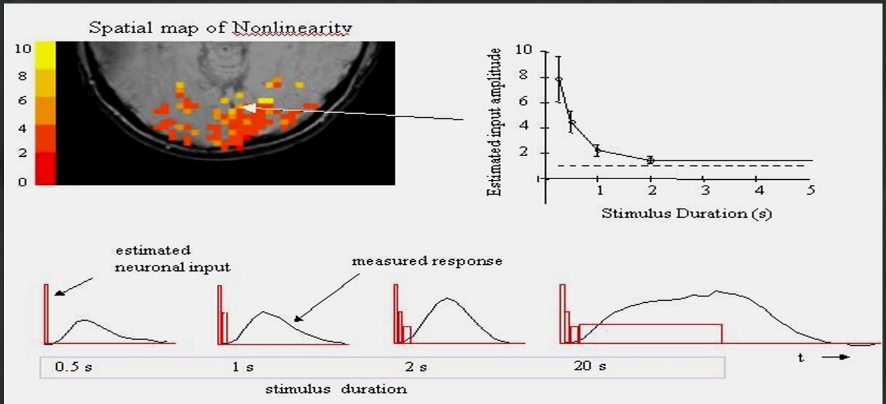
Linearity



R. M. Birn, (2001) NeuroImage, 14: 817-826.



Logothetis et al. (2001) Nature, 412, 150-157.

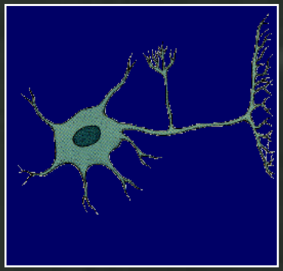


P. A. Bandettini et al, (2001) Nature Neuroscience, 4: 864-866.

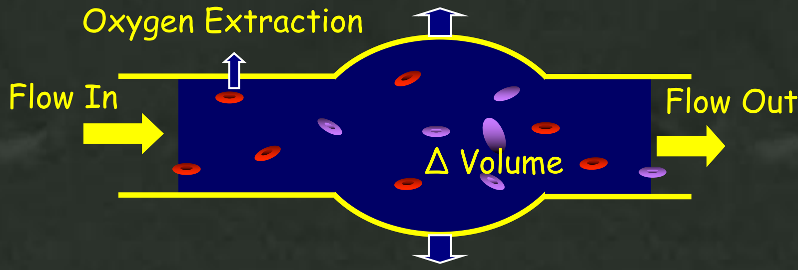
R. M. Birn, et. al, (2001) NeuroImage, 14: 817-826.

Sources of this Nonlinearity

- Neuronal

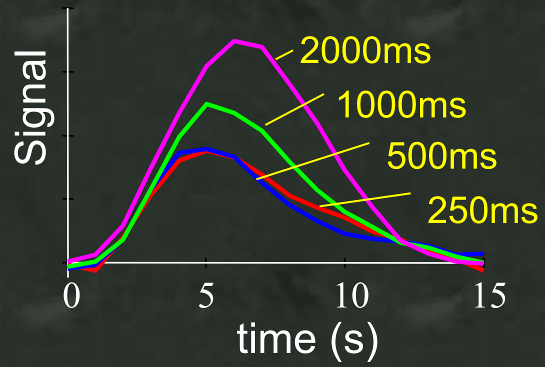


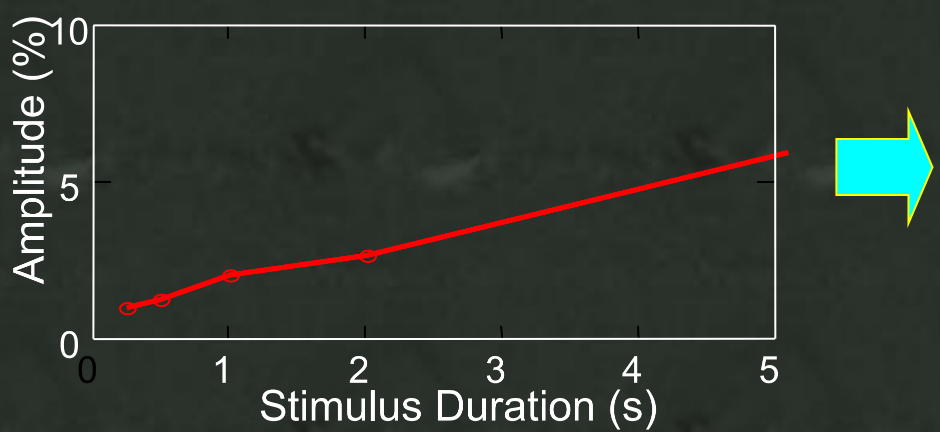
- Hemodynamic
  - Oxygen extraction
  - Blood volume dynamics



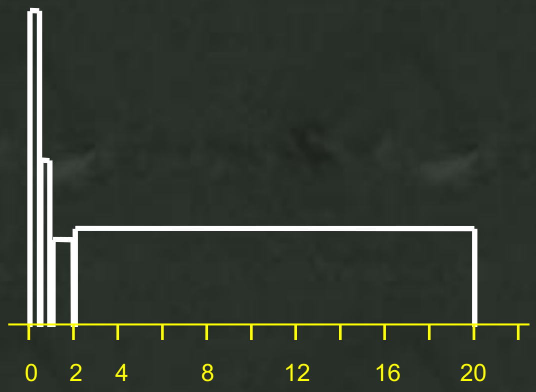
Linearity

Contrast Reversing Checkerboard



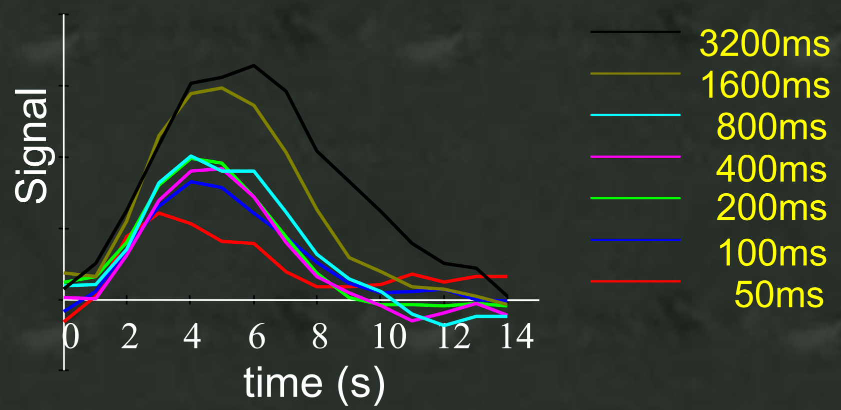


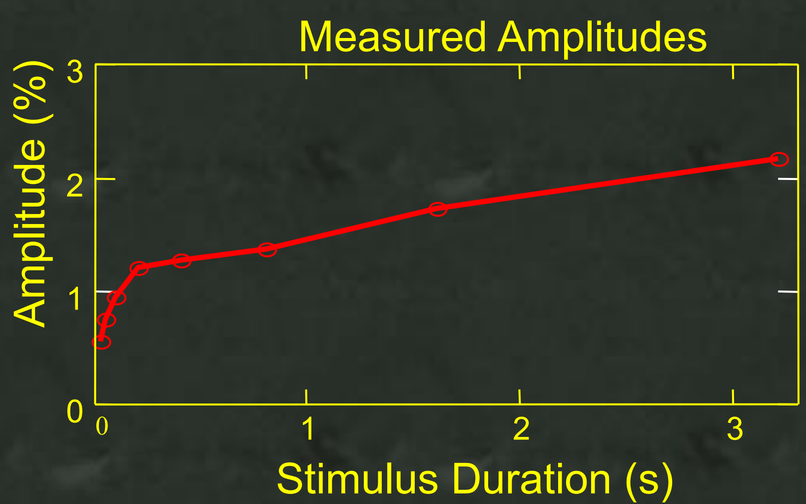
Estimated Neuronal Activity

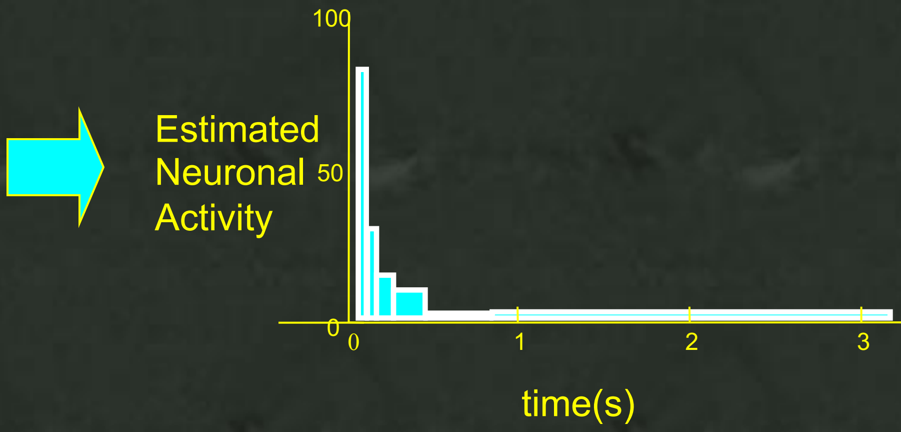


Linearity

Static Grating

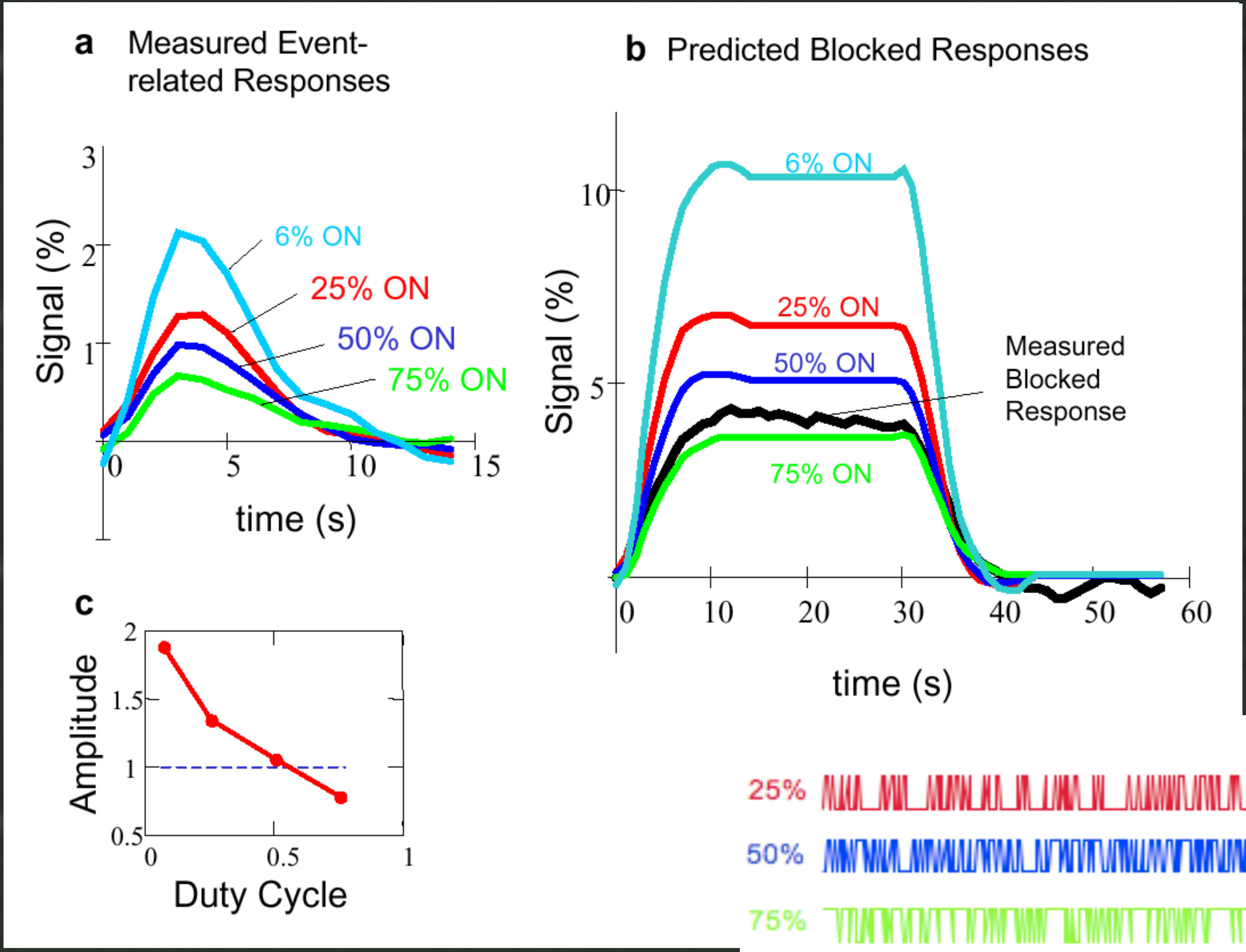


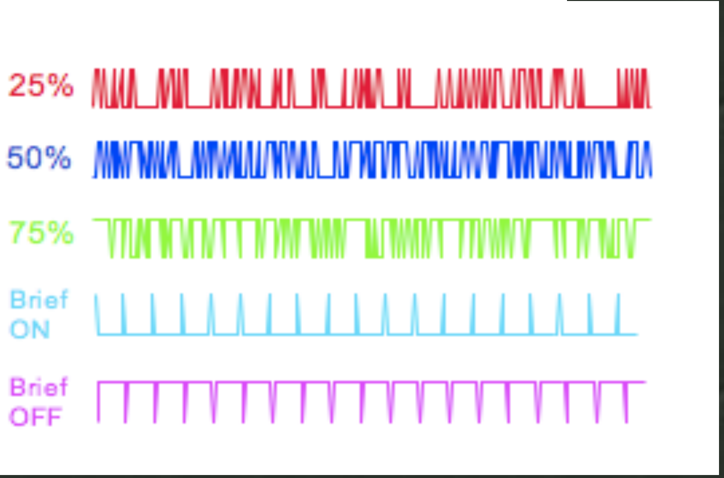




Linearity

Duty Cycle Effects

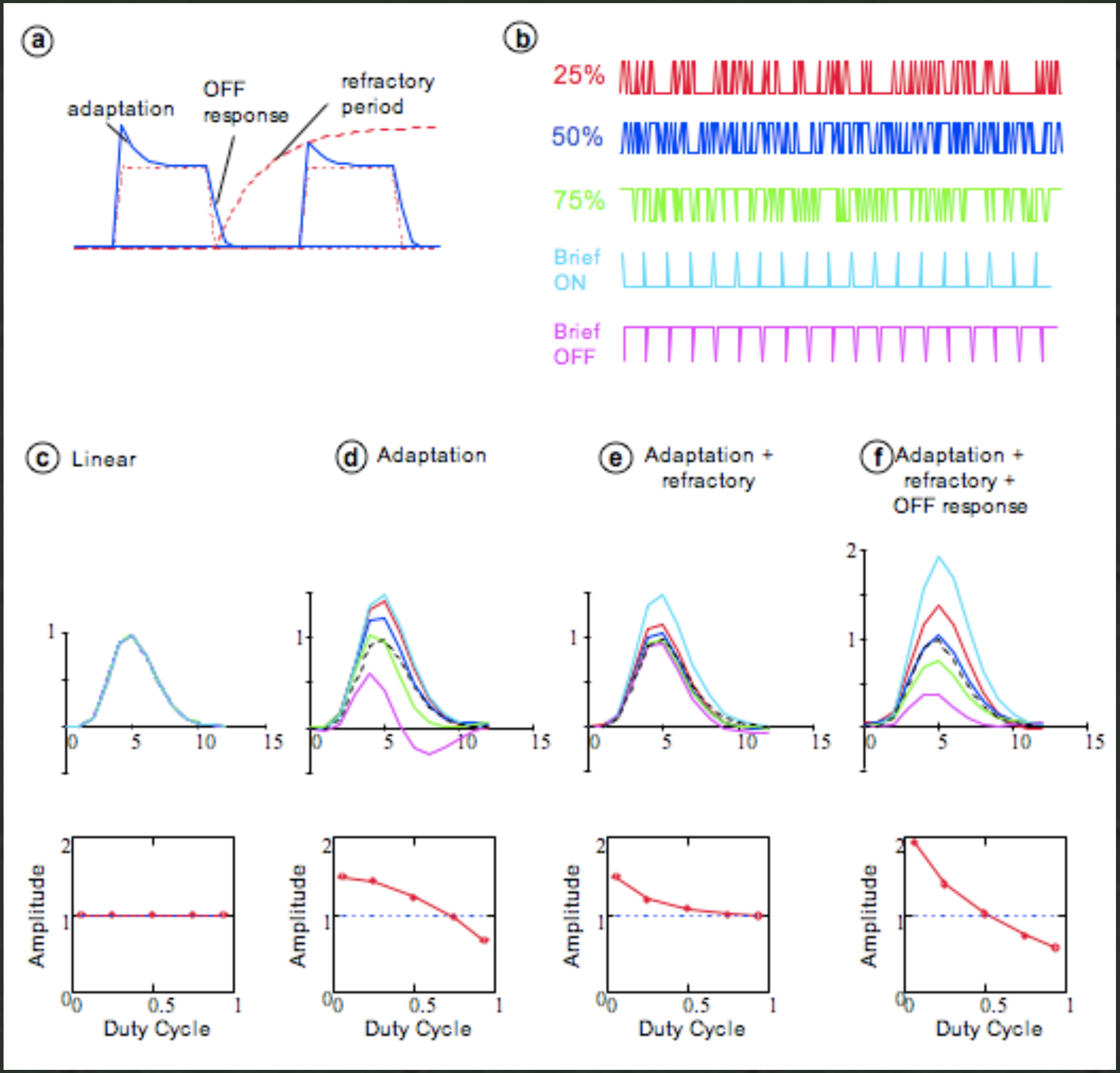




R.M. Birn, et al, NeuroImage, 27, 70-82 (2005)

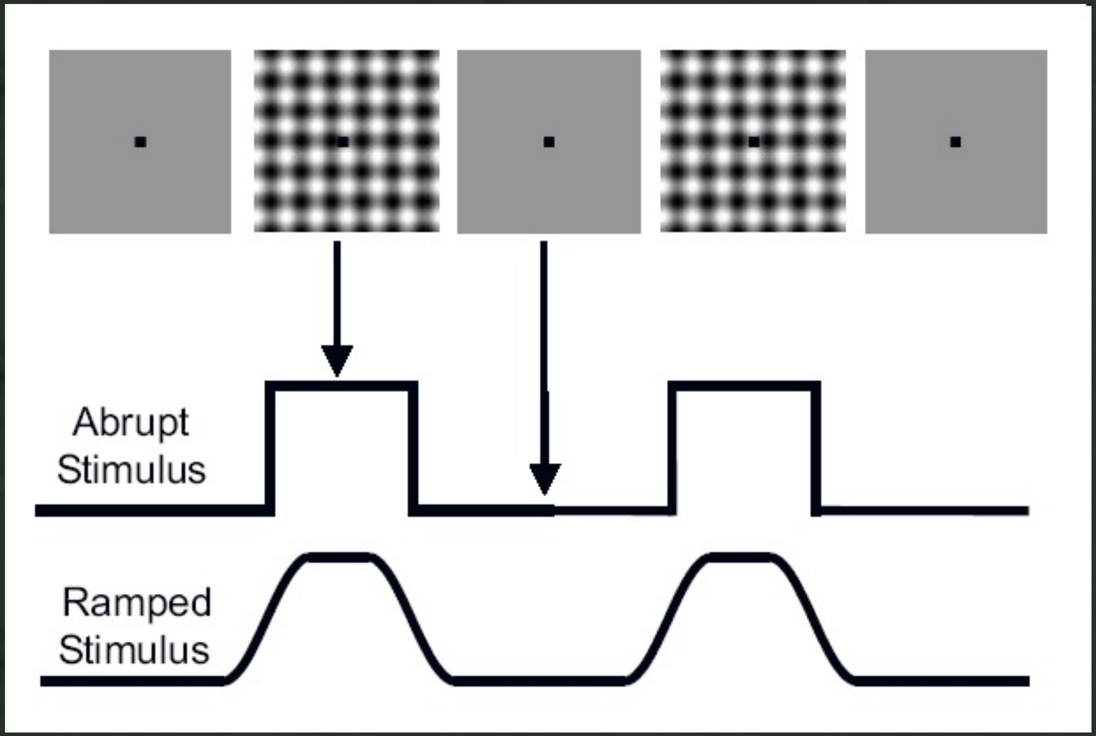
Linearity

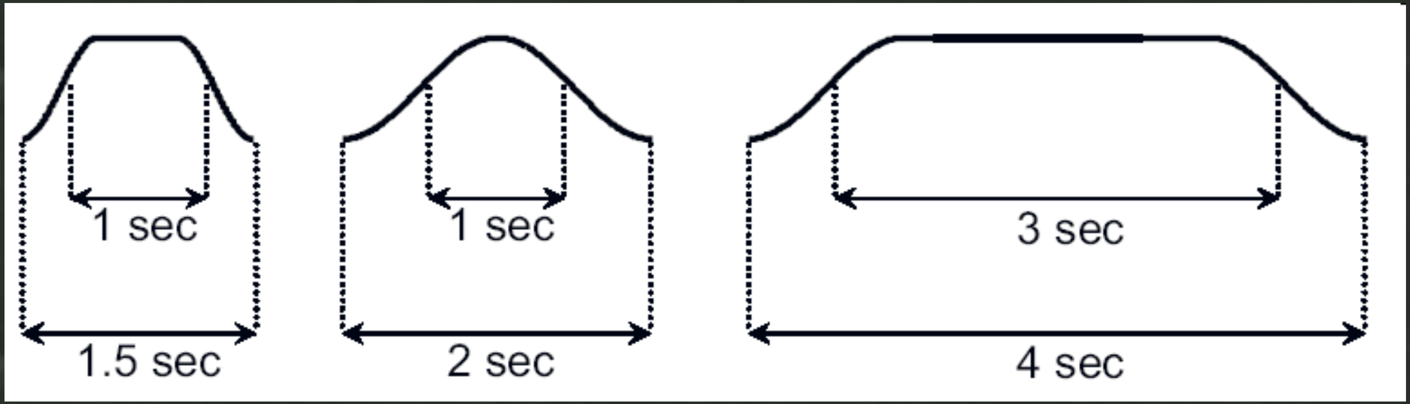
duty cycle effects



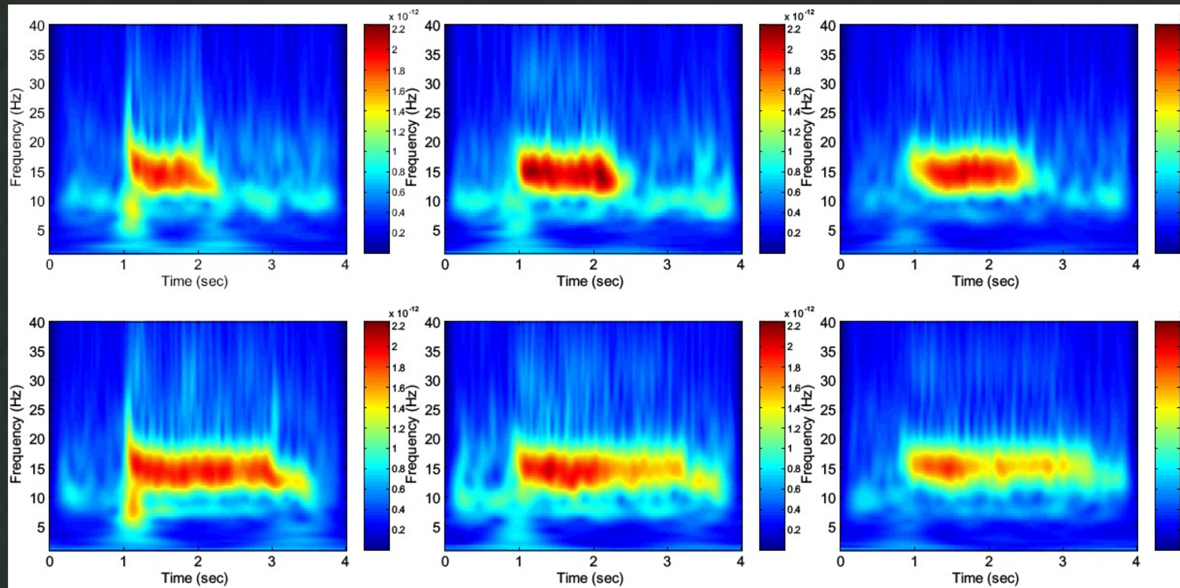
R.M. Birn, et al, NeuroImage, 27, 70-82 (2005)

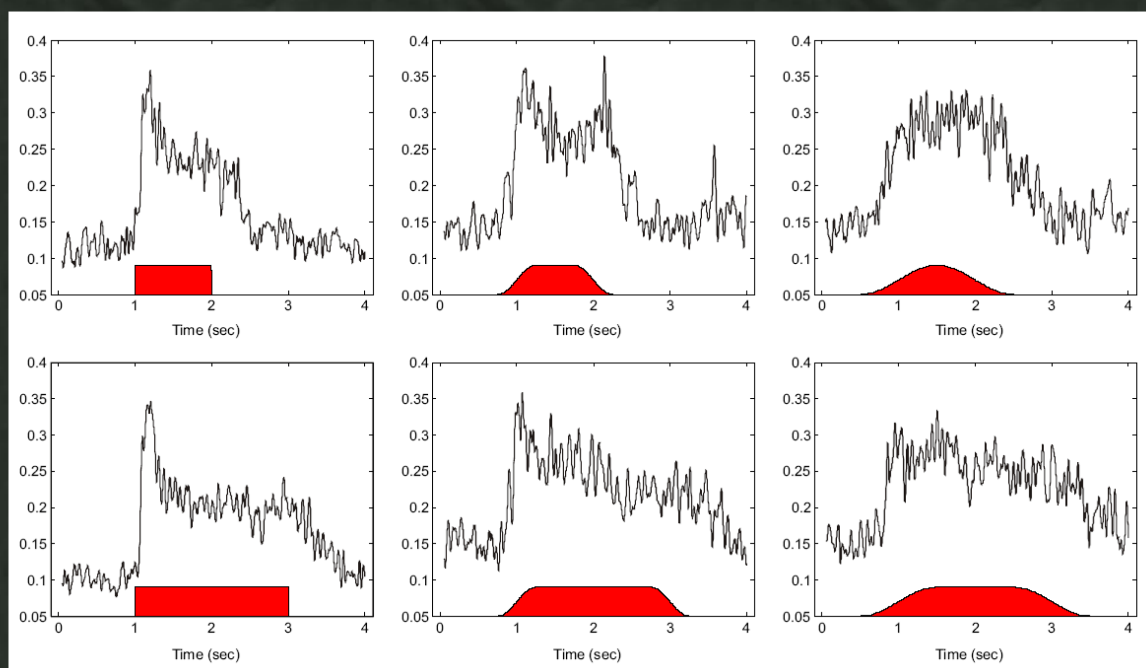
Linearity


Abrupt Stimulus
Ramped Stimulus


1 sec
1.5 sec
1 sec
2 sec
3 sec
4 sec

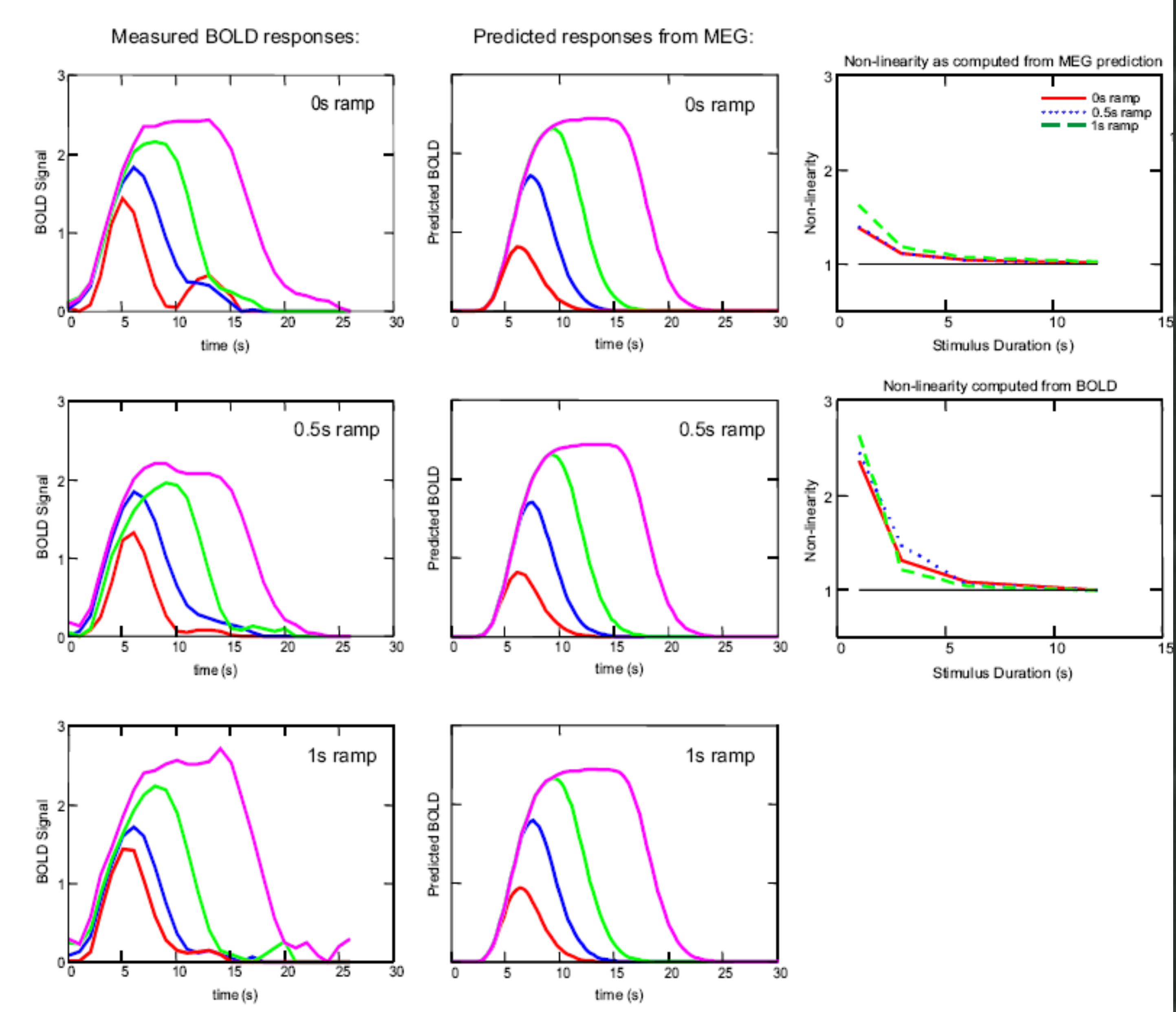
Linearity





Tuan, Birn et al.

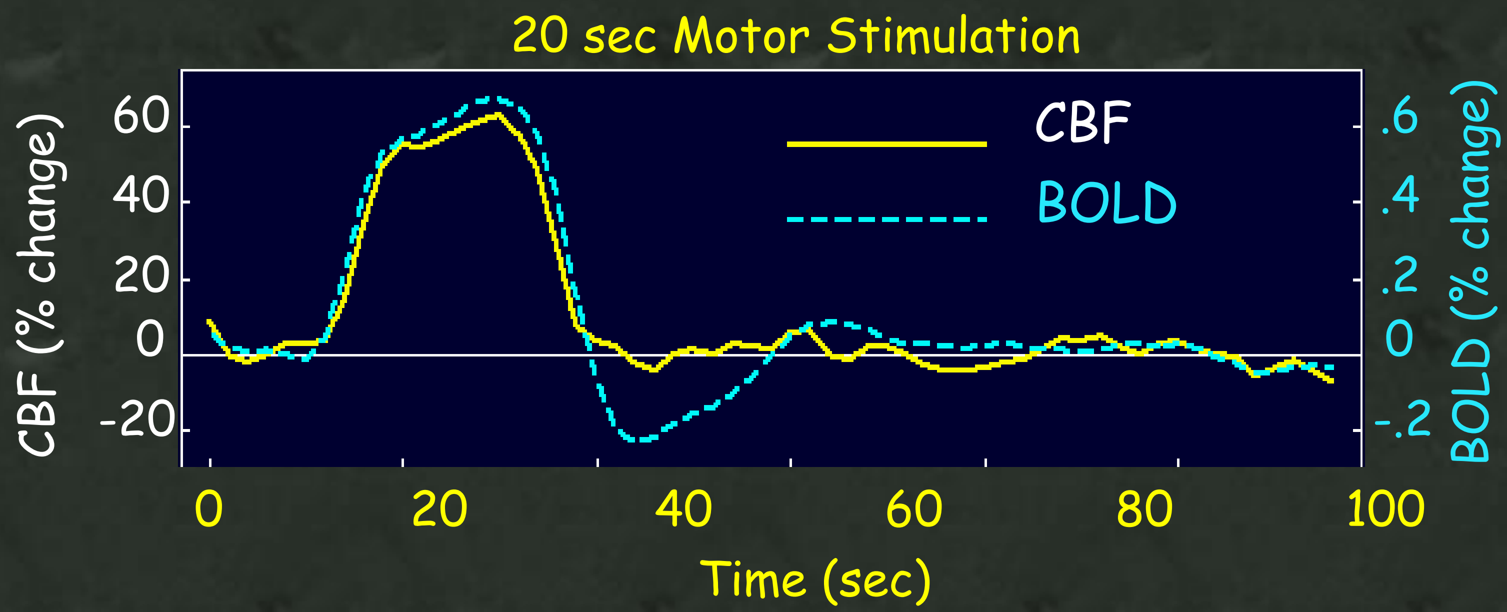
Linearity



Tuan, Birn et al.

Post Undershoot

BOLD post-stimulus undershoot

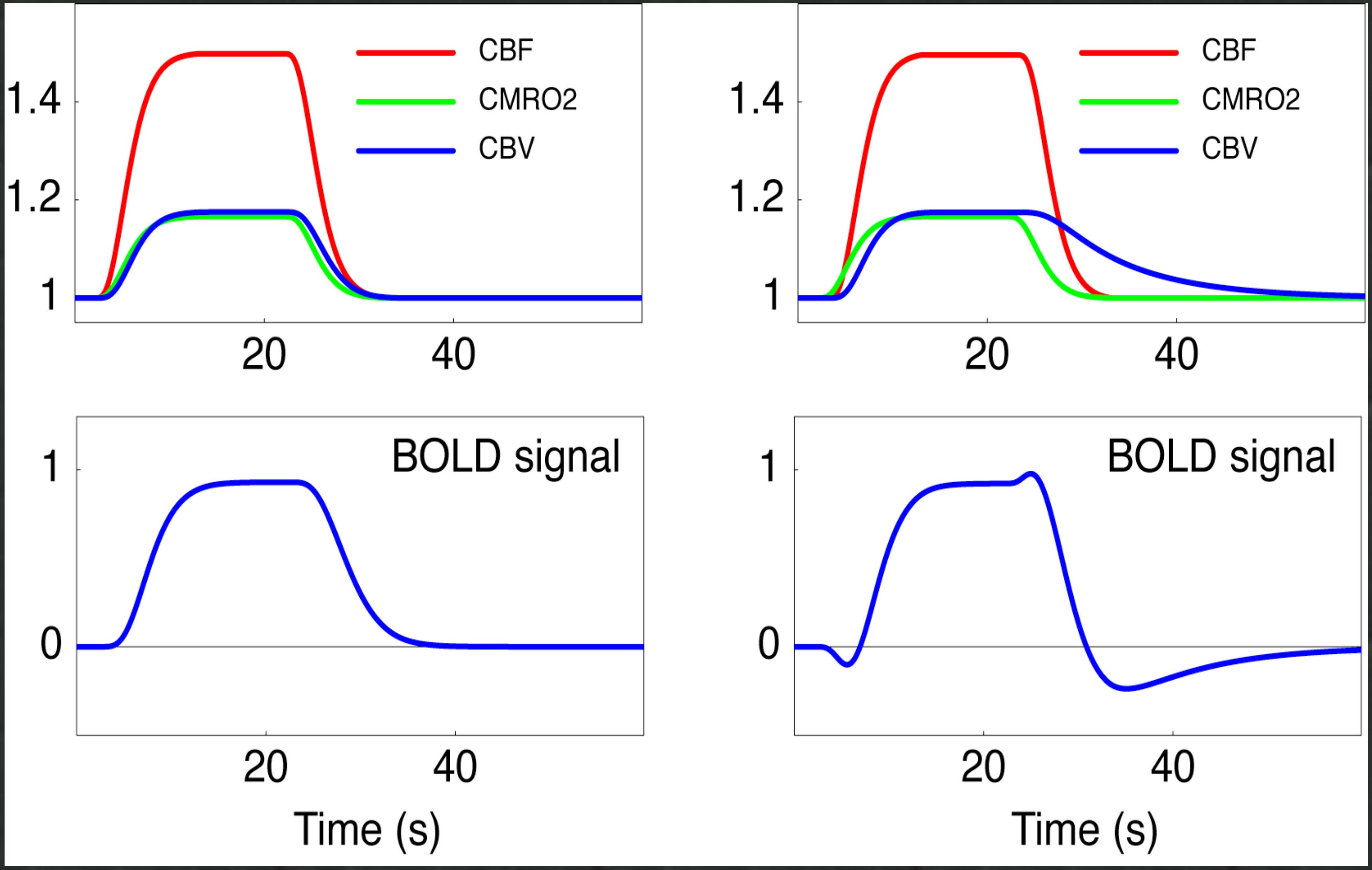


A BOLD undershoot without a CBF undershoot could be due to a slow return to baseline of either CBV or $CMRO_2$

Courtesy Rick Buxton

Post Undershoot

Simulated BOLD Signal Dynamics

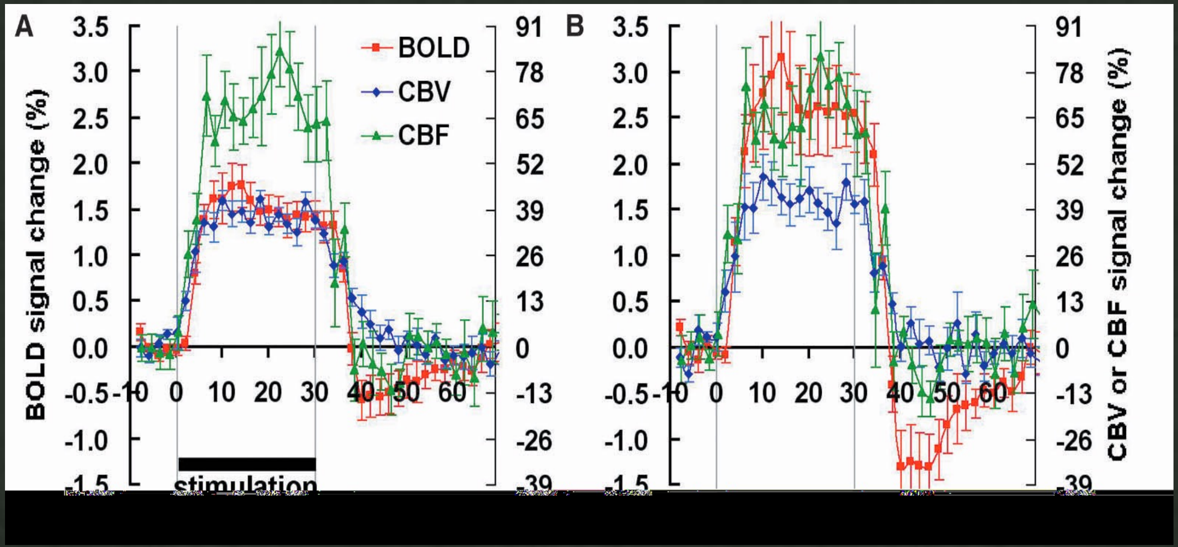


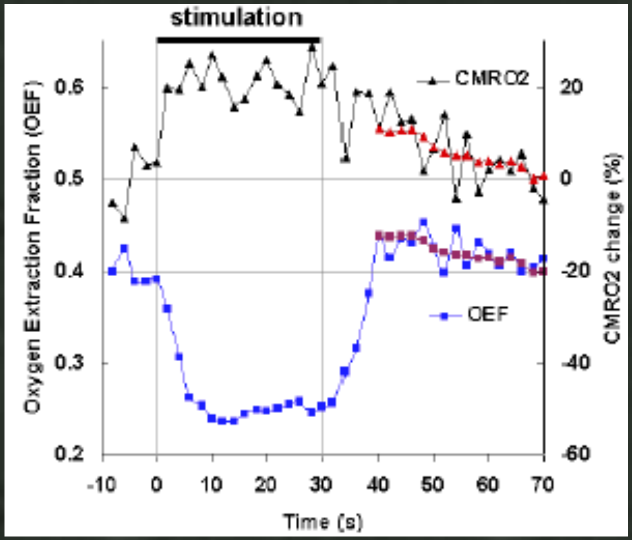
Courtesy Rick Buxton

VASO (Vascular Space Occupancy)

Evidence for sustained elevated $CMRO_2$

(VASO indicates fast return of CBV despite BOLD undershoot)





All activated voxels

Overlapped voxels

Lu, et al: JCBF+M 24:764, 2004

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