Towards a better understanding and utility of fMRI dynamics and fluctuations

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&

Functional MRI Facility

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Patricia Bandettini, July 10, 2006

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

September, 1991

Towards a better understanding and utility of fMRI dynamics and fluctuations

Dynamics

- Linearity
- Latency

Fluctuations

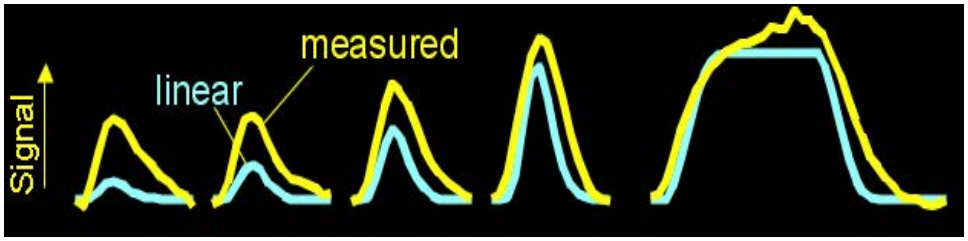
- Resting state
- Respiration related
- Time series improvement
- Respiration Response Function

High Resolution

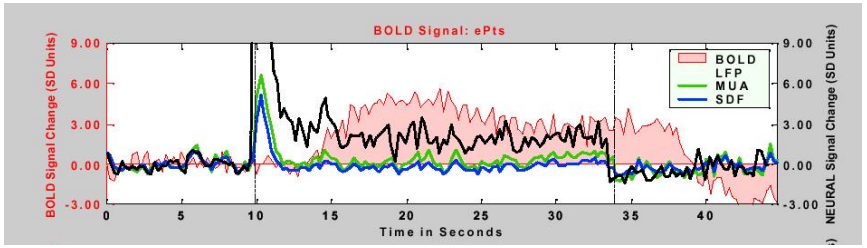
Finding the "Suggested resolution"

What to do with high resolution data?

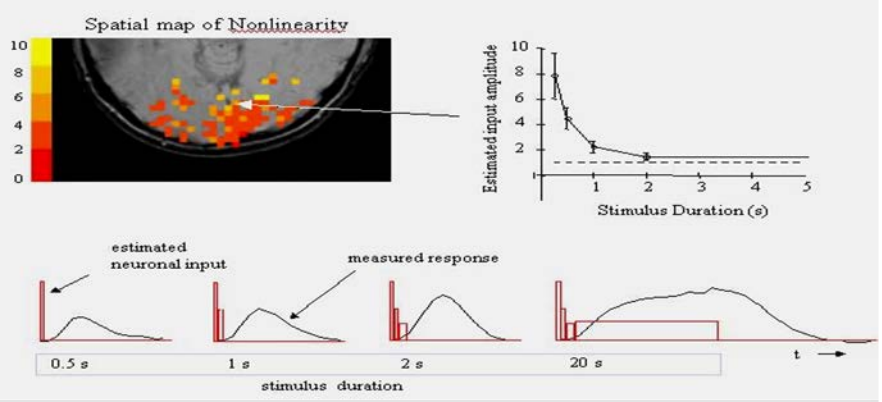
Linearity



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



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

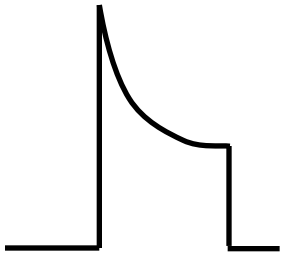


P. A. Bandettini et al, (2001) Nature Neuroscience, 4: 864-866.

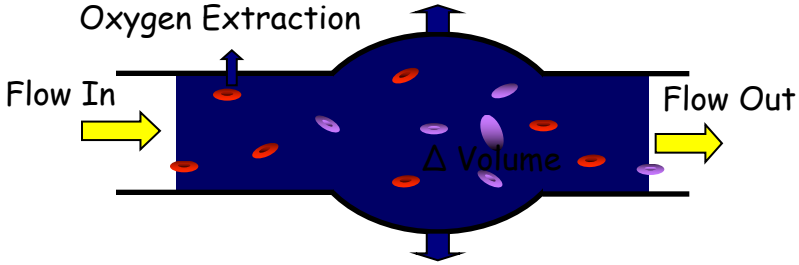
R. M. Birn, et. al, (2001) NeuroImage, 14: 817-826.

Sources of this Nonlinearity

- Neuronal

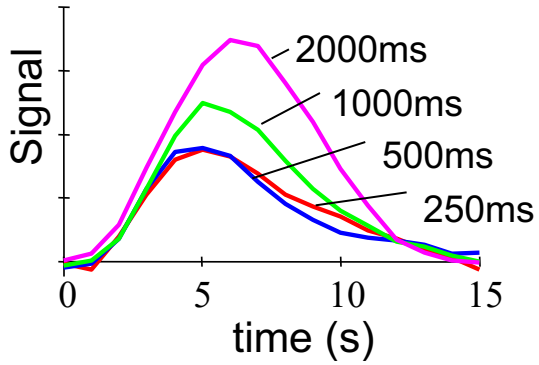


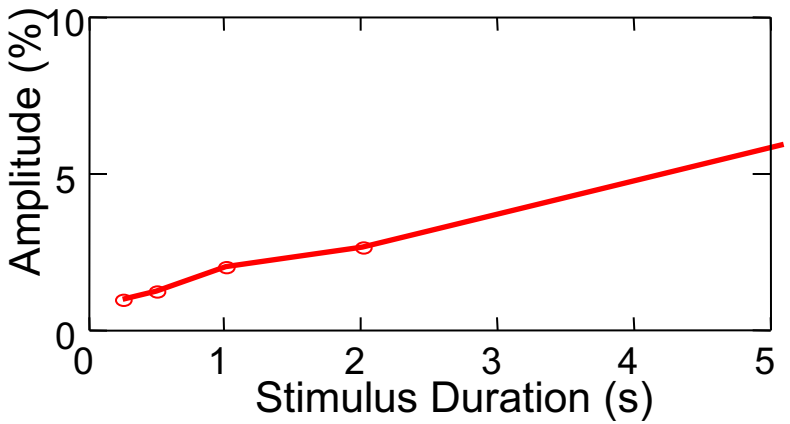
- Hemodynamic
  - -Oxygen extraction
  - -Blood volume dynamics



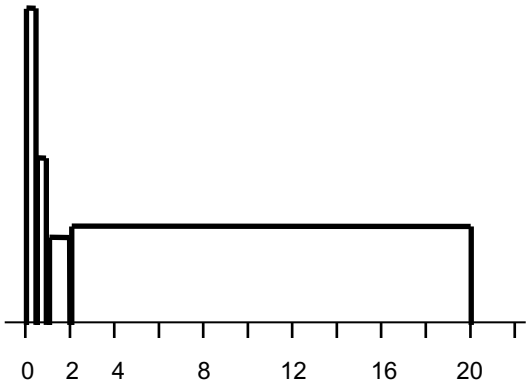
Linearity

Contrast Reversing Checkerboard



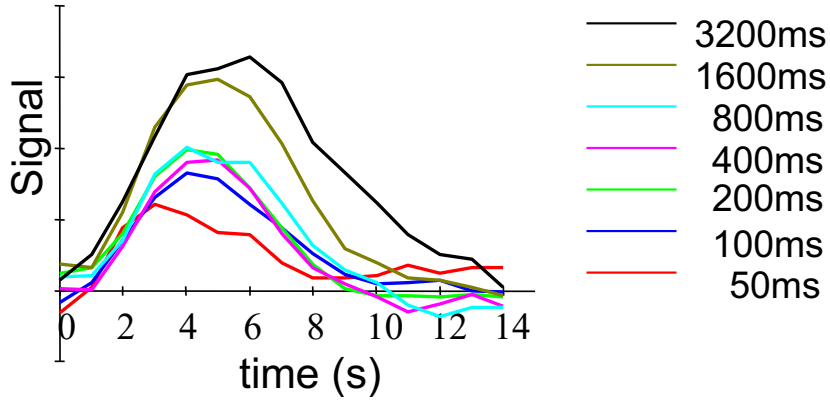


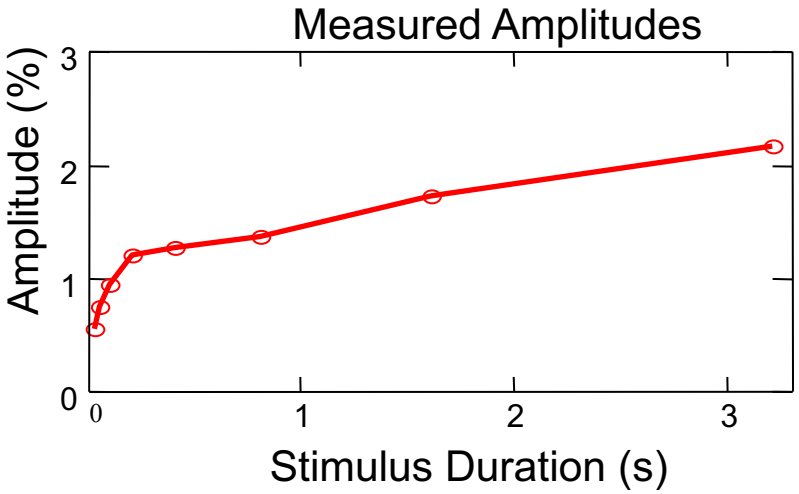
Estimated Neuronal Activity

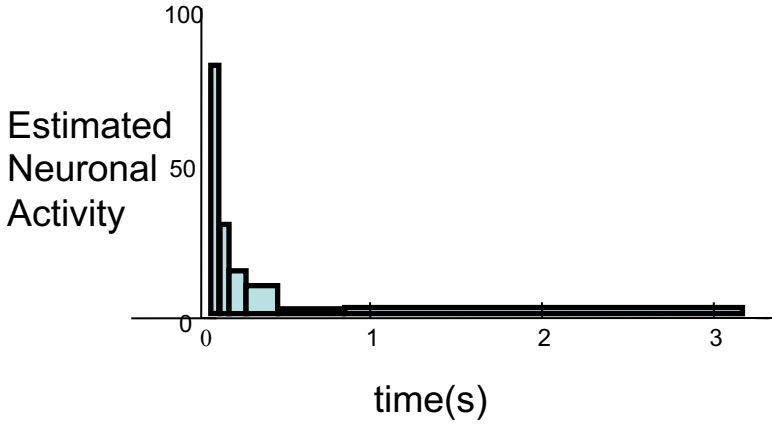


Linearity

Static Grating

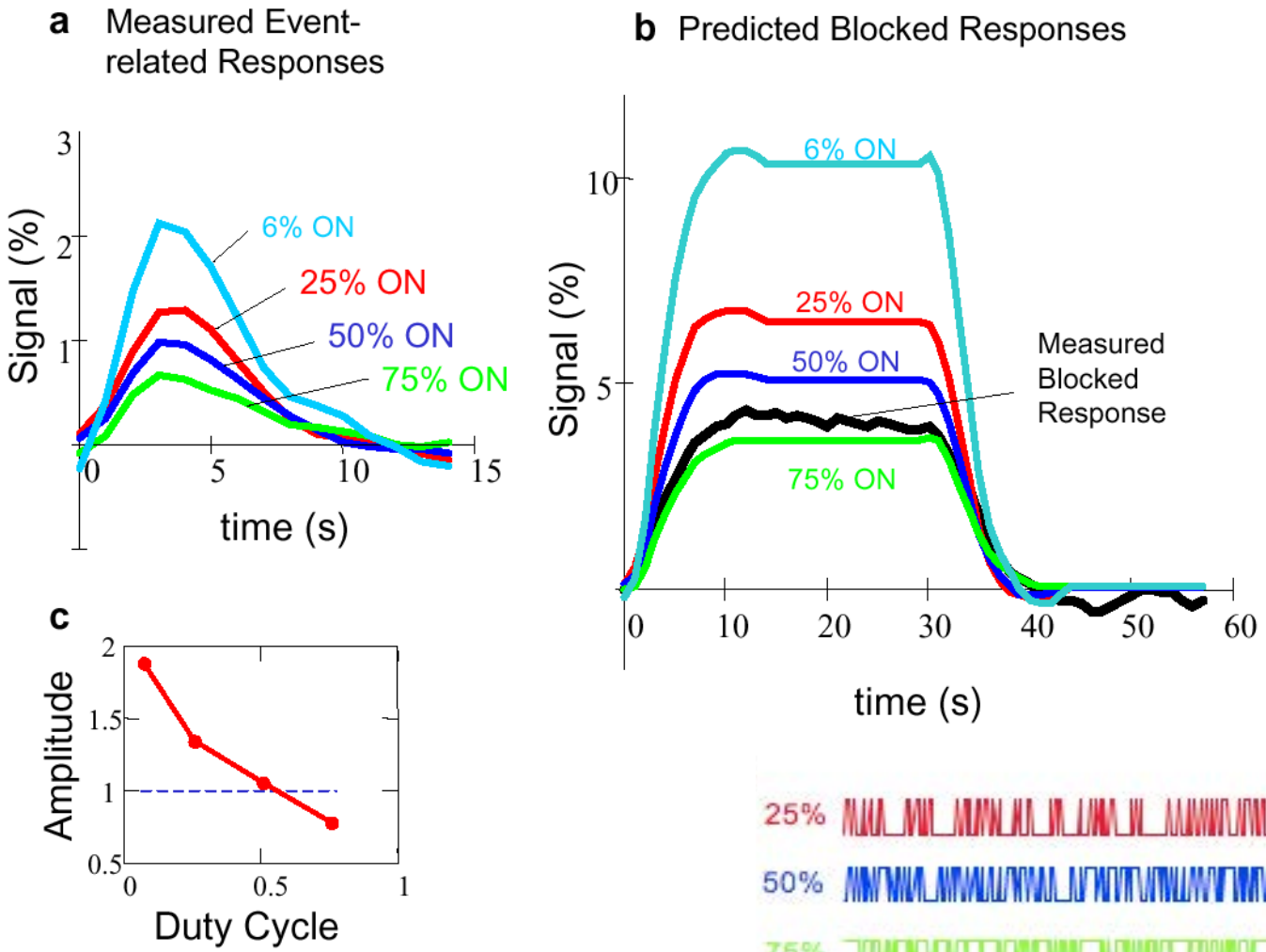






Linearity

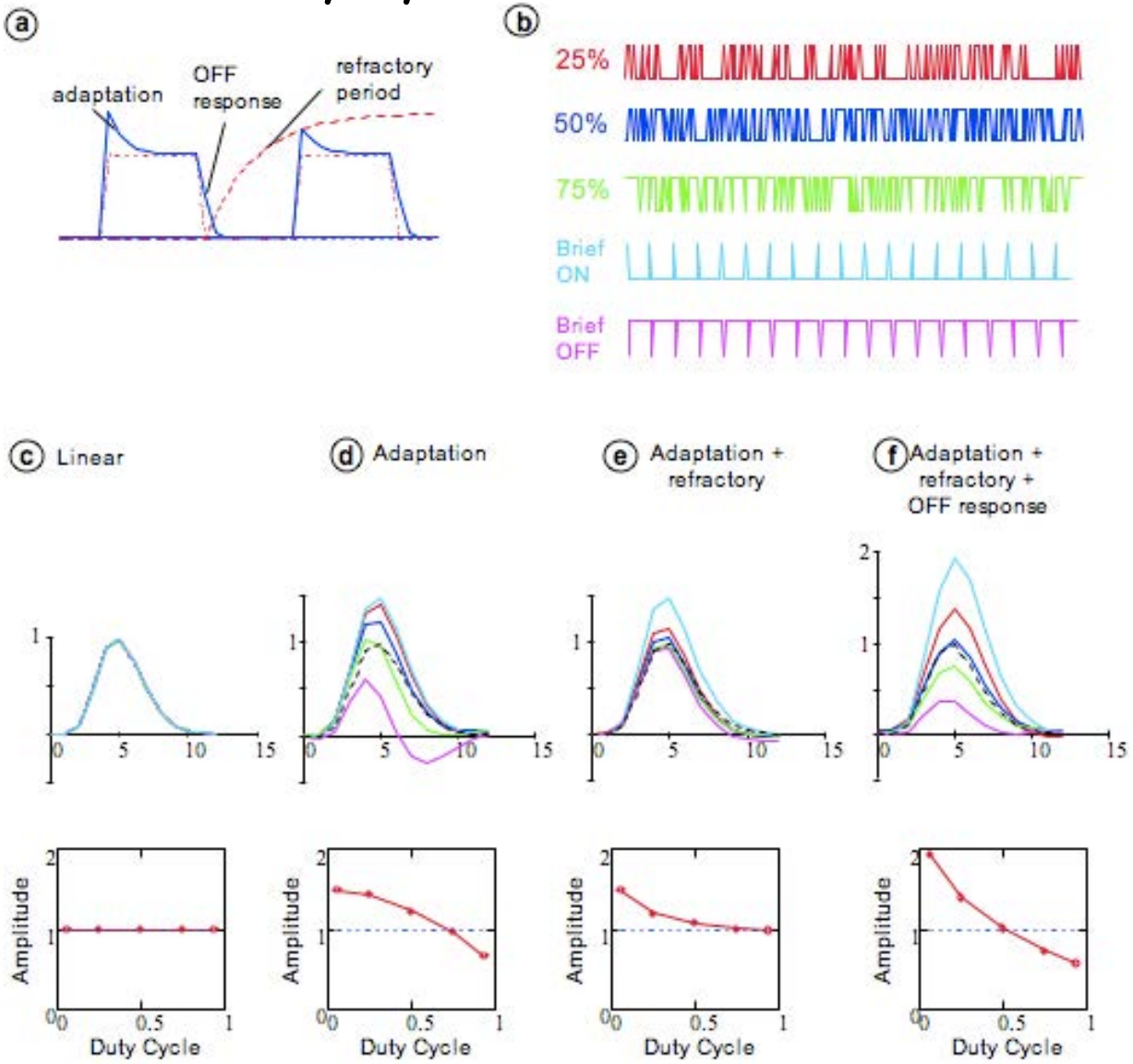
Duty Cycle Effects



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

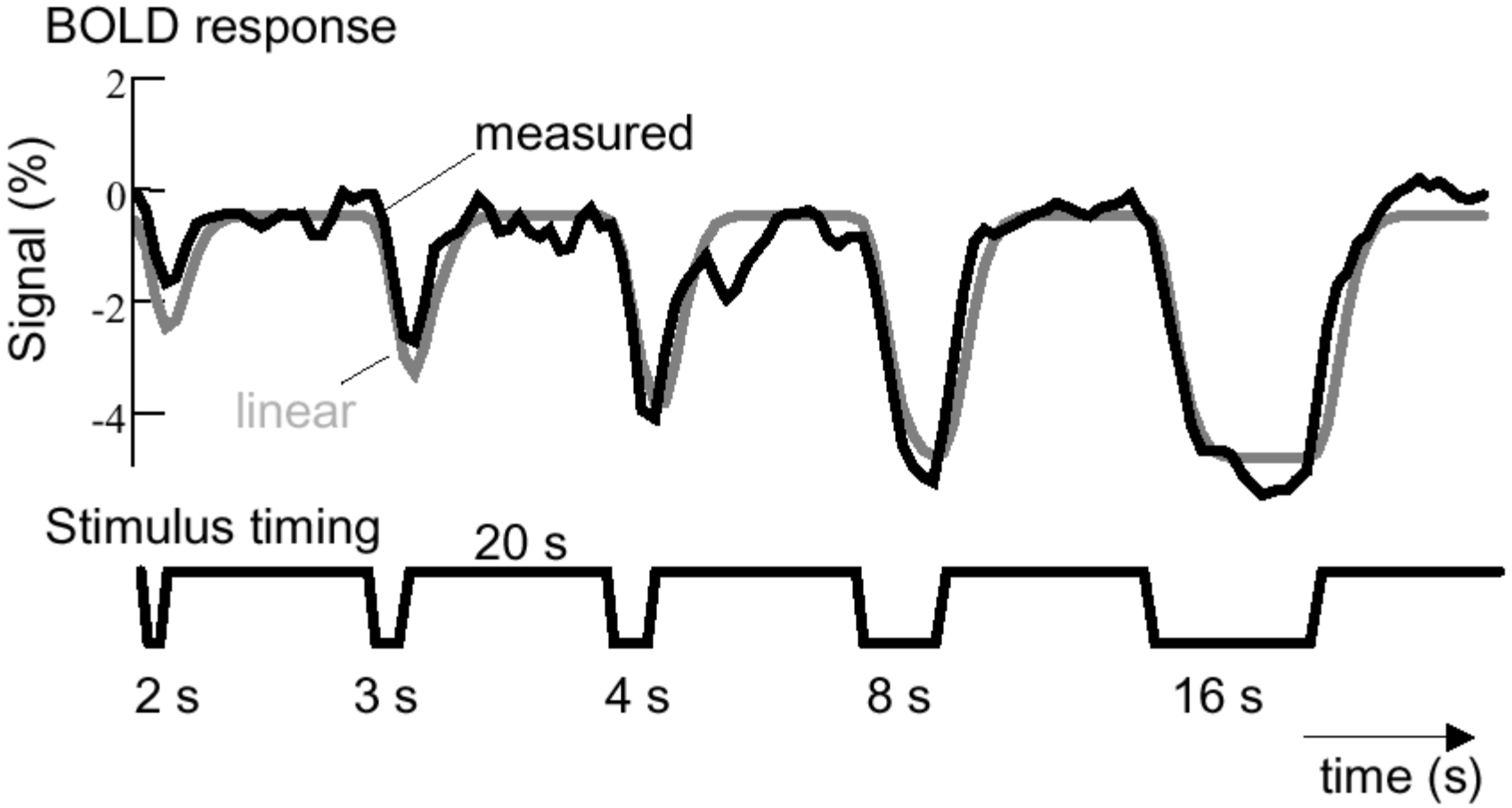
Linearity

duty cycle effects



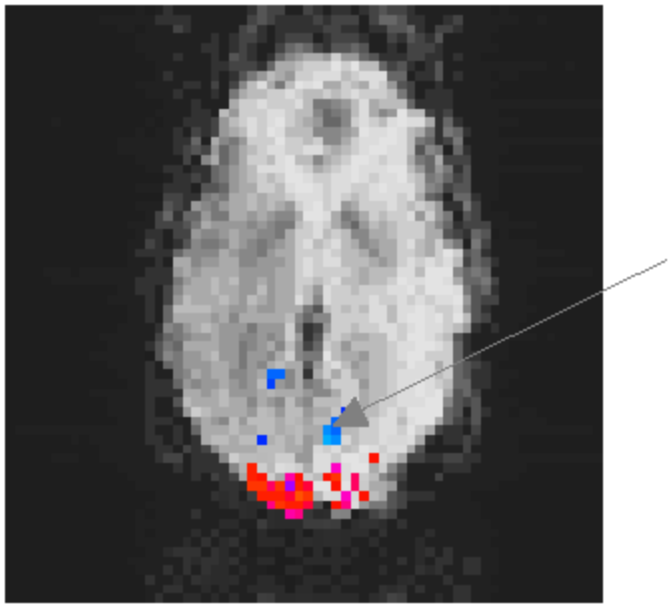
R.M. Birn, et al, NeuroImage, 27, 70-82 (2005)

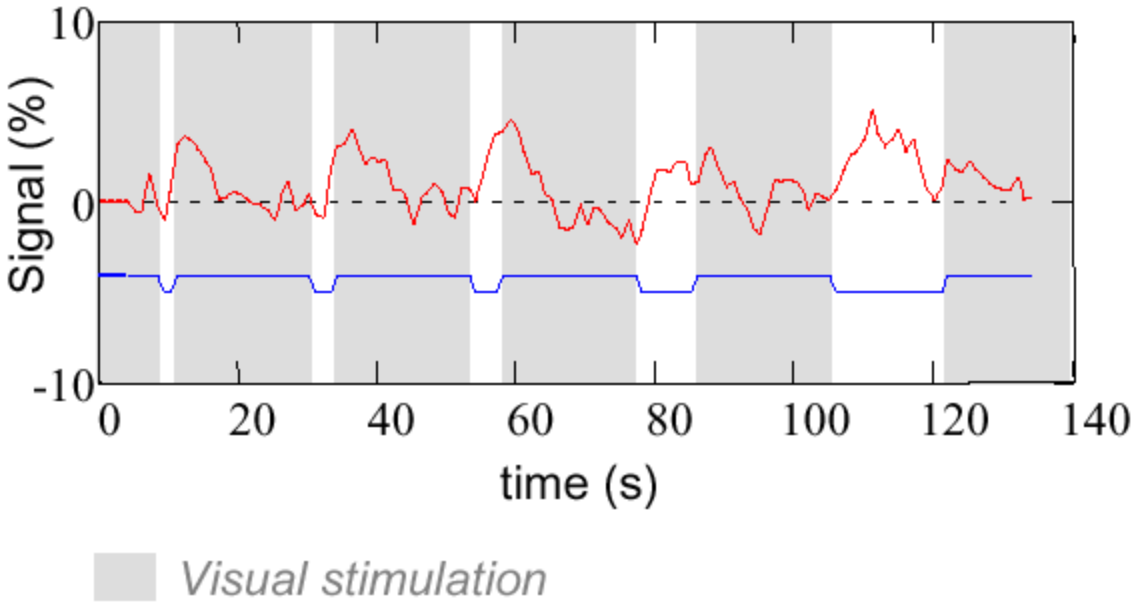
Decreases: linearity



Linearity

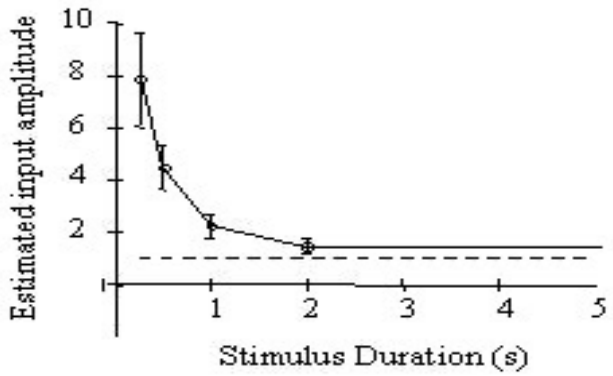
We also see increases during stimulus cessation...



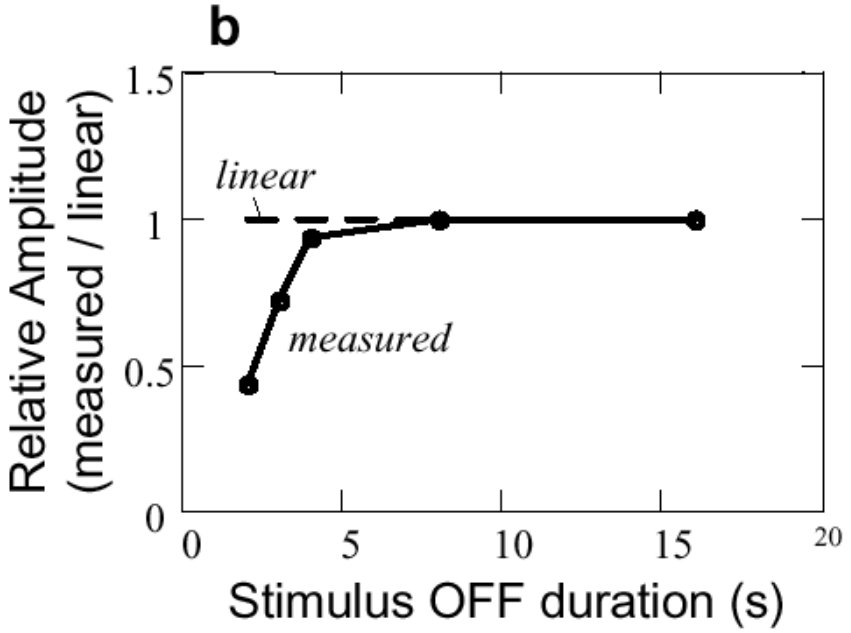


Linearity

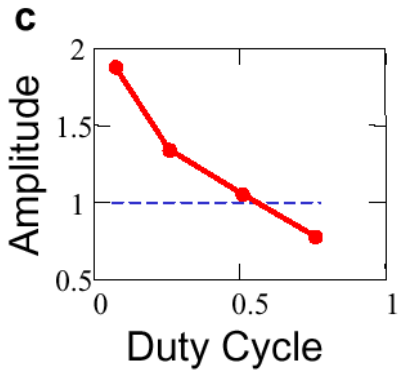
Increase: duration on



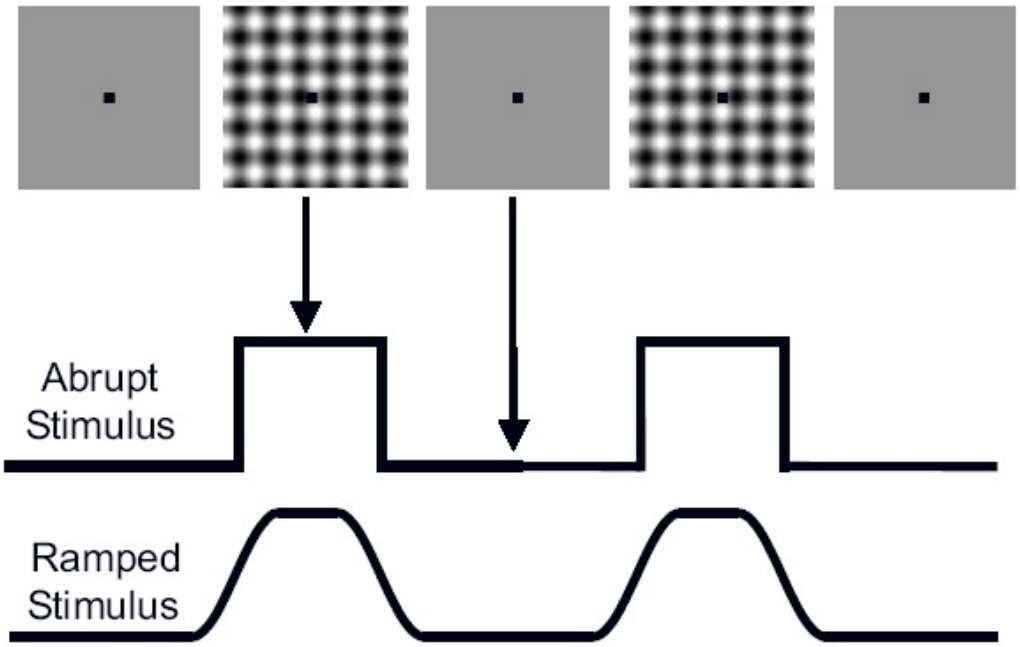
Decrease: duration off

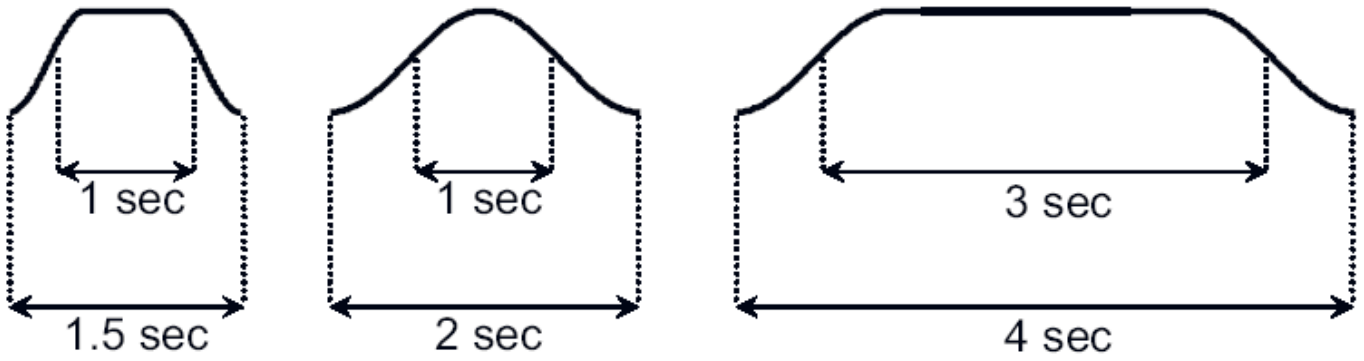


Increase: duty cycle

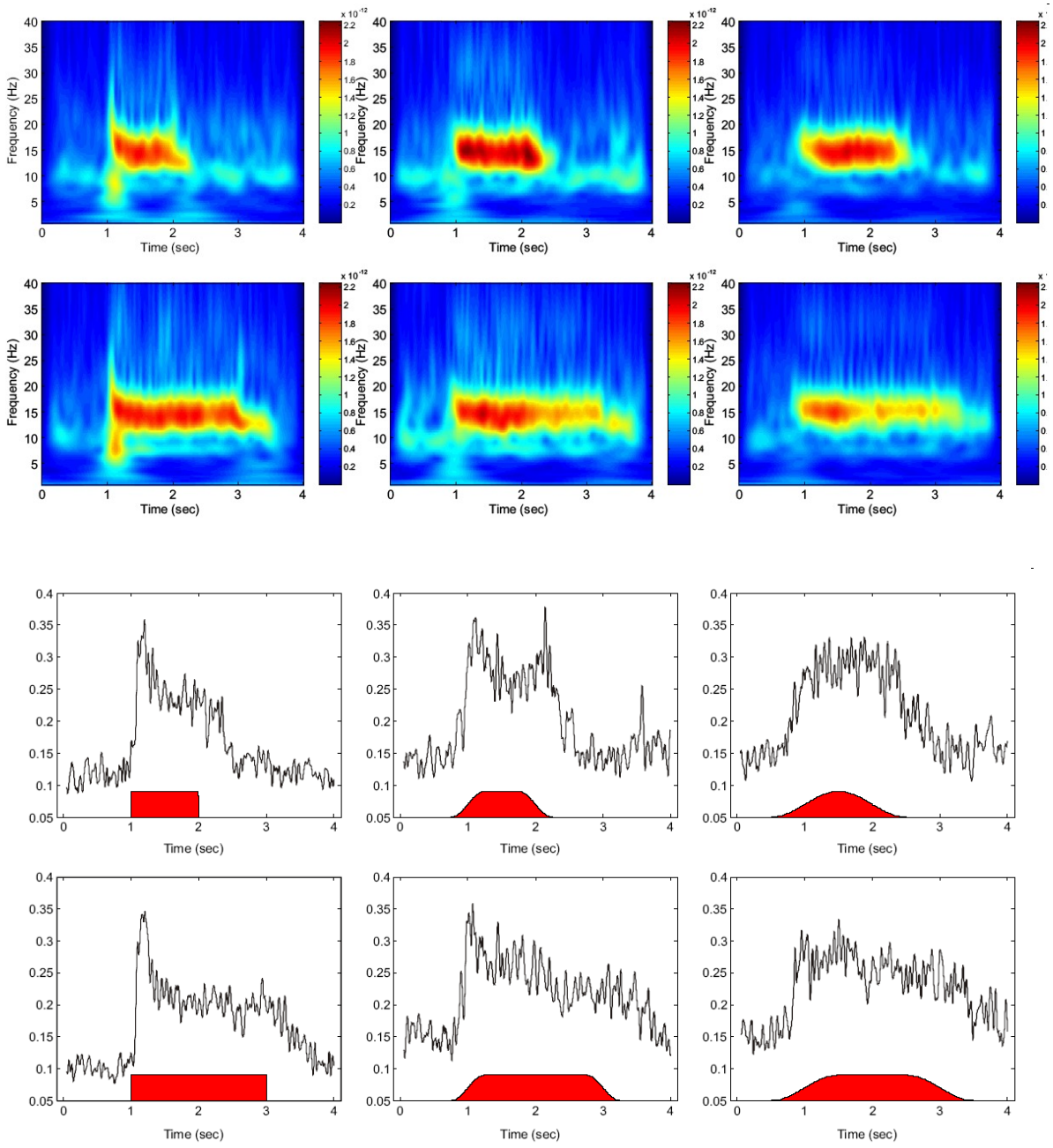


Linearity


Abrupt
Stimulus
Ramped
Stimulus

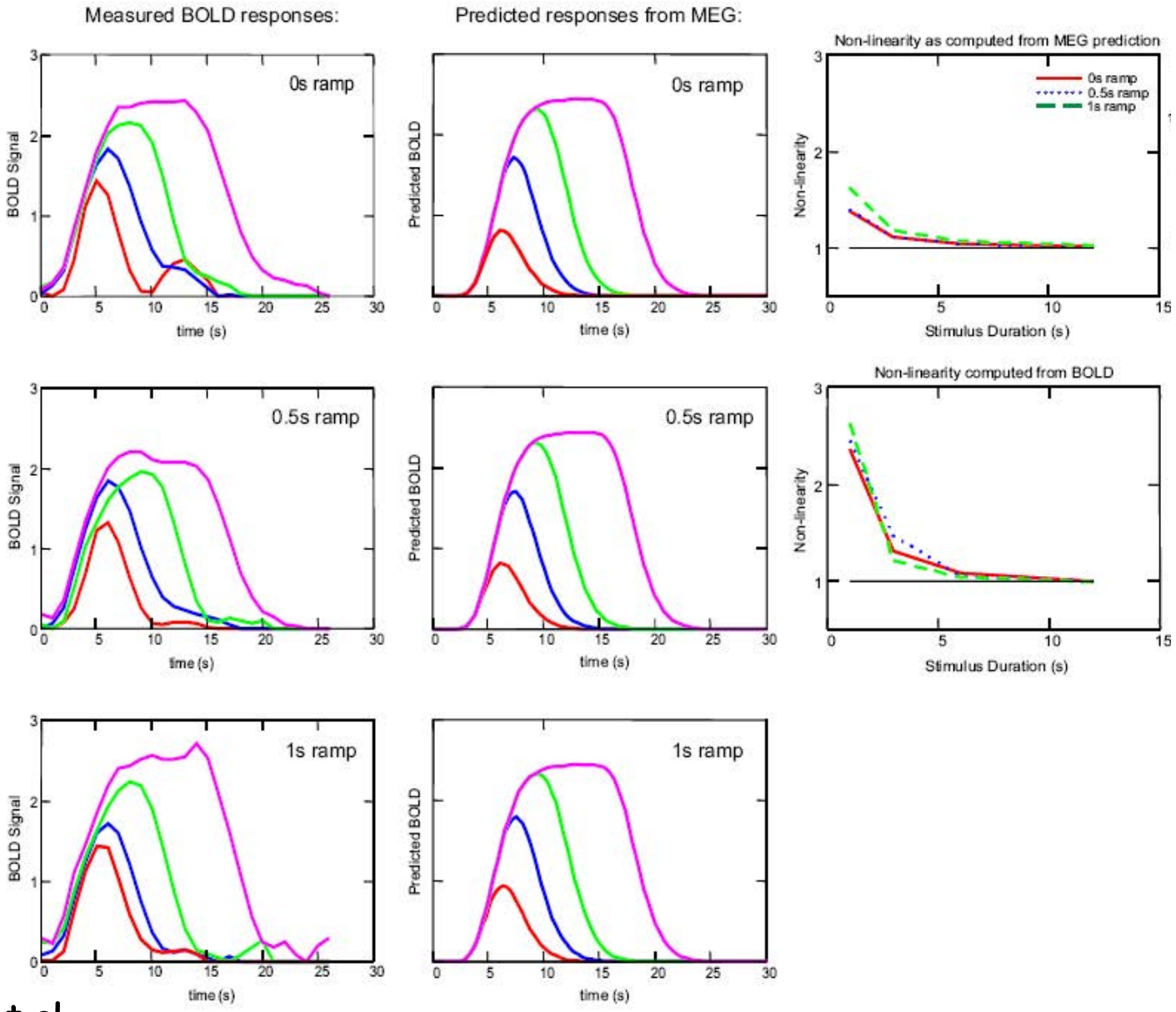

1 sec
1.5 sec
1 sec
2 sec
3 sec
4 sec

Linearity



Tuan, Birn et al.

Linearity



Tuan, Birn et al.

Towards a better understanding and utility of fMRI dynamics and fluctuations

Dynamics

- Linearity
- Latency

Fluctuations

- Resting state
- Respiration related
- Time series improvement
- Respiration Response Function

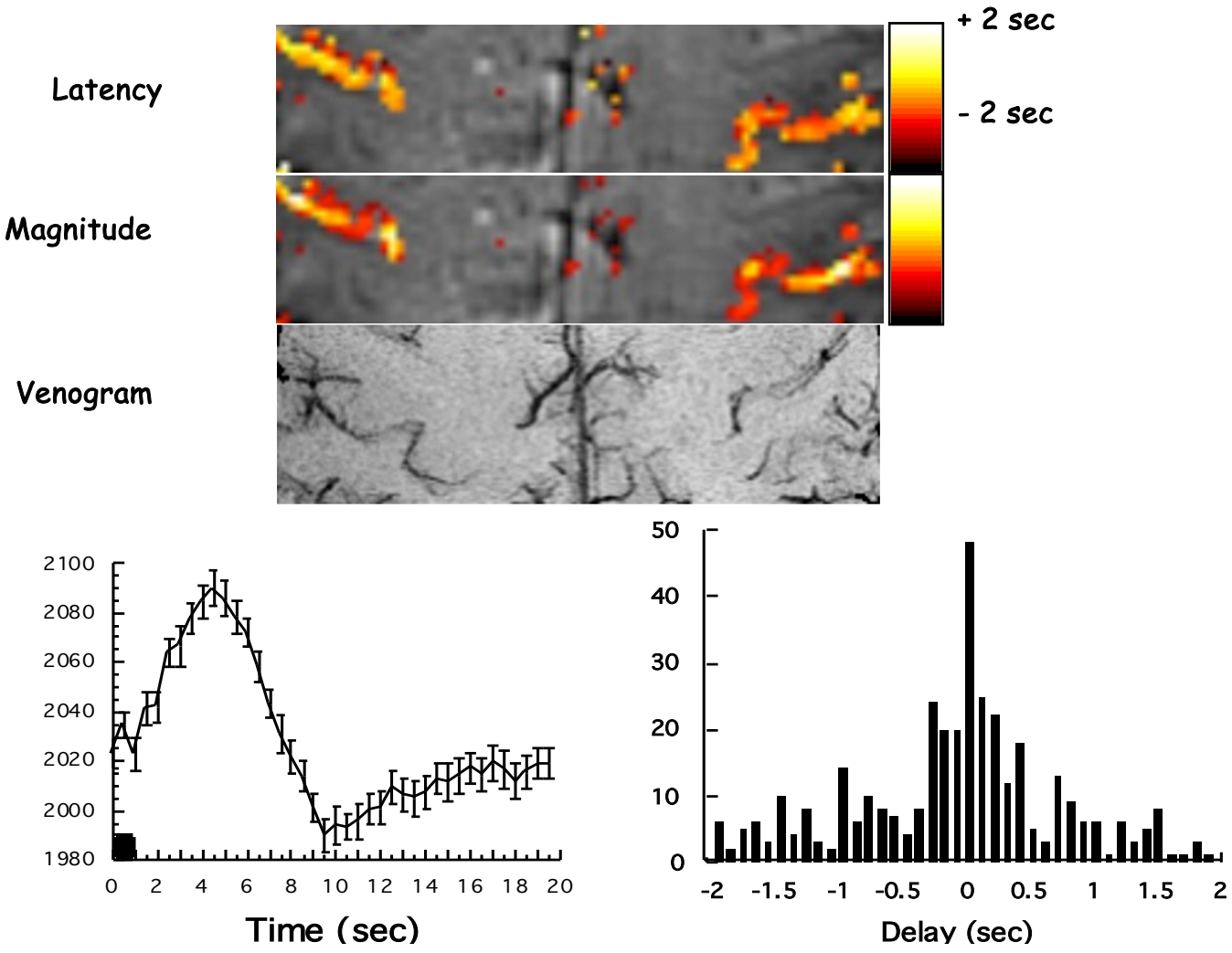
High Resolution

Finding the "Suggested resolution"

What to do with high resolution data?

Latency

Latency Variation…



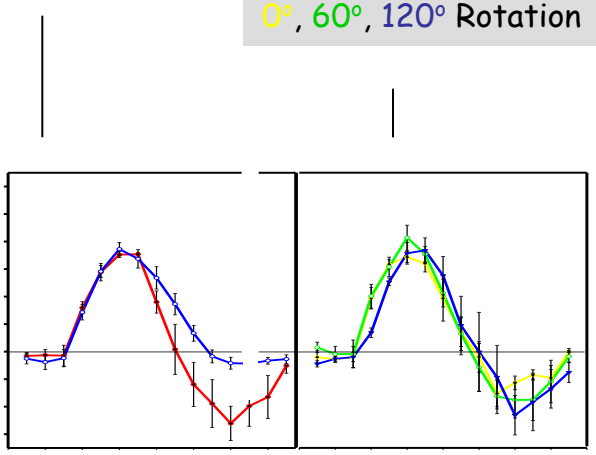
P. A. Bandettini, (1999) "Functional MRI" 205-220.

Latency

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

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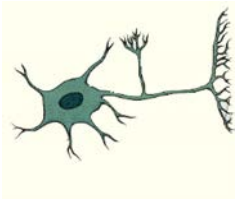
What to do with high resolution data?

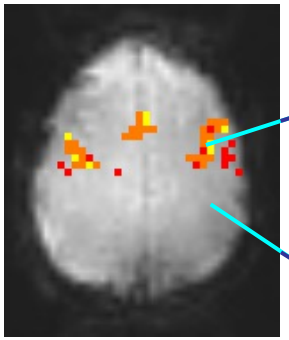
The fMRI Signal

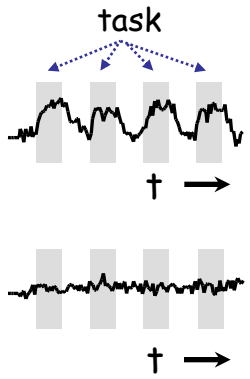
Task-related Neuronal Activity



Spontaneous Neuronal Activity

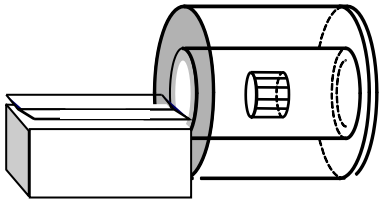
Hemodynamics





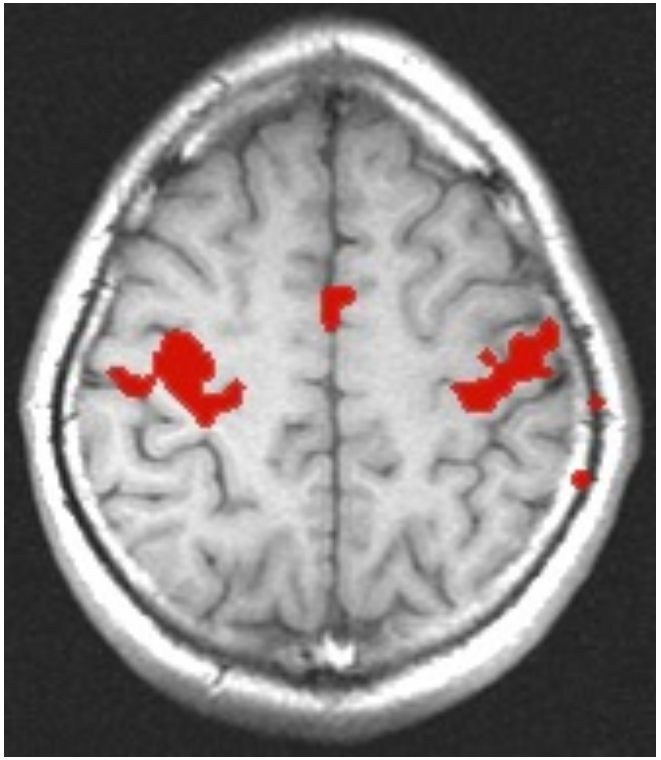
Thermal noise, Artifacts

Physiologic noise (cardiac, respiration)

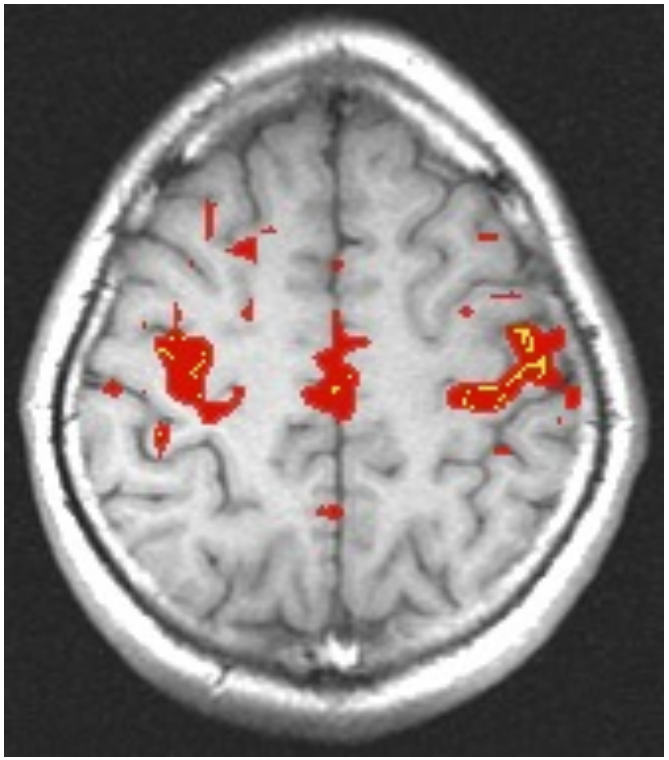


Resting State

Resting State Correlations



Activation:
correlation with reference function



Rest:
seed voxel in motor cortex

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

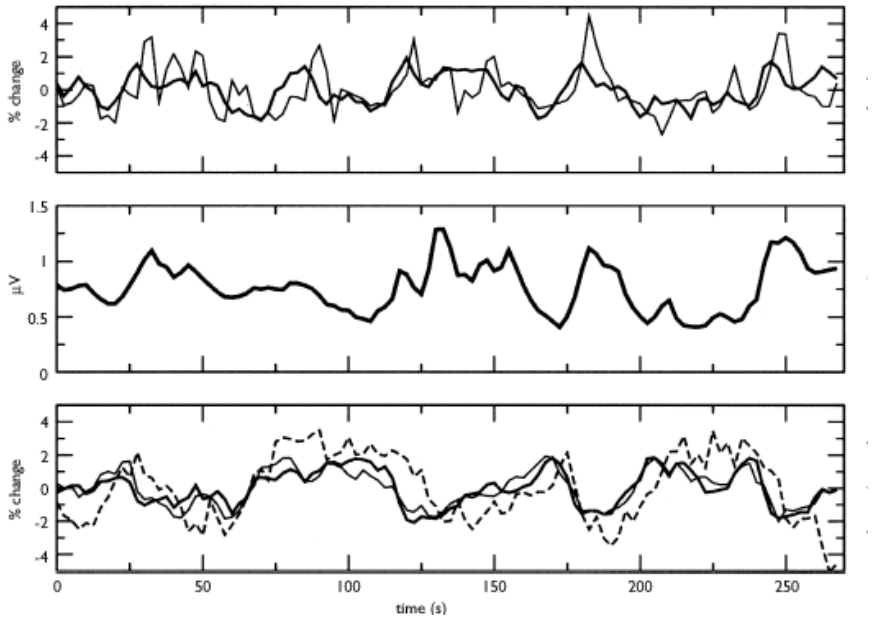
Resting State

BOLD correlated with 10 Hz power during "Rest"

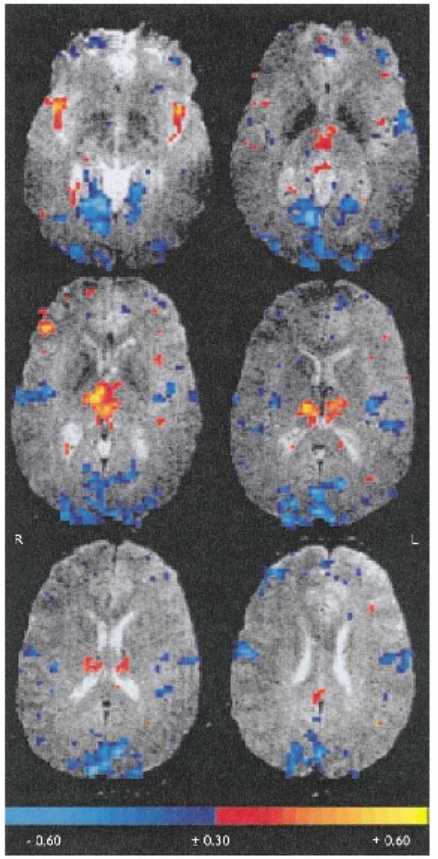
Positive

10 Hz power

Negative

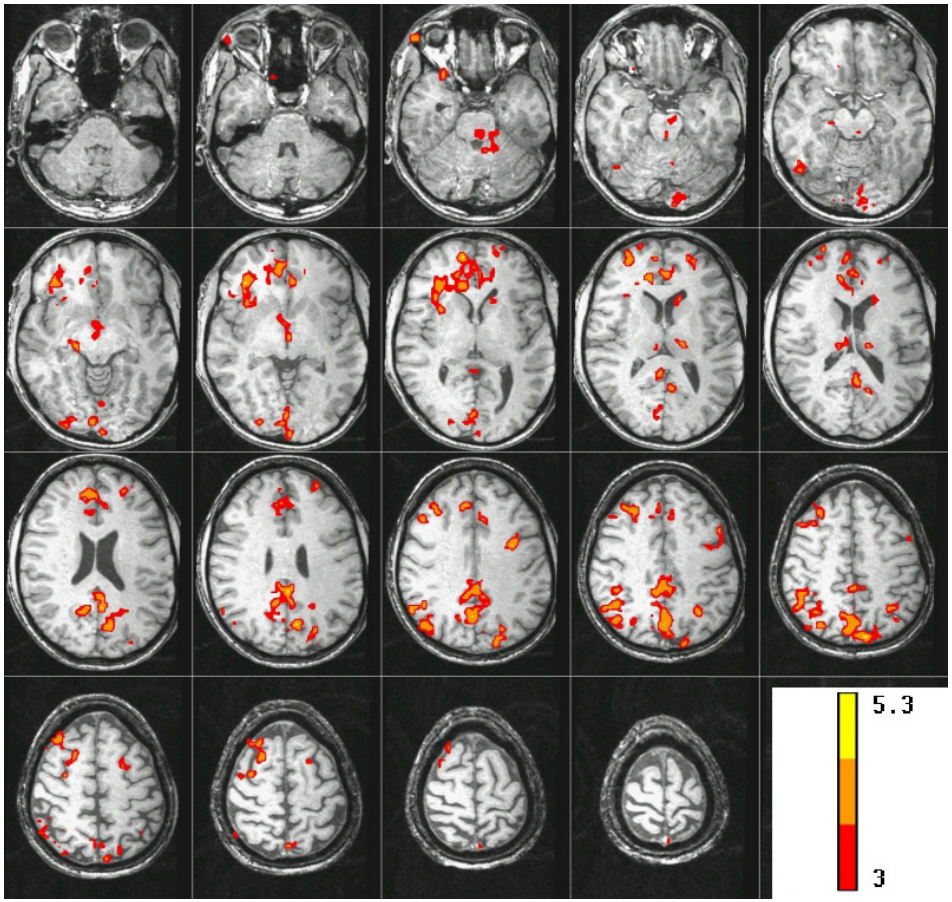


Goldman, et al (2002), Neuroreport



Resting State

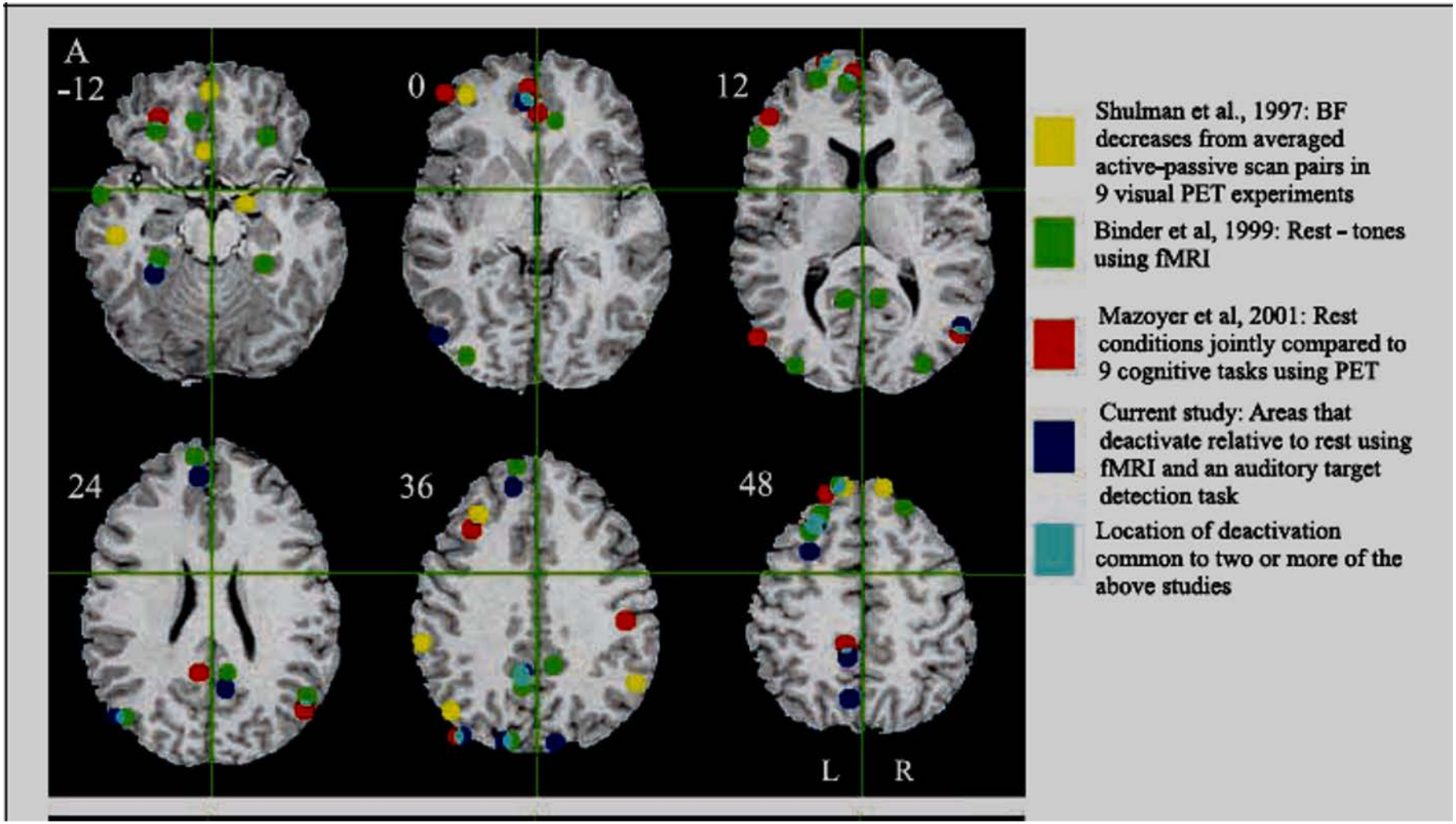
BOLD correlated with SCR during "Rest"



J. C. Patterson II, L. G. Ungerleider, and P. A Bandettini,
NeuroImage 17: 1787-1806, (2002).

Resting State

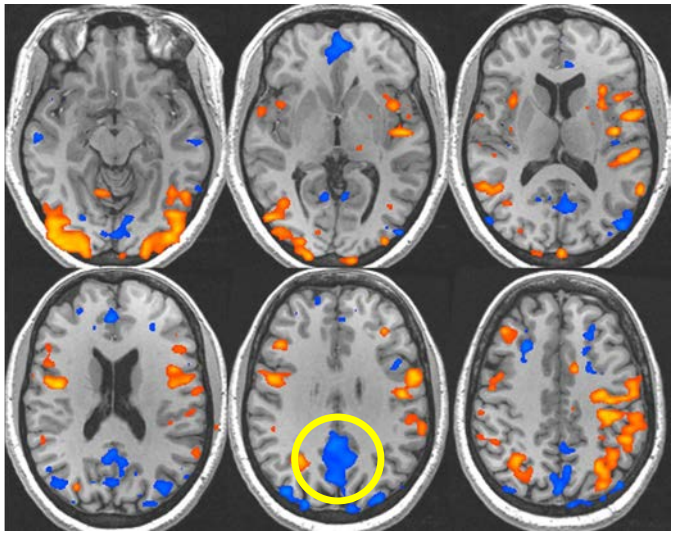
Regions showing decreases during cognitive tasks



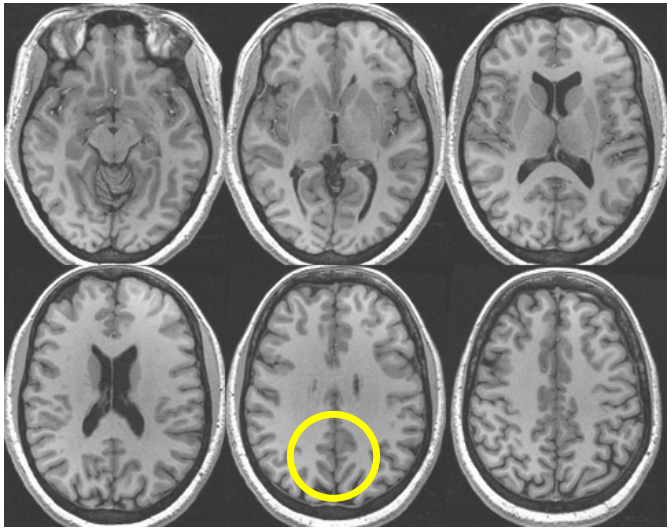
McKiernan, et al (2003), Journ. of Cog. Neurosci. 15 (3), 394-408

Resting State Correlations vs Signal Decreases

- Filter (respiration (0.3Hz), cardiac (1 Hz))
- Define ROI (e.g. deactivations in posterior cingulate)
- Average time courses (at rest) in ROI
- Correlate average time course with all voxels



Lexical task



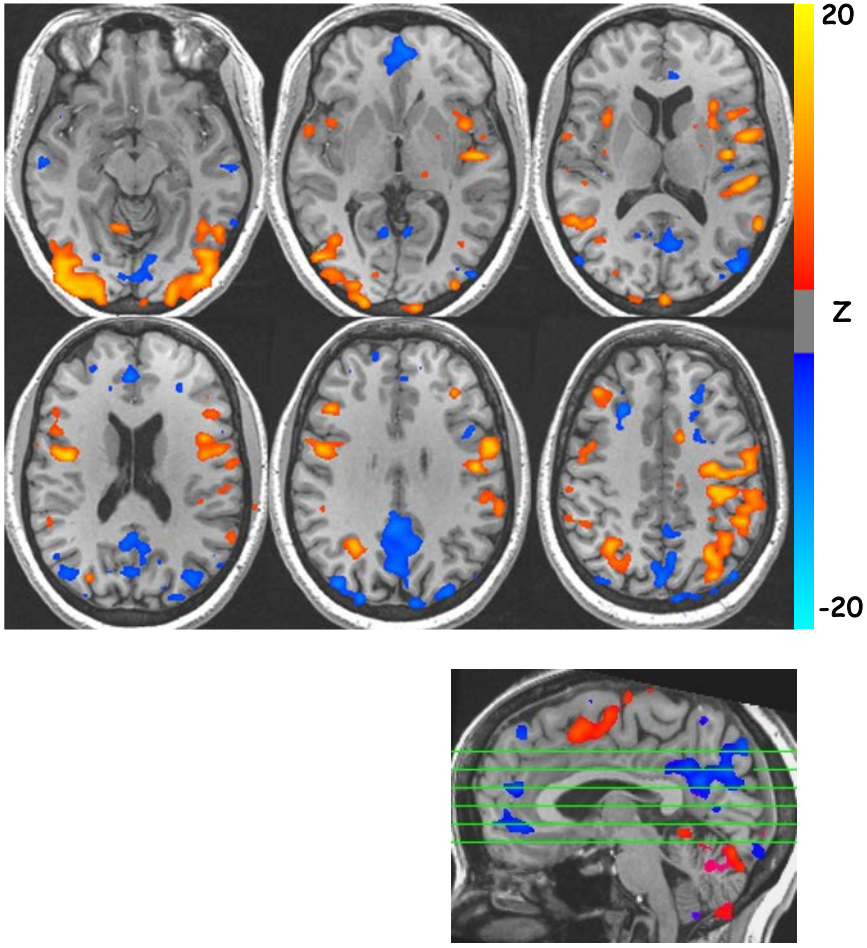
Rest

R. M. Birn, J. B. Diamond, M. A. Smith, P. A. Bandettini, Separating respiratory variation-related fluctuations from neuronal activity-related fluctuations in fMRI, NeuroImage 31, 1536-1548 (2006)

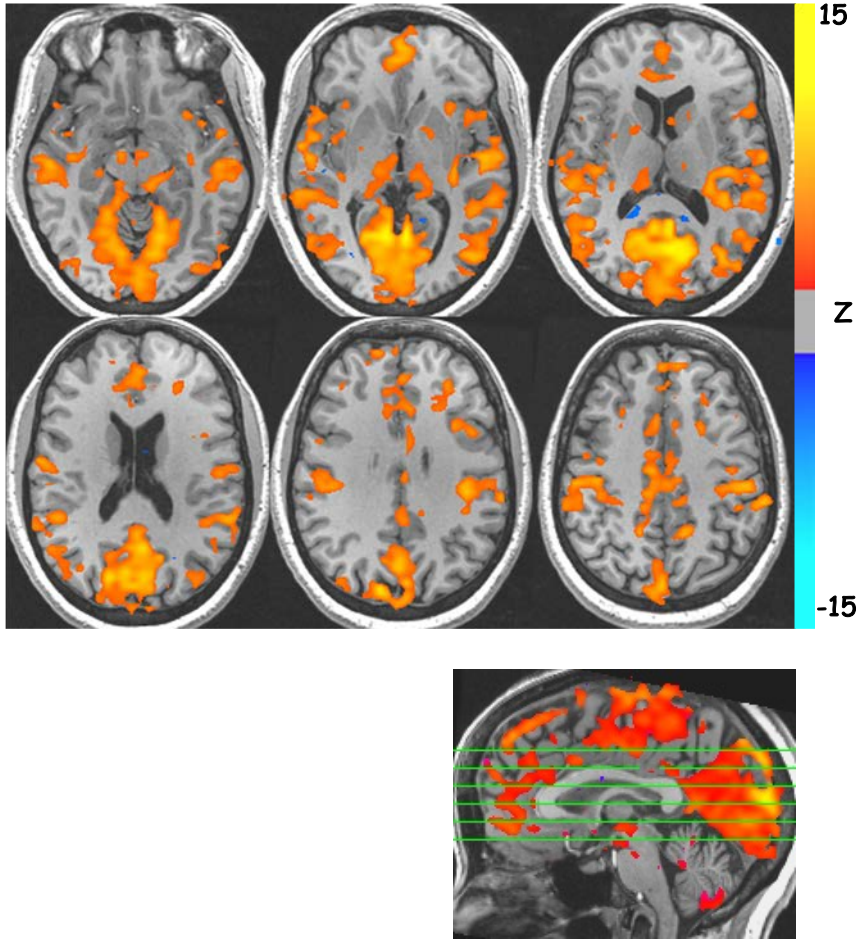
Resting State

1 subject

Activations during lexical task



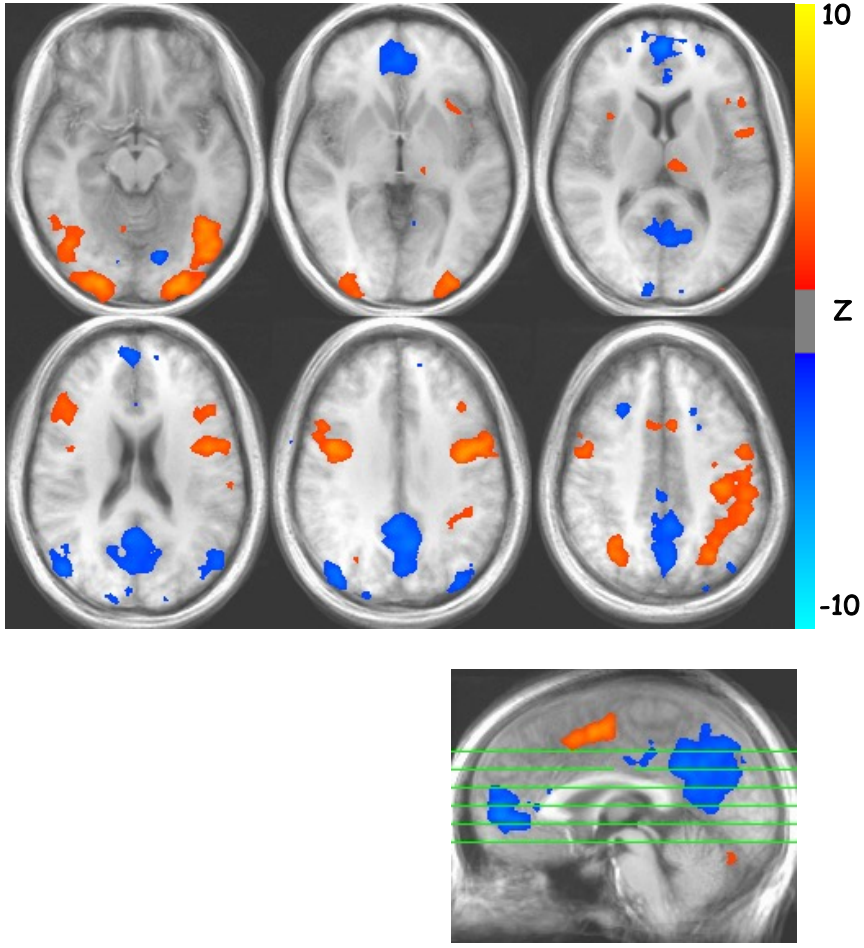
Correlation (of PC) at Rest



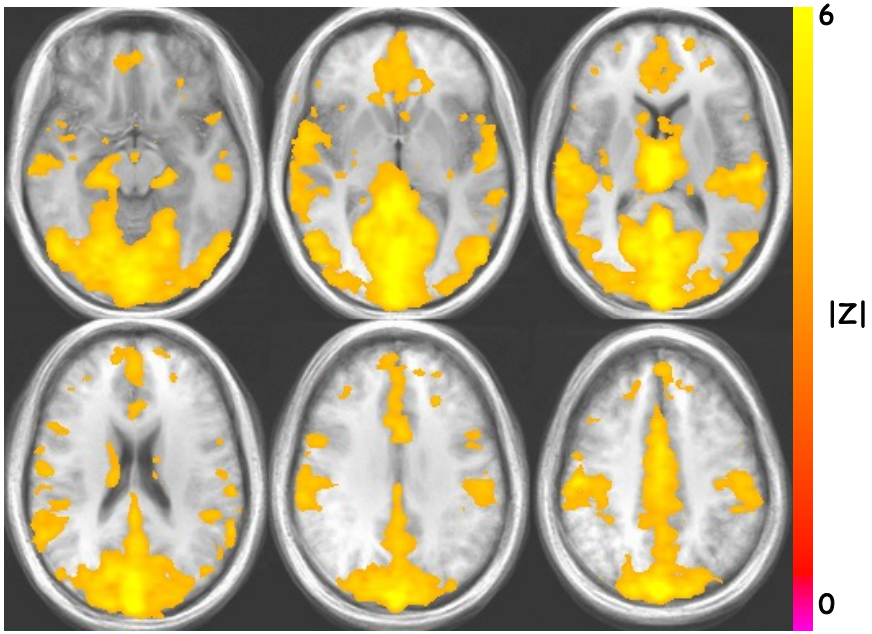
Resting State

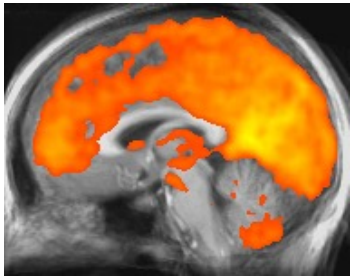
Group (n=10)

Activations during lexical task



Correlation (of PC) at Rest





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High Resolution

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What to do with high resolution data?

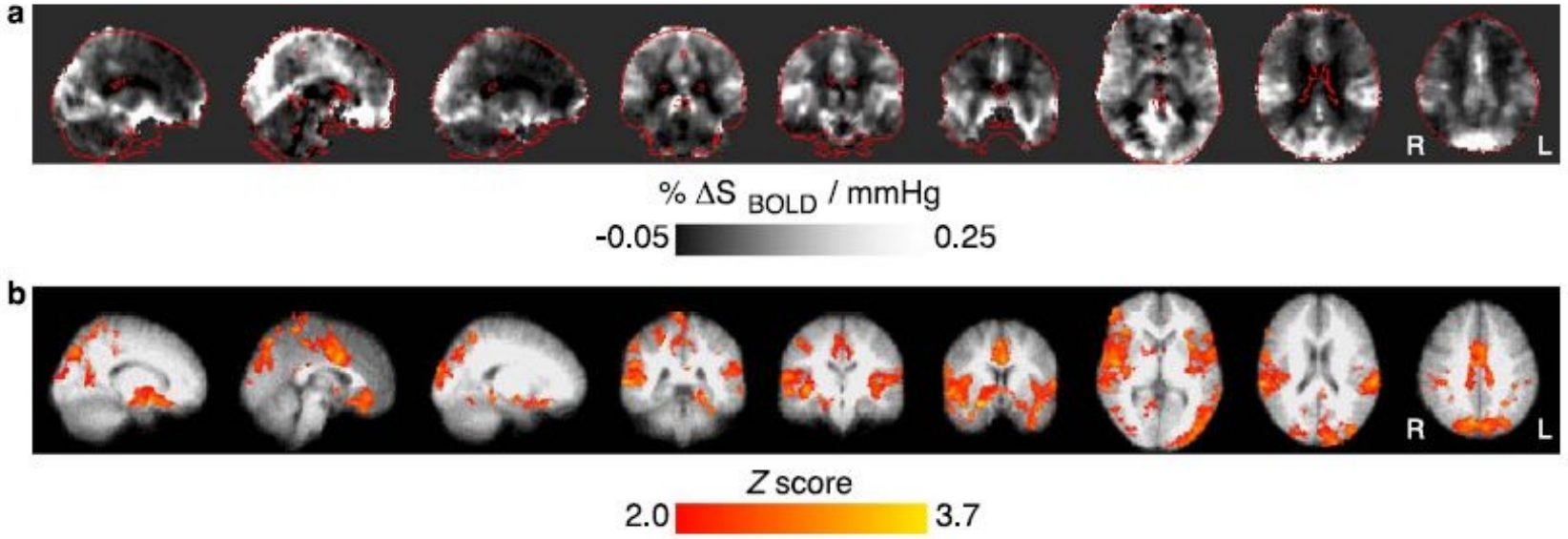
Respiration related

Resting fluctuations in respiration

Resting fluctuations in arterial carbon dioxide induce significant low frequency variations in BOLD signal

Richard G. Wise,[a,b,*] Kojiro Ide,[c,d] Marc J. Poulin,[c,d] and Irene Tracey[a,b]

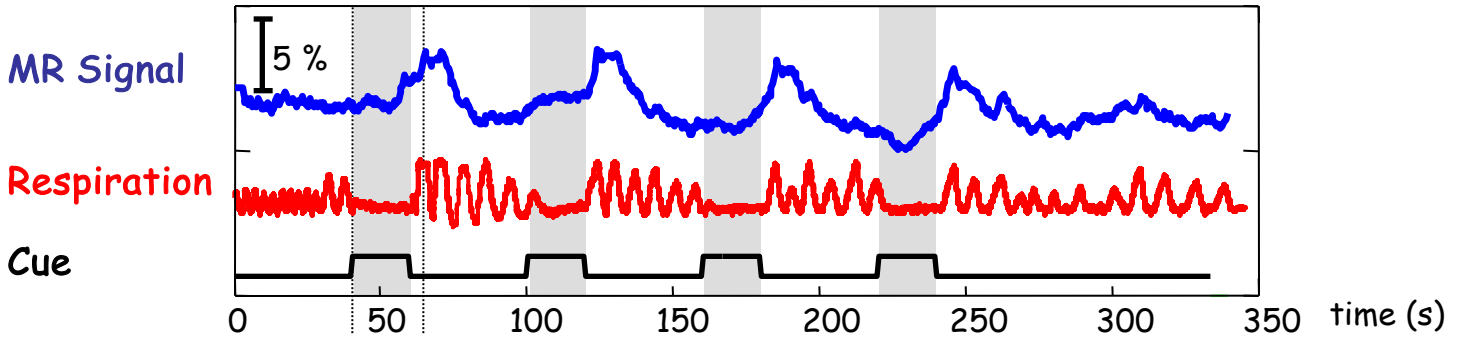
NeuroImage 21, 2004



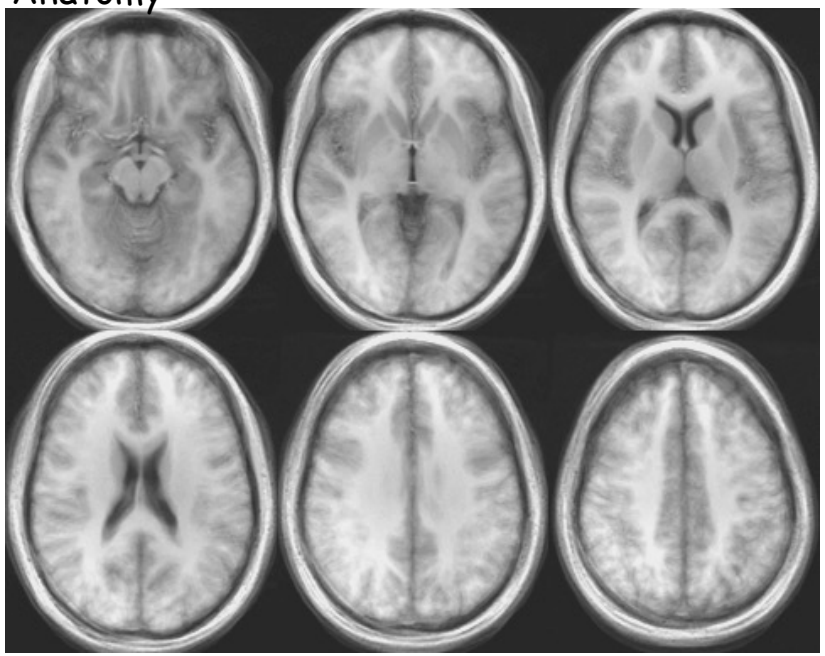
Respiration related

Breath-holding

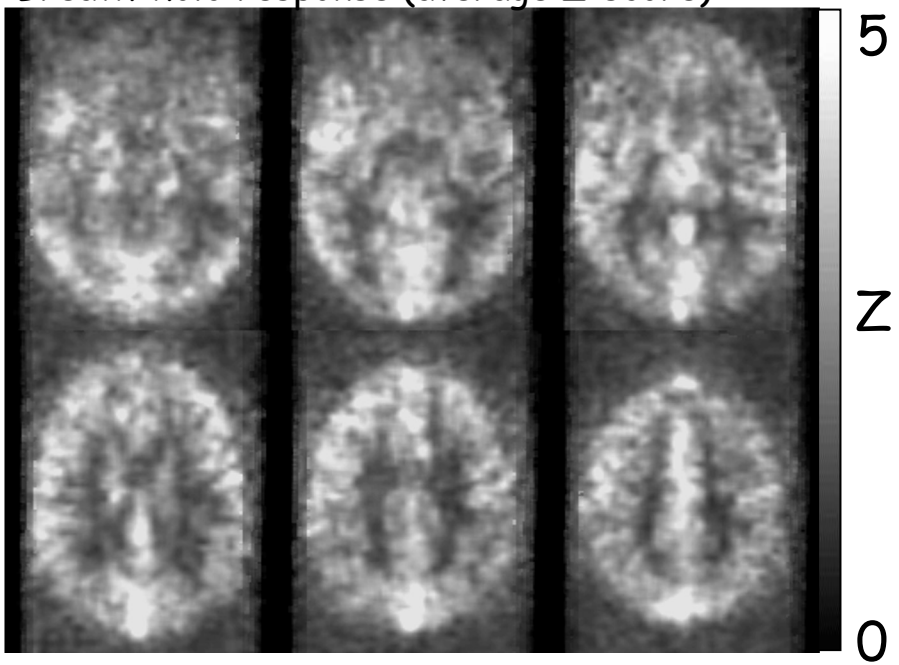
Group Maps (N = 7)



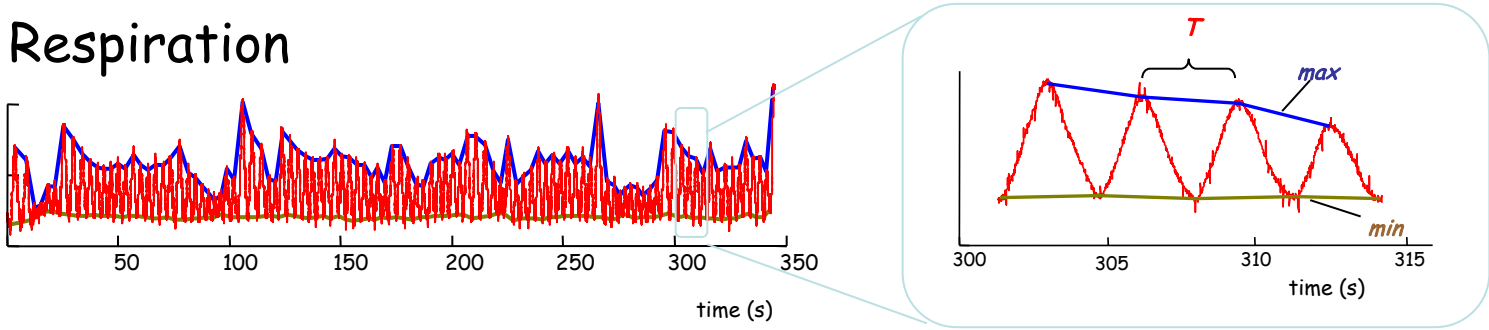
Anatomy



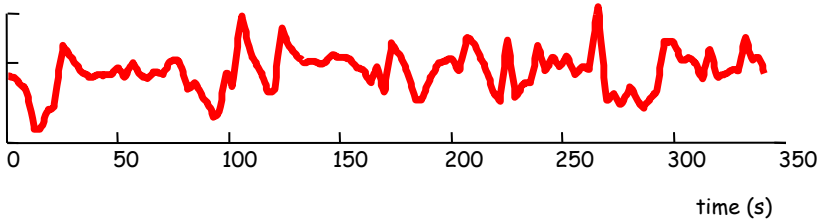
Breath-hold response (average Z-score)



Estimating respiration volume changes

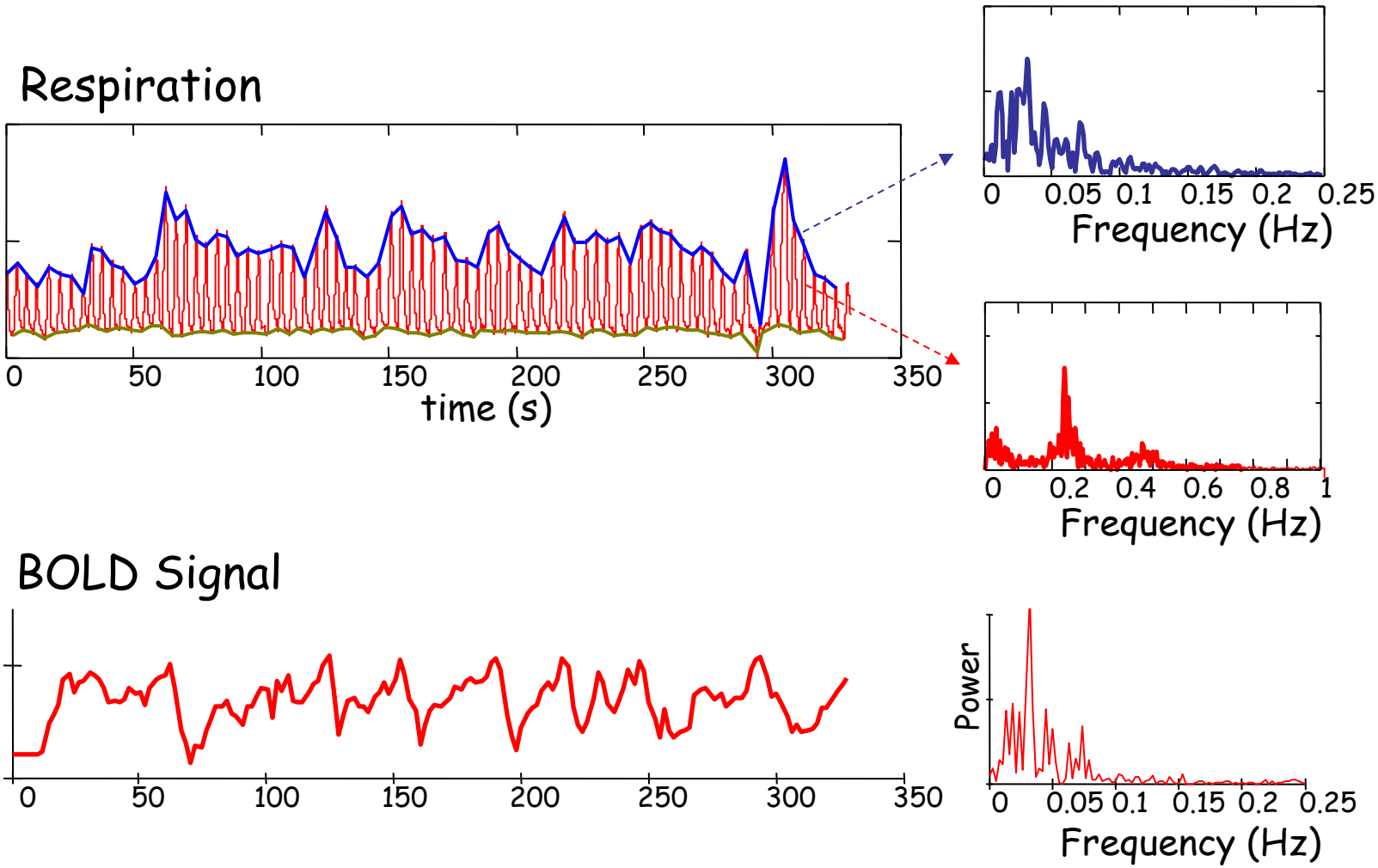


Respiration Volume / Time (RVT)



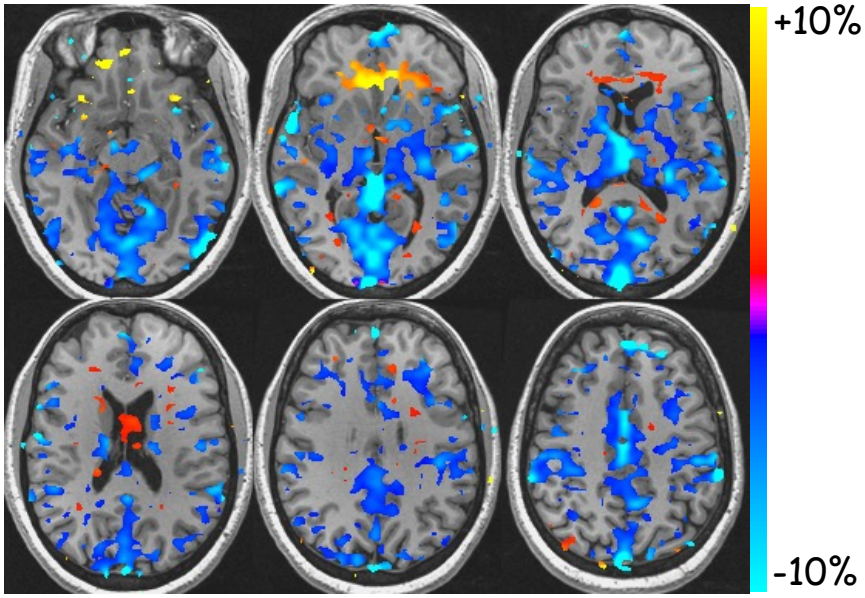
$$RVT = \frac{max - min}{T}$$

Resting fluctuations in respiration

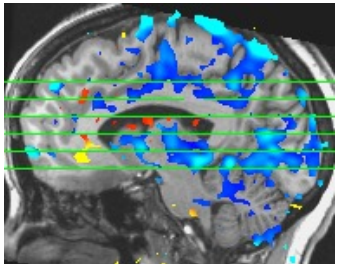


RVT related fluctuations

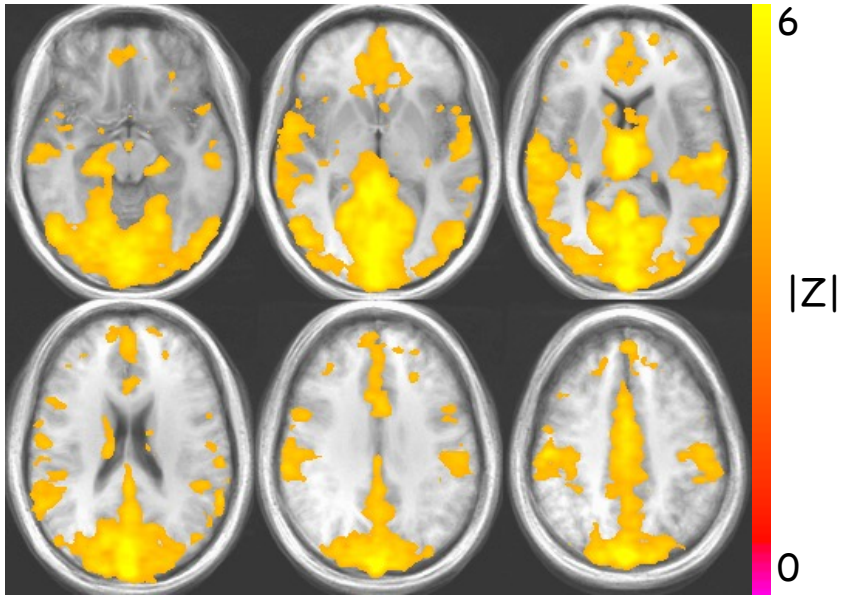
Amplitude of BOLD signal correlated w/ RVT



1 subject



Z-score of BOLD signal correlated w/ RVT



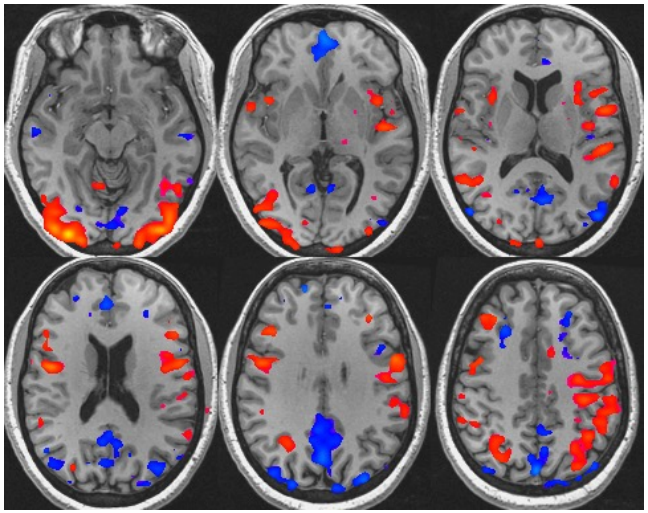
group (n=11)

RVT = Respiration Volume per Time

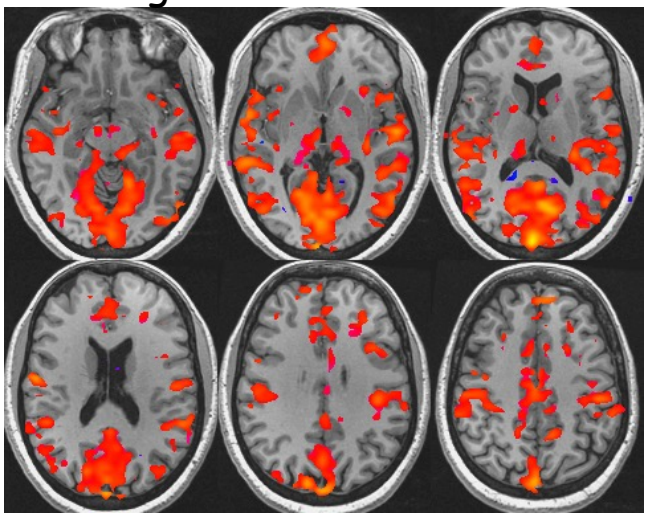
Respiration effects

RVT changes co-localize

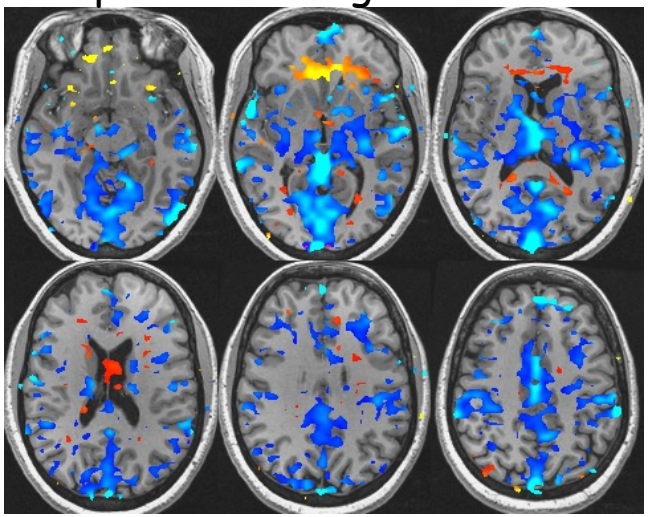
Deactivations

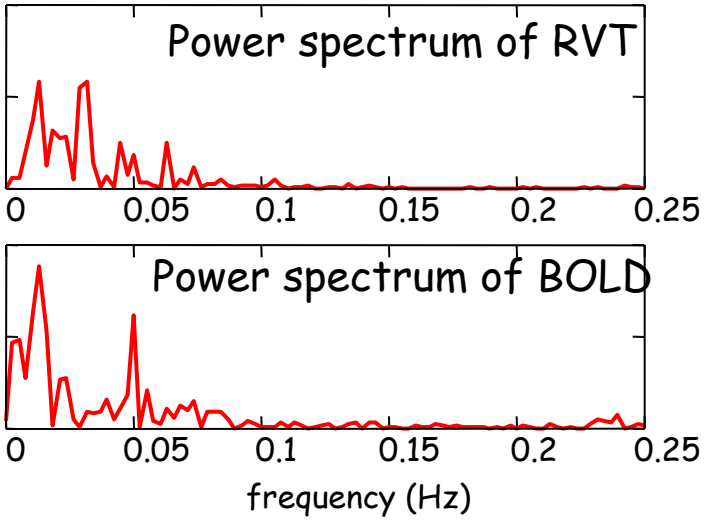


Resting-state corr. from seed ROI



Respiration changes – corr. w/ RVT

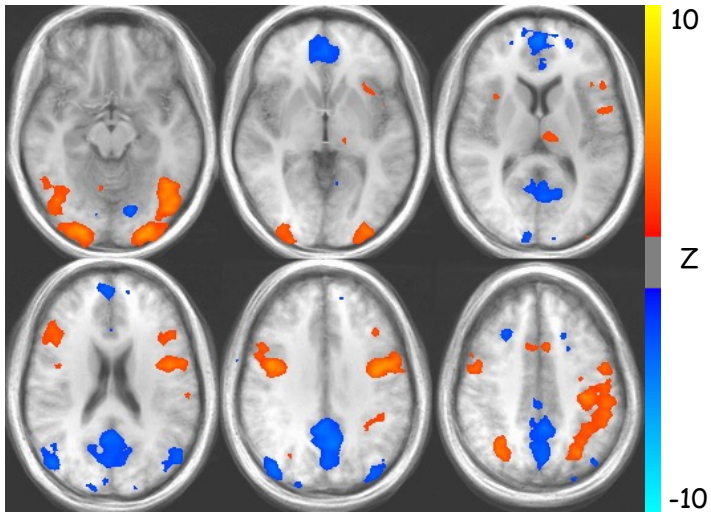




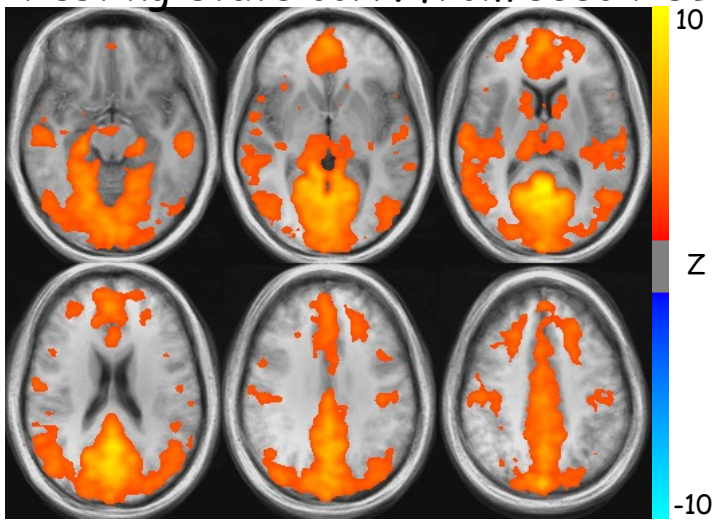
Respiration related

RVT changes co-localize

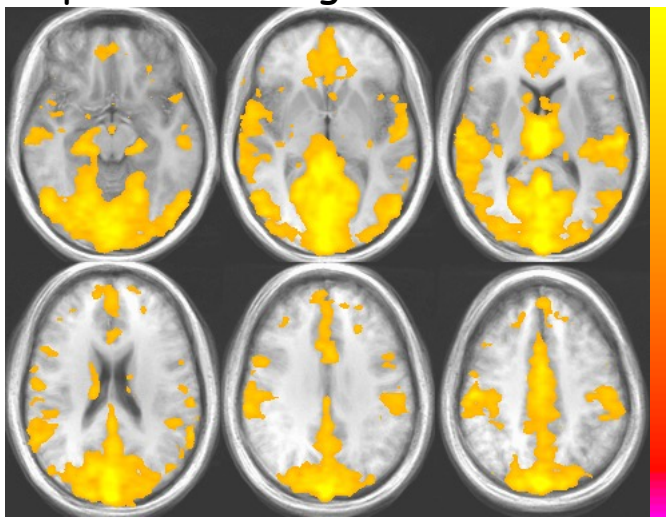
Deactivations

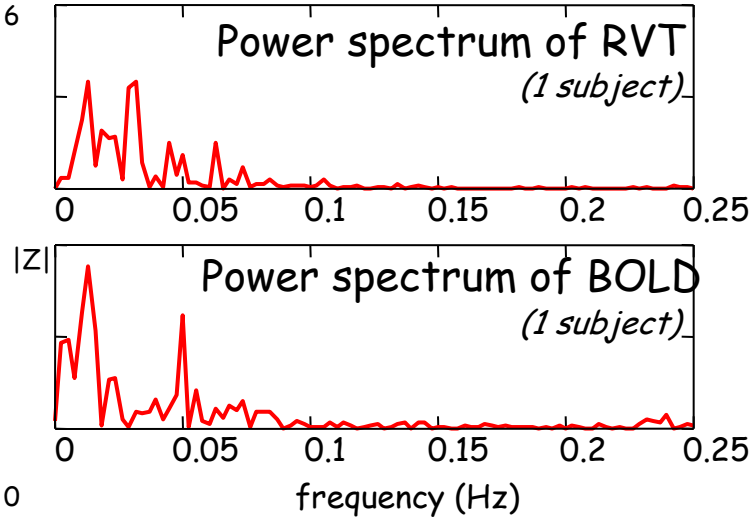


Resting-state corr. from seed ROI



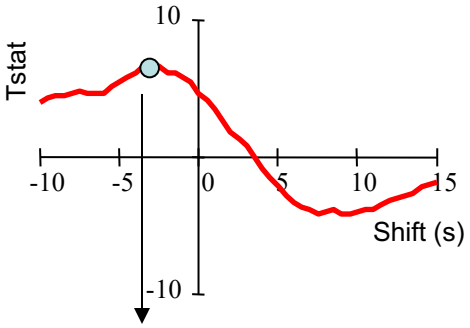
Respiration changes – corr. w/ RVT

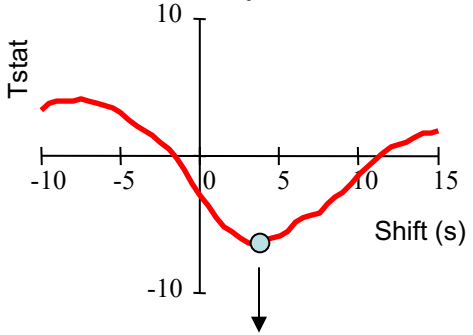


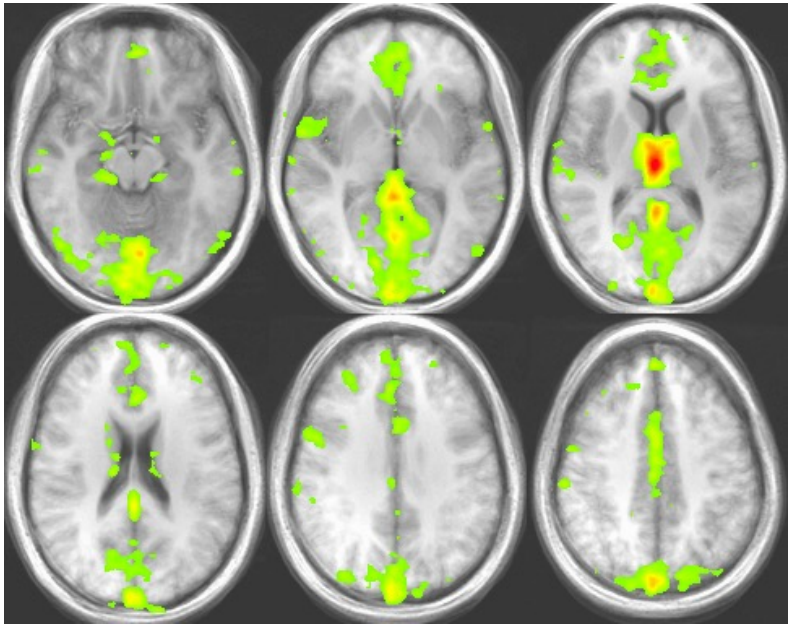


Respiration related

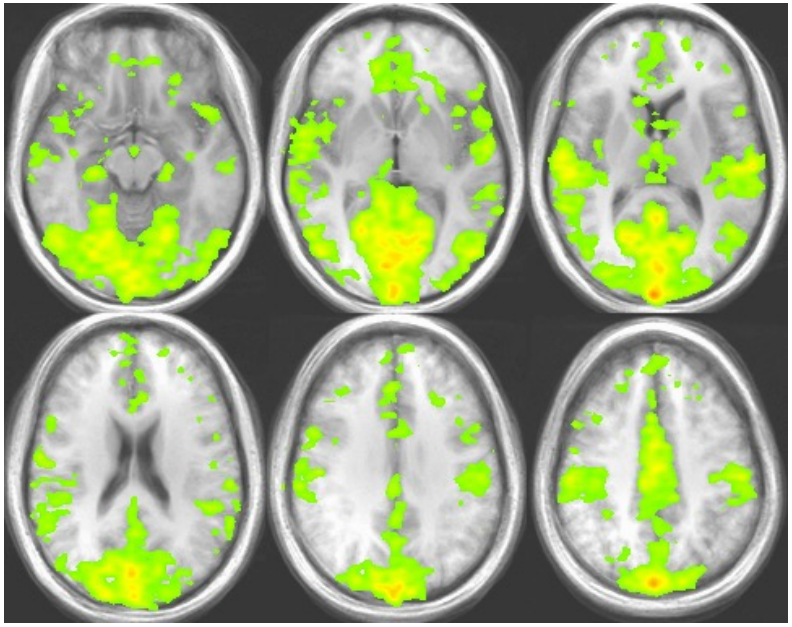
BOLD correlation with RVT as a function of RVT latency







largest positive correlation (in each voxel)



largest negative correlation (in each voxel)

Towards a better understanding and utility of fMRI dynamics and fluctuations

Dynamics

- Linearity
- Latency

Fluctuations

- Resting state
- Respiration related
- Time series improvement
- Respiration Response Function

High Resolution

Finding the "Suggested resolution"

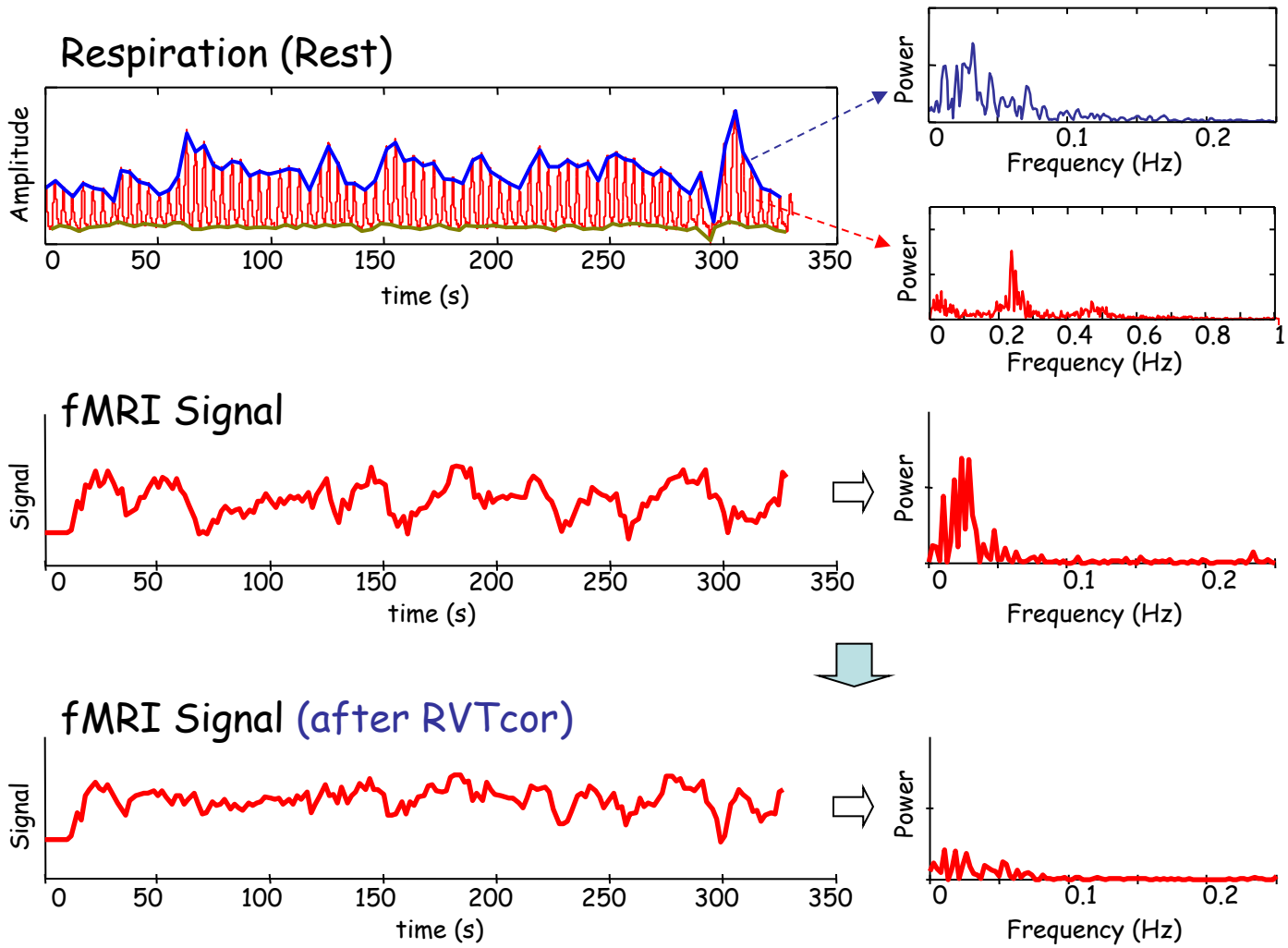
What to do with high resolution data?

Correcting for changes in respiration

- Regress out RVT
- Keep respirations constant

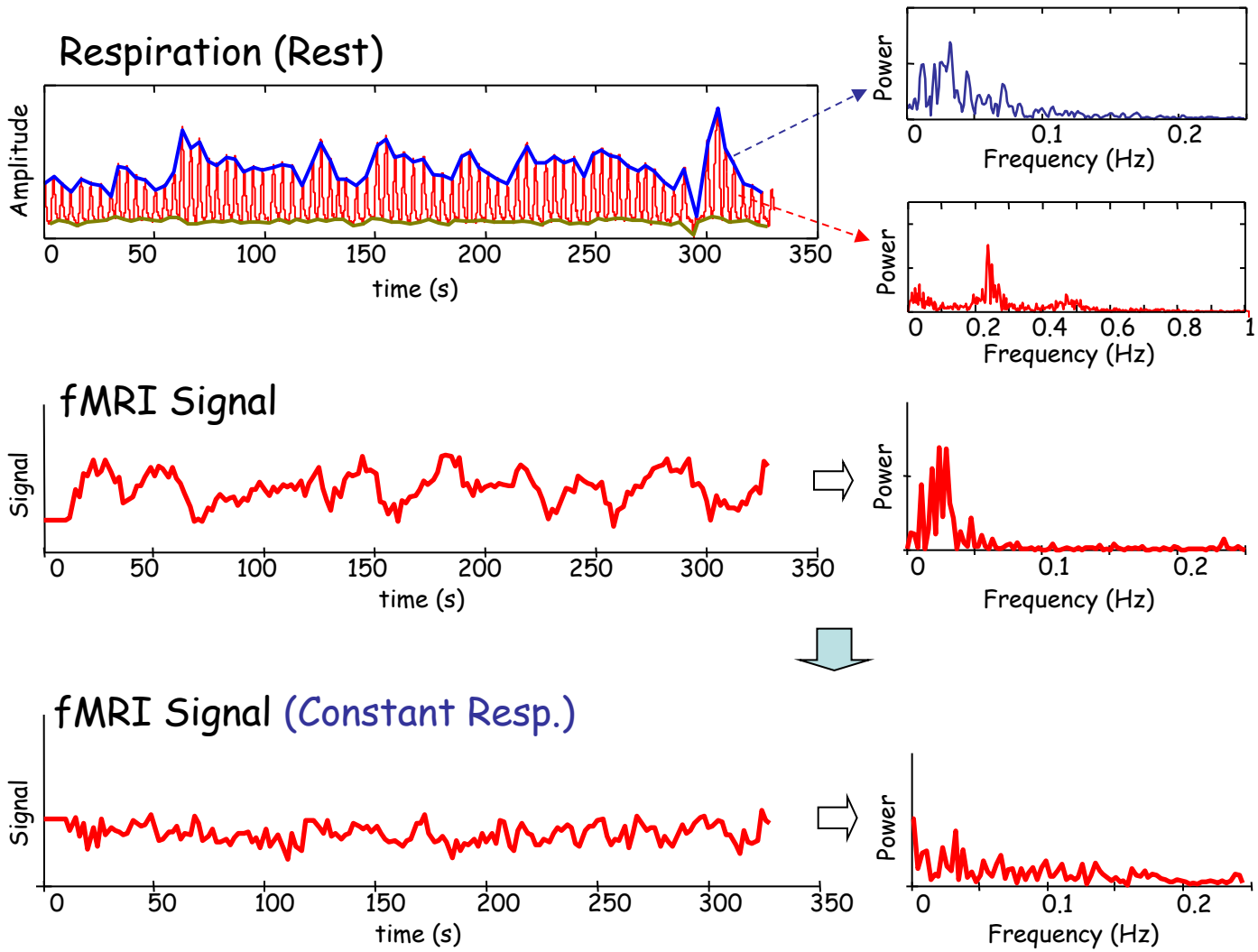
Time series improvement

Regress out Cardiac, Respiration, RVT

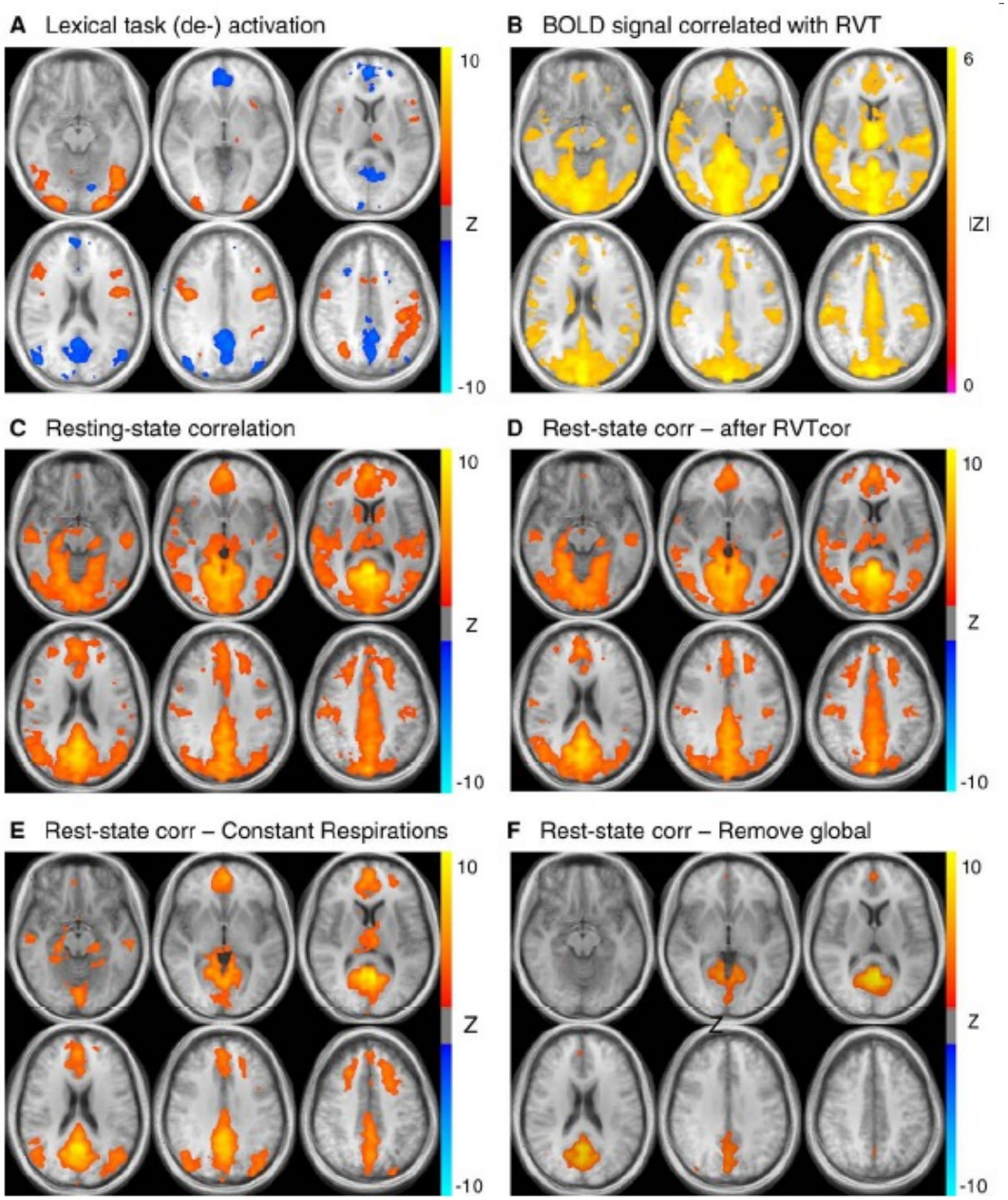


Time series improvement

Cue subject to keep breathing constant

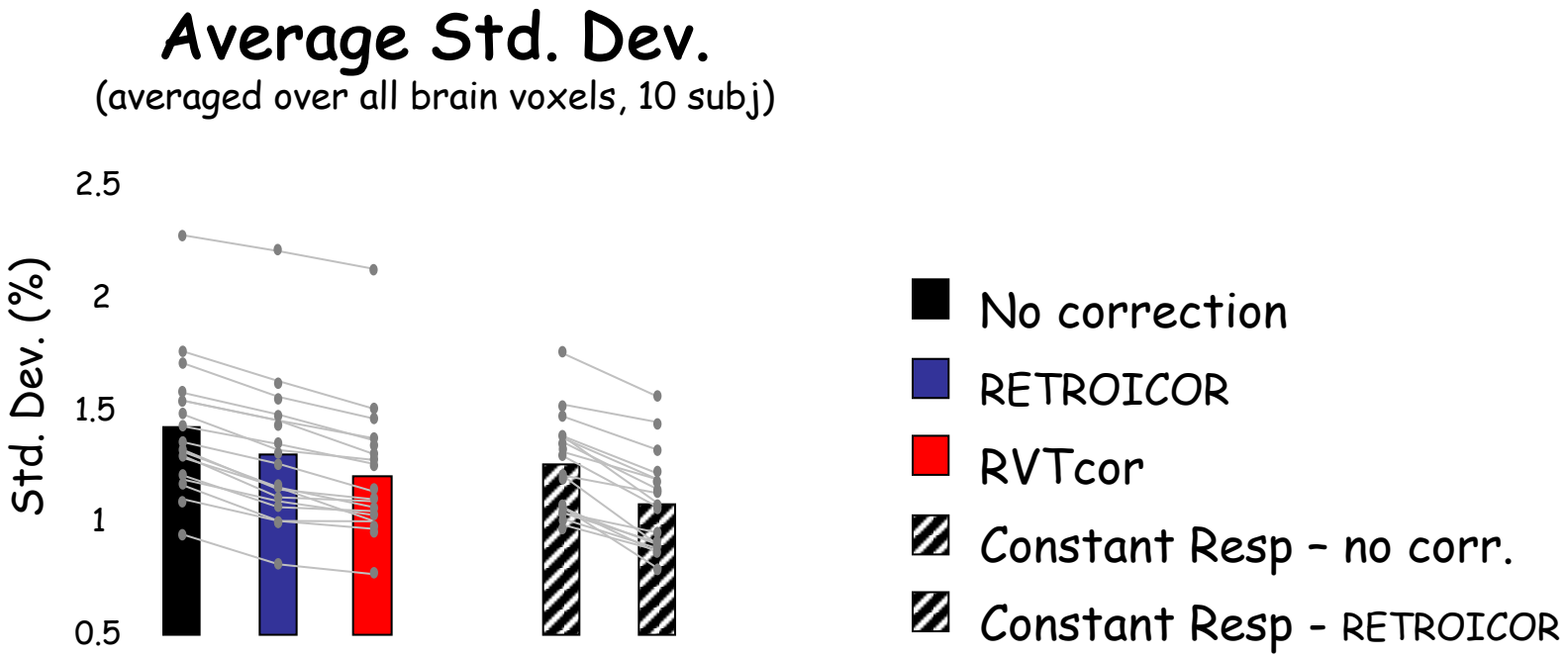


Time series improvement

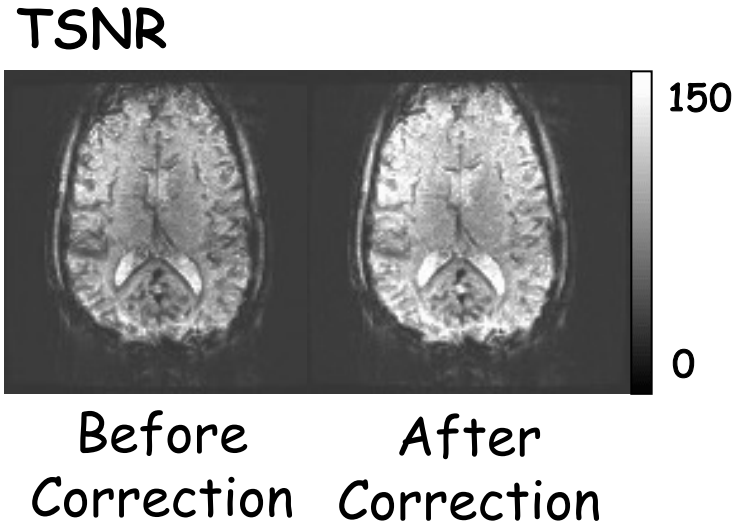


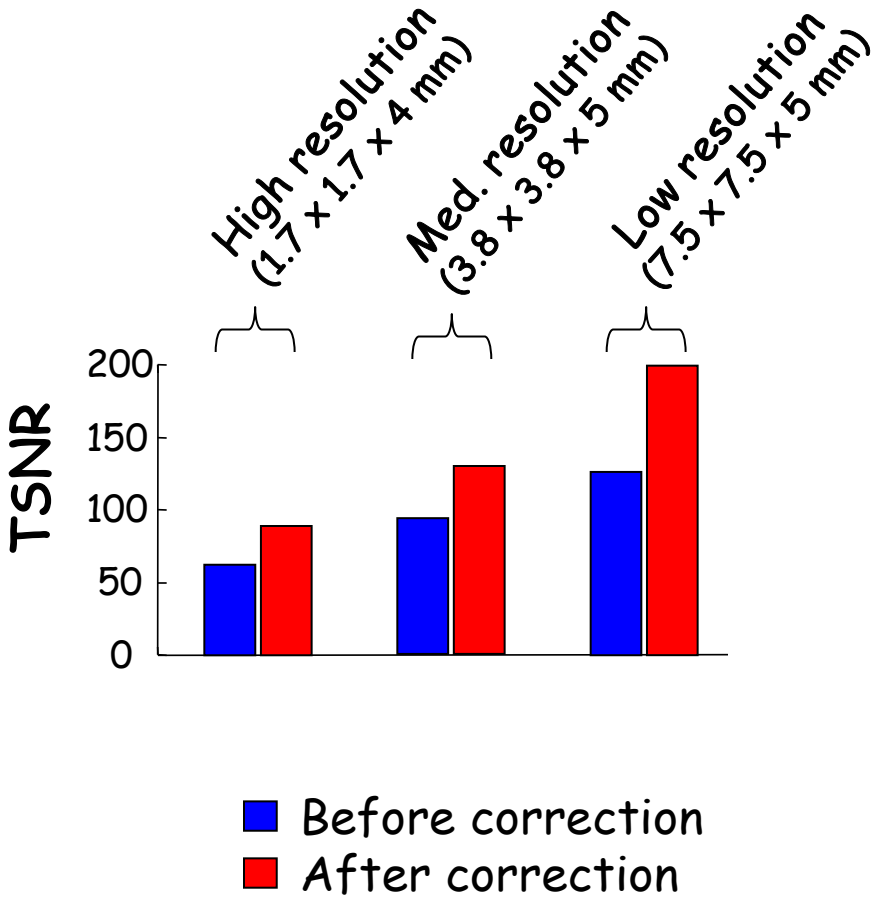
Time series improvement

Reduction of the standard deviation over time



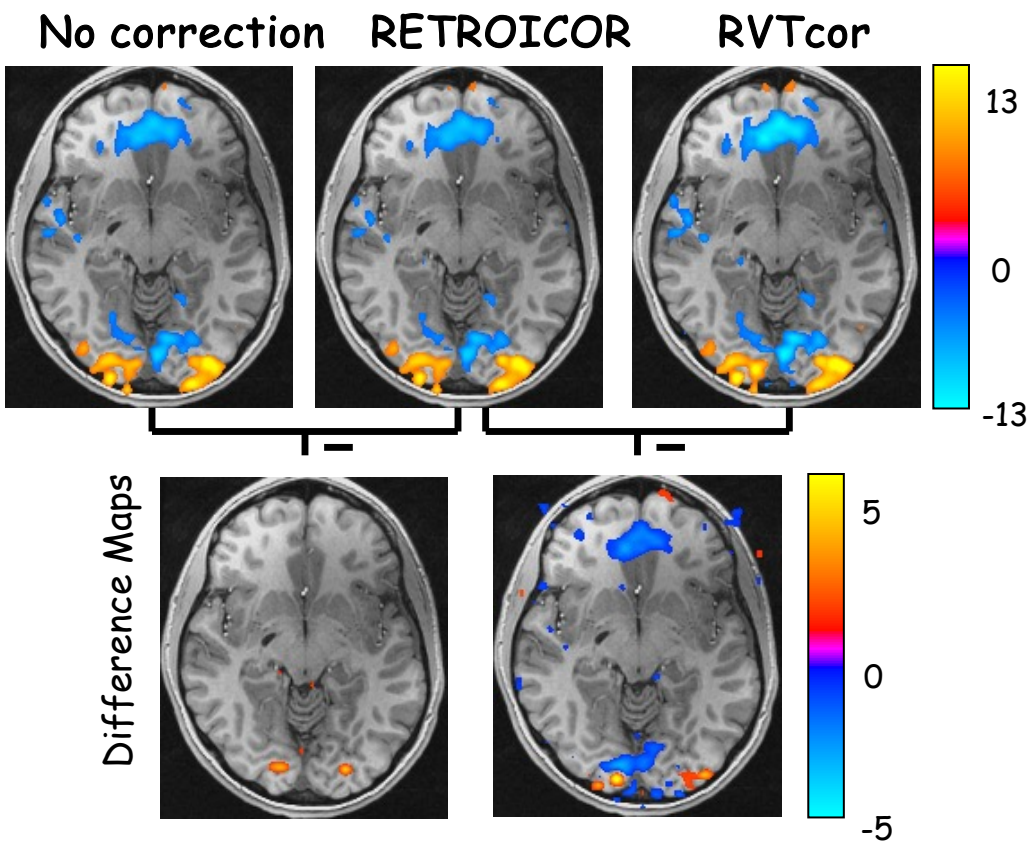
Improvement in temporal SNR (TSNR)

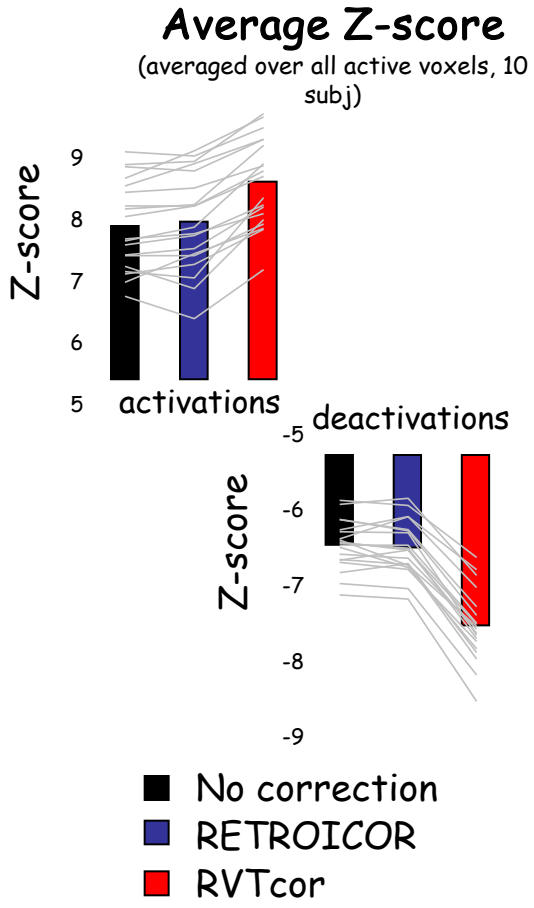




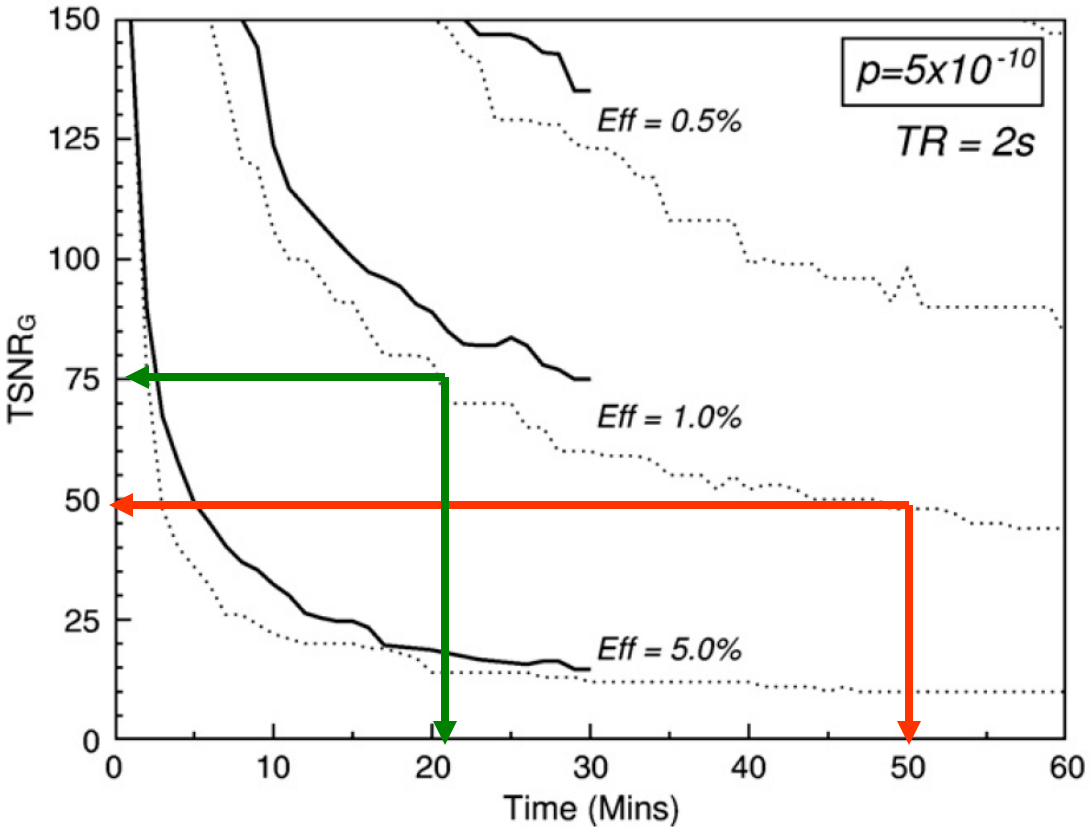
Time series improvement

Improving the detection of function





Time series improvement



K. Murphy, J. Bodurka, P. A. Bandettini, How long to scan? The relationship between fMRI temporal signal to noise and the necessary scan duration. *NeuroImage*, 34, 565-574 (2007)

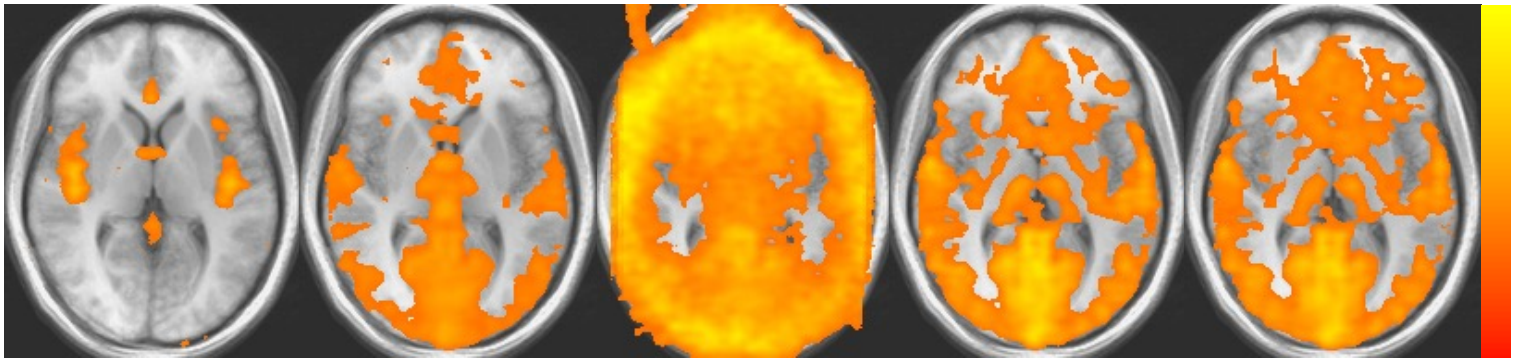
More Corrections?

- RETROICOR (cardiac, respiration)
- RVTcor (respiration volume / etCO2)
- Motion parameters
- Global detrending
- White-matter detrending

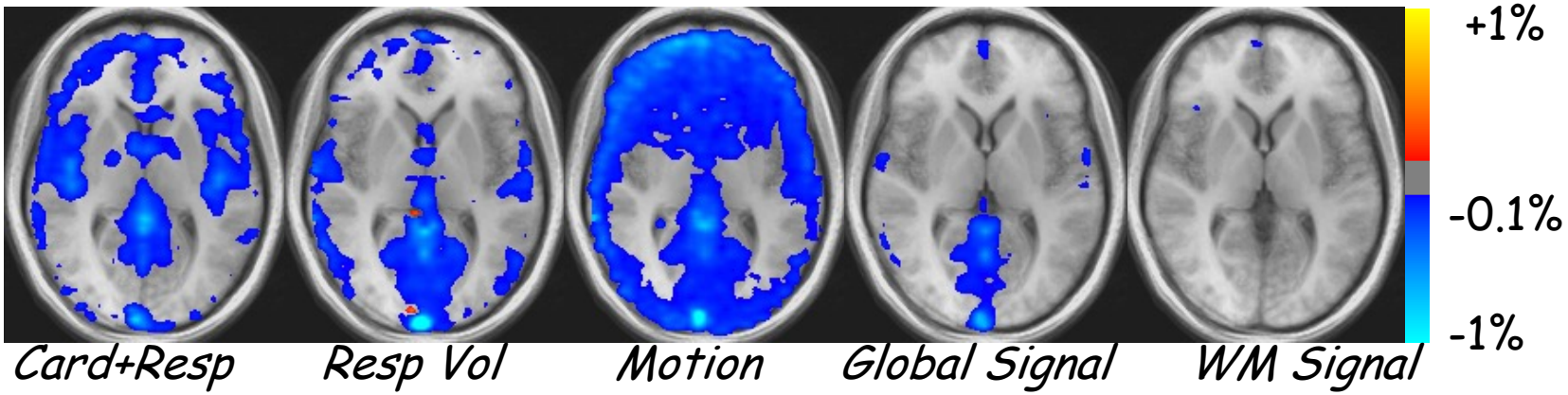
Multiple physiological corrections

Correlation with each regressor

(n = 10)



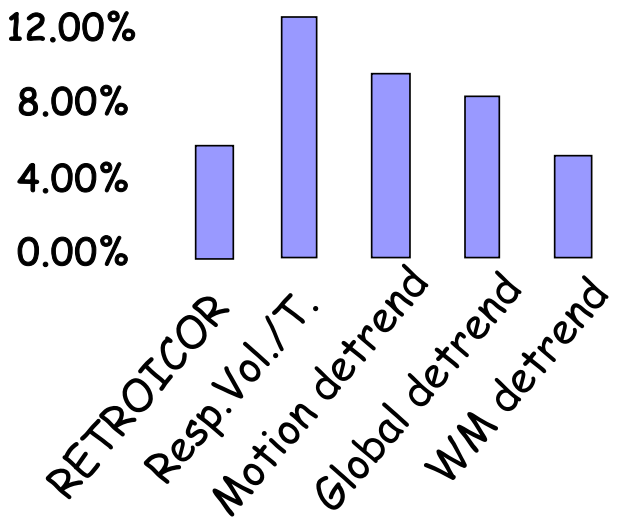
Differences in Std. Dev. when each regressor is removed



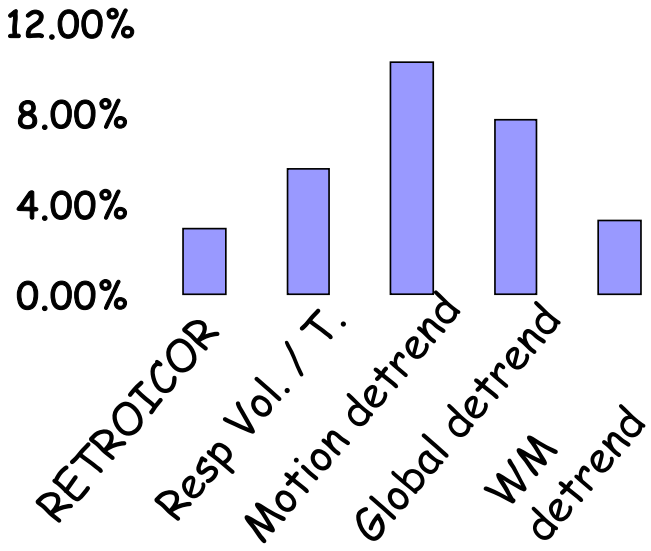
Relative contributions to noise

Averaged over Gray Matter (4 subjects)

High Resolution
(1.7 x 1.7 x 4 mm, 80 time points)



Low Resolution
(7.5 x 7.5 x 5 mm, 700 time points)



Towards a better understanding and utility of fMRI dynamics and fluctuations

Dynamics

- Linearity
- Latency

Fluctuations

- Resting state
- Respiration related
- Time series improvement
- Respiration Response Function

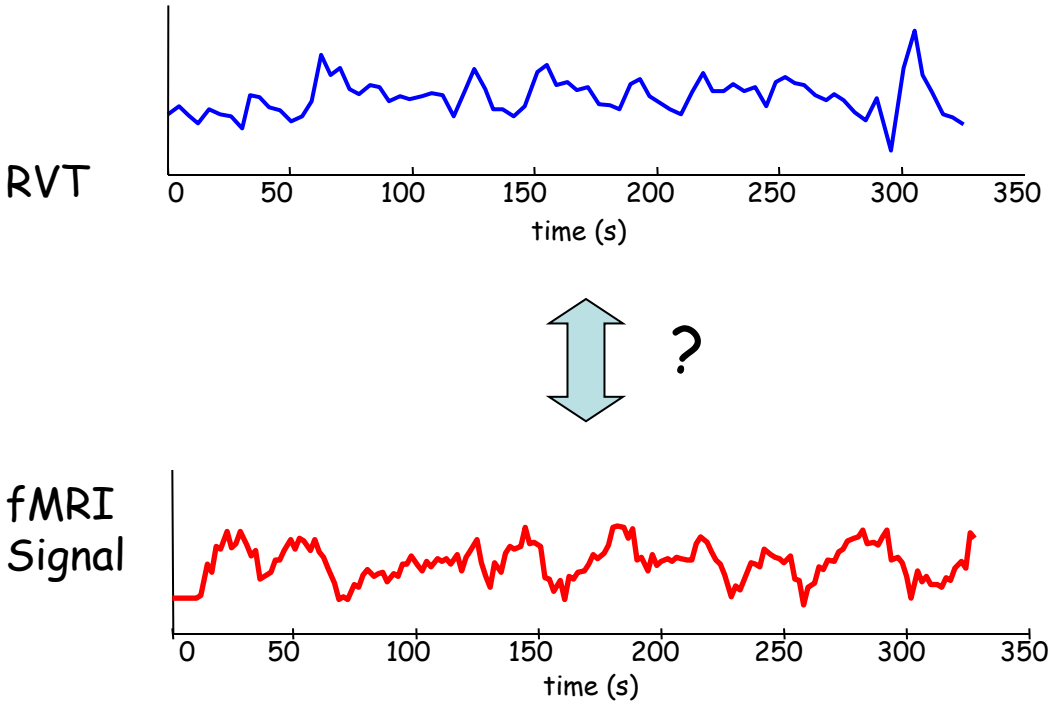
High Resolution

Finding the "Suggested resolution"

What to do with high resolution data?

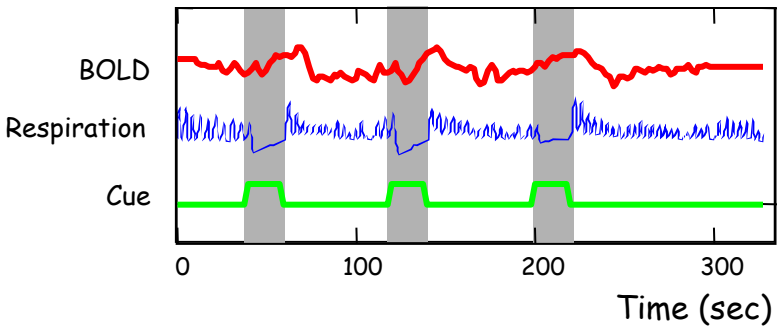
Respiration Changes vs. BOLD

How are the BOLD changes related to respiration variations?

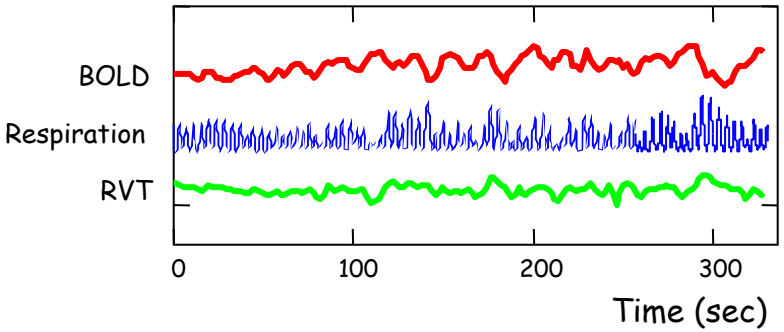


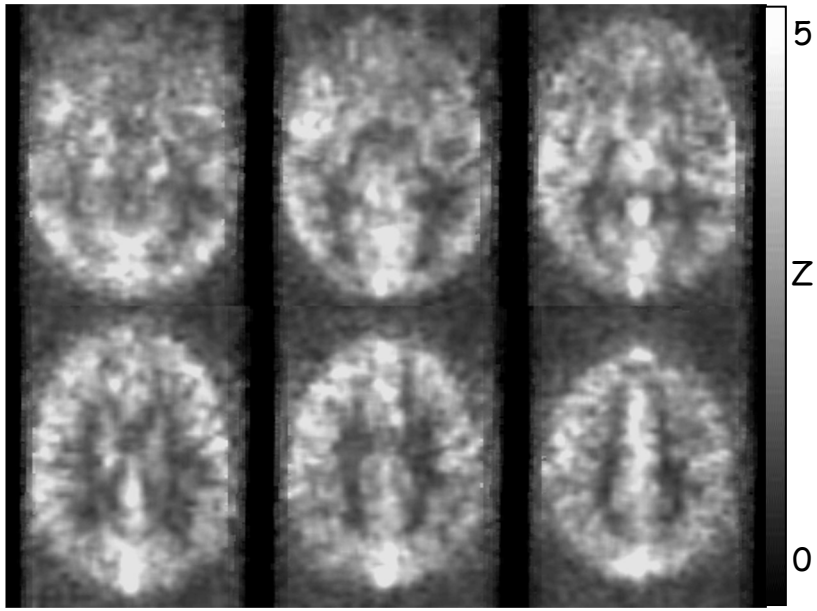
Respiration induced signal changes

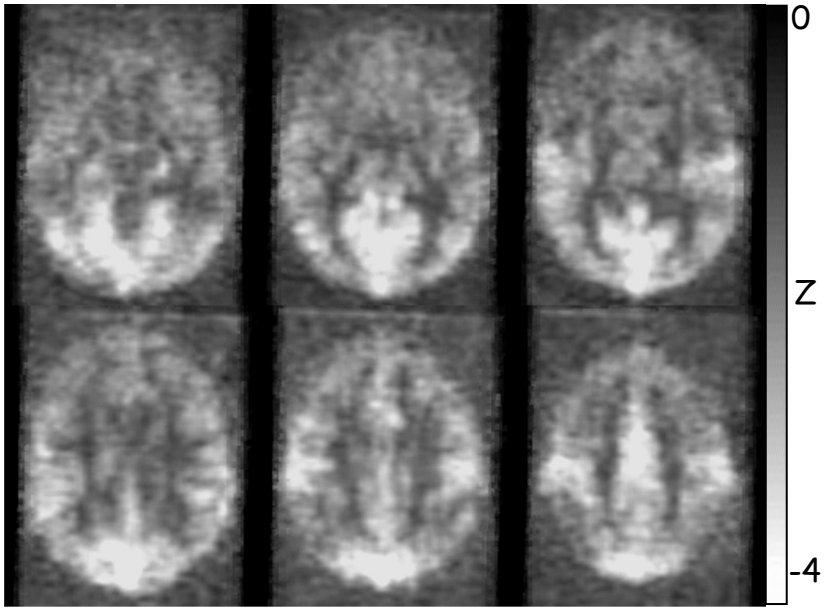
Breath-holding



Rest





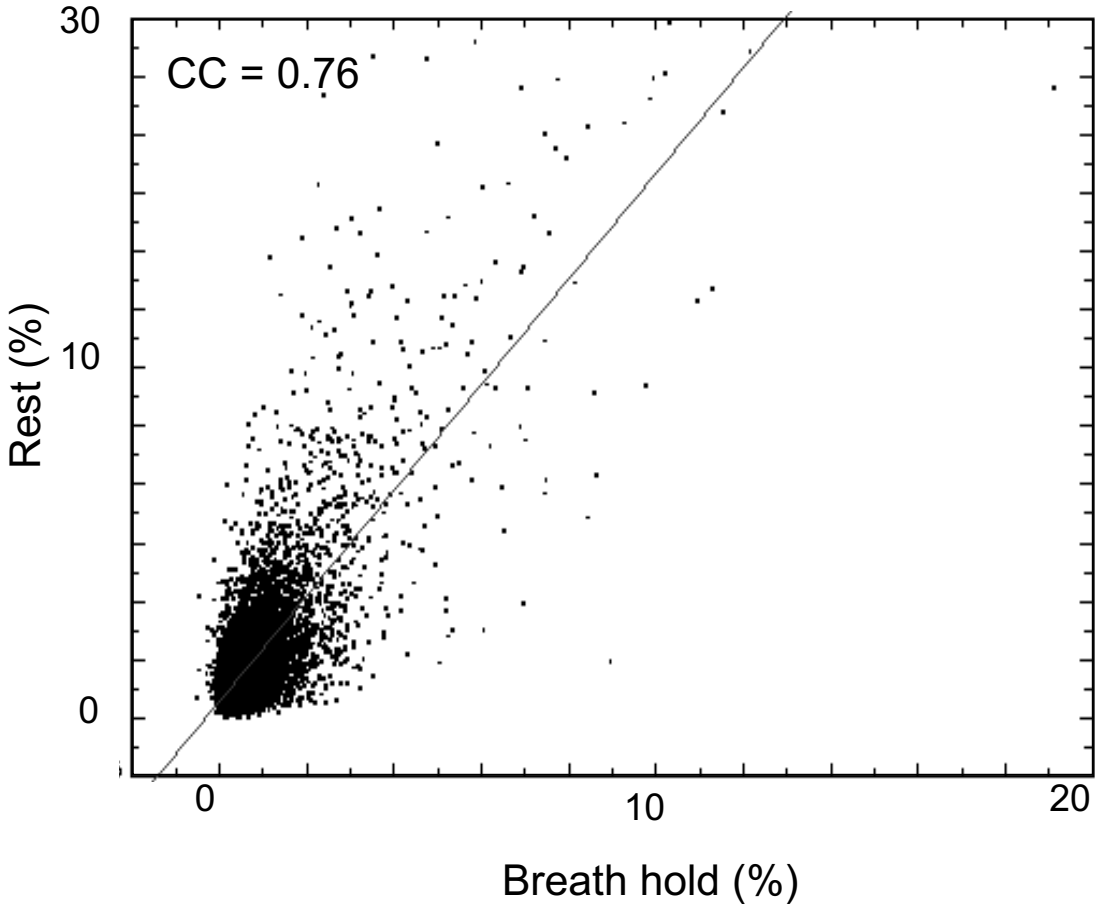


(N=7)

Respiration Response Function

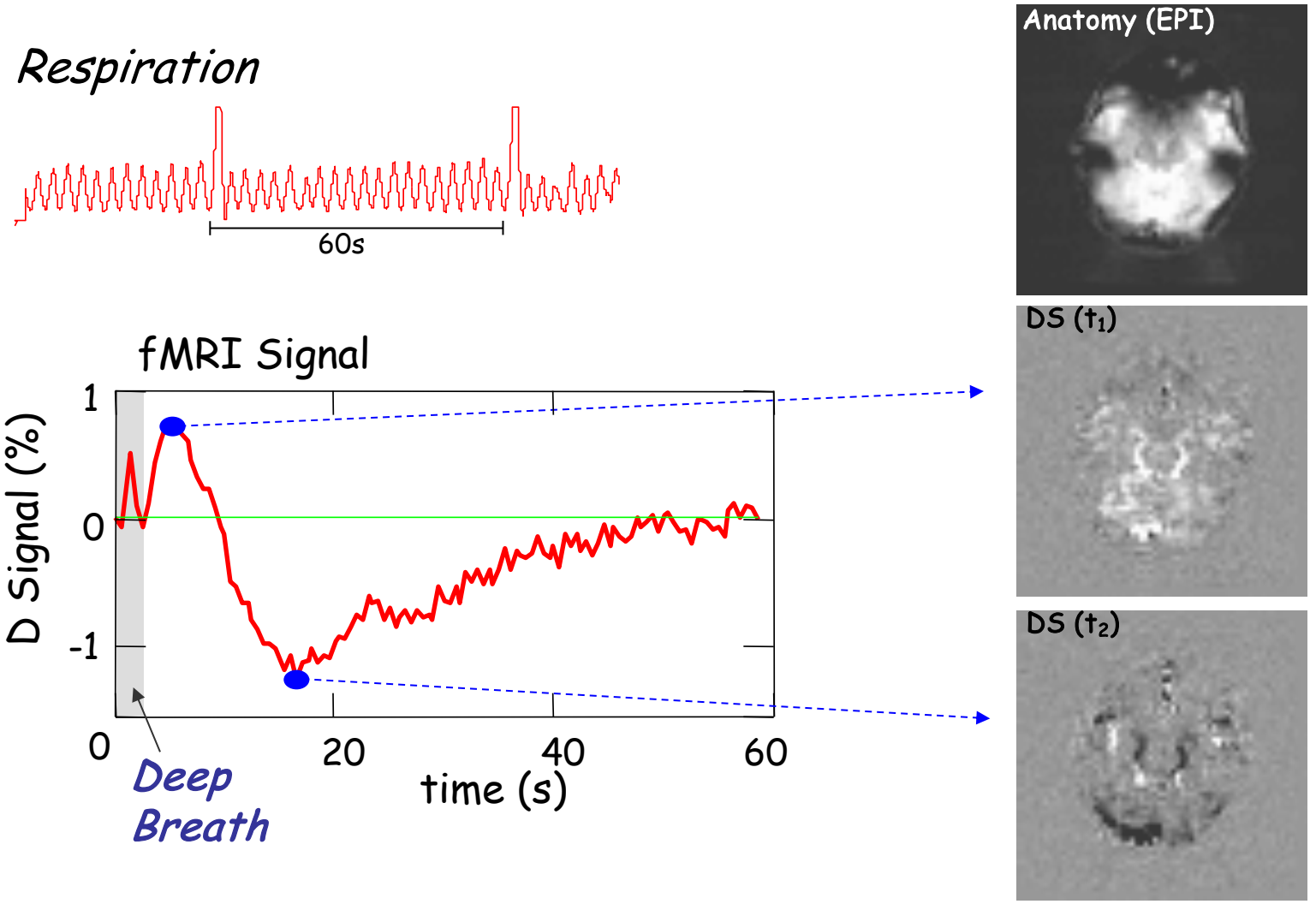
Resting changes in breathing vs. Breath-holding

Correlation with Respiration Volume / Time (RVT)

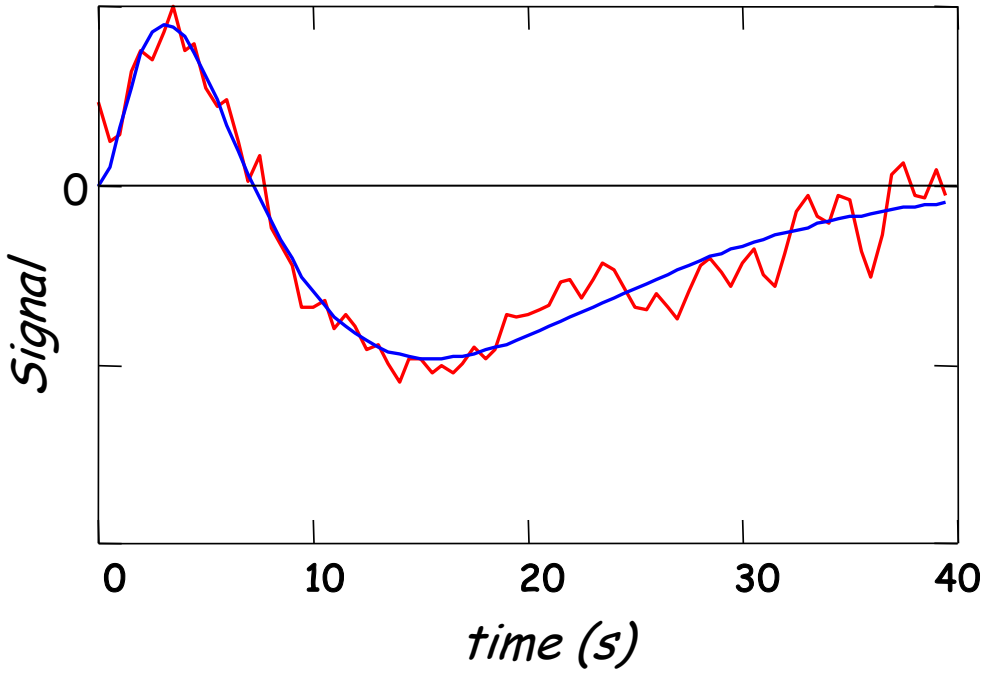


Respiration Response Function

fMRI response to a single Deep Breath



Respiration response function



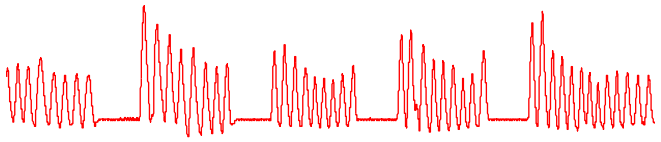
Average of 3 subjects

$$RRF(t) \quad 0.6\, t^{2.1} e^{-t/1.6} - 0.0023\, t^{3.54} e^{-t/4.25}$$

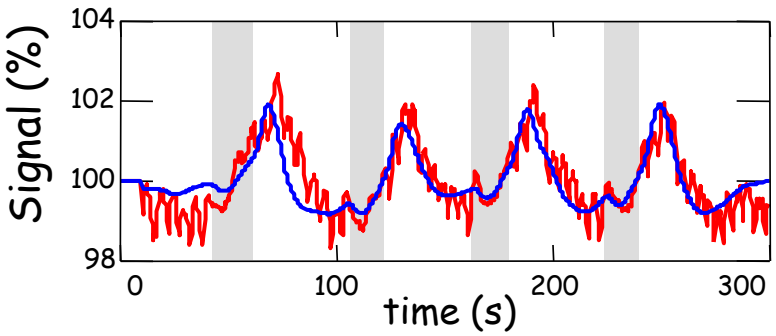
Respiration Response Function

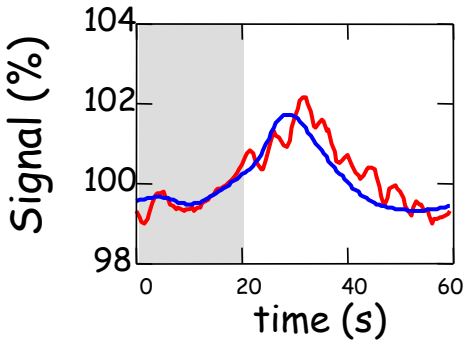
fMRI response to breathing modulations

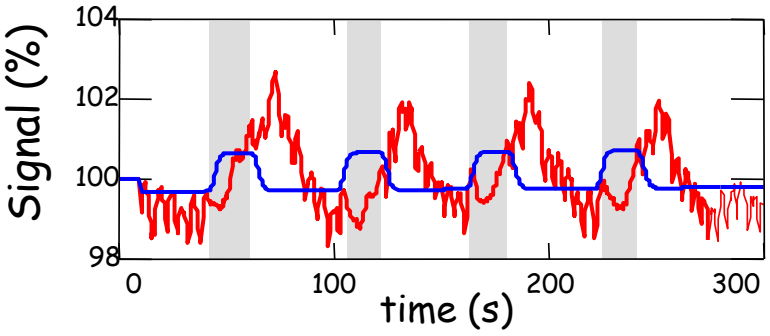
Breath-holding

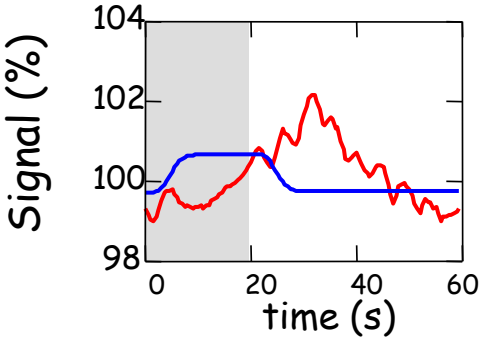


Respiration





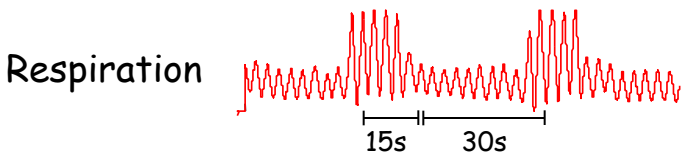


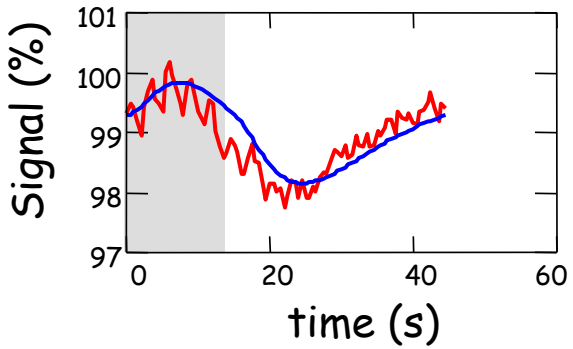


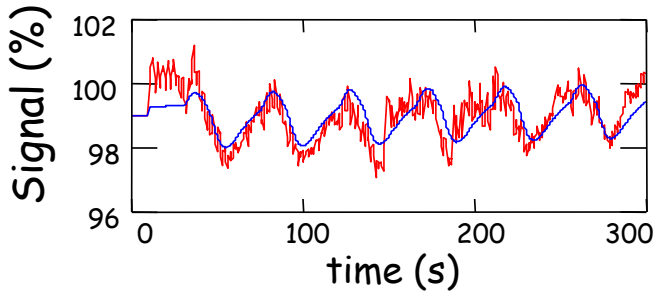
Respiration Response Function

fMRI response to breathing modulations

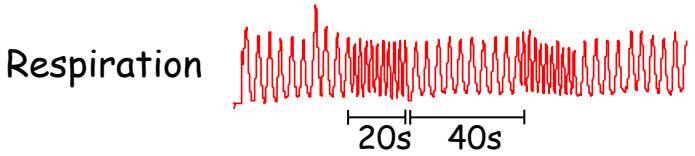
Changes in Depth

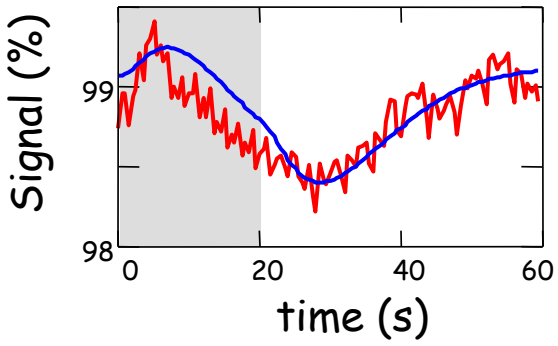


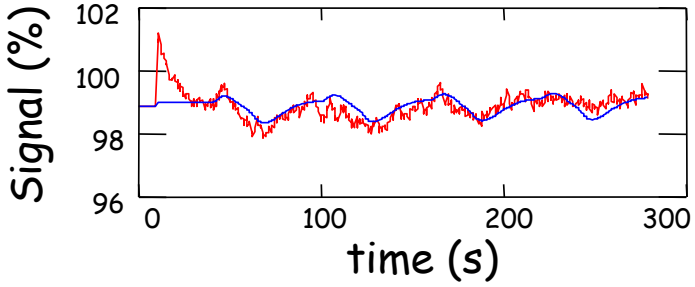




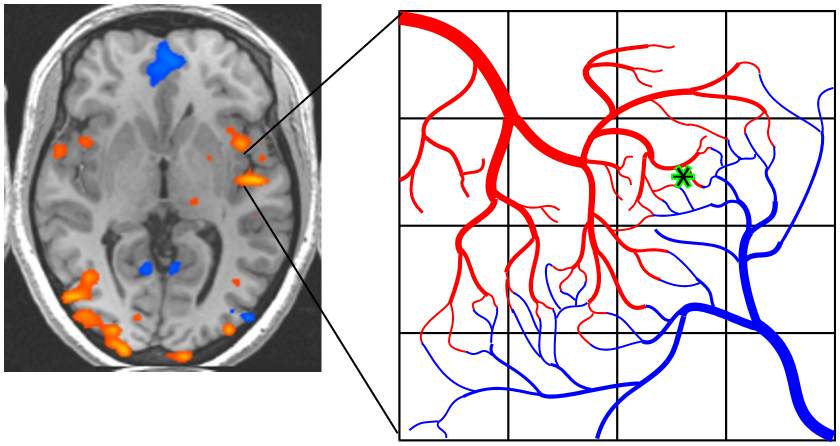
Changes in Rate







Calibration of BOLD



↑ Task

↓

↑ neuronal activity

↓ ↘

↑ BV ← ↑ BF ← ↑ $CMRO_2$

↓ ↓ ↓

↑ HbO_2 ↓ deoxy-Hb

↓

↑ MR signal

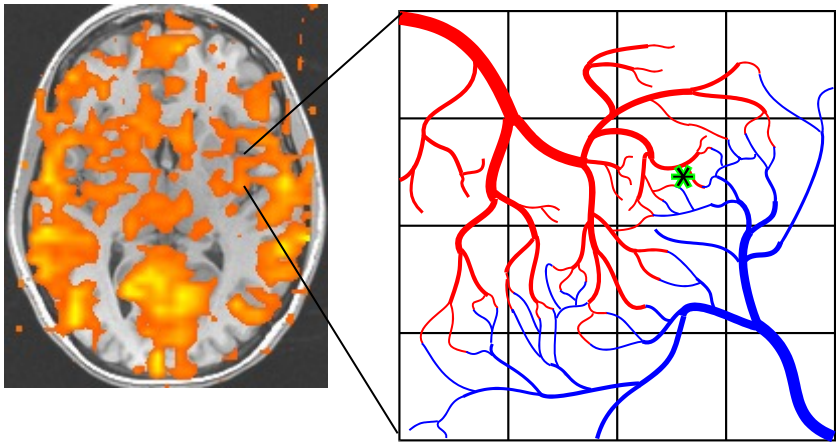
Location: *where is the neuronal activity?*

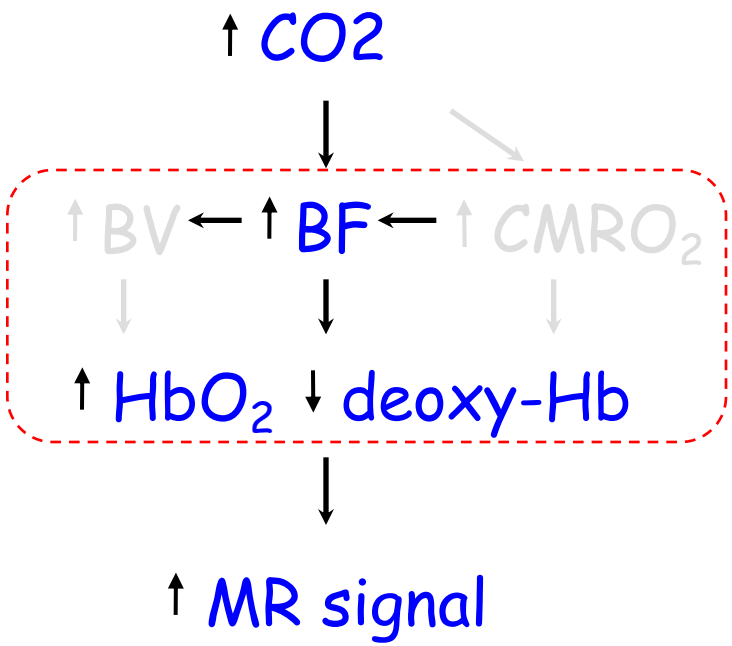
Timing: *timing of neuronal activity in different brain regions*

Amount: *How much activity is there?*

Respiration Response Function

Calibration of BOLD - CO_2 stress

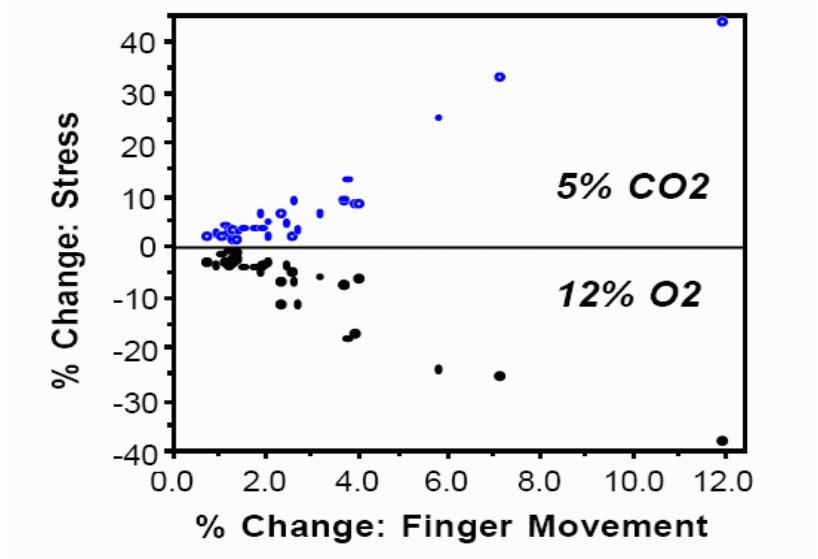


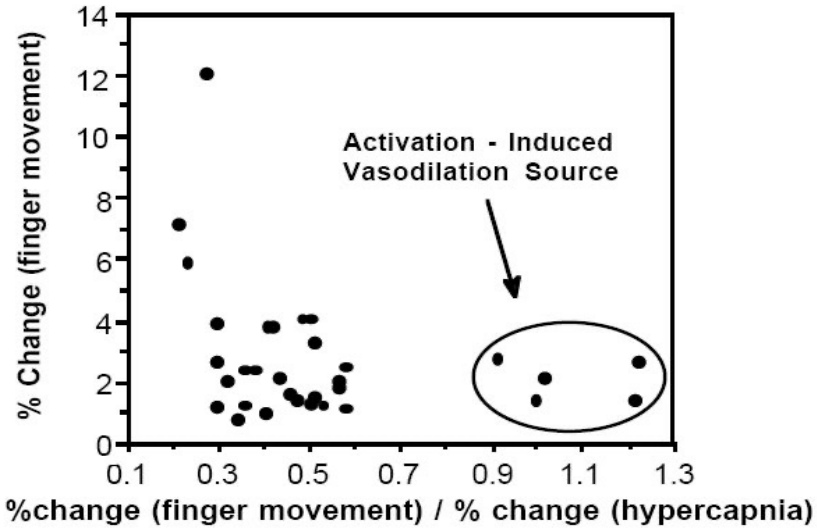


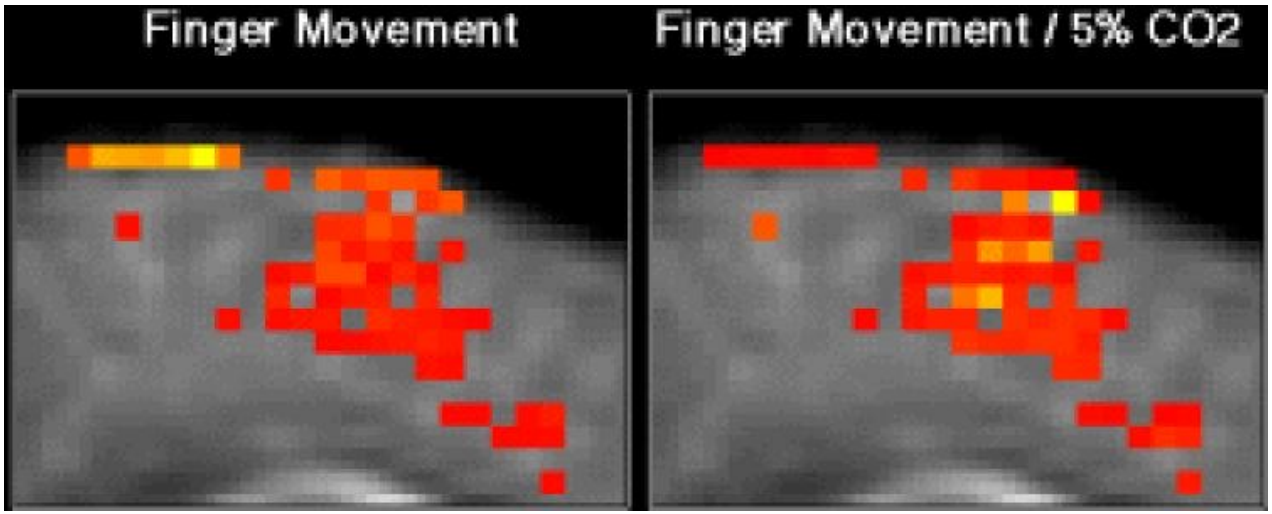
P.A. Bandettini, et al.
NMR in Biomedicine, 10, 197-203, 1997

T.L. Davis, et al.
PNAS, 95(4), 1834-1839, 1998.

Calibration of BOLD – CO2 Stress - Results







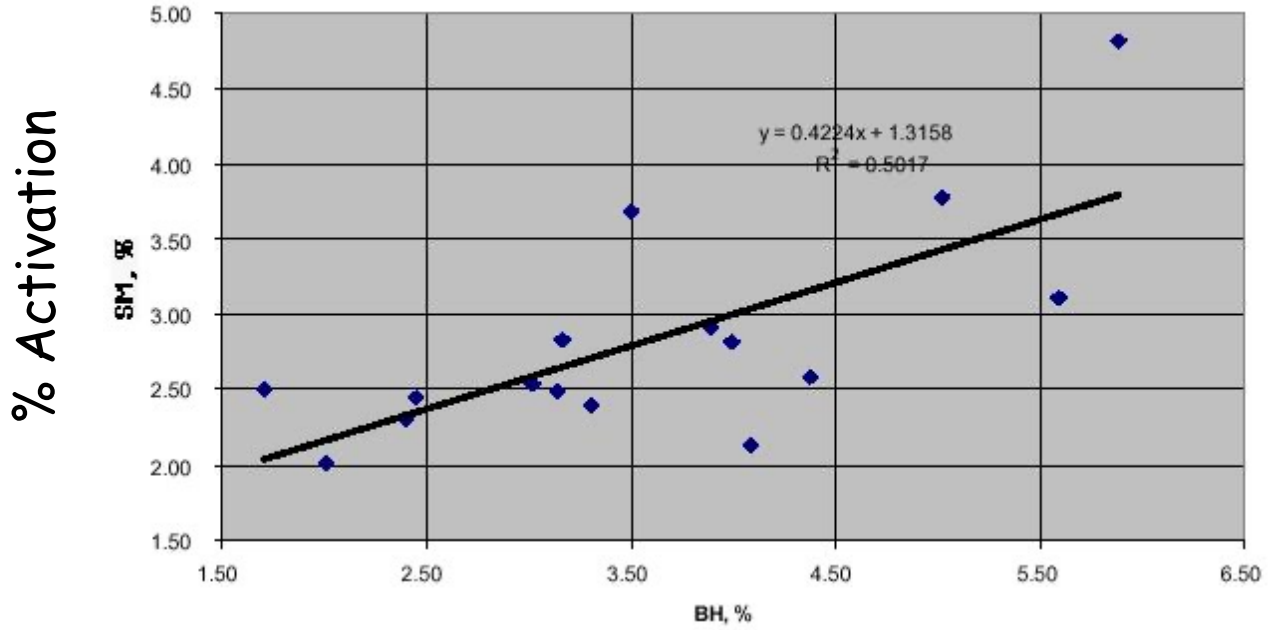
P. A. Bandettini, E. C. Wong, A hypercapnia - based normalization method for improved spatial localization of human brain activation with fMRI. *NMR in Biomedicine* 10, 197-203 (1997).

Calibration of BOLD – CO_2 stress (Breath-hold)

Calibration of fMRI Activation for the FIRST BIRN Project

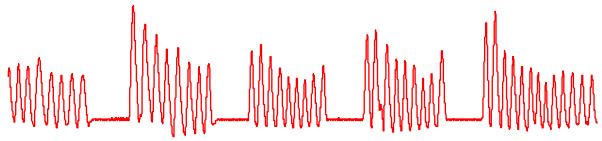
M. E. Thomason[1], L. Foland[2], F. BIRN[3], G. H. Glover[1,2]

Proc. ISMRM, 2004.

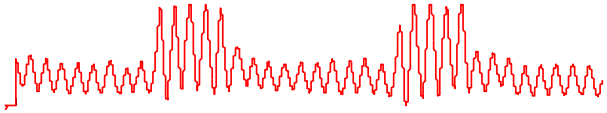


% Signal Change: Breath Hold

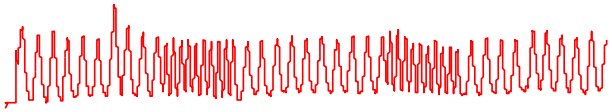
Calibration using other respiration changes



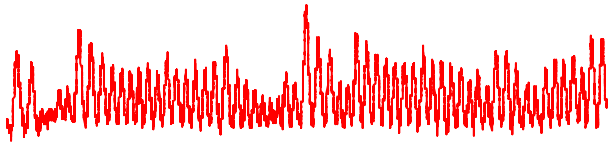
Breath-holding



Depth changes



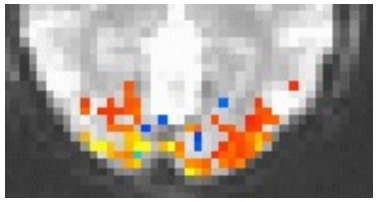
Rate changes



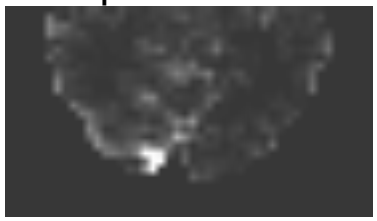
spontaneous fluctuations
in respiration during rest

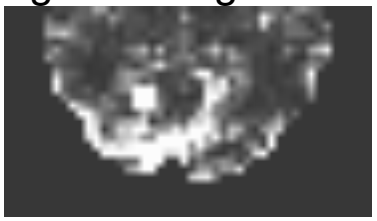
Respiration Response Function

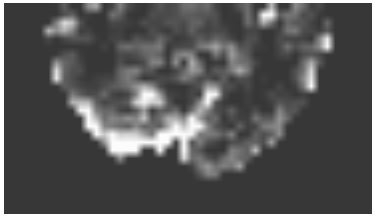
Visual Activation

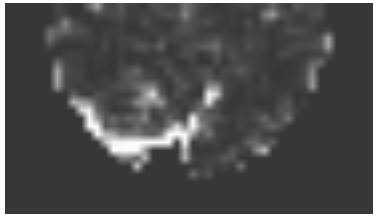


Respiration – induced signal changes

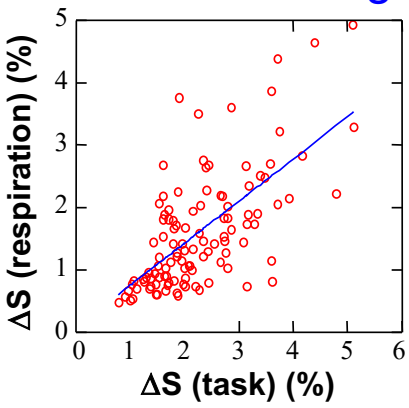




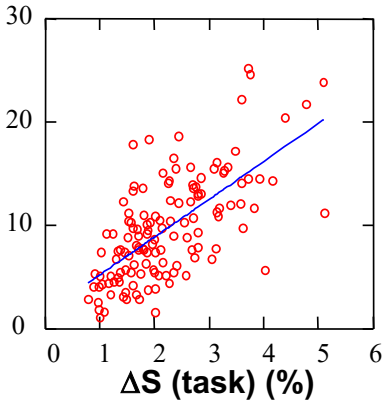




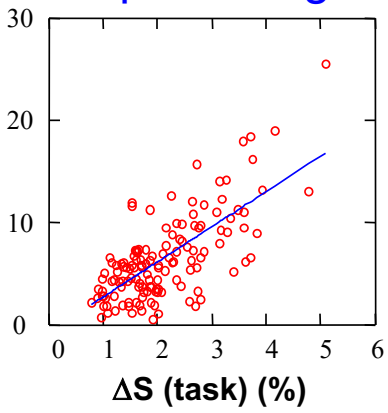
Breath-holding



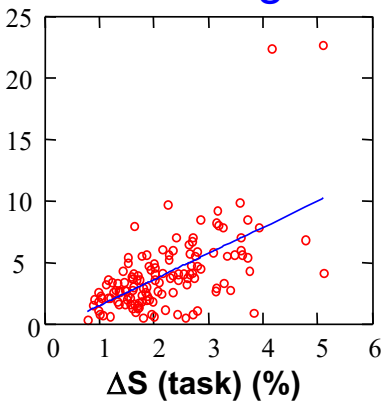
Rest

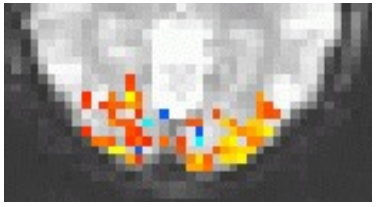


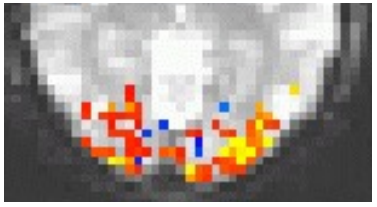
Depth changes

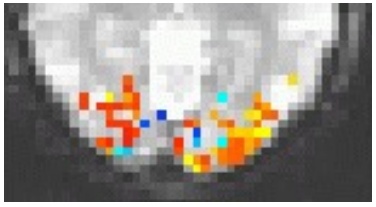


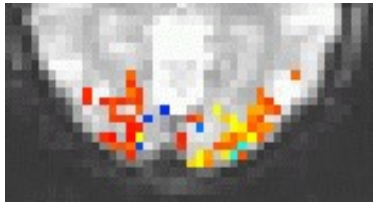
Rate changes











Towards a better understanding and utility of fMRI dynamics and fluctuations

Dynamics

- Linearity
- Latency

Fluctuations

- Resting state
- Respiration related
- Time series improvement
- Respiration Response Function

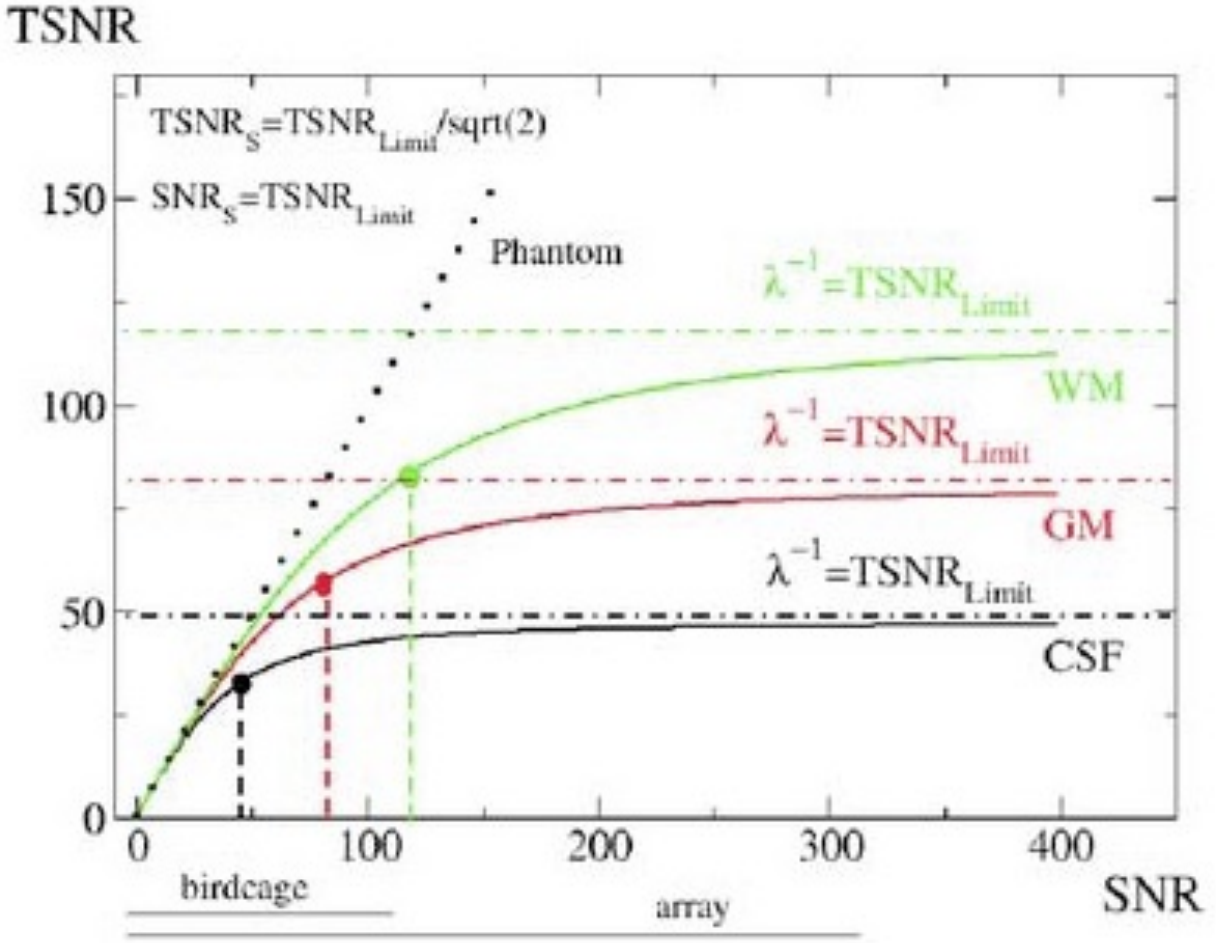
High Resolution

Finding the "Suggested resolution"

What to do with high resolution data?

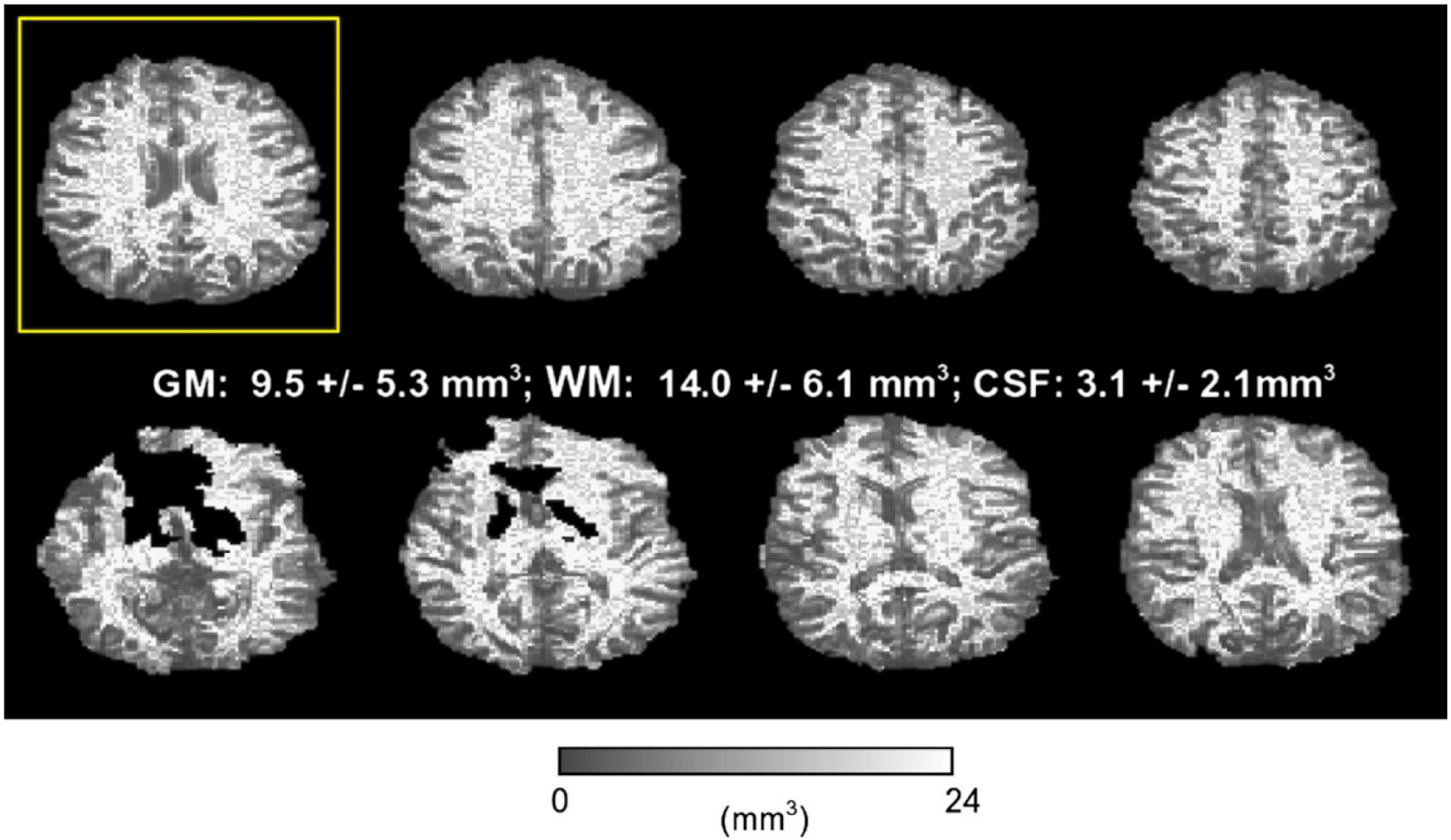
Finding the "Suggested resolution"

SNR vs TSNR



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"



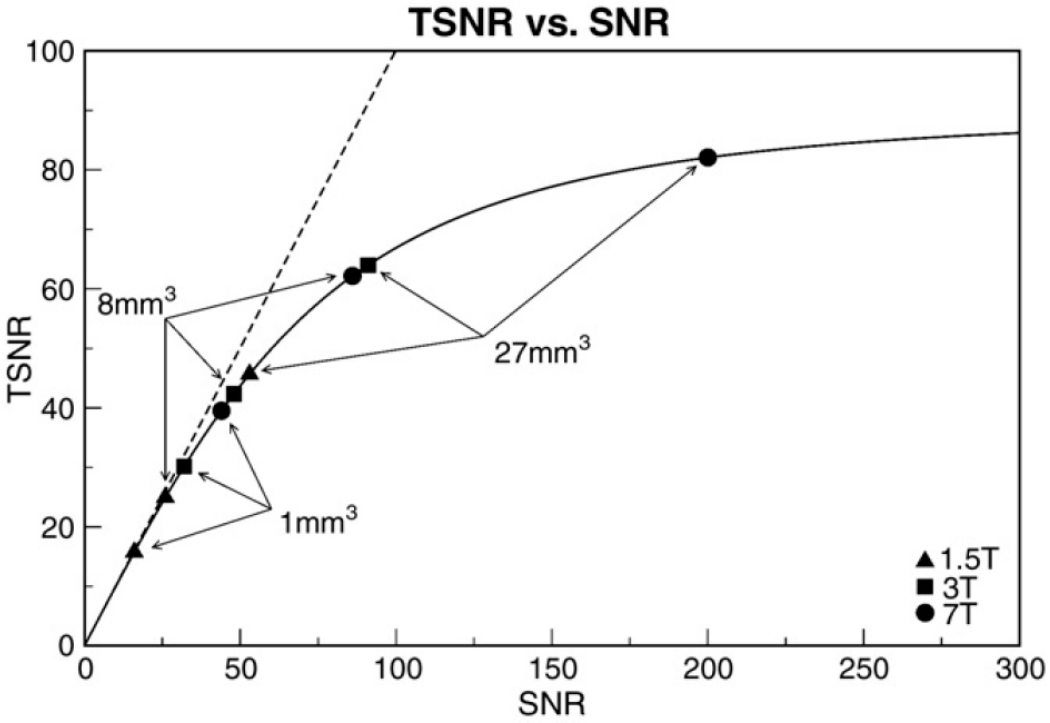


Fig. 1. A schematic of the relationship between TSNR and SNR in gray matter is shown. The dashed line represents this relationship in the absence of physiological noise. In vivo, gains in TSNR are limited by physiological noise as SNR is increased and this relationship is displayed with the solid line. 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 $1\times1\times1$ mm^3=1 mm^3, $2\times2\times2$ mm^3=8 mm^3 and $3\times3\times3$ mm^3=27 mm^3.

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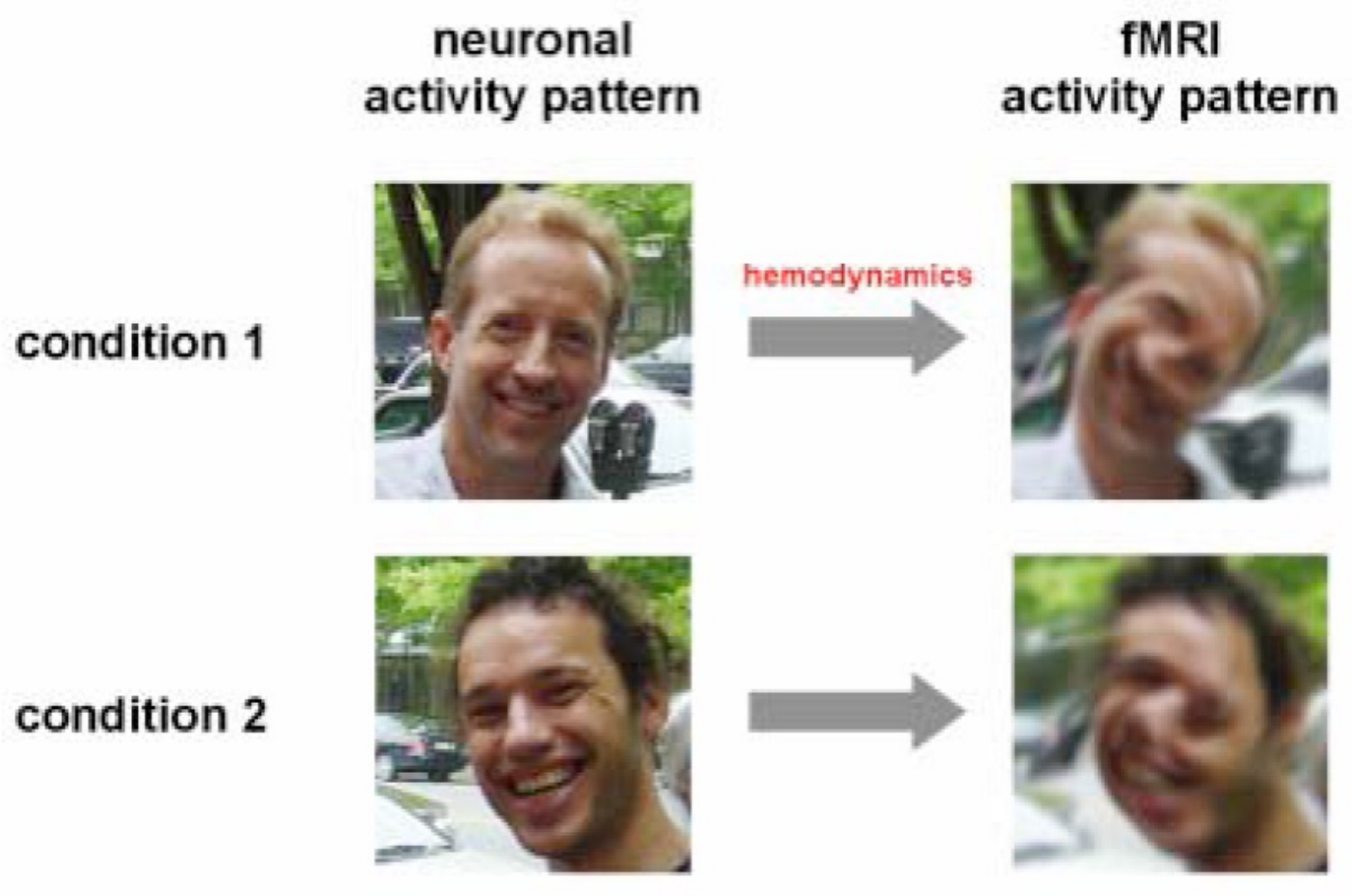

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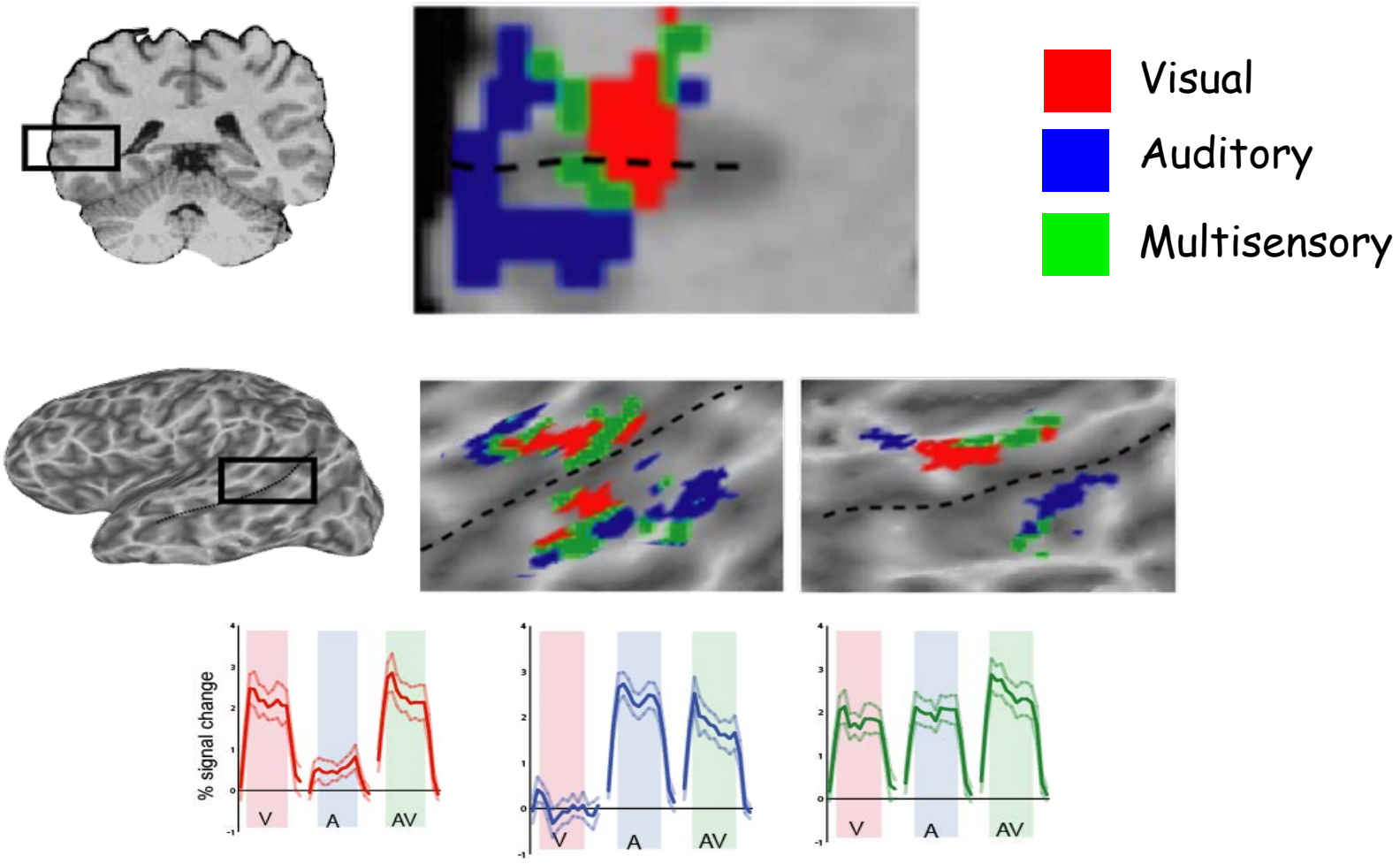
Multi-sensory integration

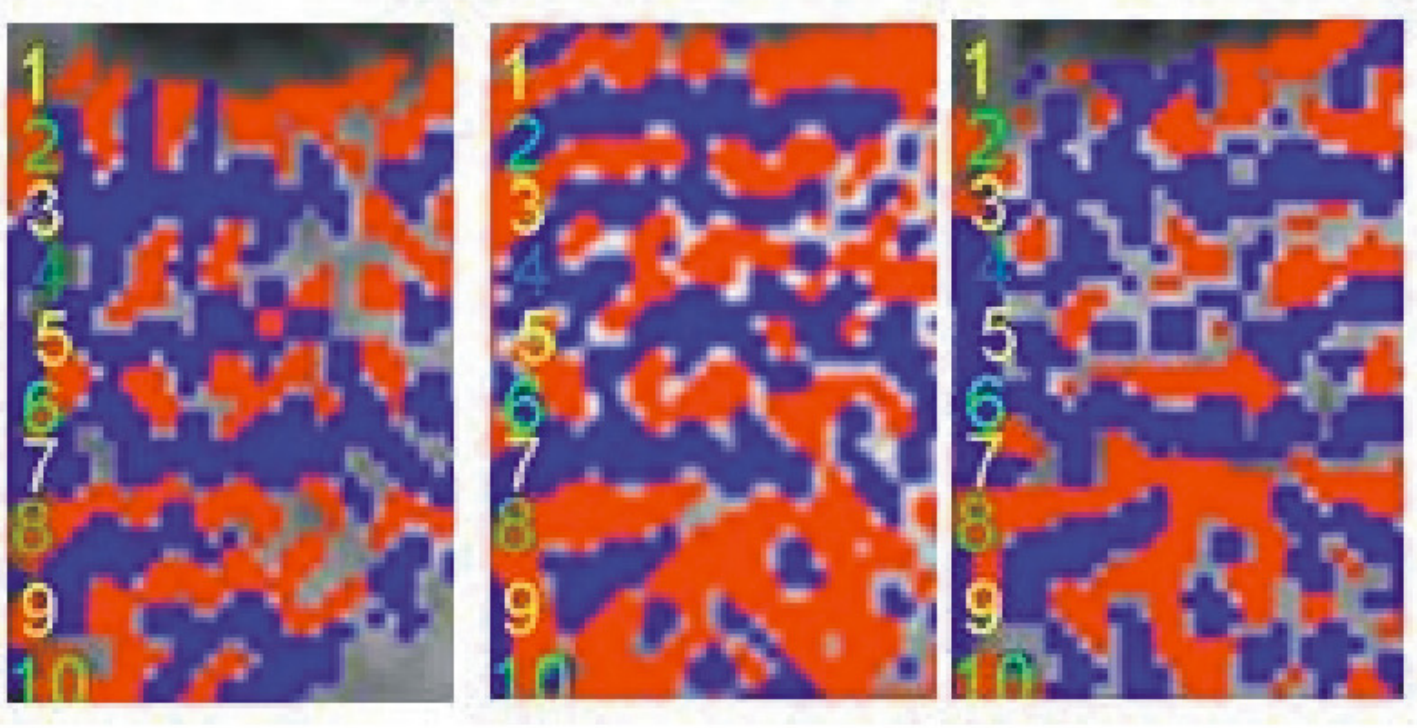
M.S. Beauchamp et al.,



What to do with high resolution data?

HSE-BOLD demonstration of ocular dominance columns

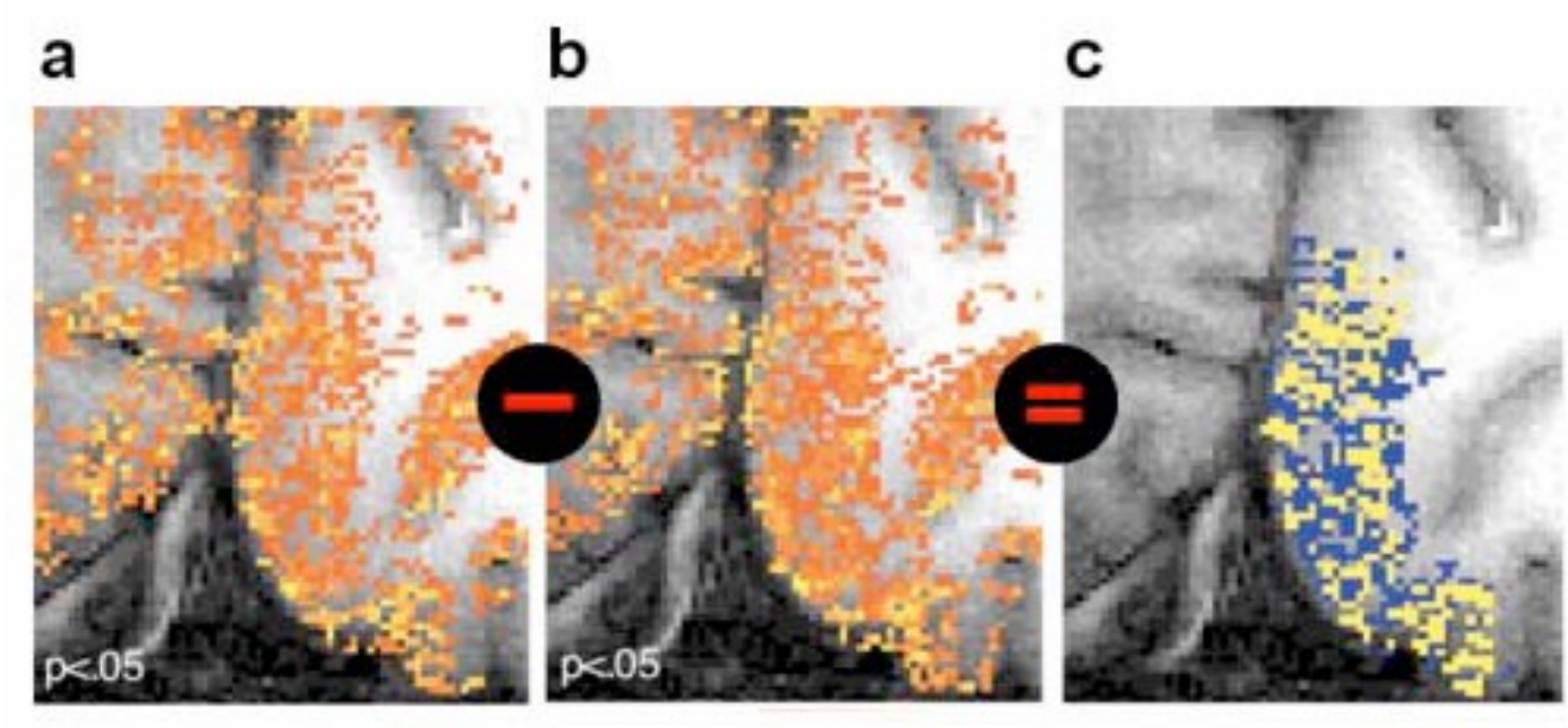
human, 7T, 0.5×0.5×3 mm^3



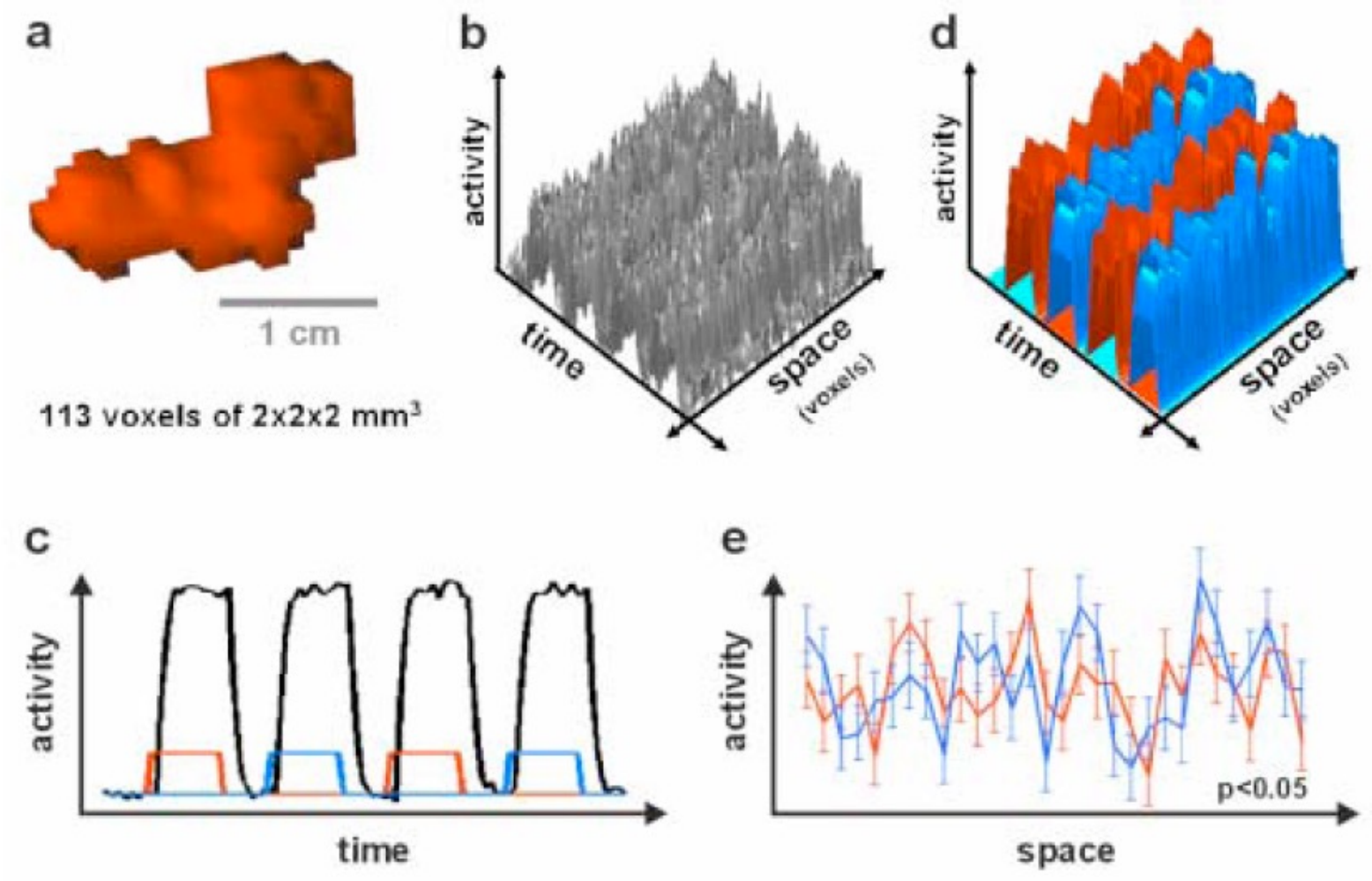
day 1 **day 2** **day 3**

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

What to do with high resolution data?



What to do with high resolution data?



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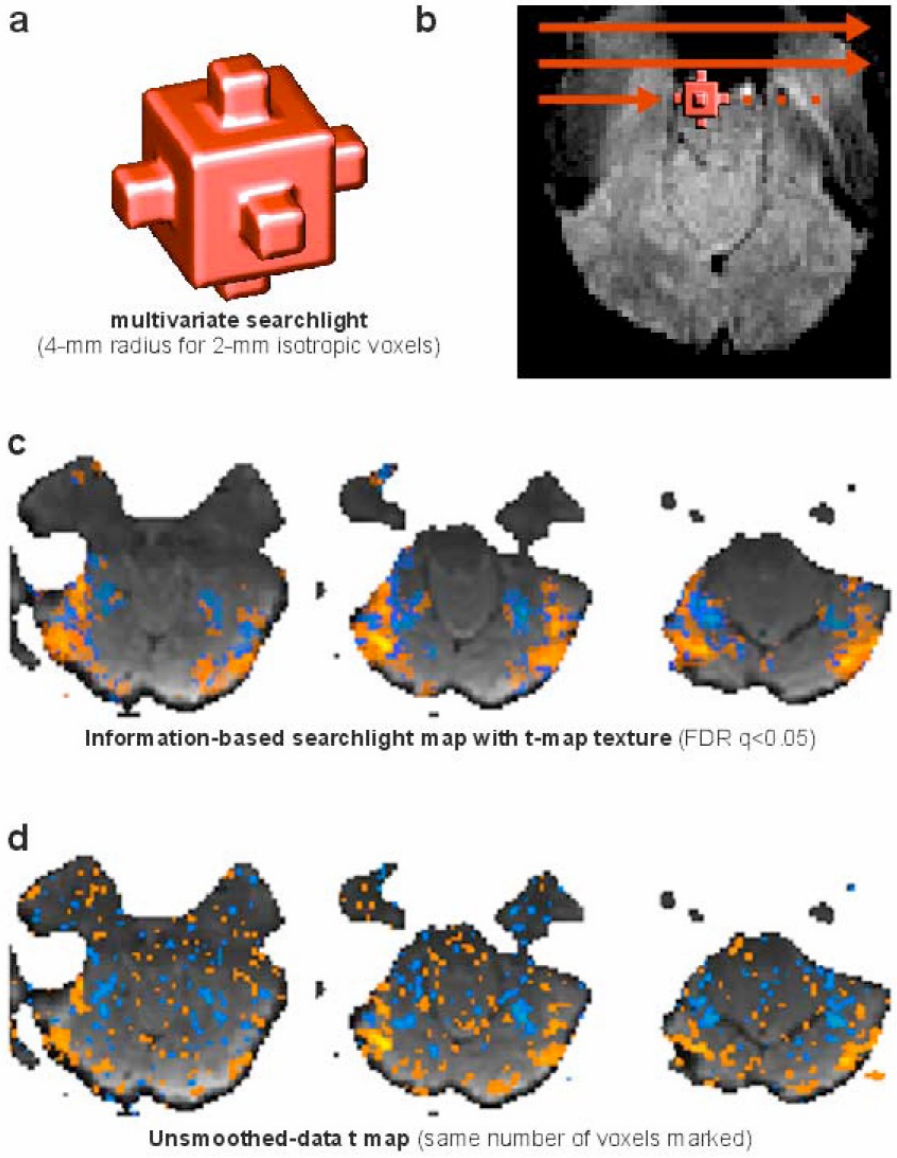

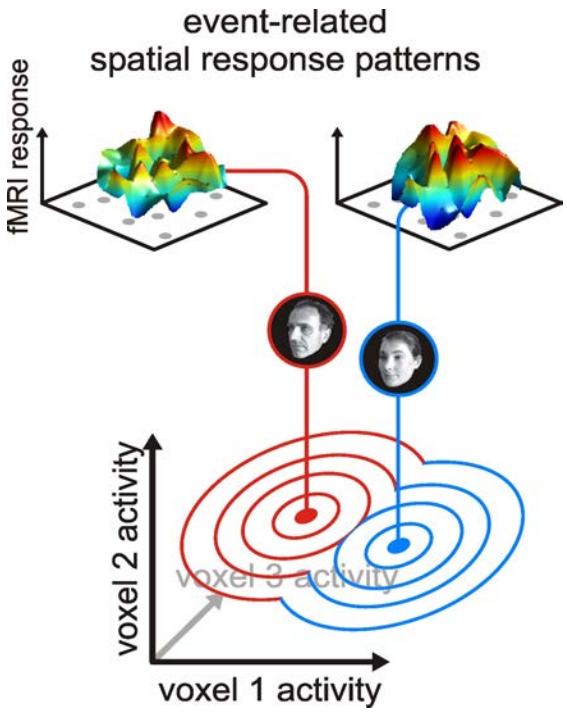

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