Fluctuations and Networks: Thinking and Breathing

Peter A. Bandettini, Ph.D.

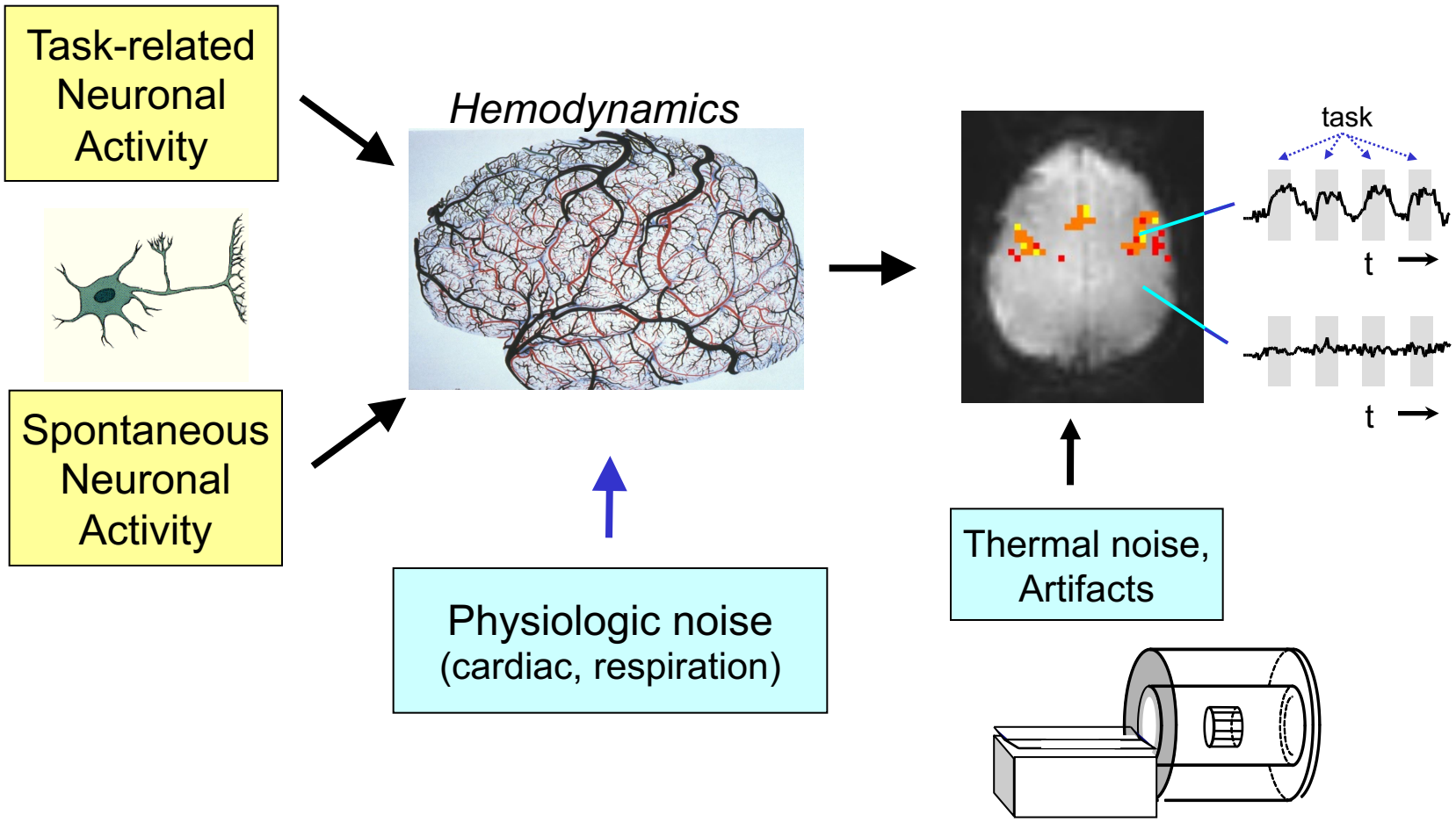
Section on Functional Imaging Methods & Functional MRI Facility
National Institutes of Mental Health, NIH

Overview

- "Functional connectivity"
  - Correlations in fMRI signal at rest
  - "Default Mode Network"
- Respiration changes in fMRI
- Respiration + Functional Connectivity
- Modeling respiration-induced fMRI changes

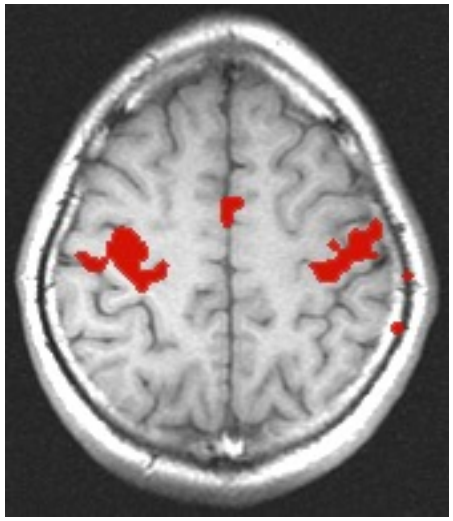
Rasmus Birn

The fMRI Signal

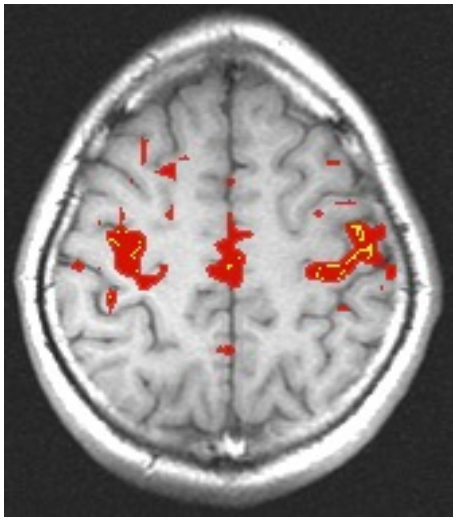


Resting-state functional connectivity

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



Activation during finger-tapping



Correlations with “seed voxel” in motor cortex at rest

Further work:

M.J. Lowe, et al., NeuroImage 7(2), 1998.
D. Cordes, et al., AJNR 21(9), 2000.

⋮

“Default-Mode Network”

A default mode of brain function

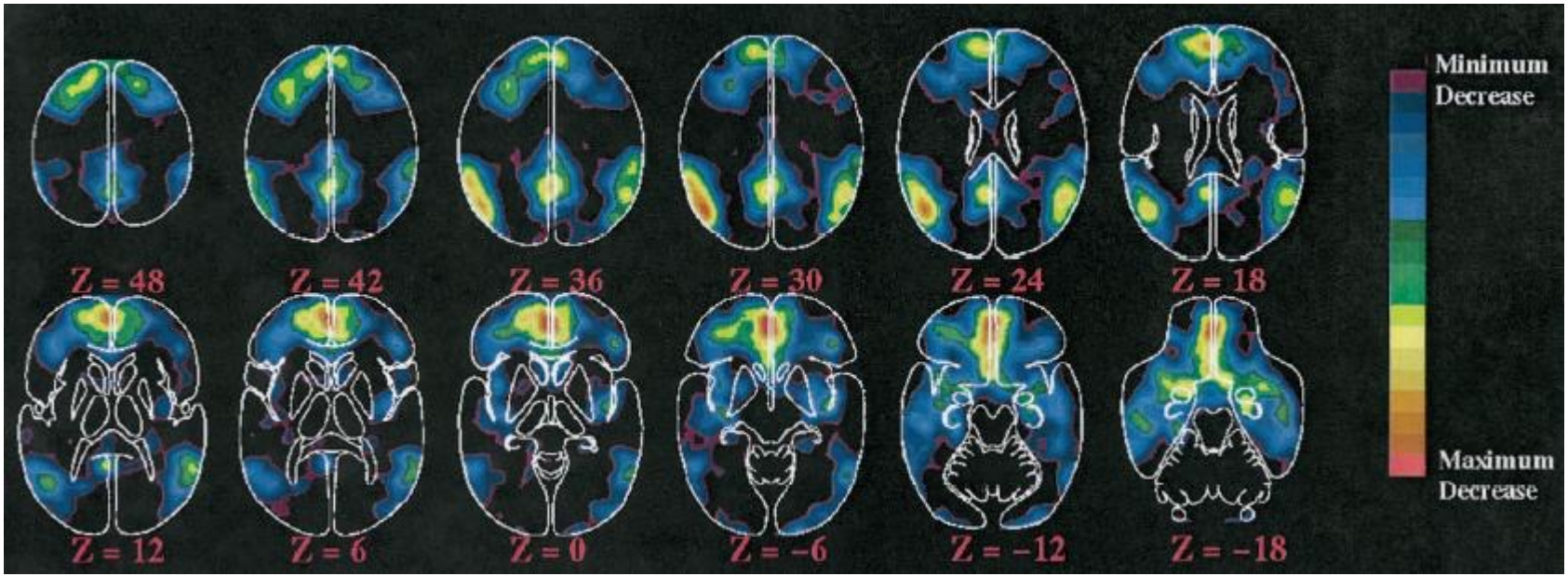
Marcus E. Raichle*†, Ann Mary MacLeod*, Abraham Z. Snyder*, William J. Powers‡, Debra A. Gusnard*§, and Gordon L. Shulman‡

*Mallinckrodt Institute of Radiology and Departments of ‡Neurology and §Psychiatry, Washington University School of Medicine, St. Louis, MO 63110

This contribution is part of the special series of Inaugural Articles by members of the National Academy of Sciences elected on April 30, 1996.

Contributed by Marcus E. Raichle, October 26, 2000

PNAS 98, 2001



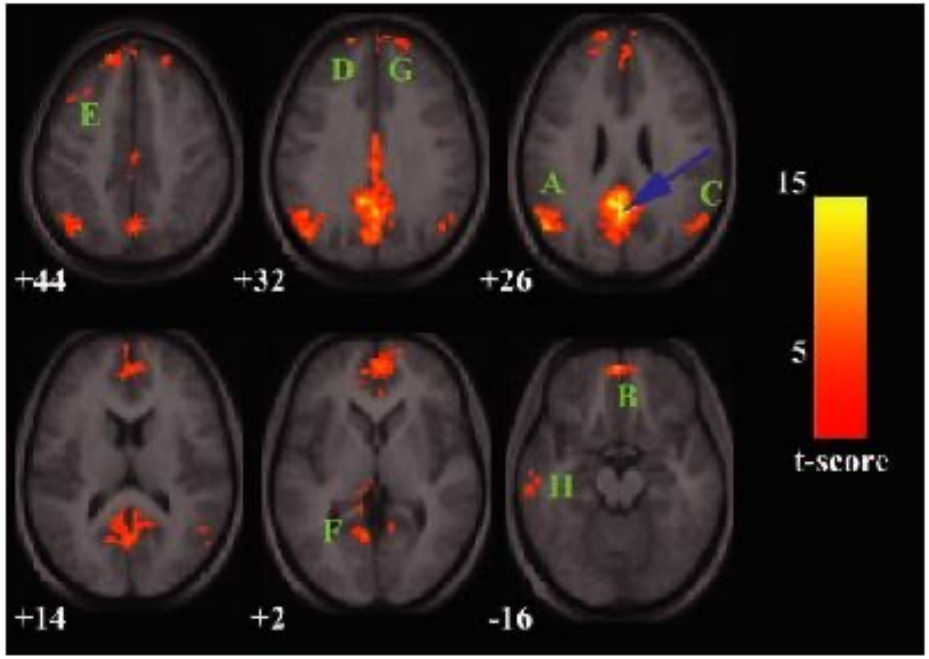
Resting-state functional connectivity

Functional connectivity in the resting brain: A network analysis of the default mode hypothesis

Michael D. Greicius*†‡, Ben Krasnow*, Allan L. Reiss*§¶, and Vinod Menon*§¶

Departments of *Psychiatry and Behavioral Sciences and †Neurology and Neurological Sciences, §Program in Neurosciences, and ¶Stanford Brain Research Center, Stanford University School of Medicine, Stanford, CA 94305-5719

Edited by Marcus E. Raichle, Washington University School of Medicine, St. Louis, MO, and approved November 12, 2002 (received for review August 21, 2002)



PNAS 100, 2003

Deactivations ⟺ Resting correlations

Jason Diamond

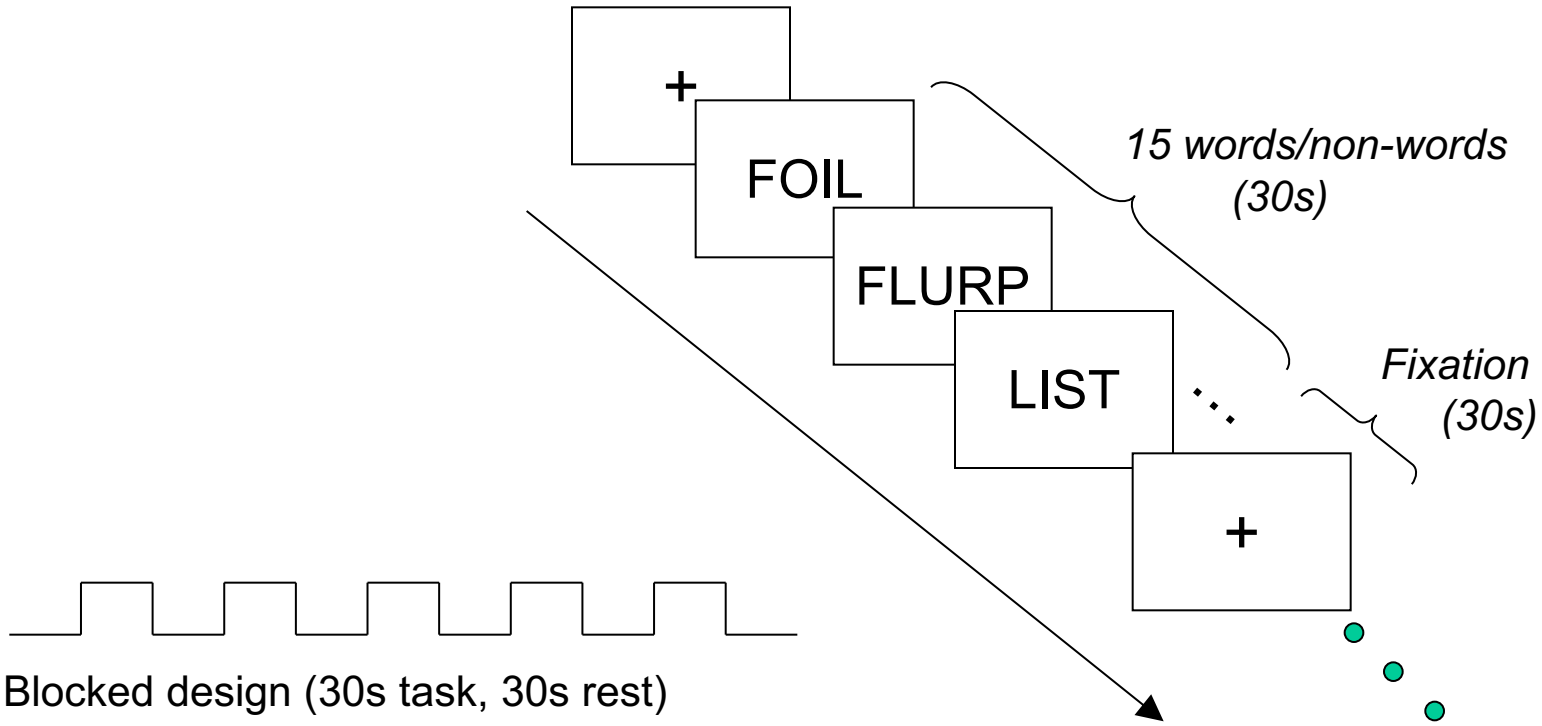
- *Are there differences?*
  - Deactivation (blocked design)
  - Rest (functional connectivity)
- *Are deactivations related to the task, or to the brain "state"?*
  - Mixed blocked / event-related

Methods

R.M. Birn, J.B. Diamond, M.A. Smith, P.A. Bandettini, NeuroImage 31, 2006

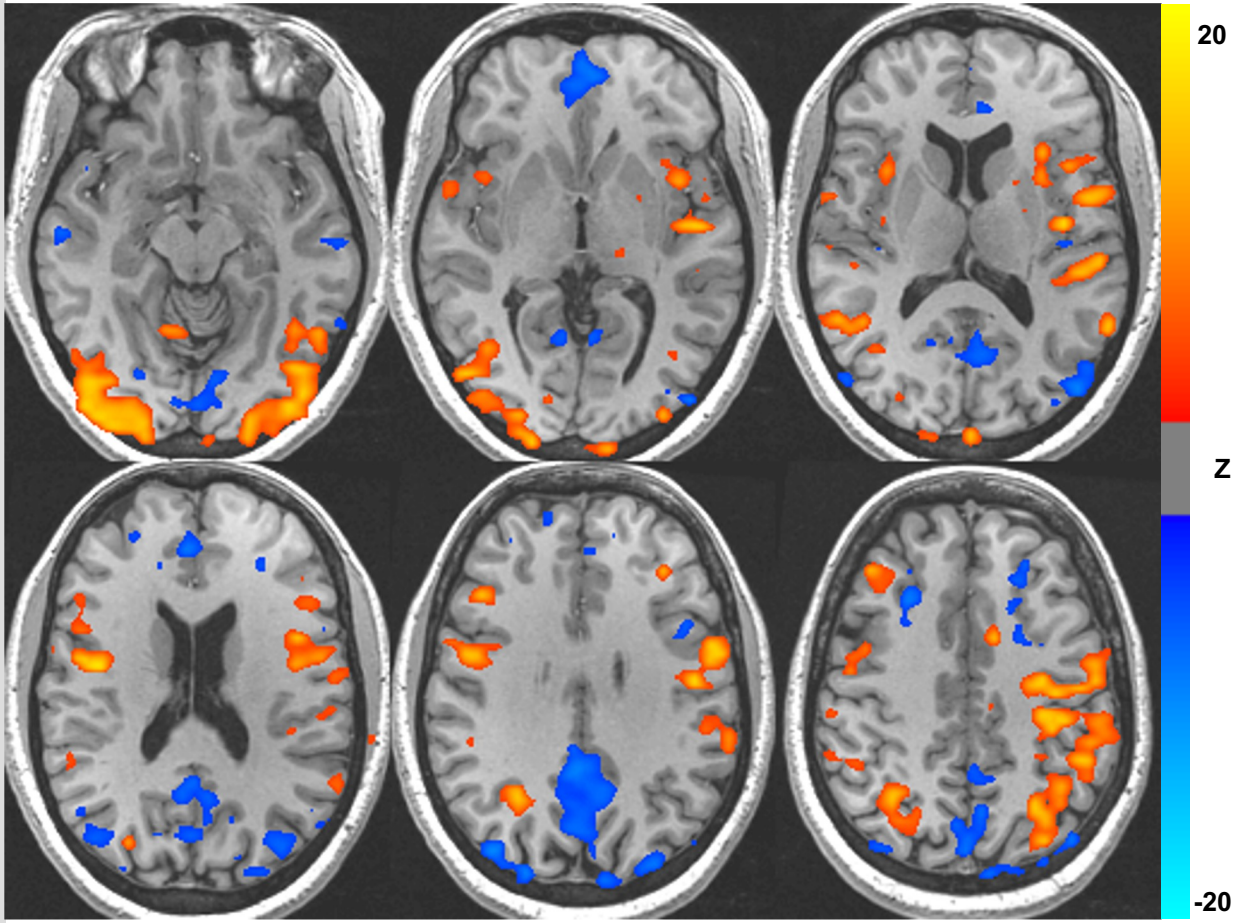
Task

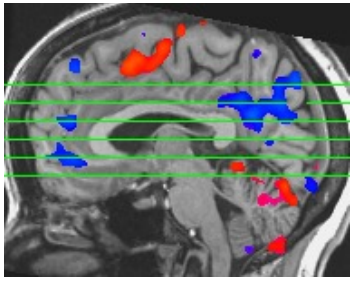
1. ***Rest (eyes-closed)***
2. ***Lexical Decision:*** "word" or "non-word"?



Results – Lexical Task

Activations and De-activations during lexical task

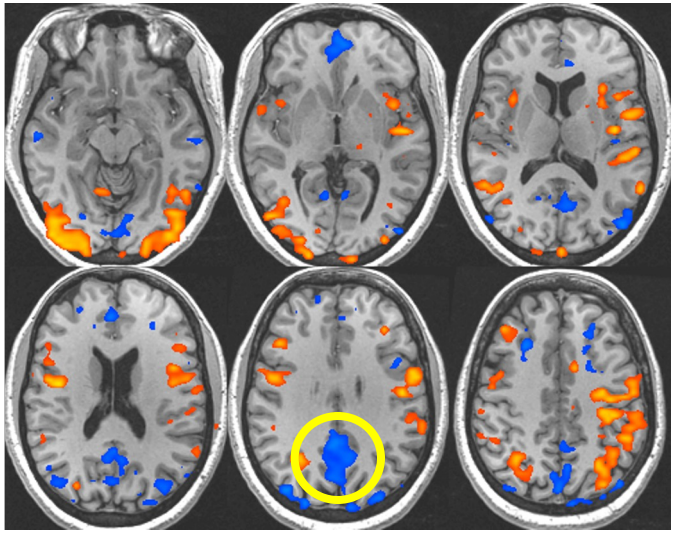




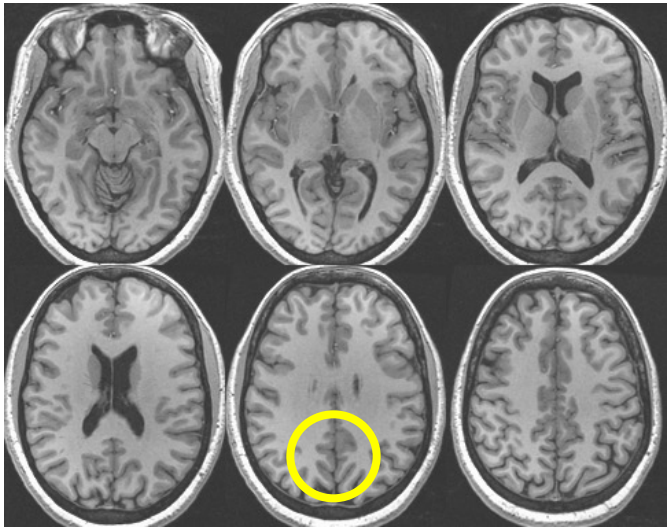
Methods

Functional Connectivity Analysis

- 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



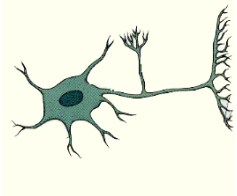
Lexical task



Rest

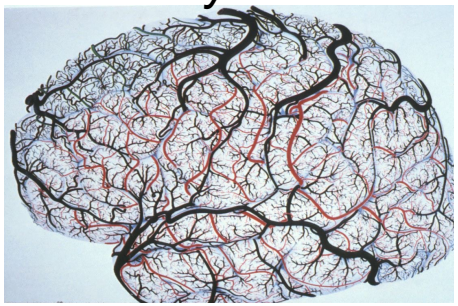
The fMRI Signal

Task-related Neuronal Activity

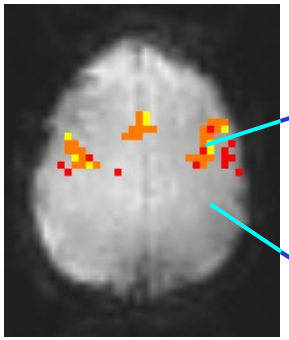


Spontaneous Neuronal Activity

Hemodynamics



Physiologic noise
(cardiac, respiration)

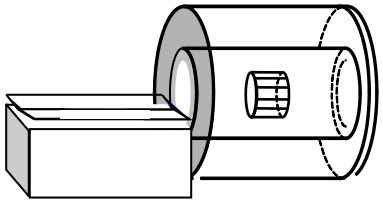


task

t

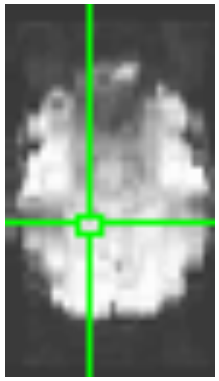
t

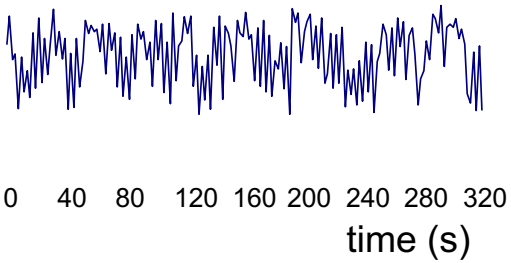
Thermal noise,
Artifacts

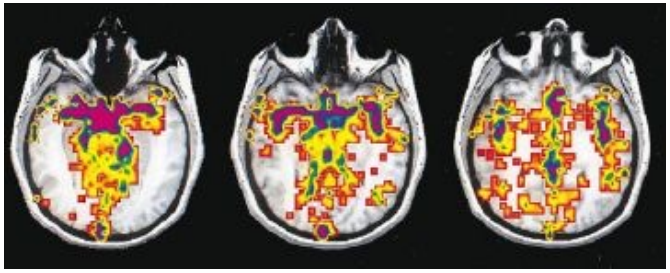


Physiological fluctuations

Cardiac

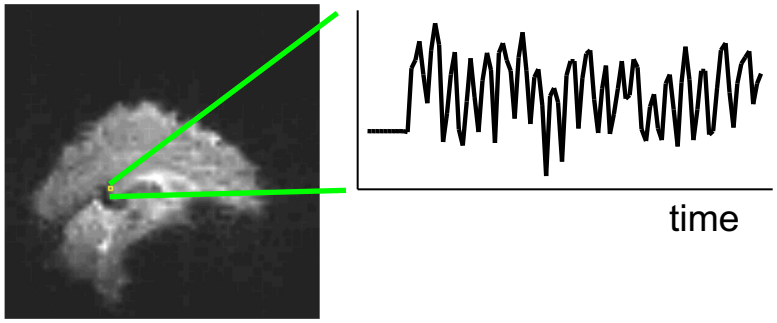


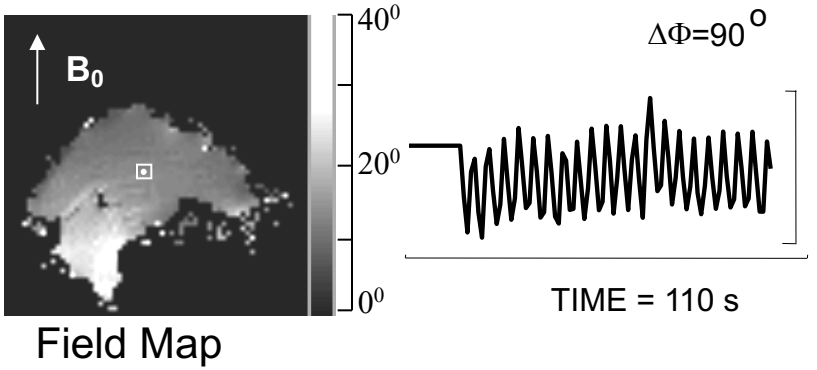




M.S. Dagli et al., NeuroImage 9, 1999

Respiration



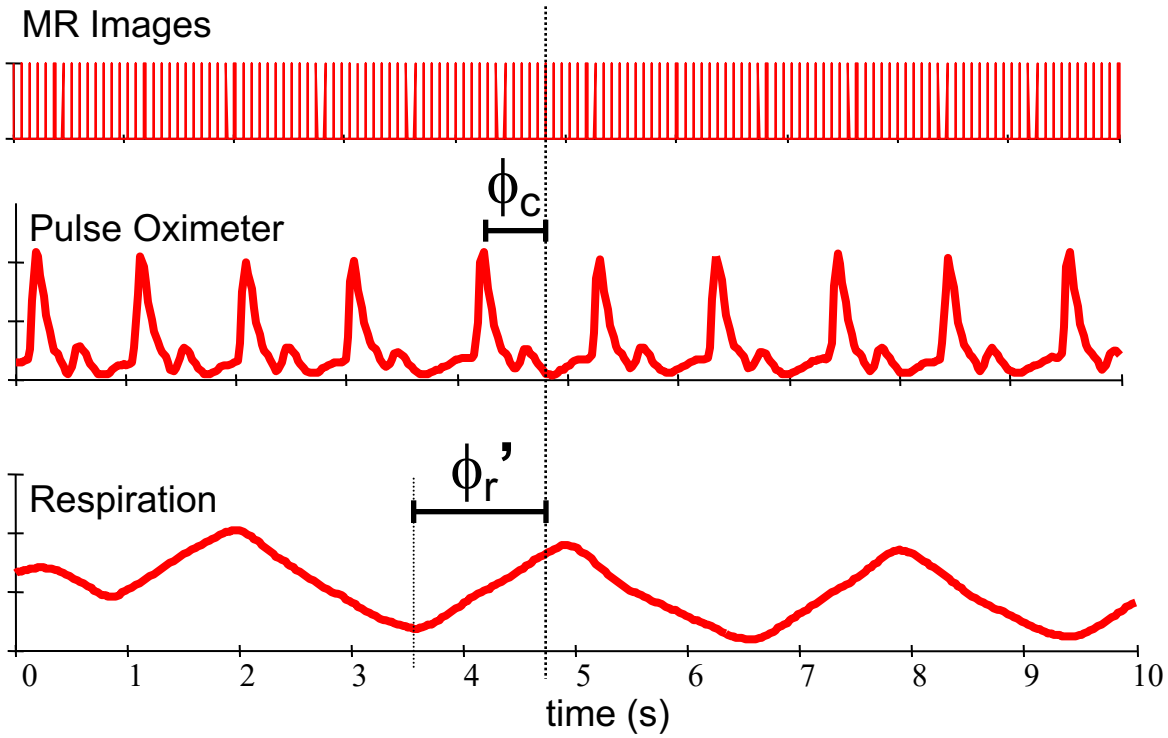


Field Map

Figure courtesy of J. Bodurka

Correction of physiological noise

RETROICOR *(G. Glover et al., Magn. Reson. Med. 44, 2000.)*



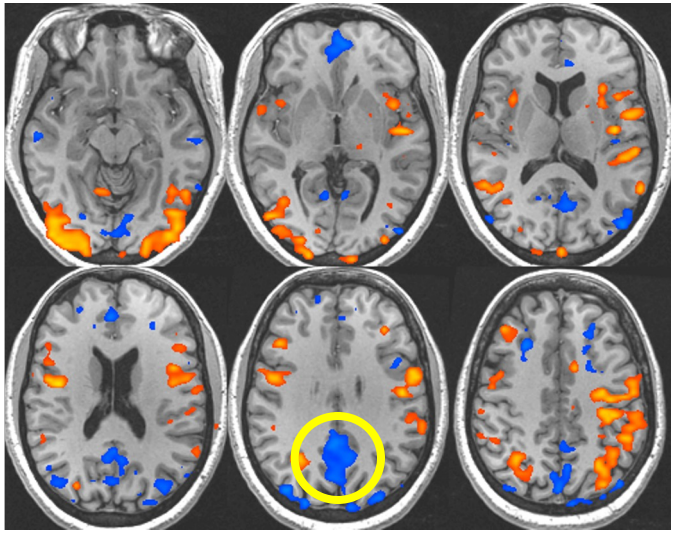
Additional Regressors:

$$\left\{\begin{array}{l}\sin(\phi_c)\\ \cos(\phi_c)\\ \sin(2\phi_c)\\ \cos(2\phi_c)\end{array}\right.\quad\left\{\begin{array}{l}\sin(\phi_r)\\ \cos(\phi_r)\\ \sin(2\phi_r)\\ \cos(2\phi_r)\end{array}\right.$$

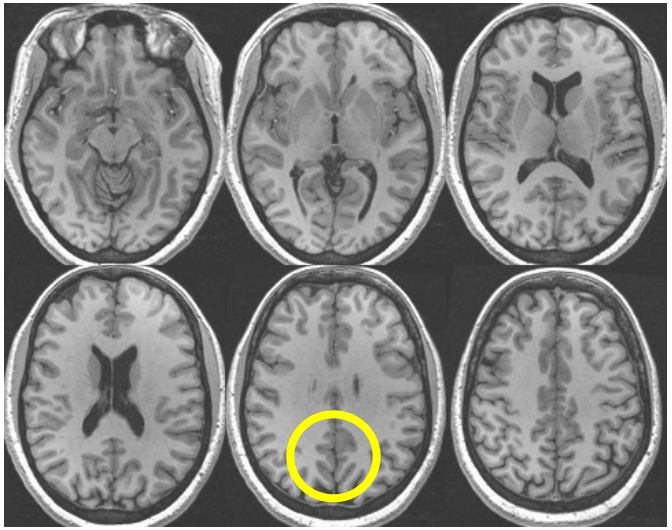
Methods

Functional Connectivity Analysis

- 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

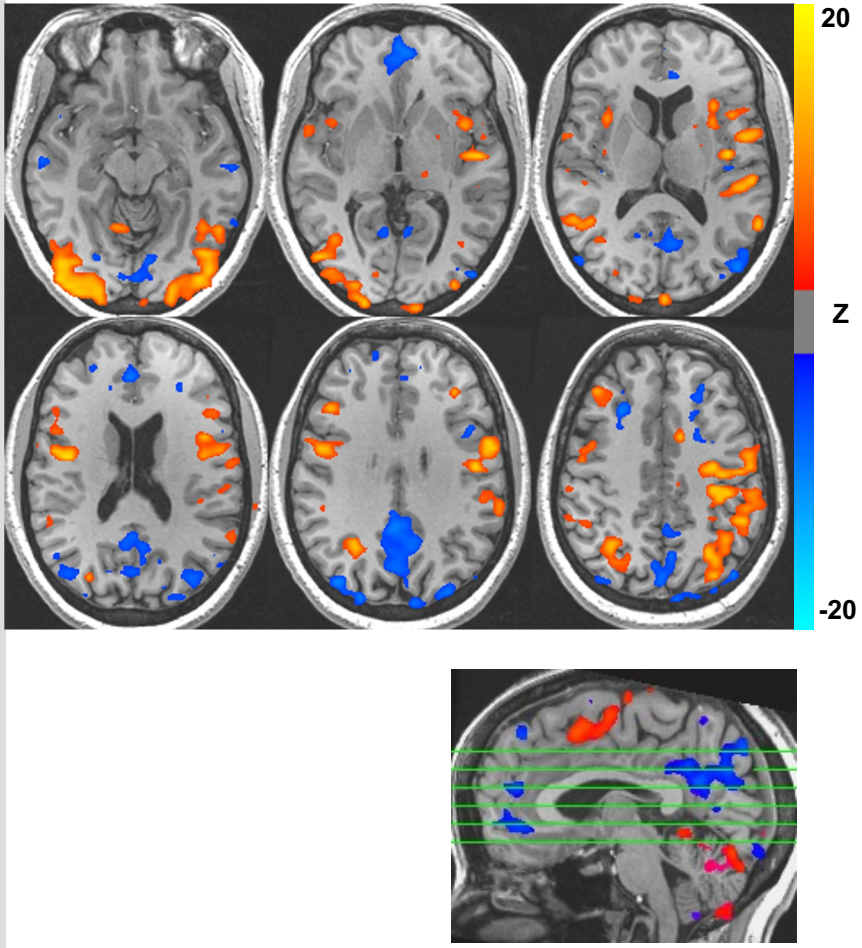


Rest

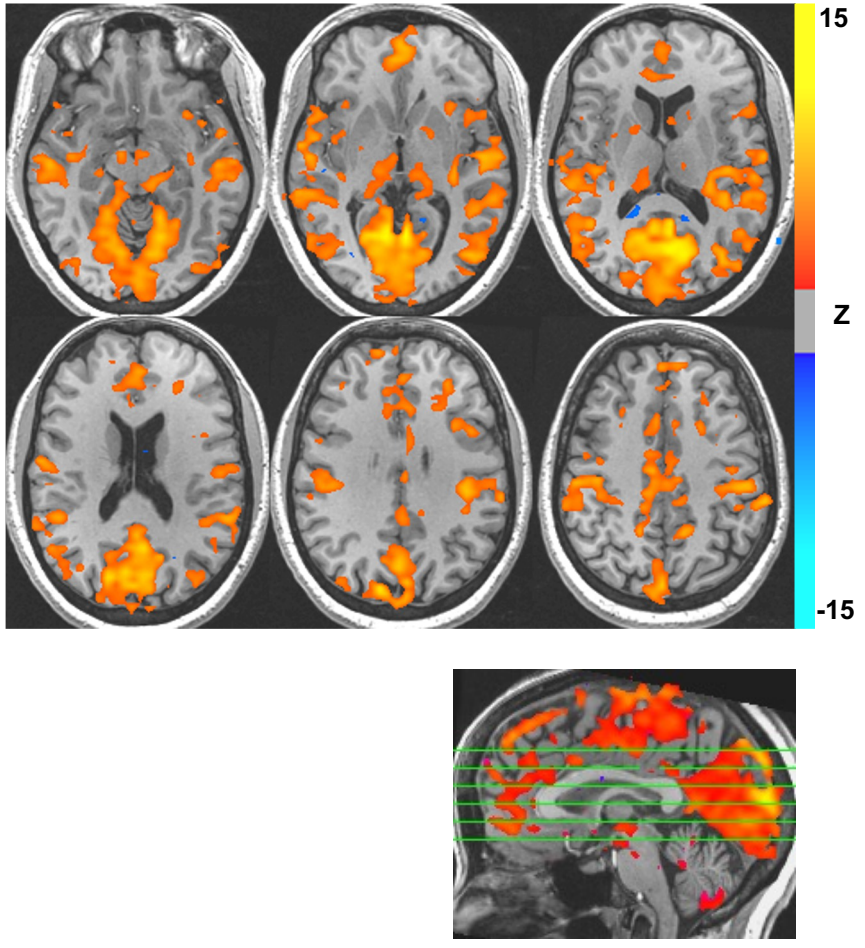
Functional Connectivity Analysis

1 subject

Activations during lexical task



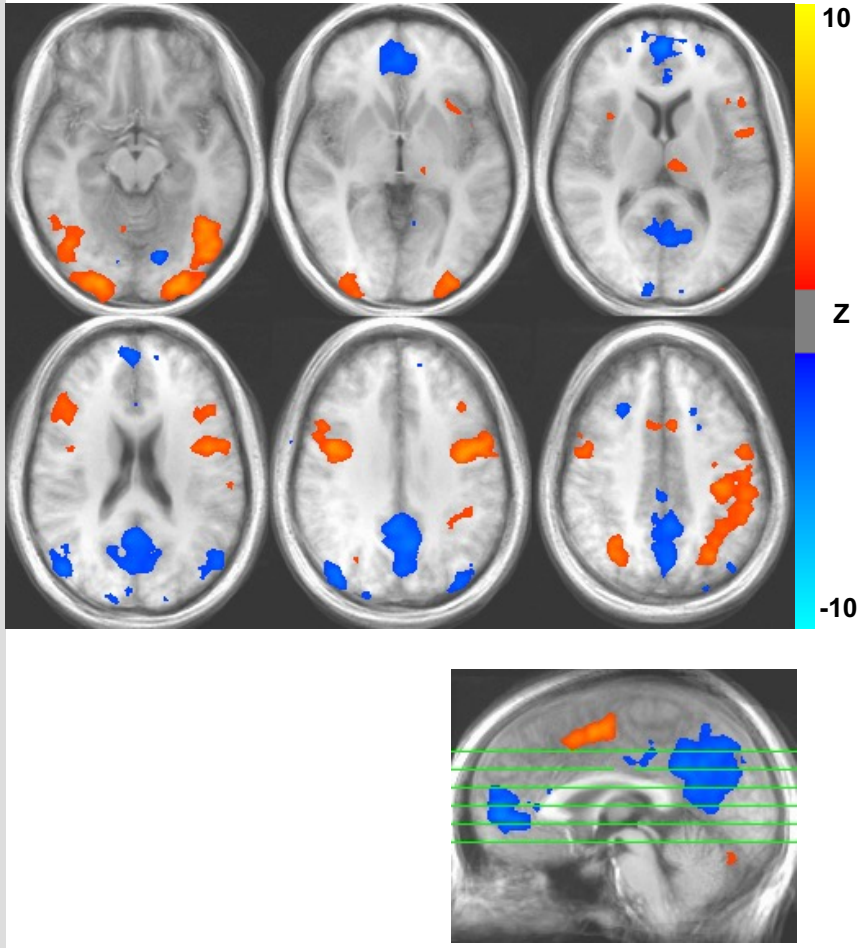
Correlation (of PC) at Rest



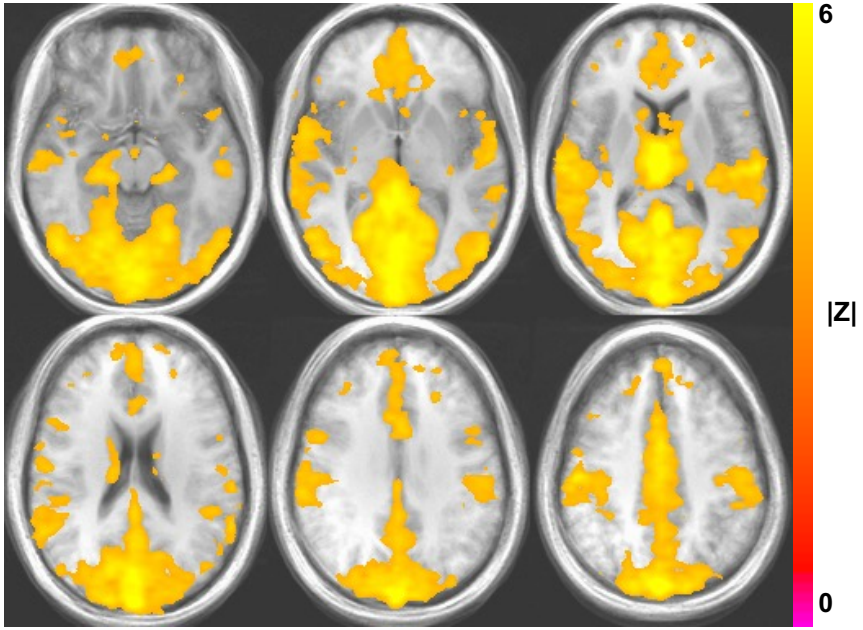
Functional Connectivity Analysis

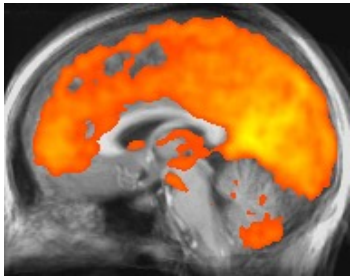
Group (n=10)

Activations during lexical task



Correlation (of PC) at Rest



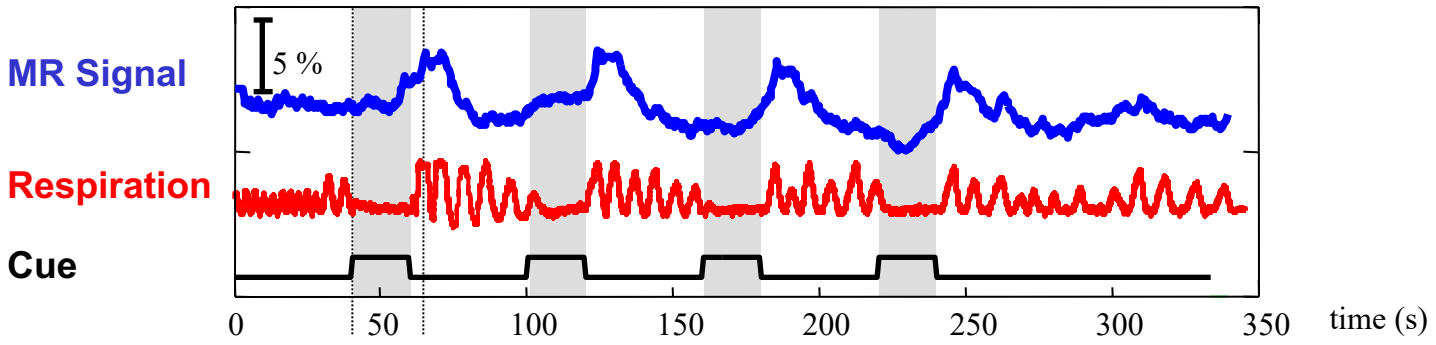


Overview

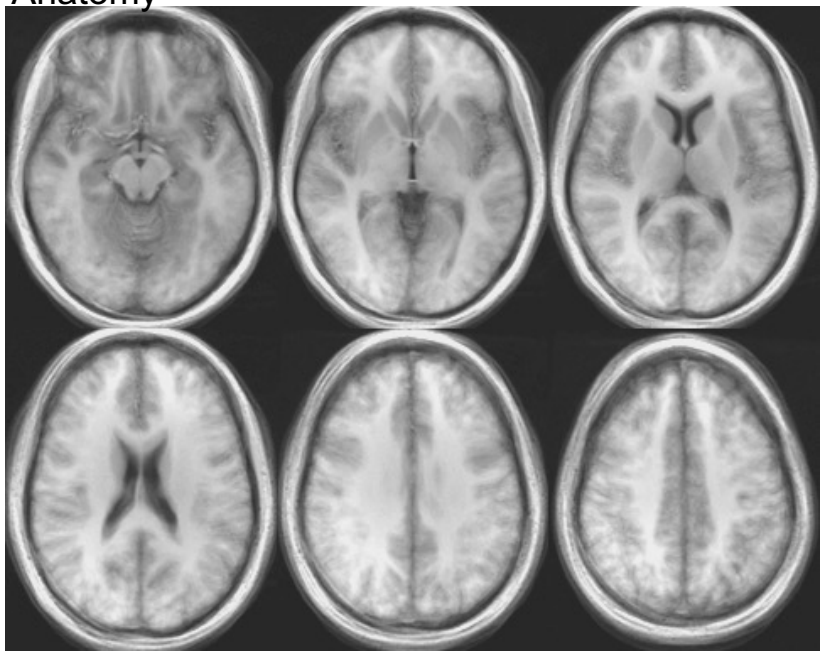
- "Functional connectivity"
  - Correlations in fMRI signal at rest
  - "Default Mode Network"
- Respiration changes in fMRI
- Respiration + Functional Connectivity
- Modeling respiration-induced fMRI changes

Breath-holding

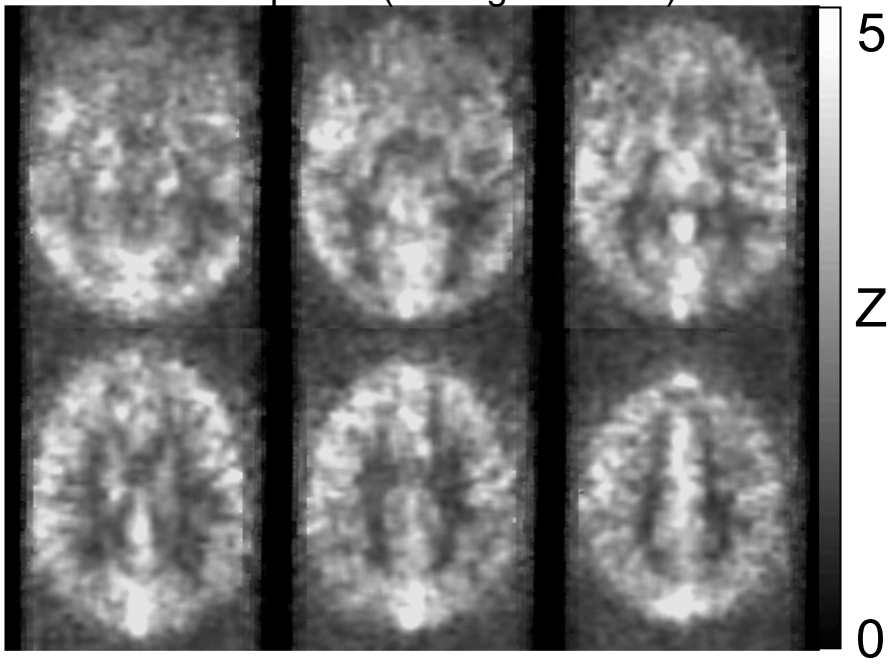
Group Maps (N = 7)



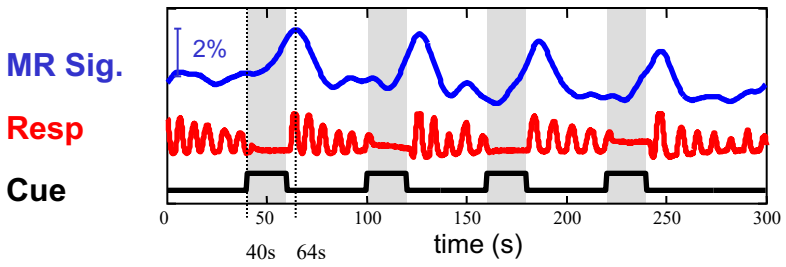
Anatomy

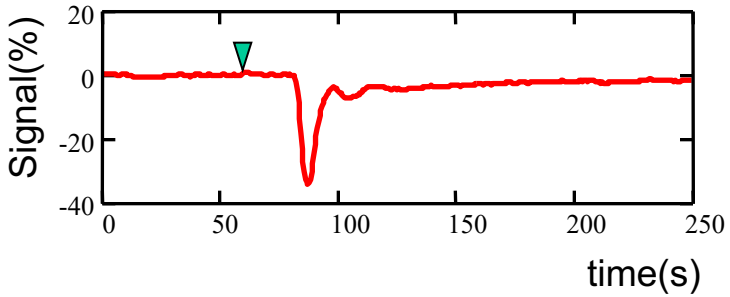


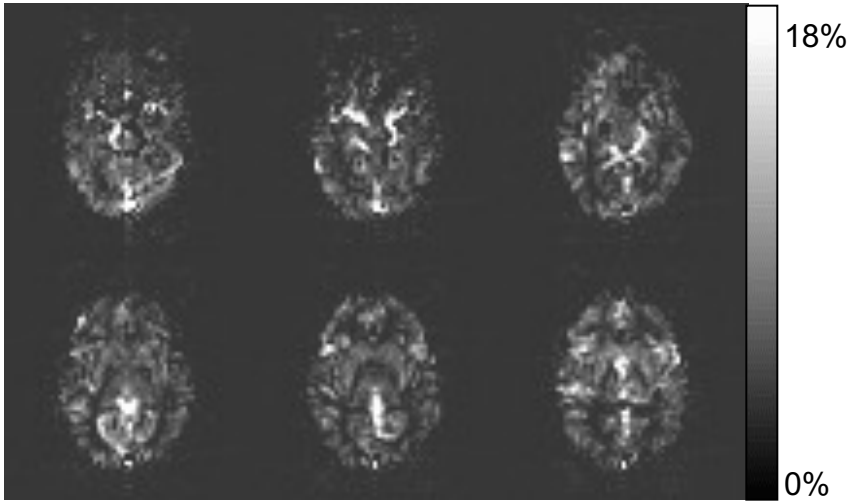
Breath-hold response (average Z-score)

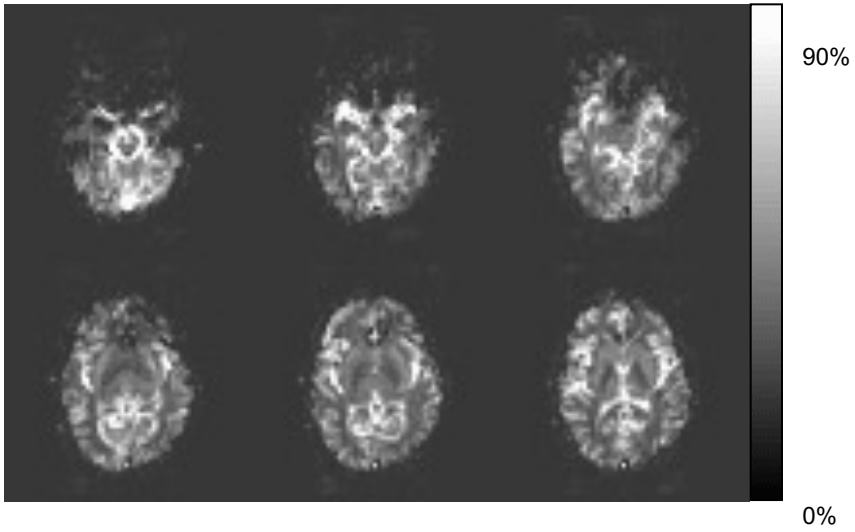


Breath-hold vs. bolus contrast (Gd-DTPA)





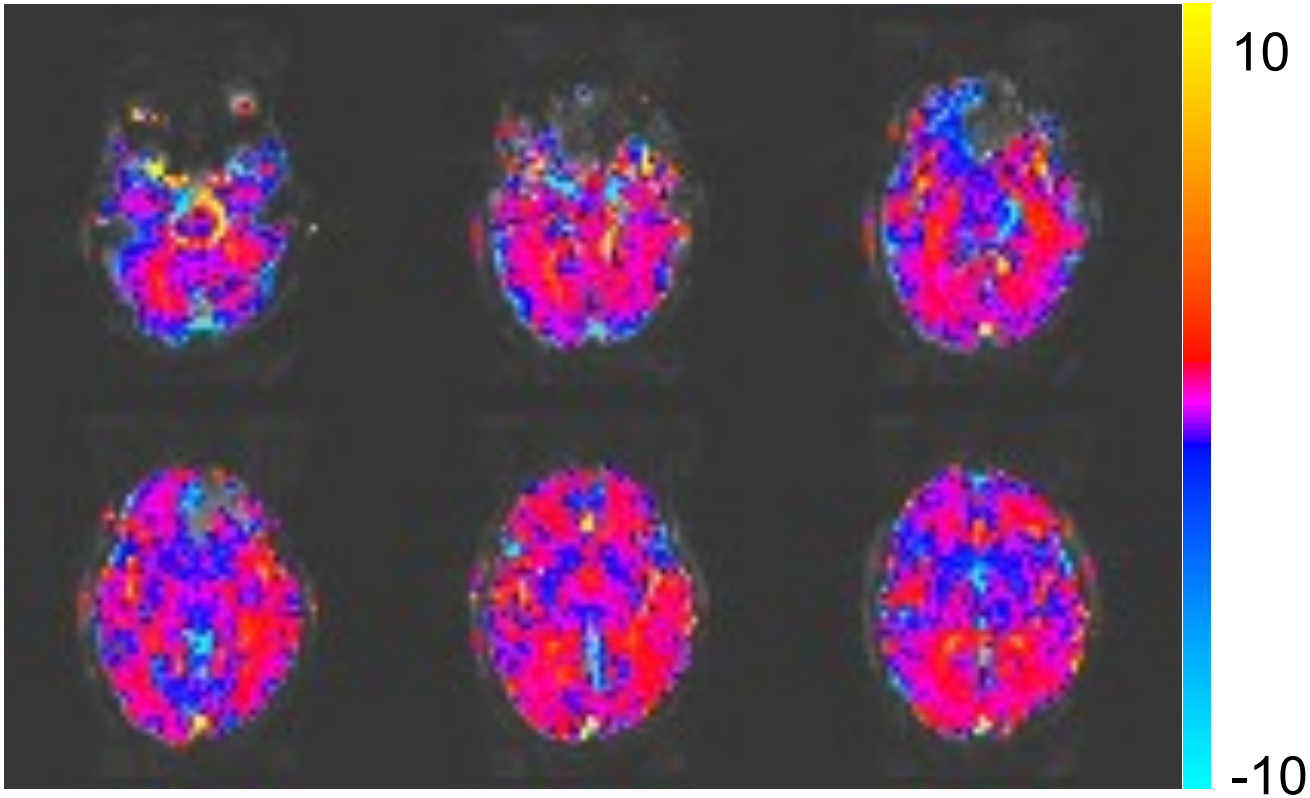




Breath-hold vs. bolus contrast (Gd-DTPA)

Relative difference: ΔS (Gd-DTPA) – ΔS (Breath-hold)

Arteries vs. Veins ?

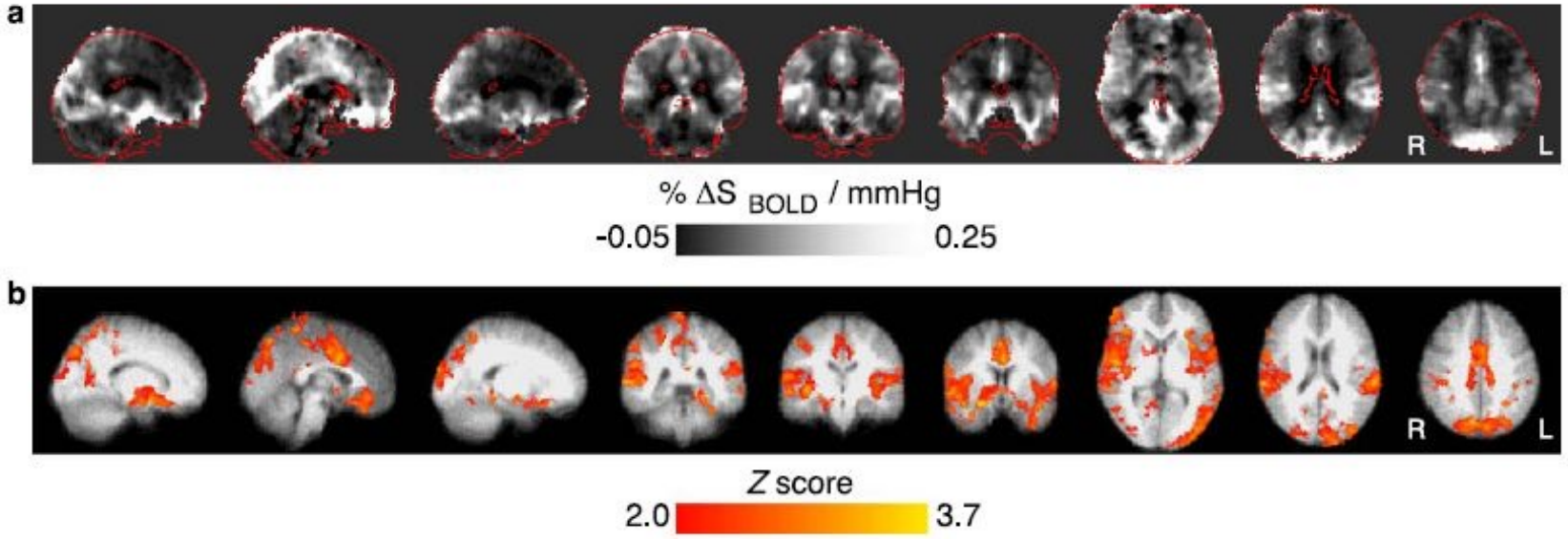


Resting fluctuations in respiration

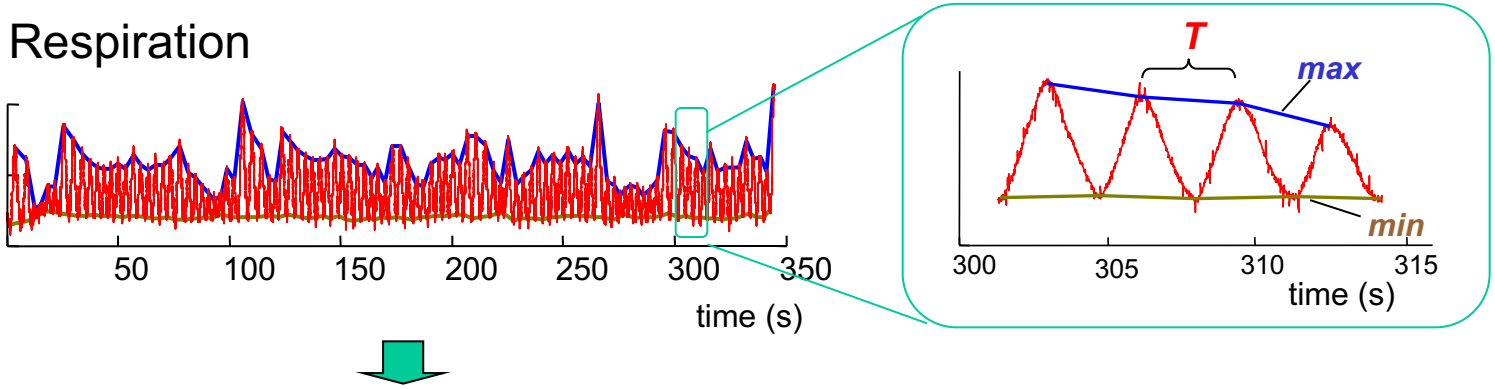
Resting fluctuations in arterial carbon dioxide induce significant low frequency variations in BOLD signal

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

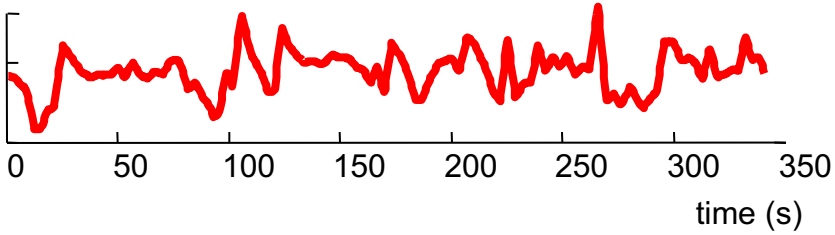
NeuroImage 21, 2004



Estimating respiration volume changes



Respiration Volume / Time (**RVT**)



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

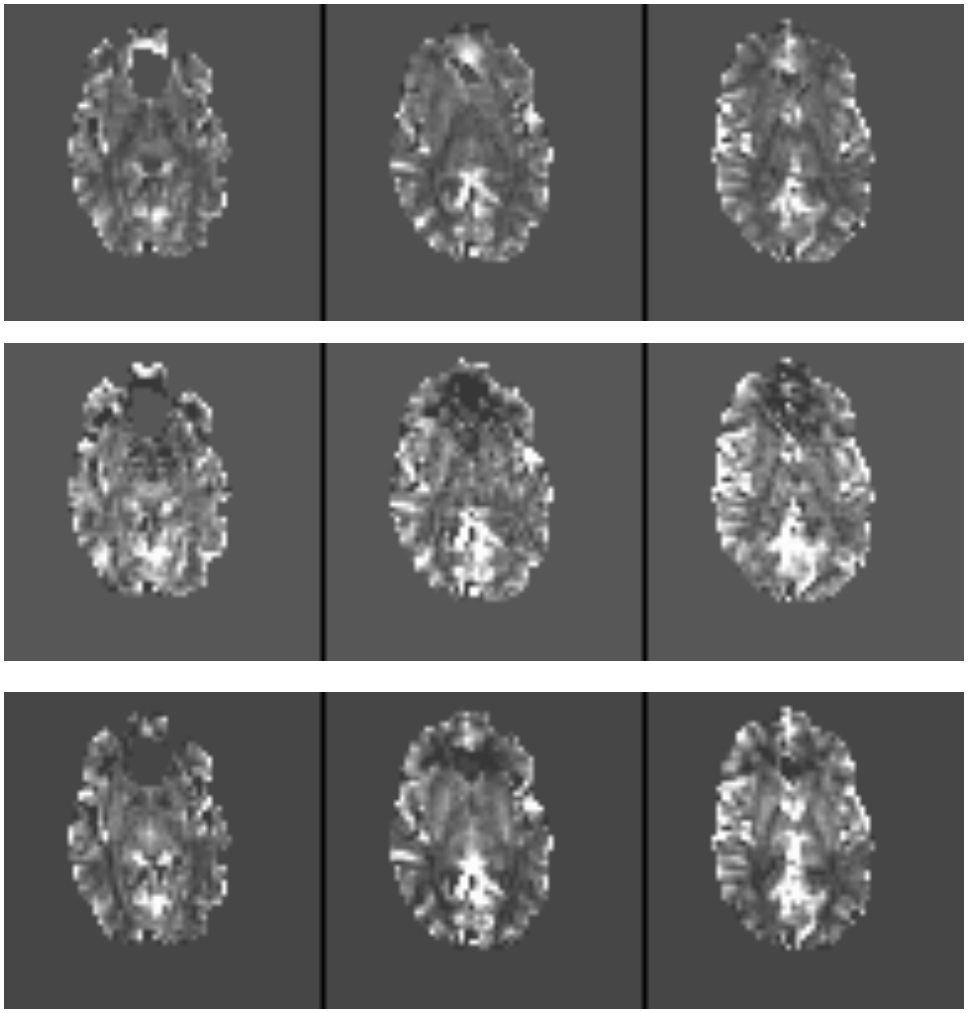
Resting fluctuations in respiration

Correlation of fMRI time course with:

RVT

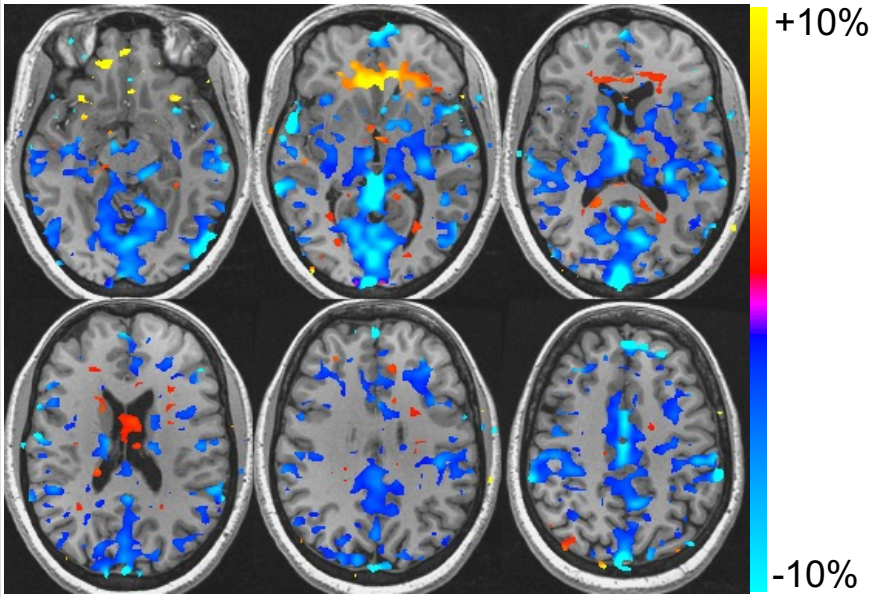
etCO2

BH

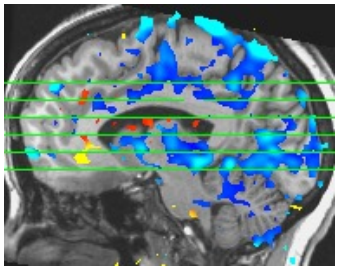


Resting fluctuations in respiration

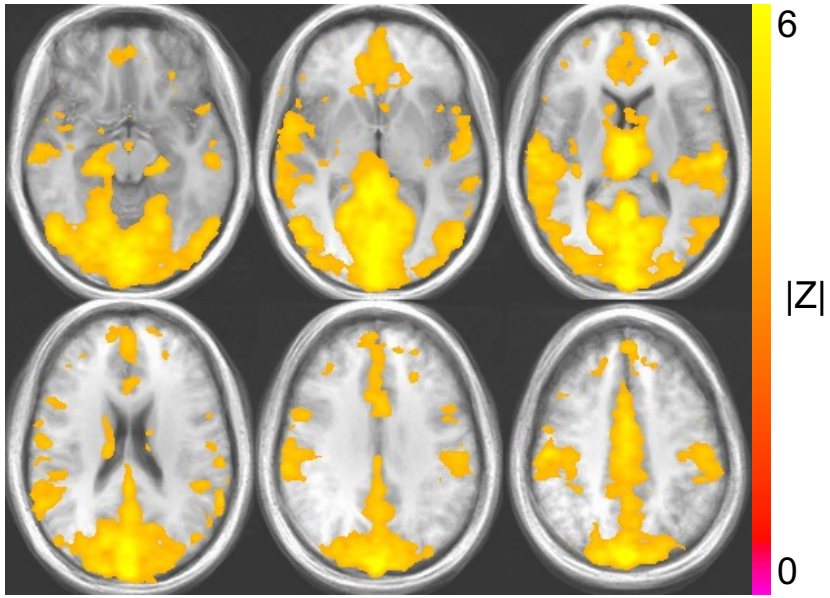
Amplitude of BOLD signal correlated w/ RVT



1 subject



Z-score of BOLD signal correlated w/ RVT

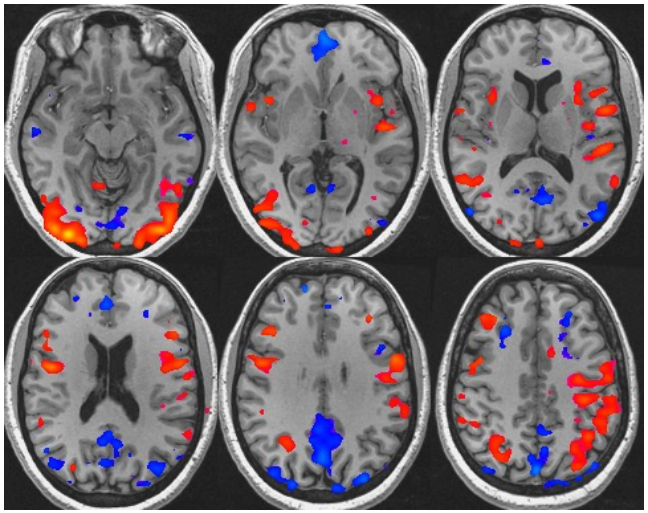


group (n=11)

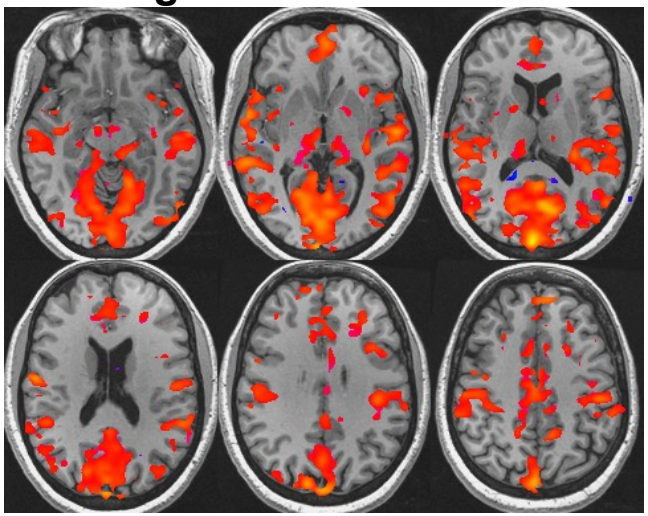
RVT = ***R****espiration* ***V****olume per* ***T****ime*

Respiration changes co-localize

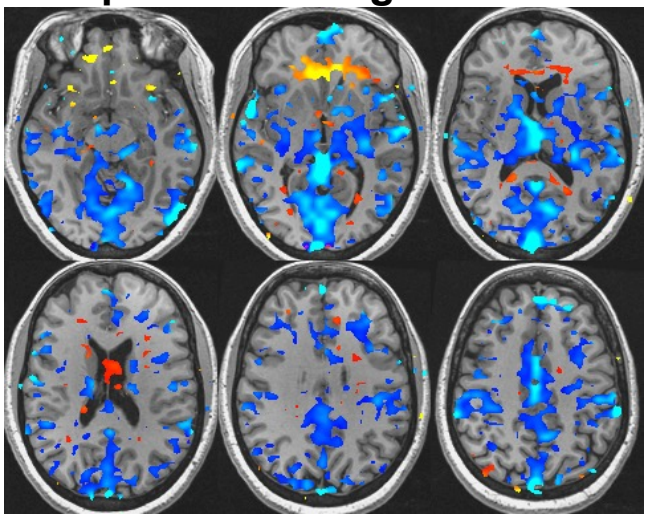
Deactivations

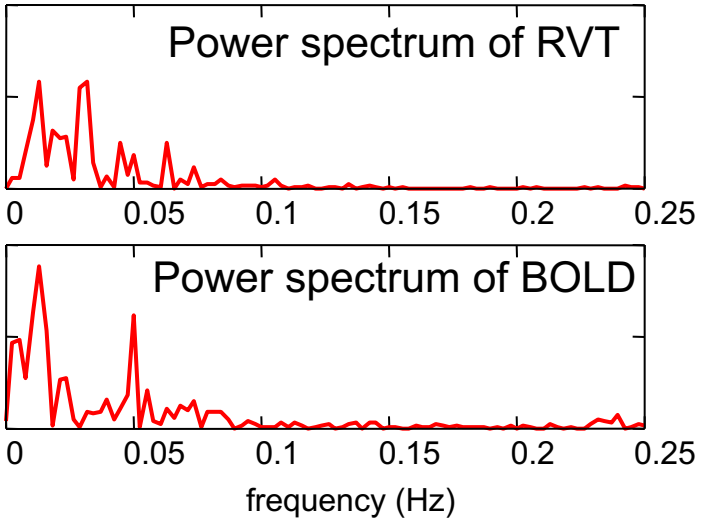


Resting-state corr. from seed ROI



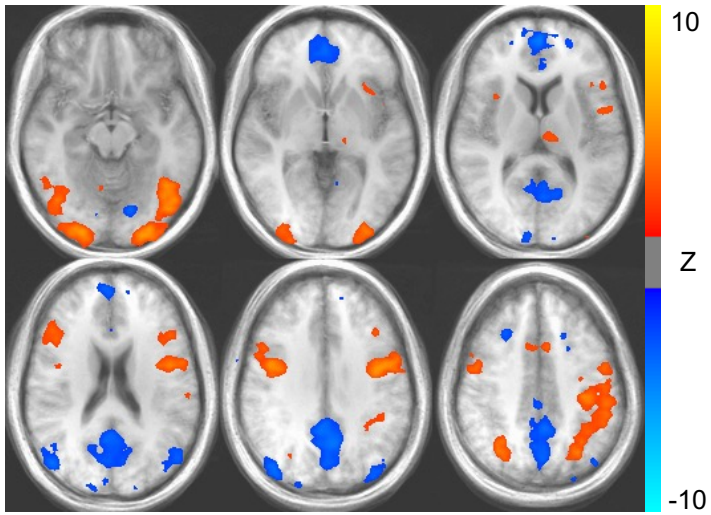
Respiration changes – corr. w/ RVT



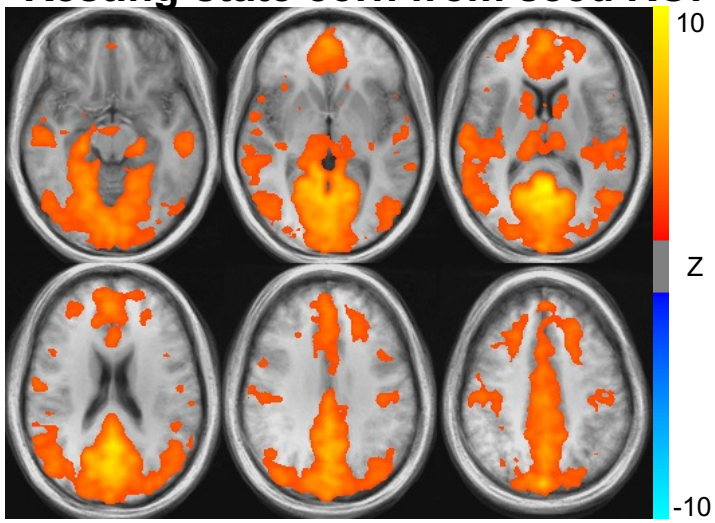


Respiration changes co-localize

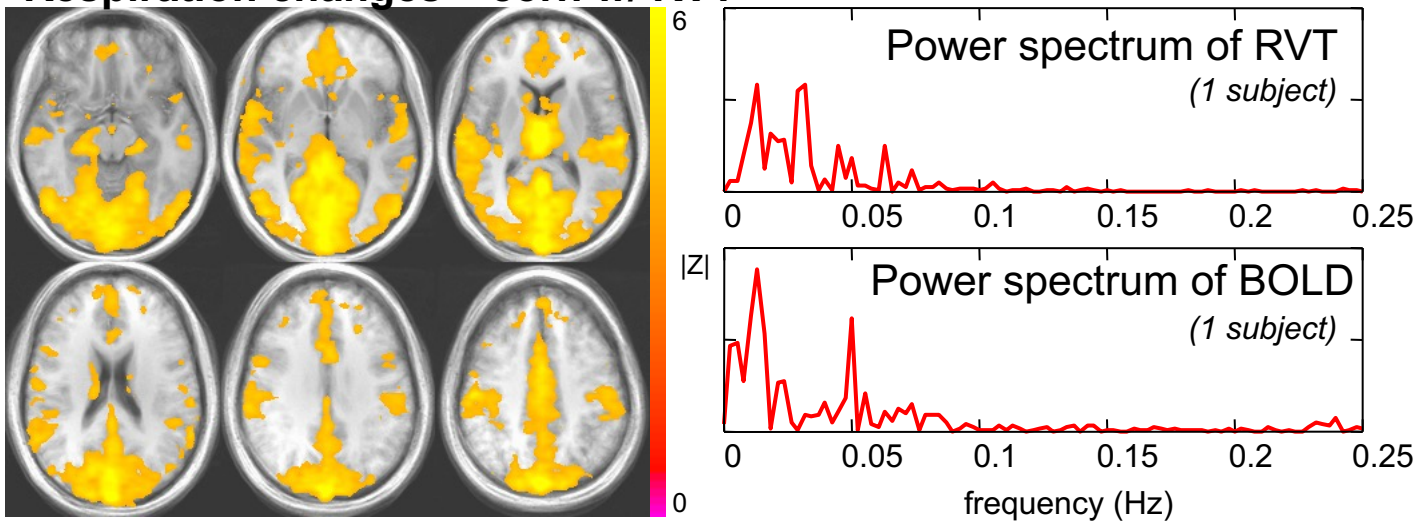
Deactivations



Resting-state corr. from seed ROI



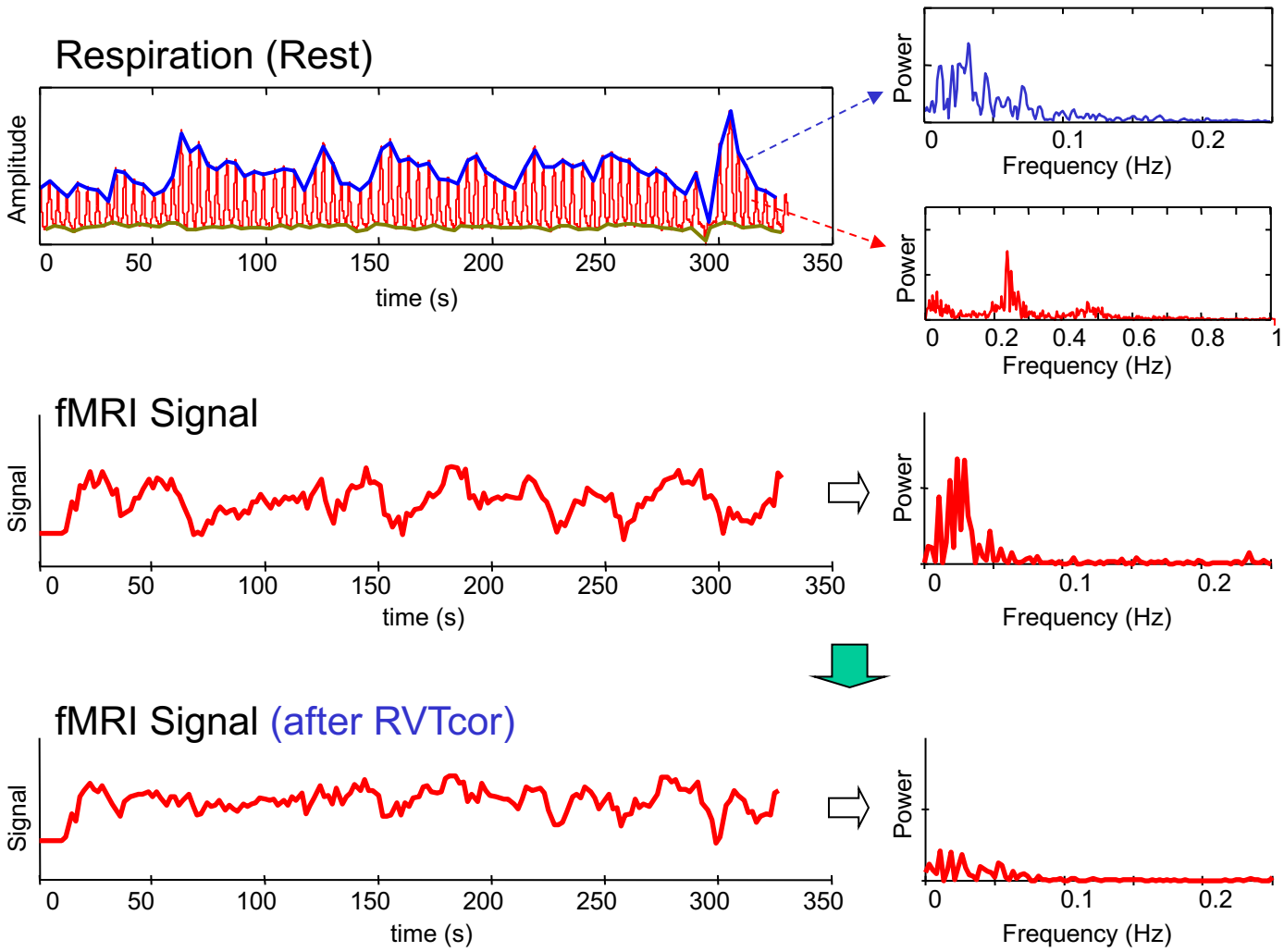
Respiration changes – corr. w/ RVT



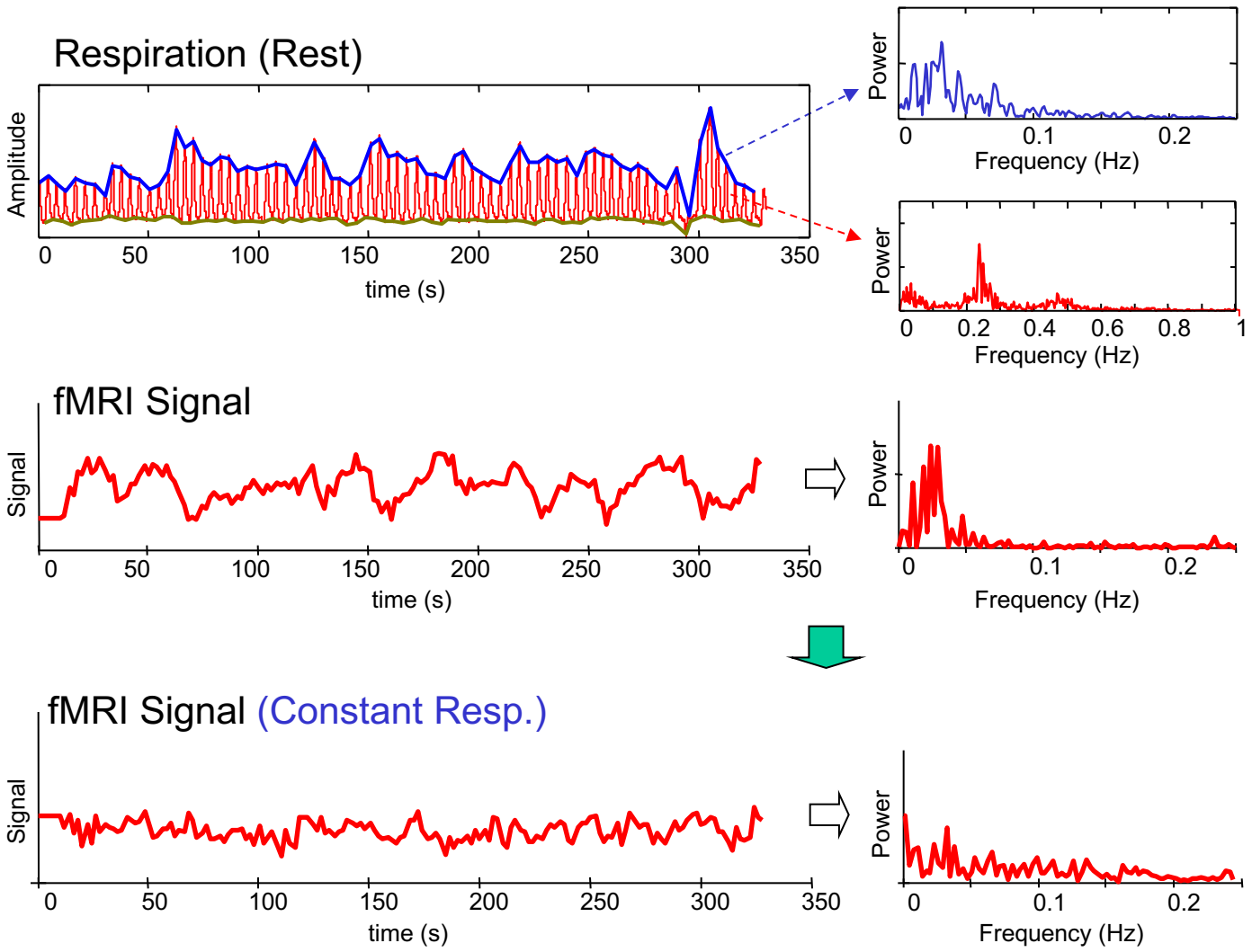
Correcting for changes in respiration

- Regress out RVT
- Keep respirations constant

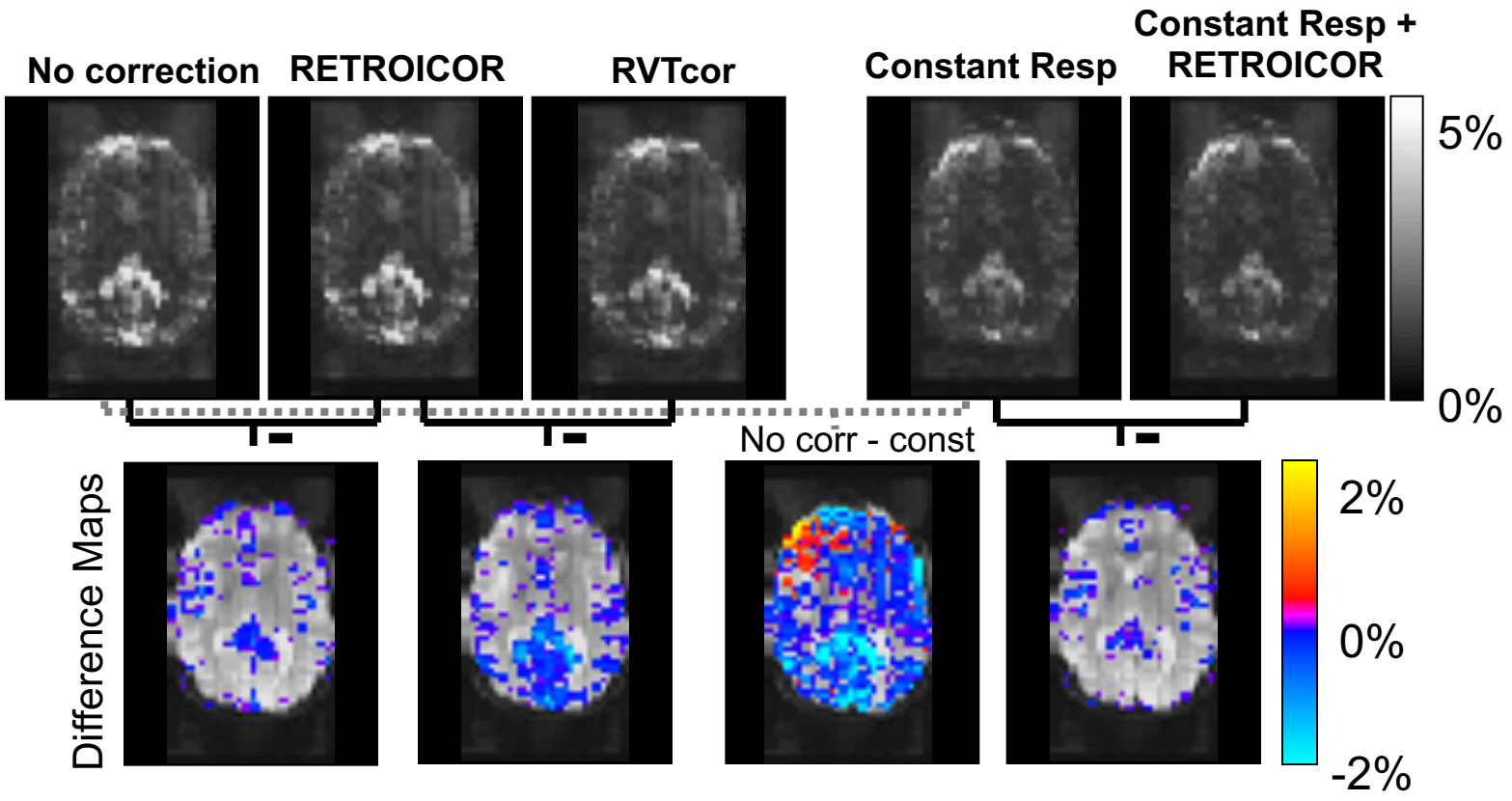
Regress out Cardiac, Respiration, RVT



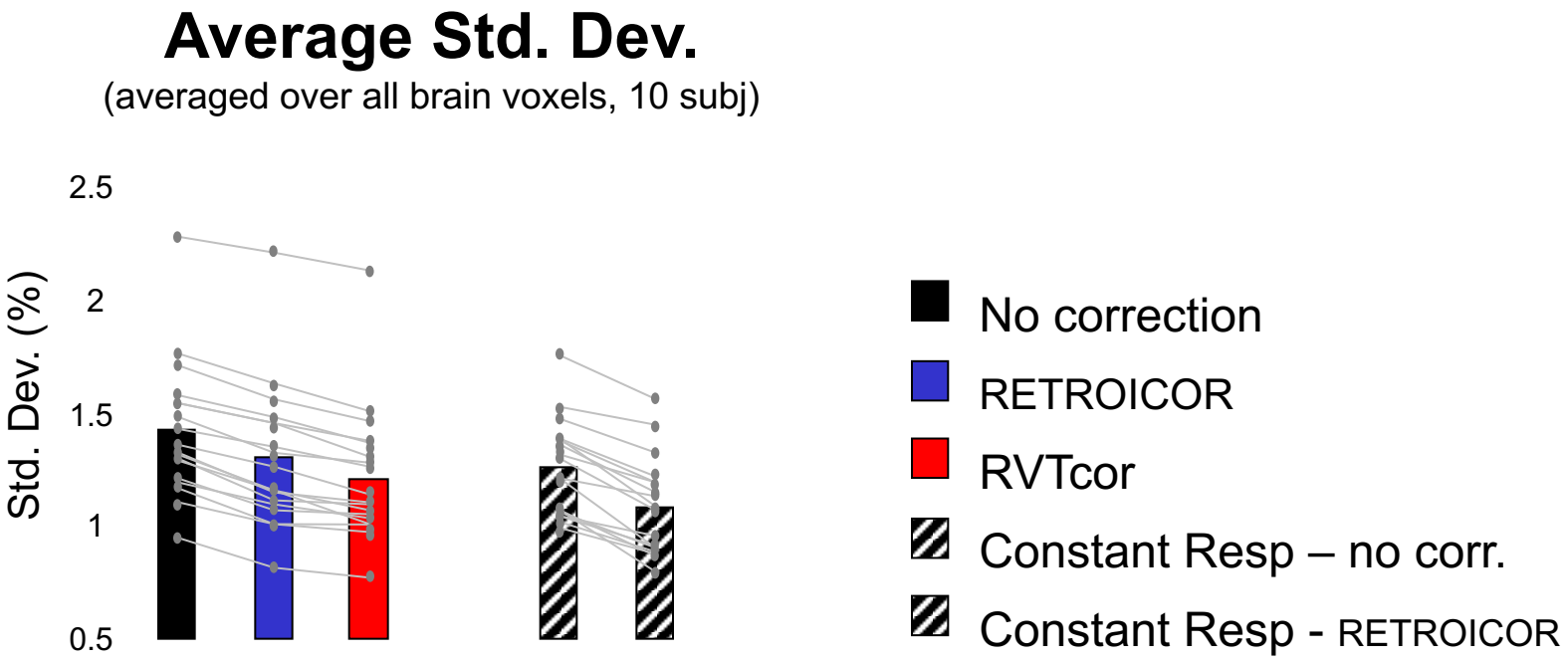
Cue subject to keep breathing constant



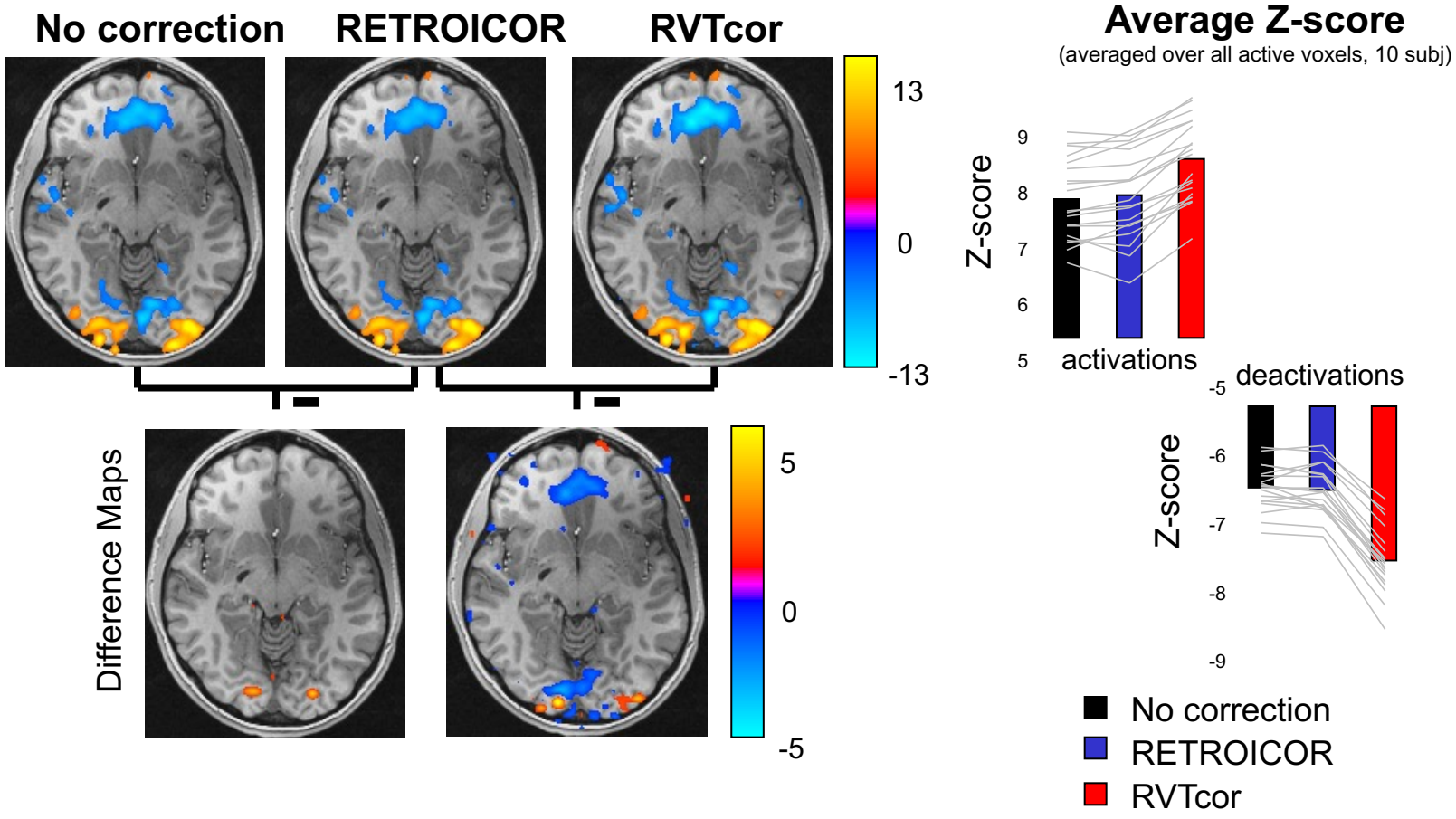
Standard Deviation over time



Standard Deviation over time



Improving the detection of function



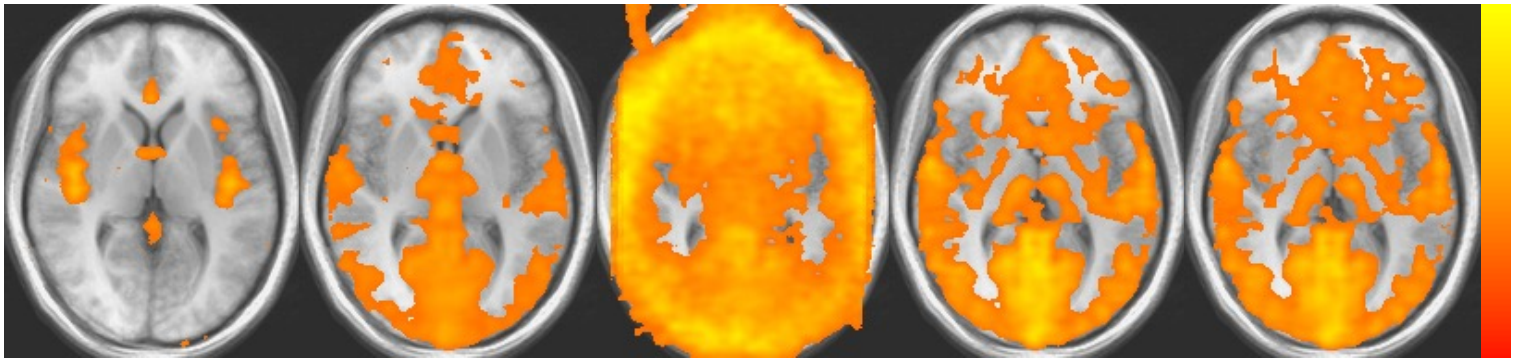
More Corrections?

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

Multiple physiological corrections

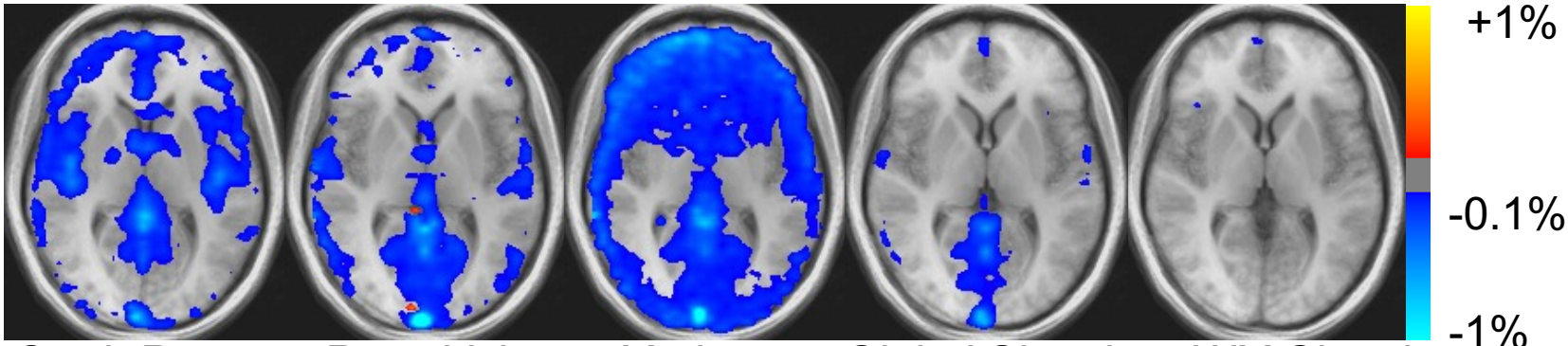
Correlation with each regressor

(n = 10)



Card+Resp *Resp Vol* *Motion* *Global Signal* *WM Signal*

Differences in Std. Dev. when each regressor is removed

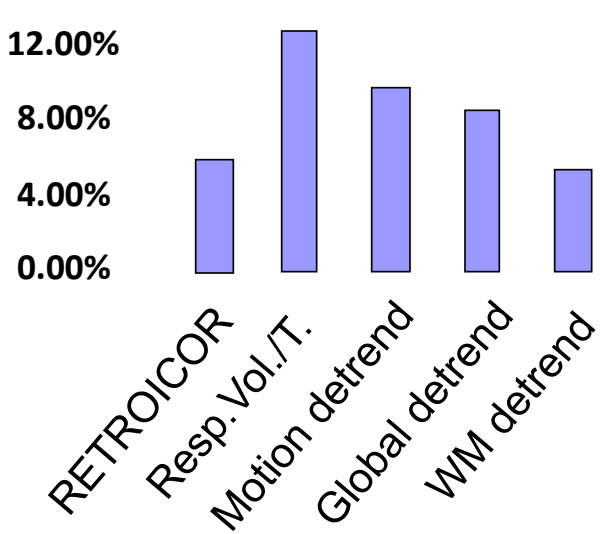


Card+Resp *Resp Vol* *Motion* *Global Signal* *WM Signal*

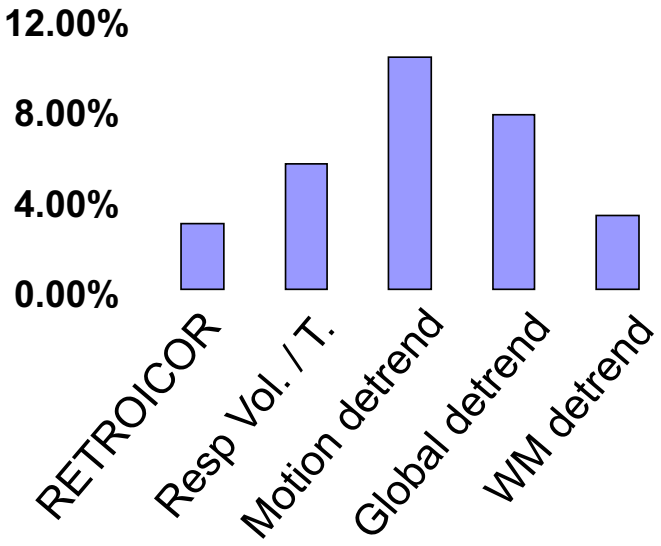
Relative contributions to noise

Averaged over Gray Matter (4 subjects)

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

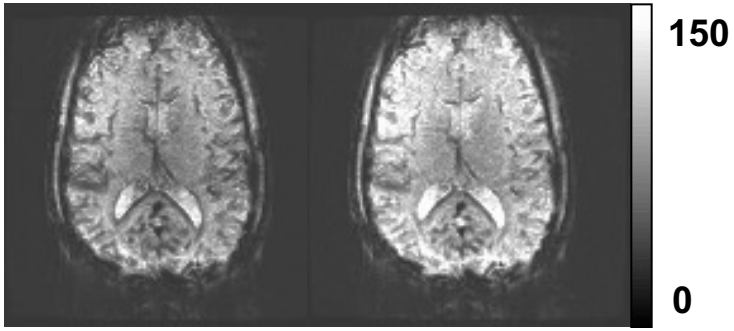


Low Resolution
(7.5 x 7.5 x 5 mm, 700 time points)



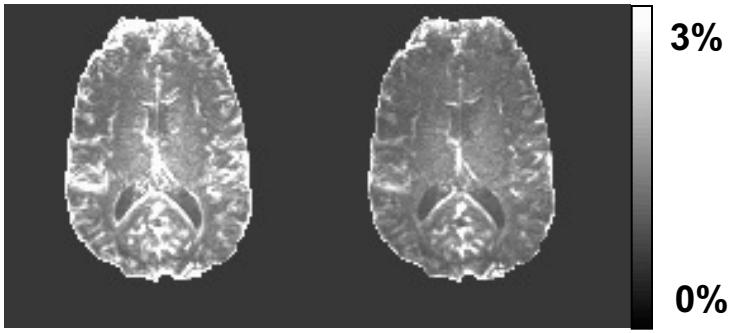
How much is the noise reduced?

TSNR

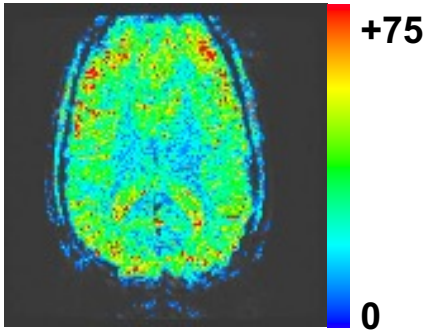


Before Correction | After Correction

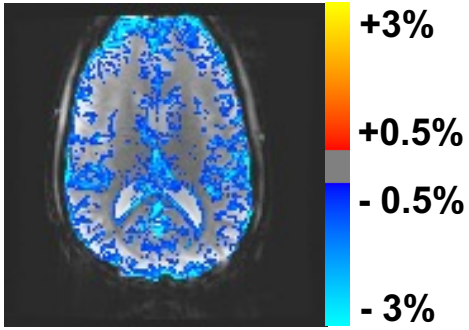
Std. Dev. over time



Before Correction | After Correction

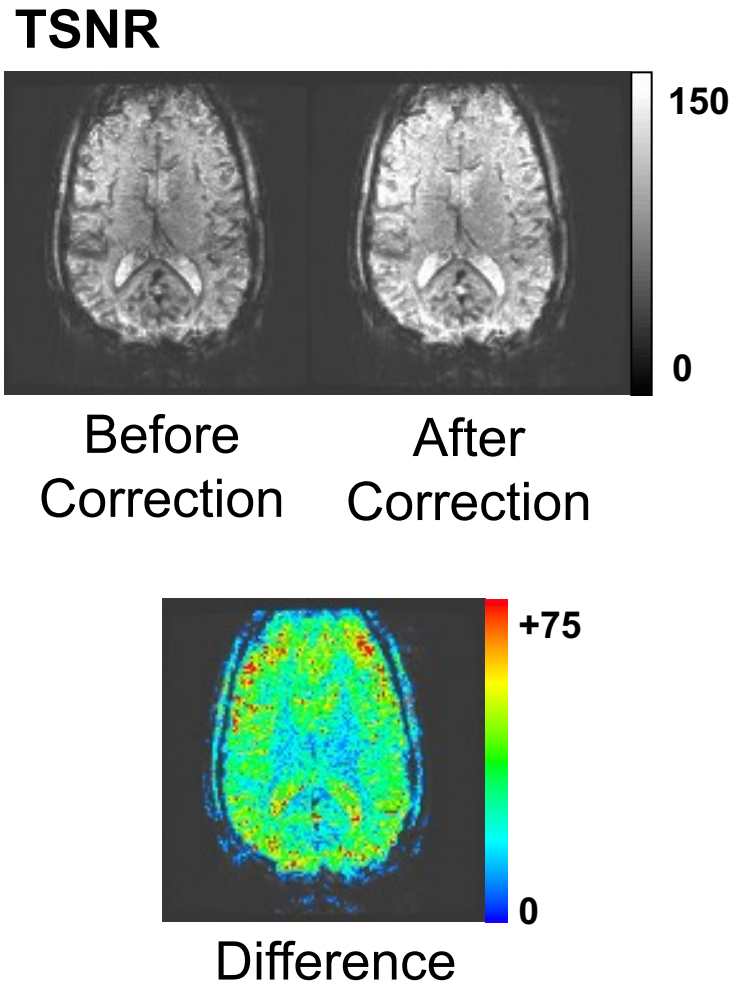


Difference

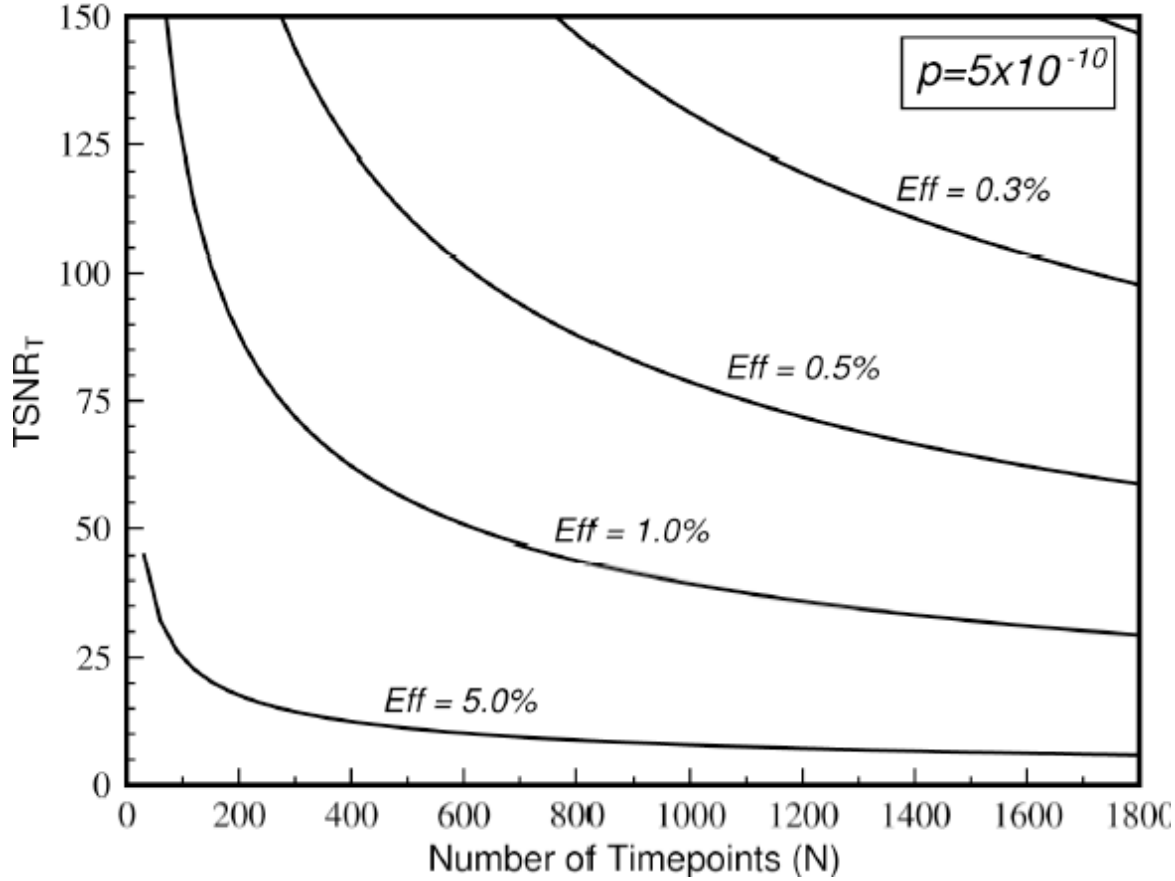


Difference

Improvement in temporal SNR (TSNR)

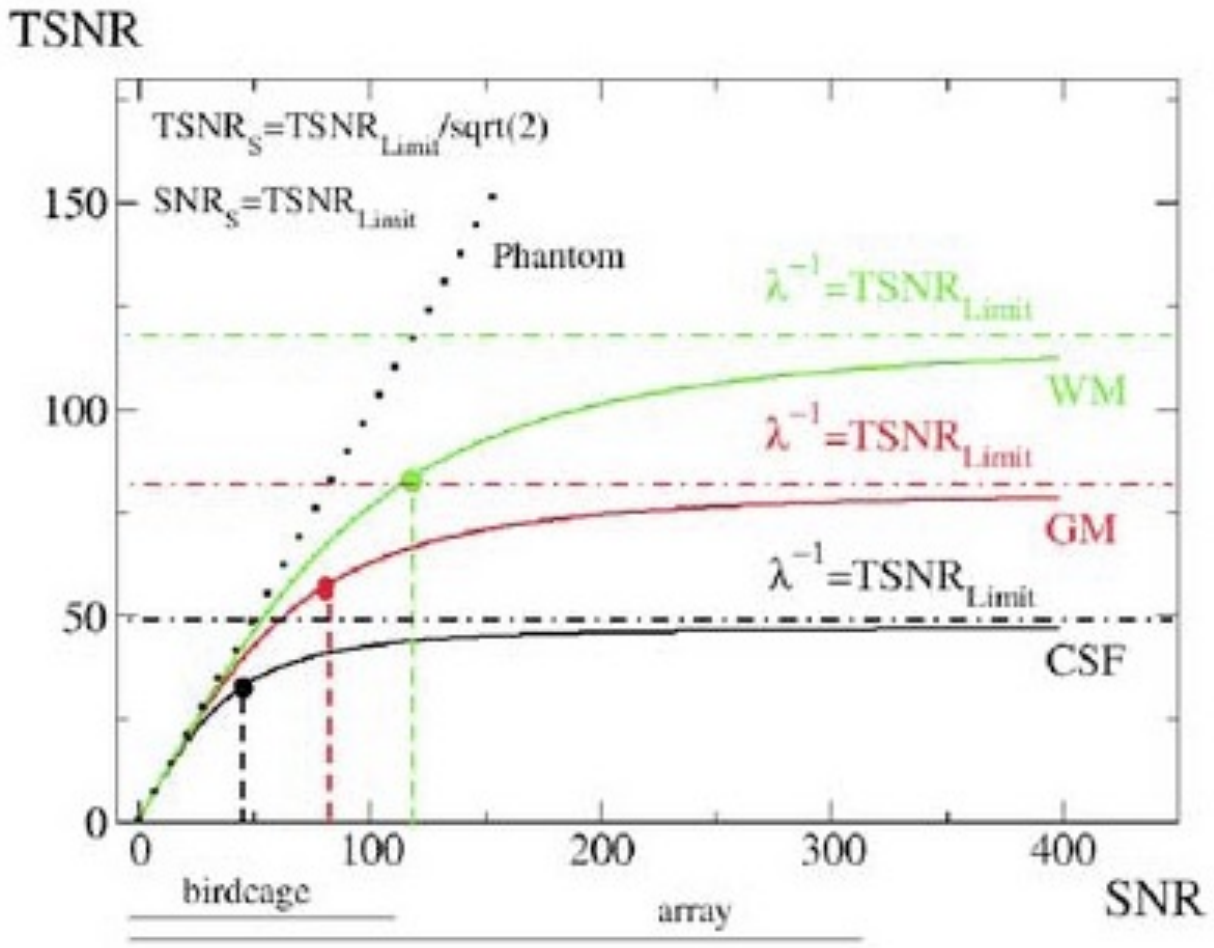


How Improved TSNR Translates



Murphy K, Bodurka J, Bandettini P, "How long to scan: The relationship between temporal signal to noise ratio and necessary scan duration," NeuroImage (in press)

SNR vs TSNR

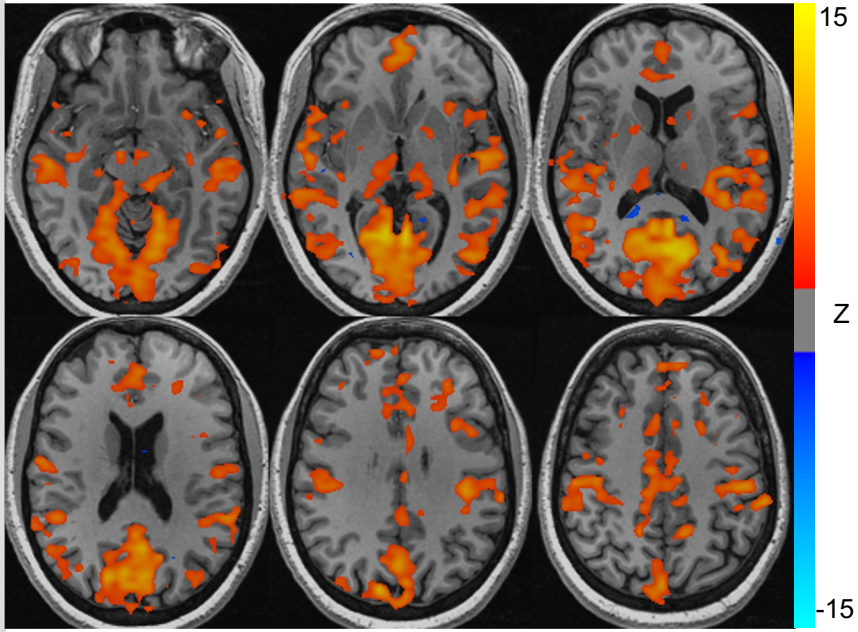


Bodurka J, Bandettini P, “Mapping the MRI voxel volume in which thermal noise matches physiological noise - implications for fMRI”, NeuroImage (in press)

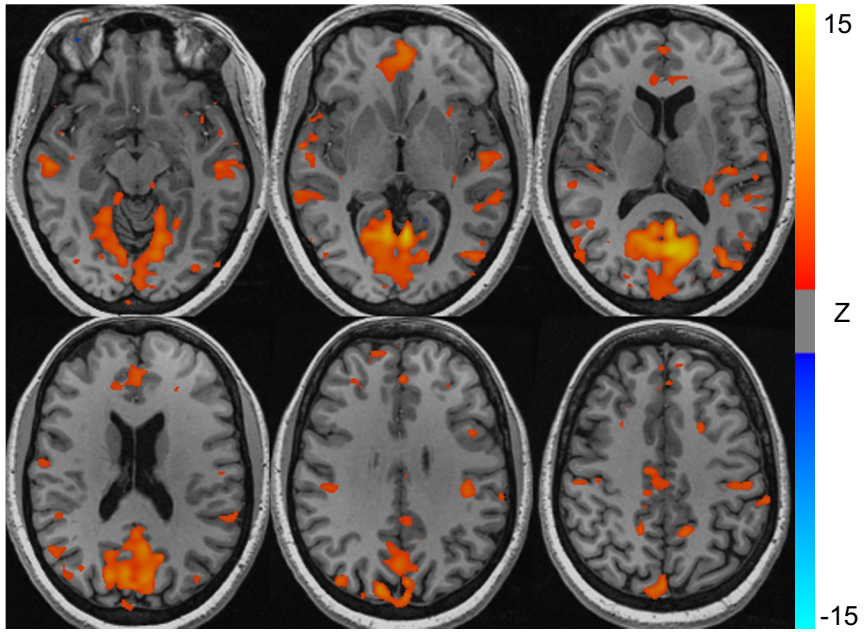
Resting-state correlations

Areas correlated with posterior cingulate *1 subject*

after RETROICOR



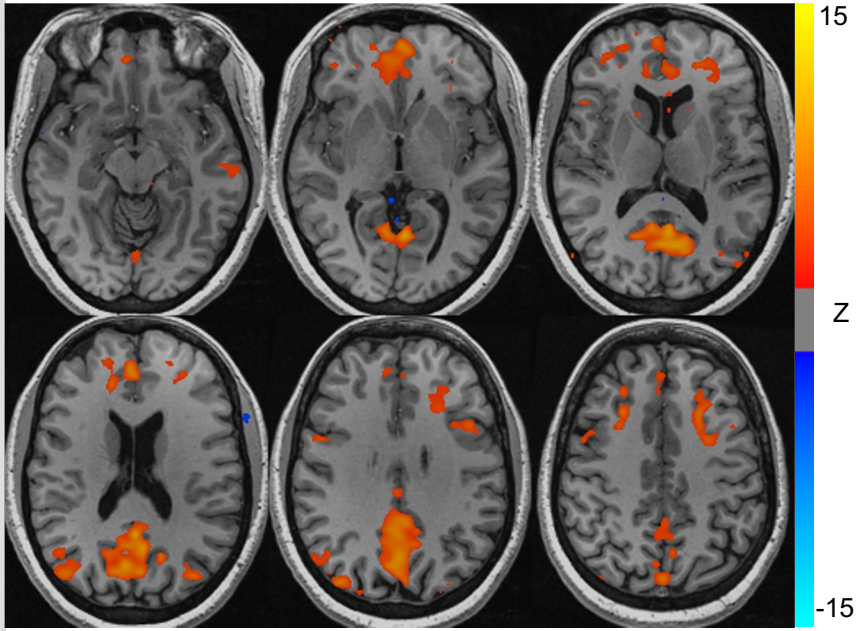
after RETROICOR + RVTcor



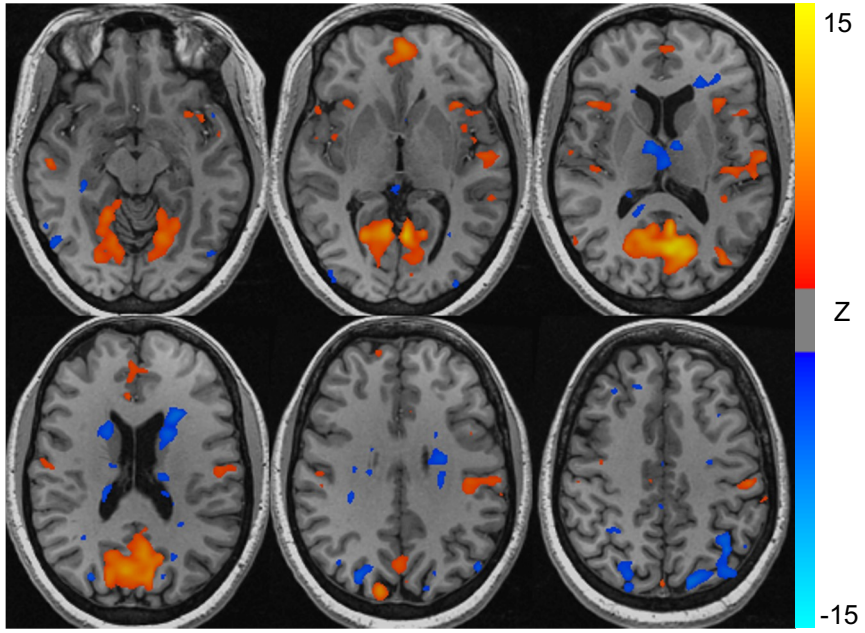
Resting-state correlations

Areas correlated with posterior cingulate *1 subject*

Constant Respirations



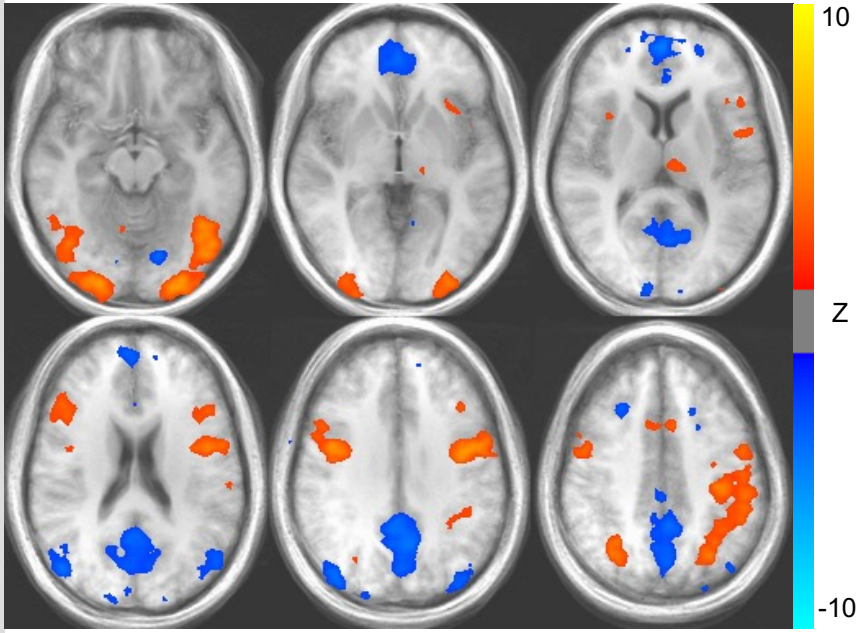
Remove global signal changes



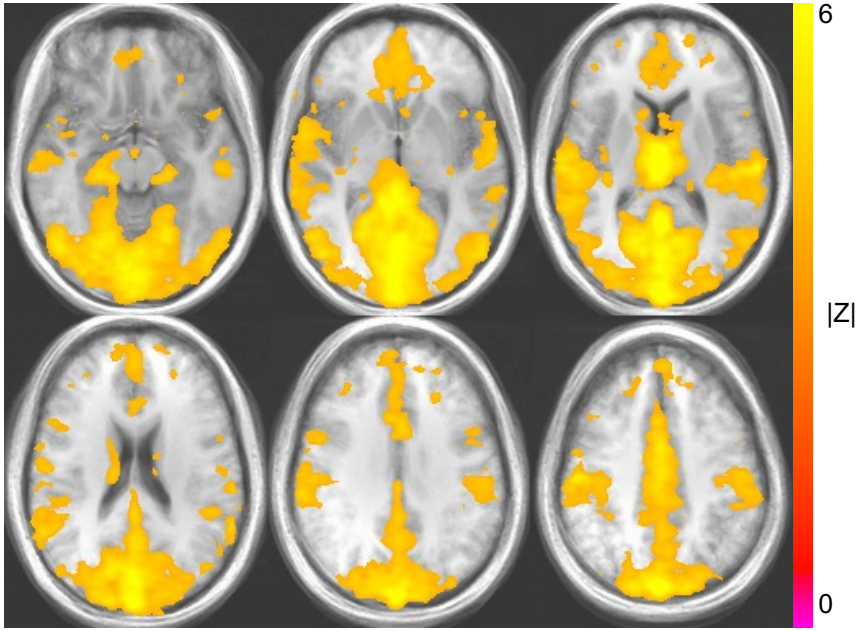
BOLD signal changes – *Group data*

Group data (n=10)

Lexical Task



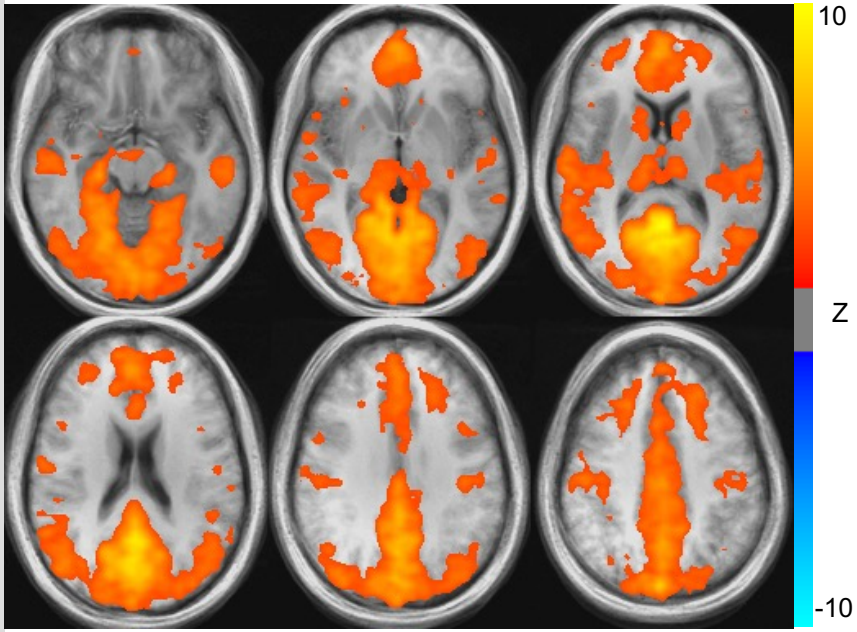
Respiration changes



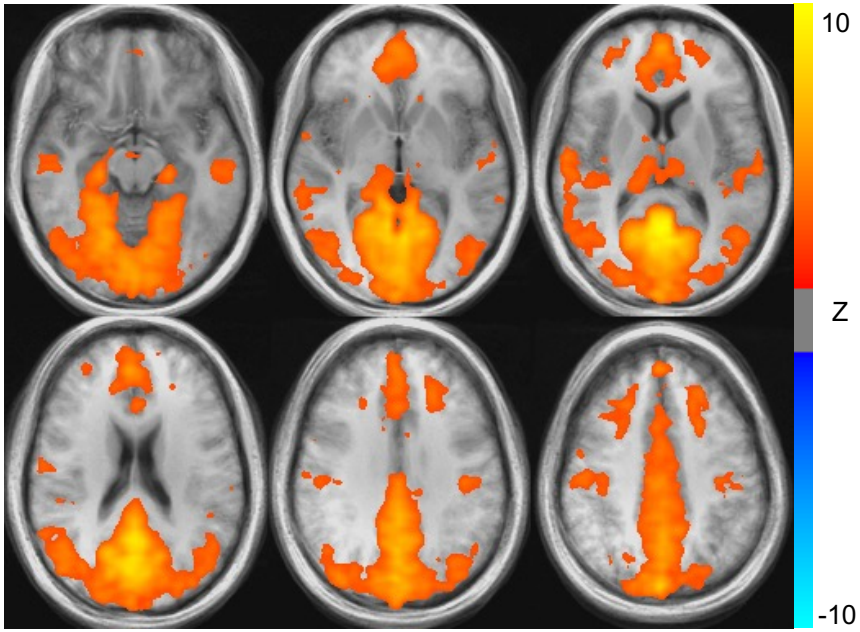
Resting-state correlations

Areas correlated with posterior cingulate *Group data (n=10)*

after RETROICOR



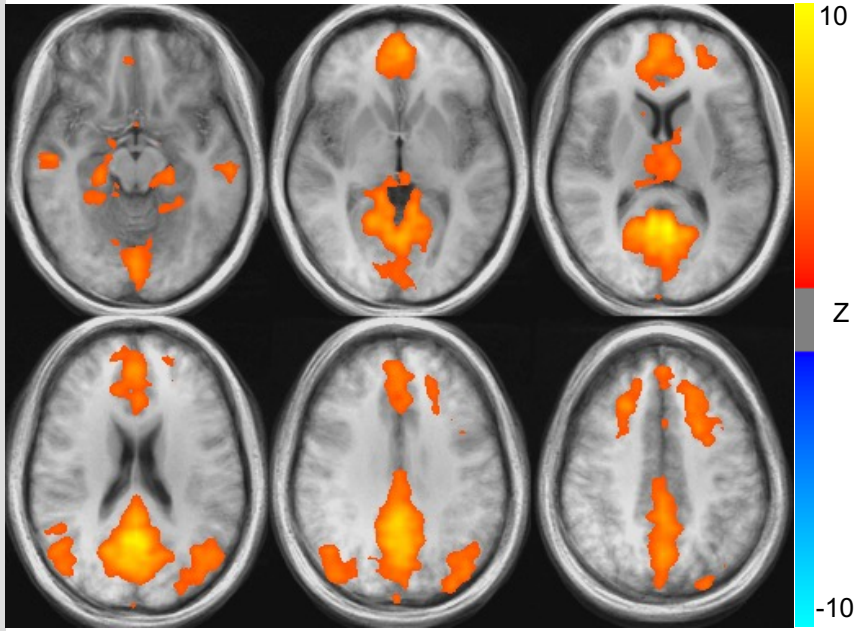
after RETROICOR + RVTcor



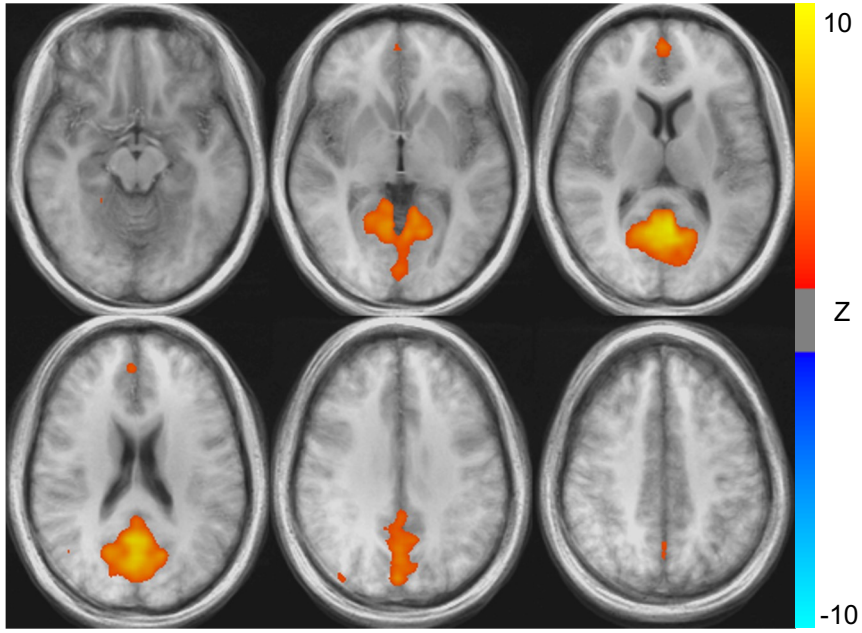
Resting-state correlations

Areas correlated with posterior cingulate *Group data (n=10)*

Constant Respirations



Remove global signal changes

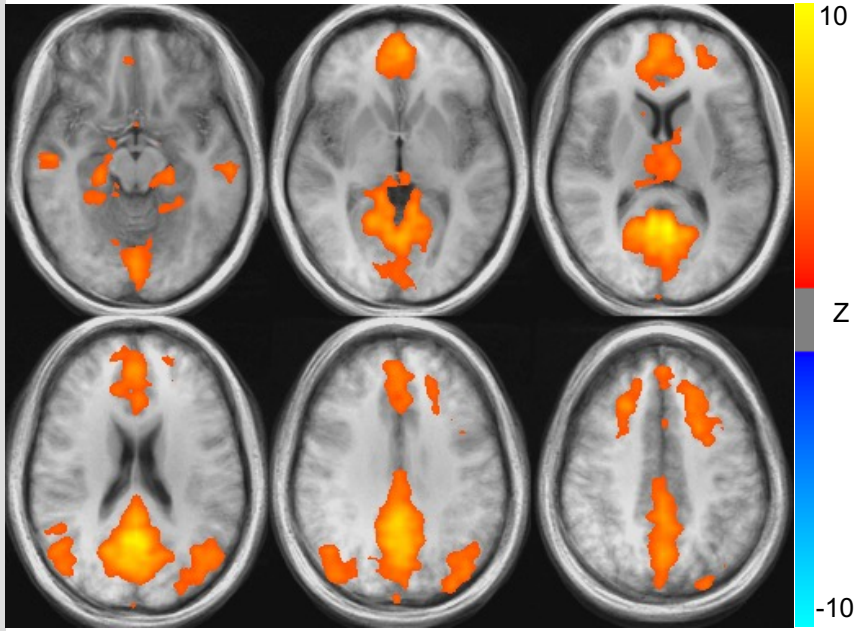


Click here for unthresholded maps

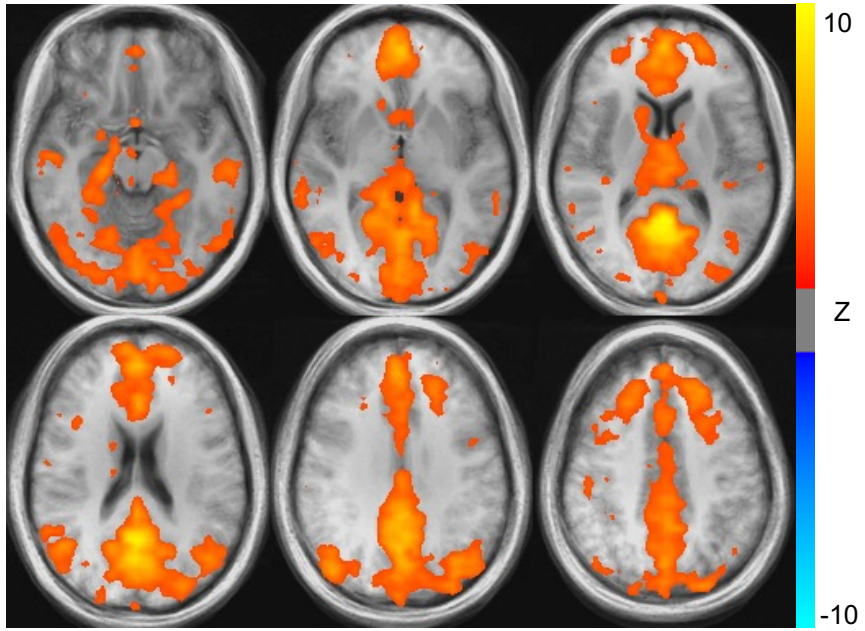
Resting-state correlations

Areas correlated with posterior cingulate *Group data (n=10)*

Constant Respirations



Cued Variable Respirations



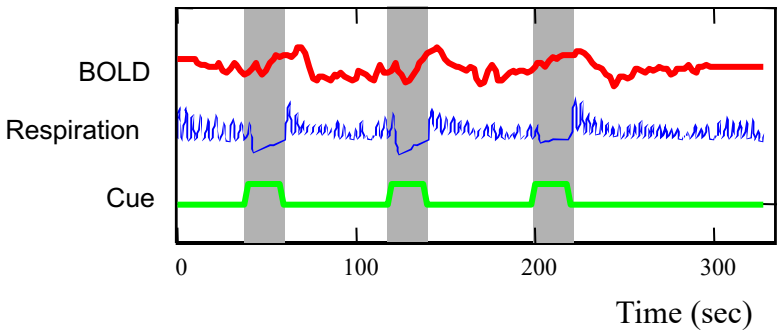
End

A closer look at respiration changes

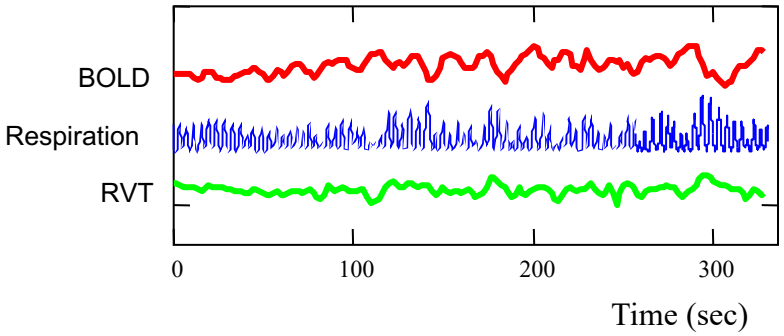
- Breath-hold vs. Resting variations in breathing
- The respiration “impulse response function”
  - *How do respiration changes really affect the BOLD signal? (shape, latency, …)*
- Echo-time (TE) dependence

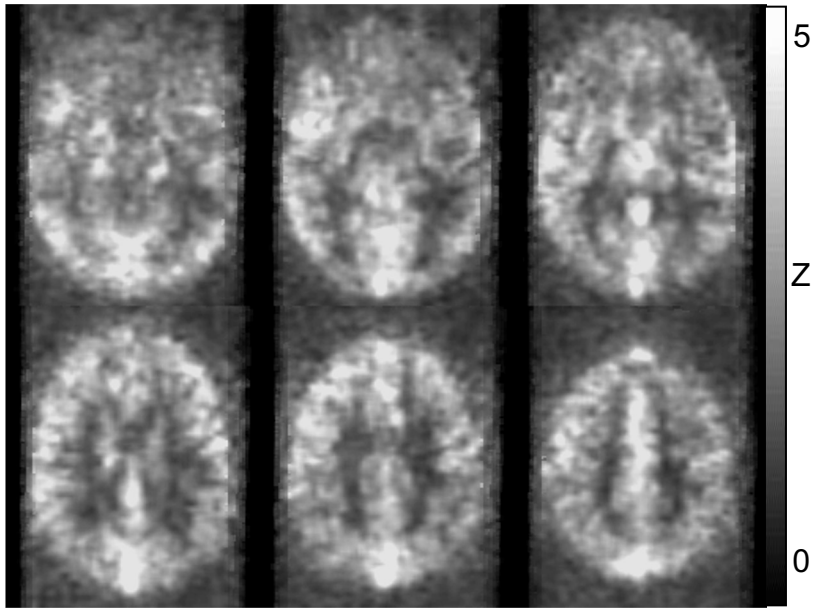
Respiration induced signal changes

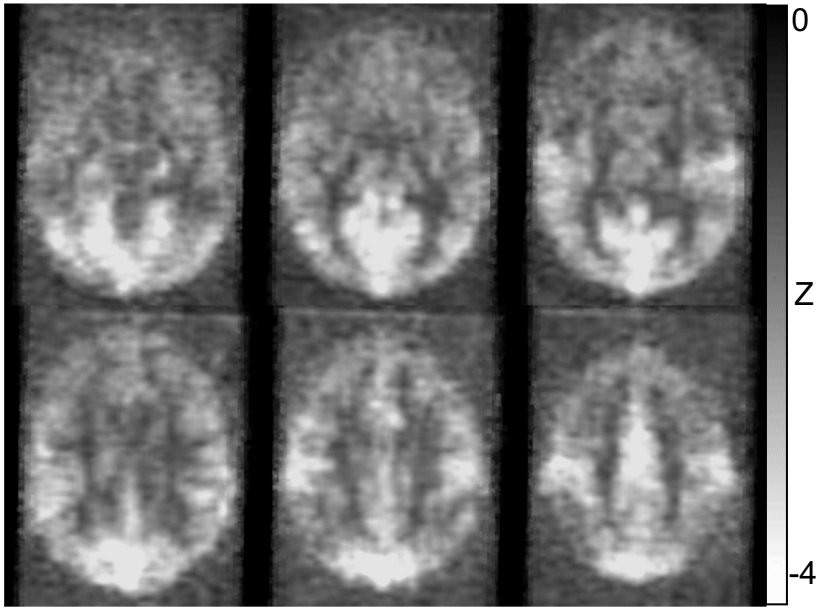
Breath-holding



Rest



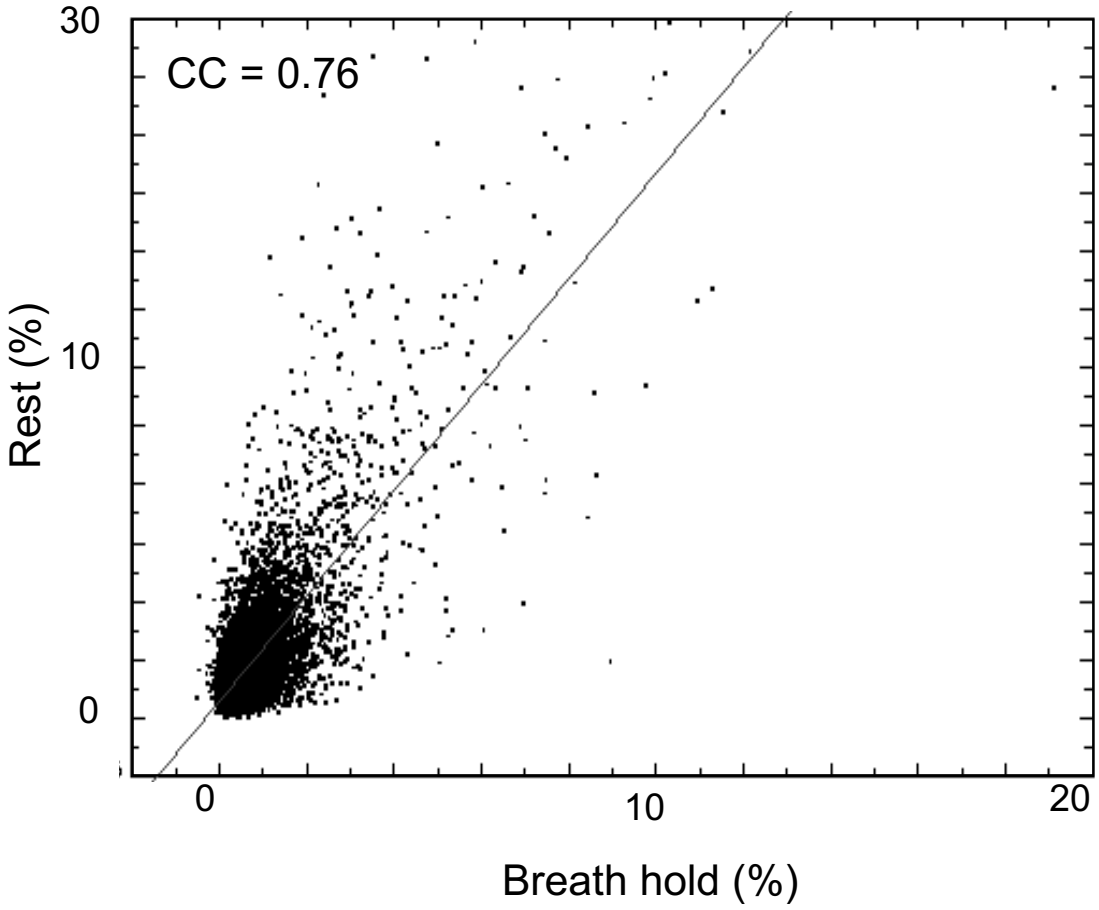




(N=7)

Resting changes in breathing vs. Breath-holding

Correlation with Respiration Volume / Time (RVT)

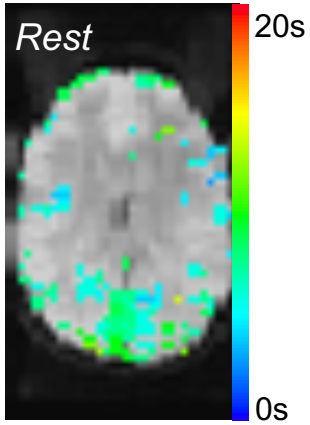


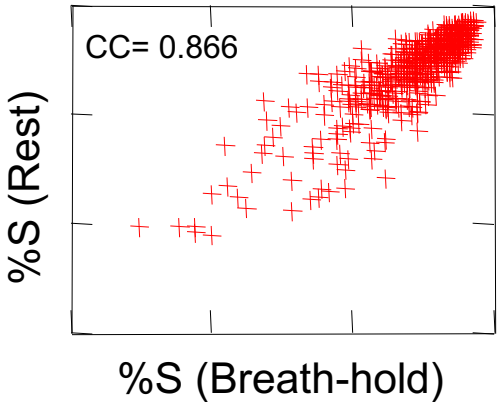
Resting changes in breathing vs. Breath-holding

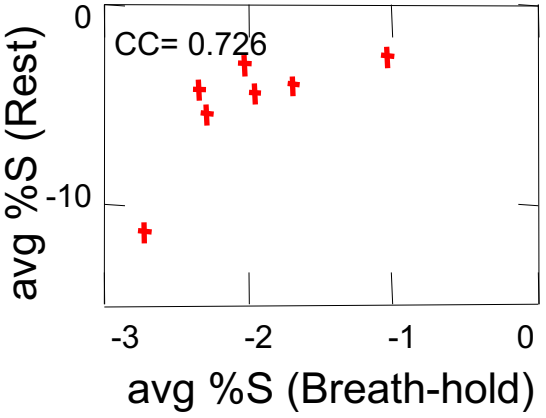
Rest vs. BH
within subject

Rest vs. BH
across subjects
(averaged over space)

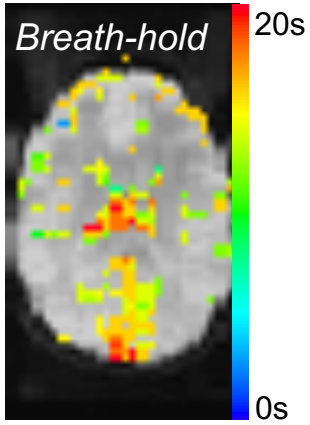
Latency

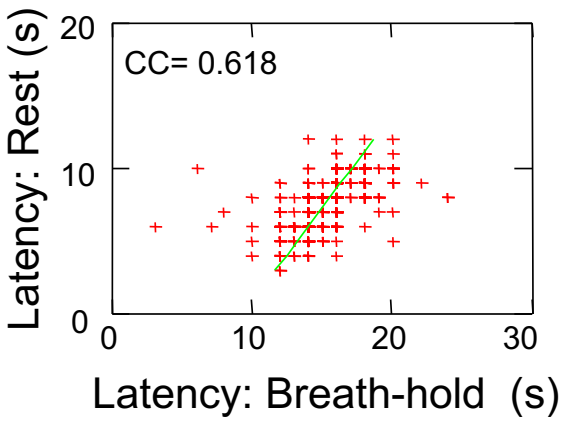


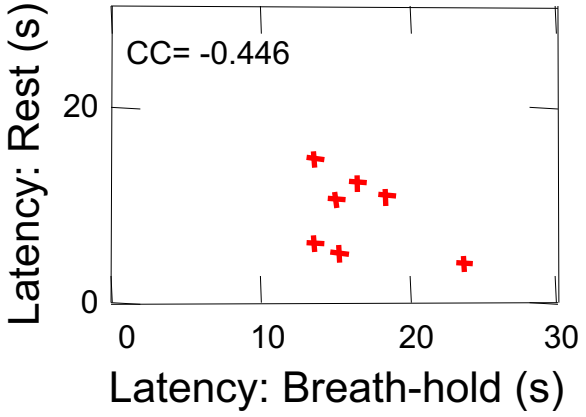




Latency

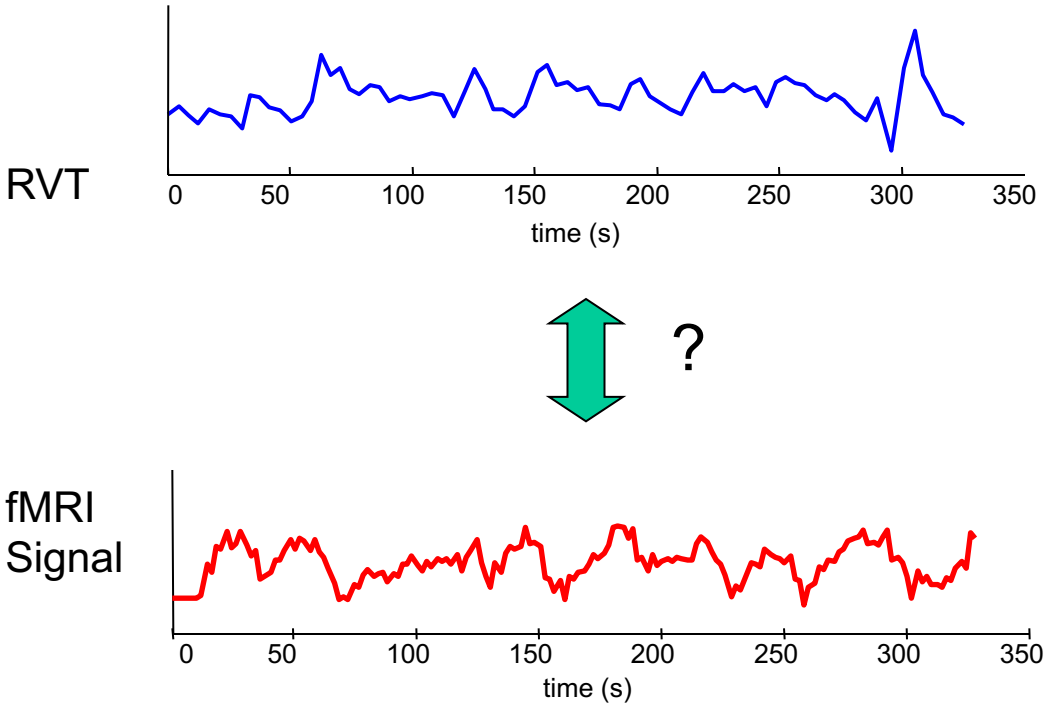




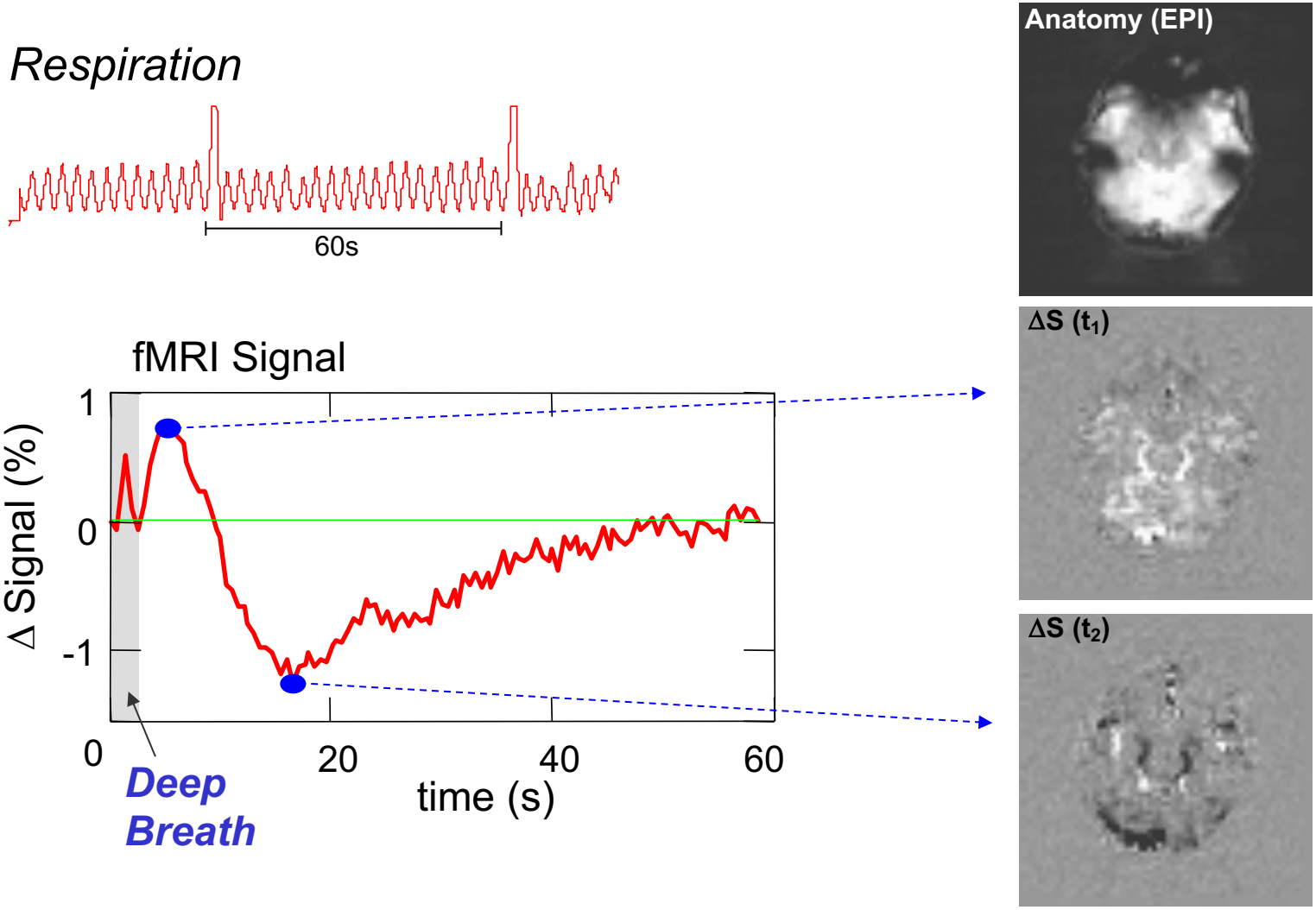


Respiration Changes vs. BOLD

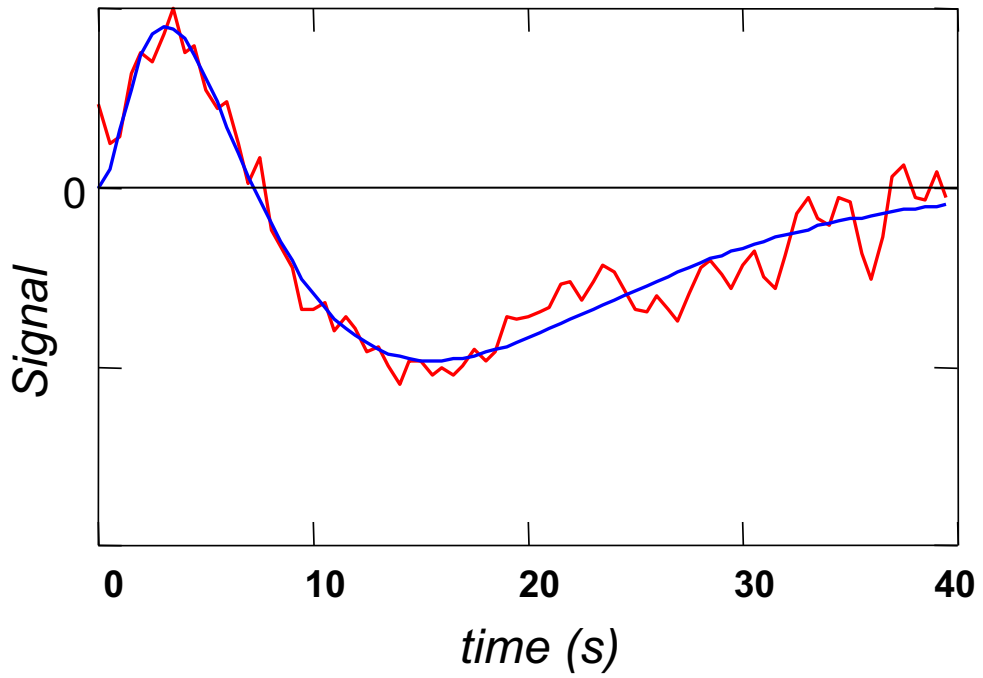
How are the BOLD changes to respiration variations?



fMRI response to a single Deep Breath



Respiration response function

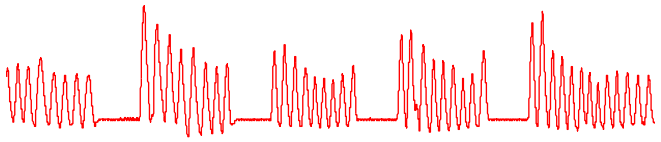


Average of 3 subjects

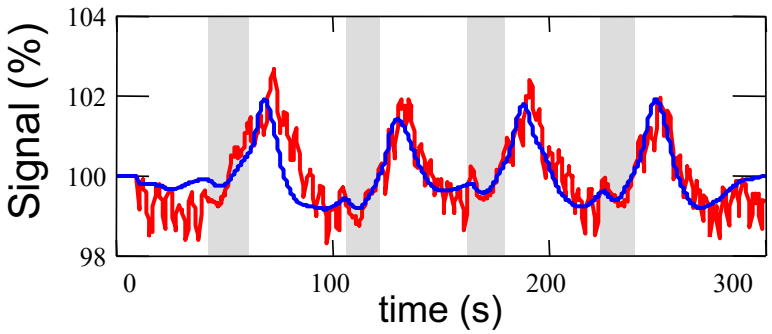
$$RRF(t) \quad 0.6\, t^{2.1} e^{-t/1.6} - 0.0023\, t^{3.54} e^{-t/4.25}$$

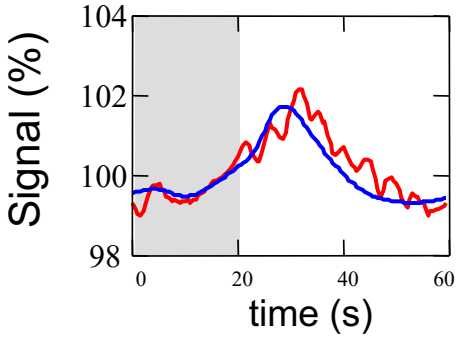
fMRI response to breathing modulations

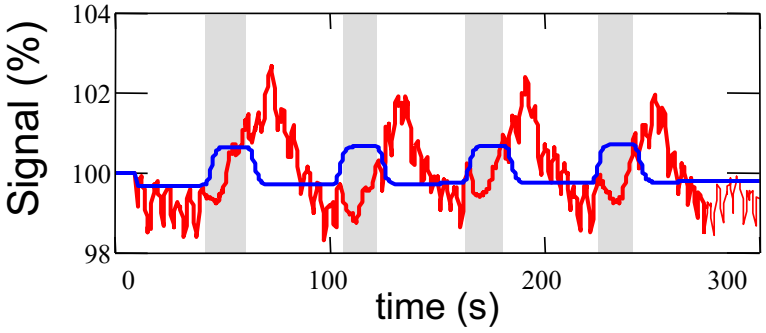
Breath-holding

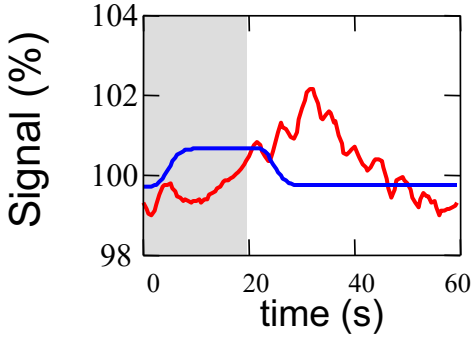


Respiration



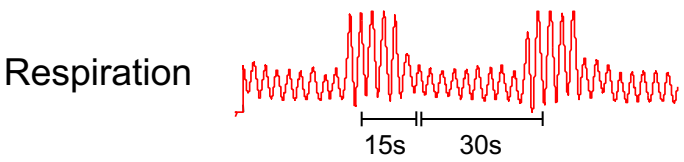


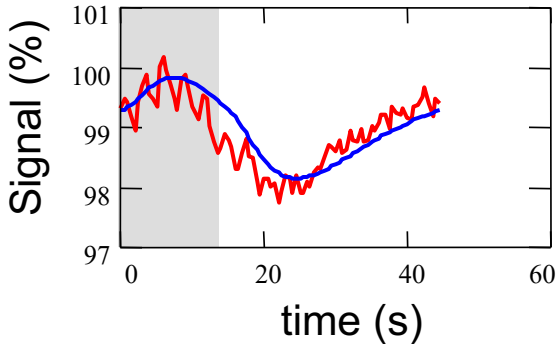


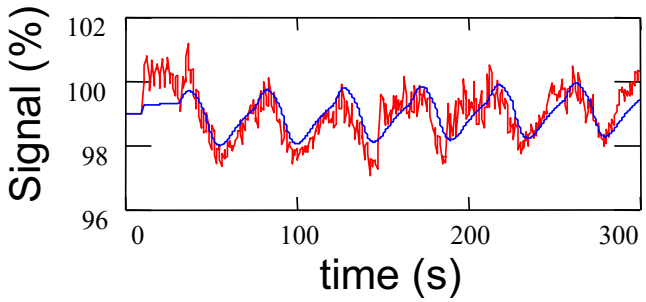


fMRI response to breathing modulations

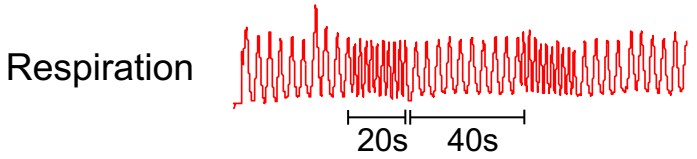
Changes in Depth

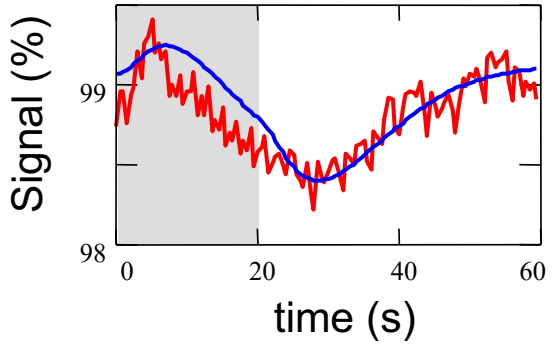


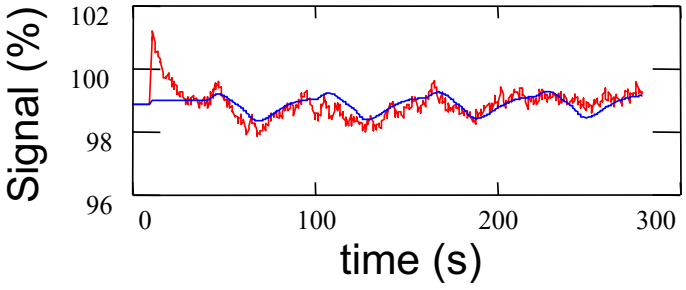




Changes in Rate

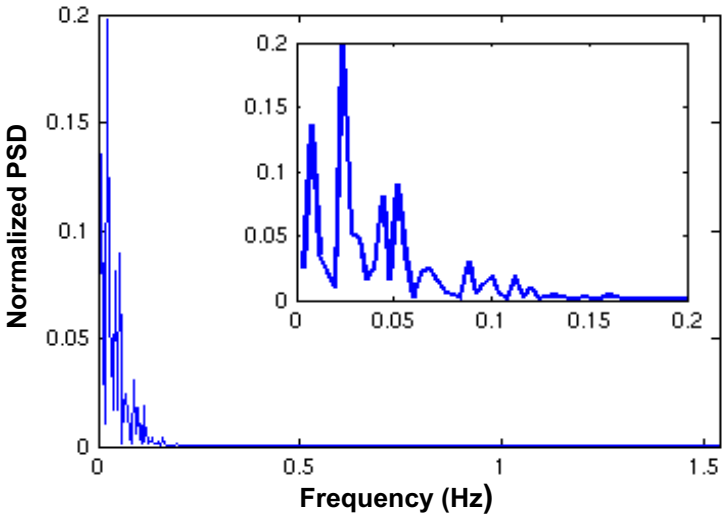


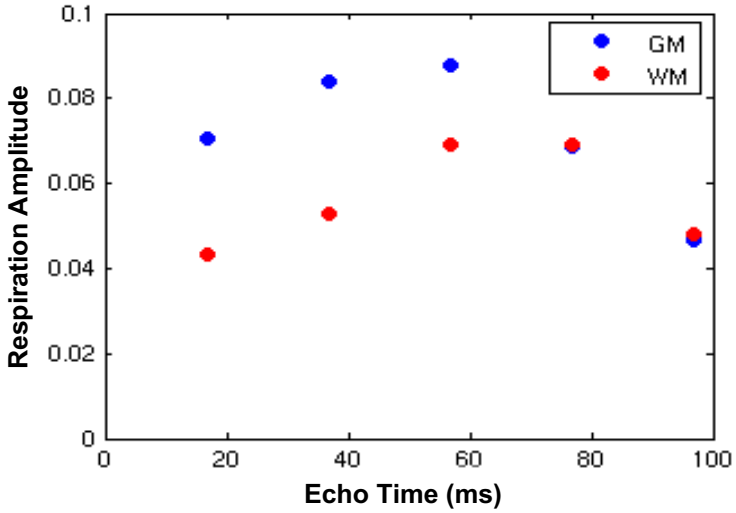




TE dependence of respiration changes

K. Murphy, R.M. Birn, P.A. Bandettini
The frequency profile of TE-dependent BOLD physiological fluctuations
ISMRM 2006





Future directions

- How do we best model respiration-induced BOLD signal changes?
  - New IRF from One Deep breath
- How are resting respiration changes different from cued respiration changes?
- Are these respiration and signal fluctuations related to changes in neuronal function?
  - EEG/fMRI, MEG
- Can we use resting respiration fluctuations for BOLD calibration?

Acknowledgements

*Laboratory of Brain and Cognition / * Functional MRI Facilty*

Rasmus Birn *
Jerzy Bodurka *
Kevin Murphy
Jason Diamond
Monica Smith

Scientific and Statistical Computing Core

Robert W. Cox
Ziad S. Saad
Gang Chen

Unit on Cognitive Neurophysiology and Imaging

David A. Leopold

Research Services Branch

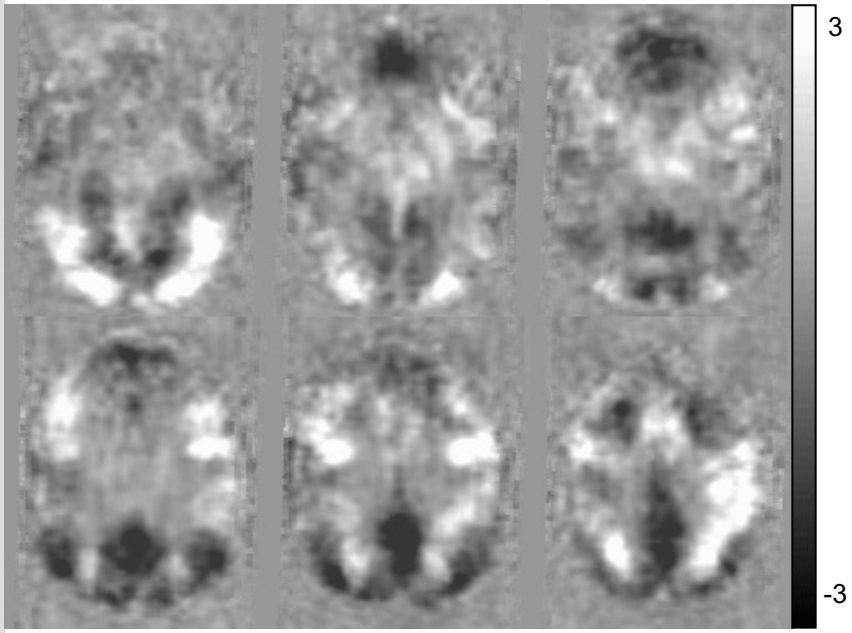
George Dold

More…

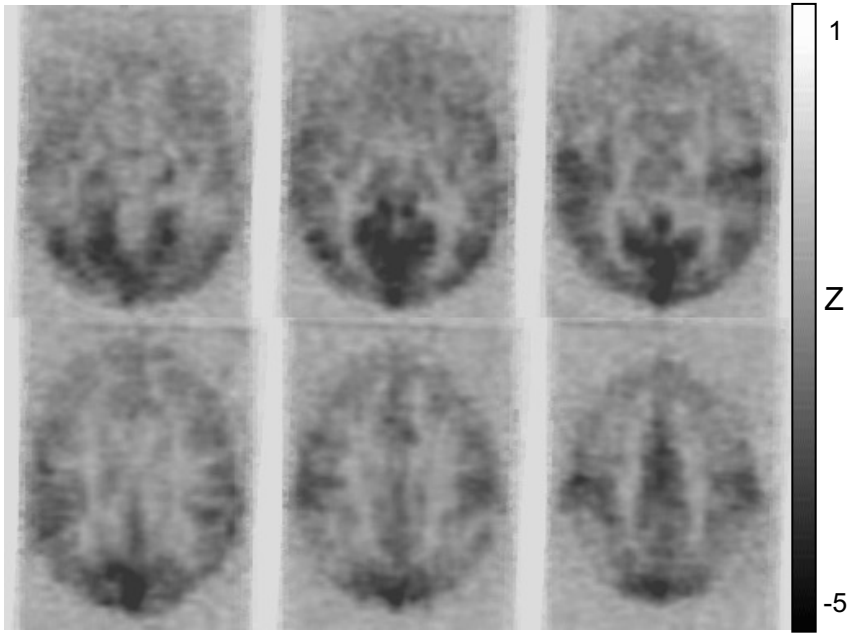
BOLD signal changes – *Group data*

Group data (n=10)

Lexical Task



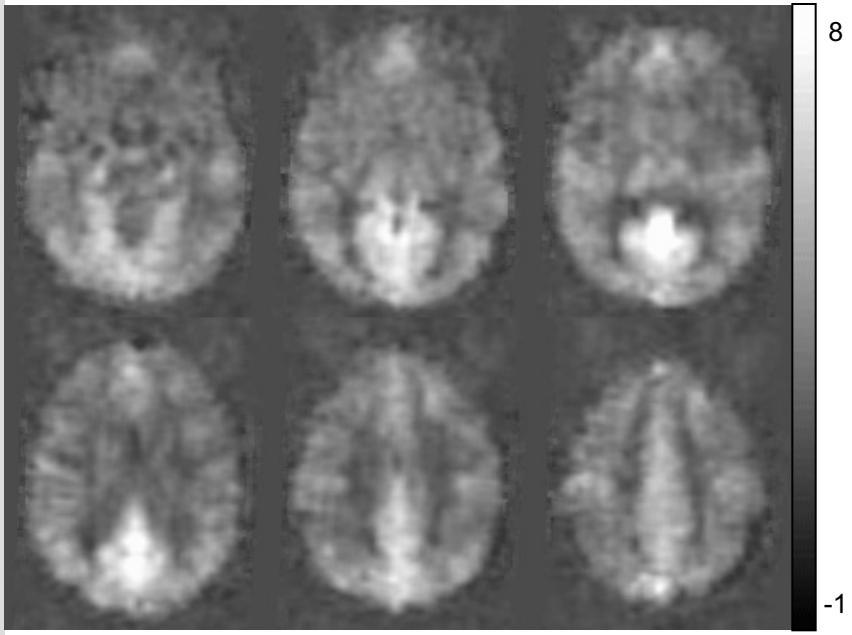
Respiration changes



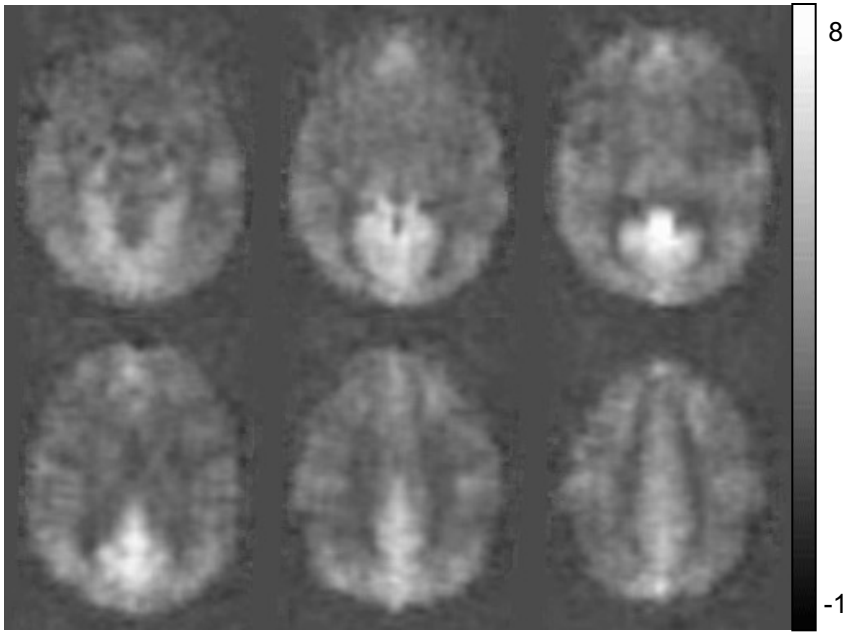
Resting-state correlations

Areas correlated with posterior cingulate *Group data (n=10)*

after RETROICOR



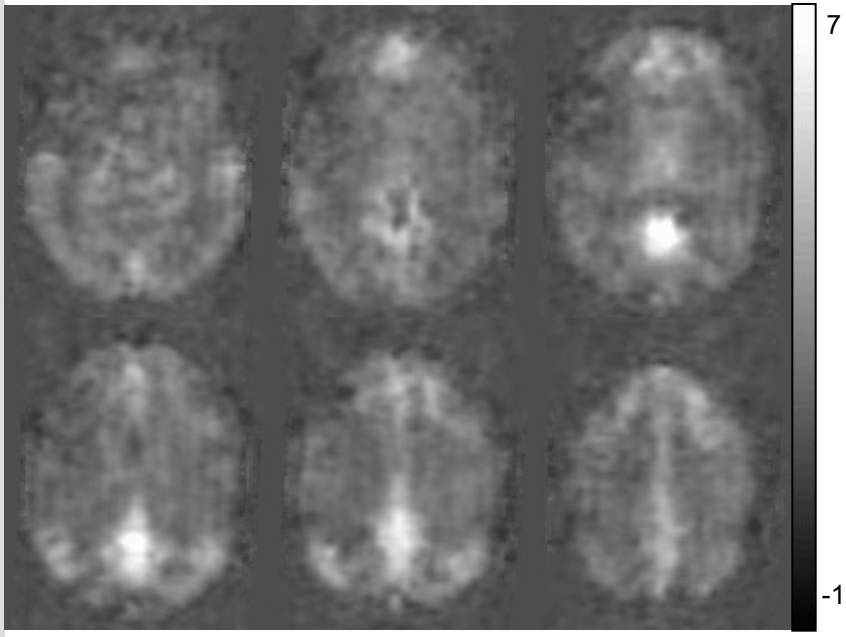
after RETROICOR + RVTcor



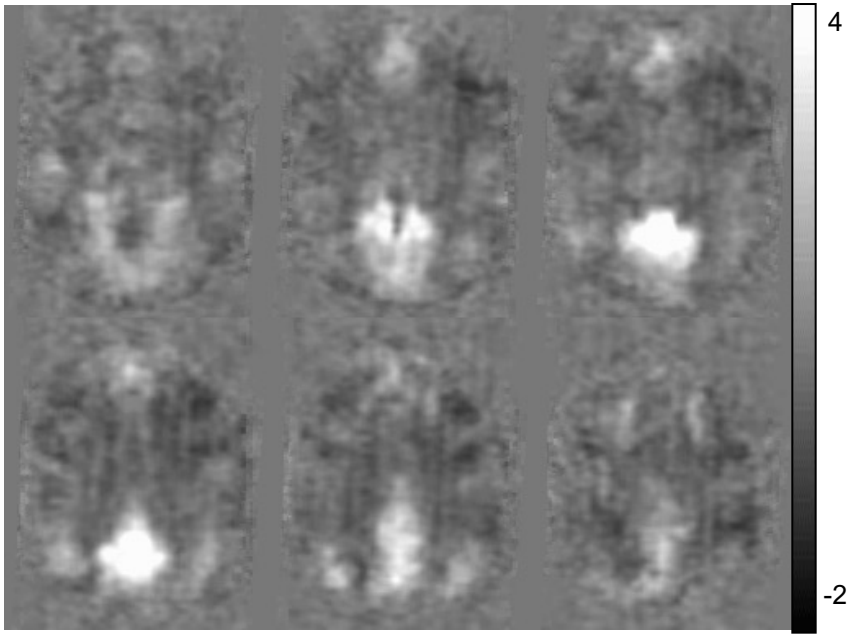
Resting-state correlations

Areas correlated with posterior cingulate *Group data (n=10)*

Constant Respirations



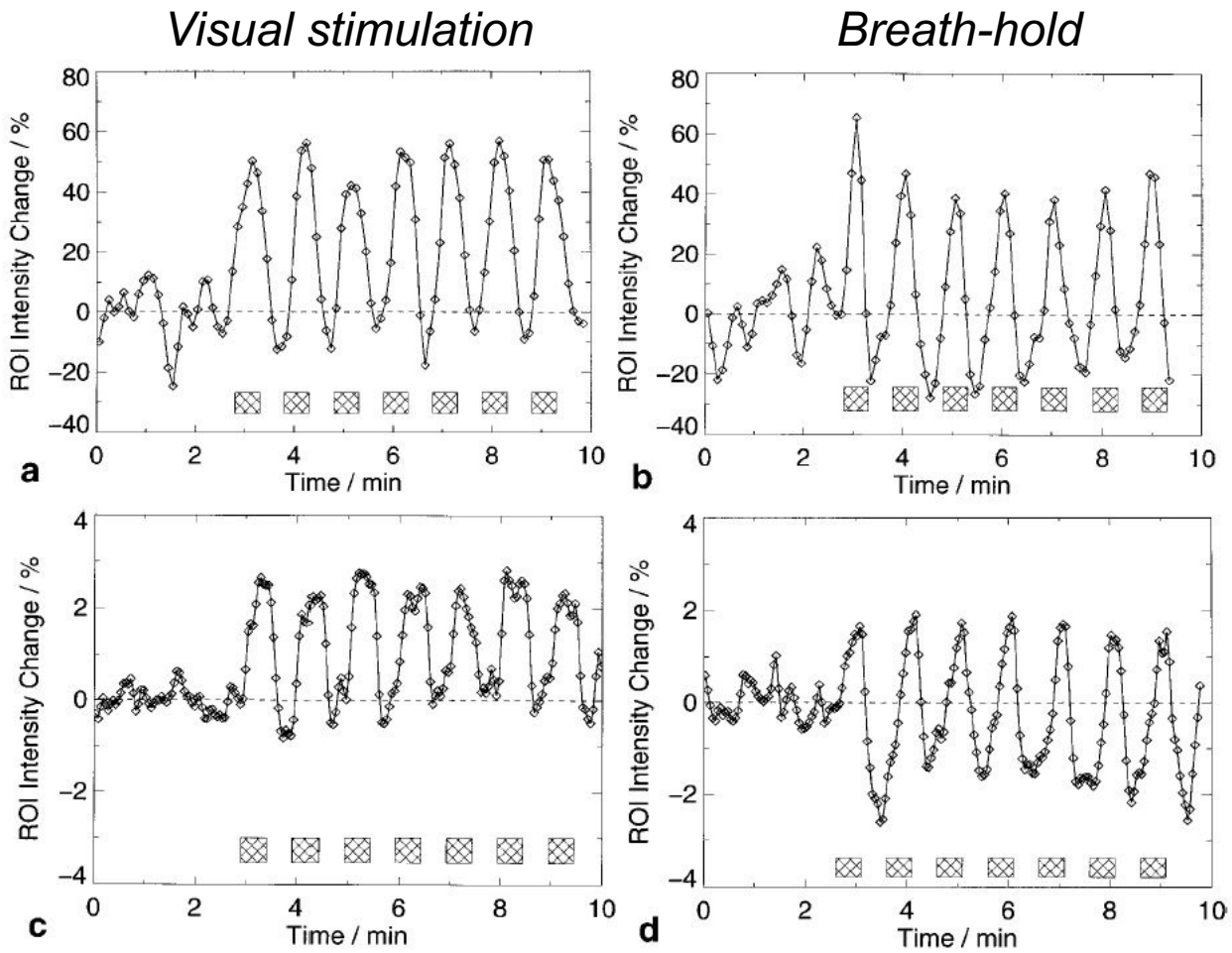
Remove global signal changes



back

Breath-hold changes

Breath-hold induced BOLD + Flow changes



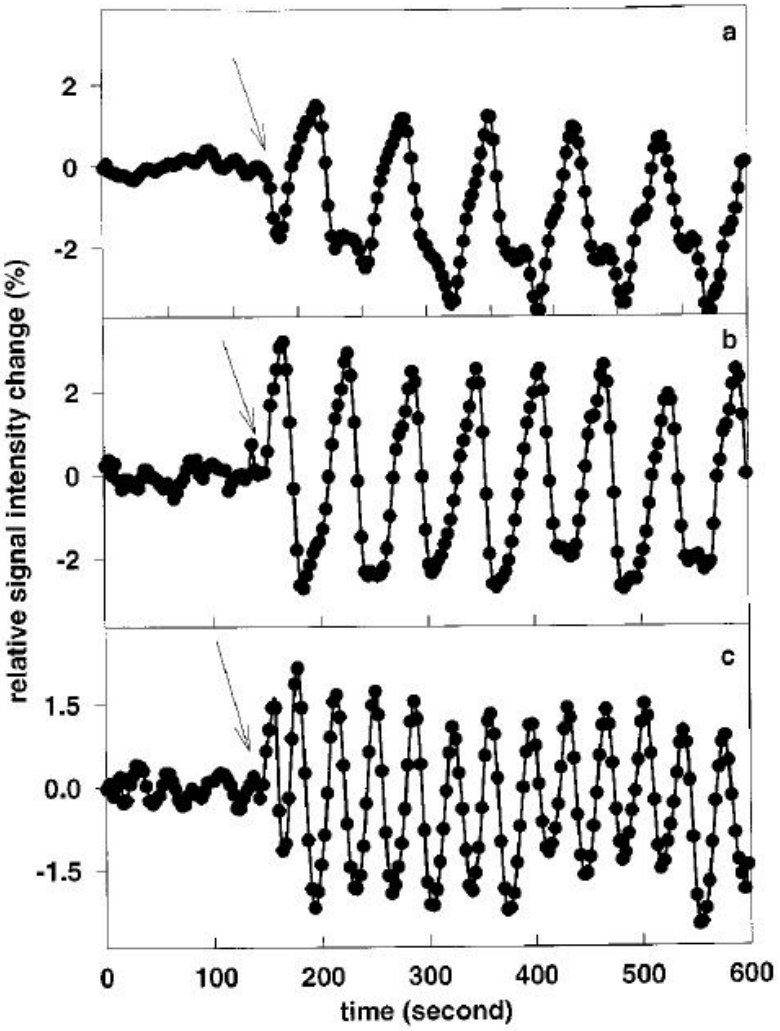
BOLD

FAIR (CBF)

FIG. 2. Change in intensity of FAIR and BOLD signals during photic stimulation (**a** and **c**, respectively) and during breath holding (**b** and **d**, respectively). Time courses are of mean signal intensities in activated areas from the same subject as in Fig. 1.

A. Kastrup, et al. NeuroImage 25, 2005

Breath-hold induced BOLD changes



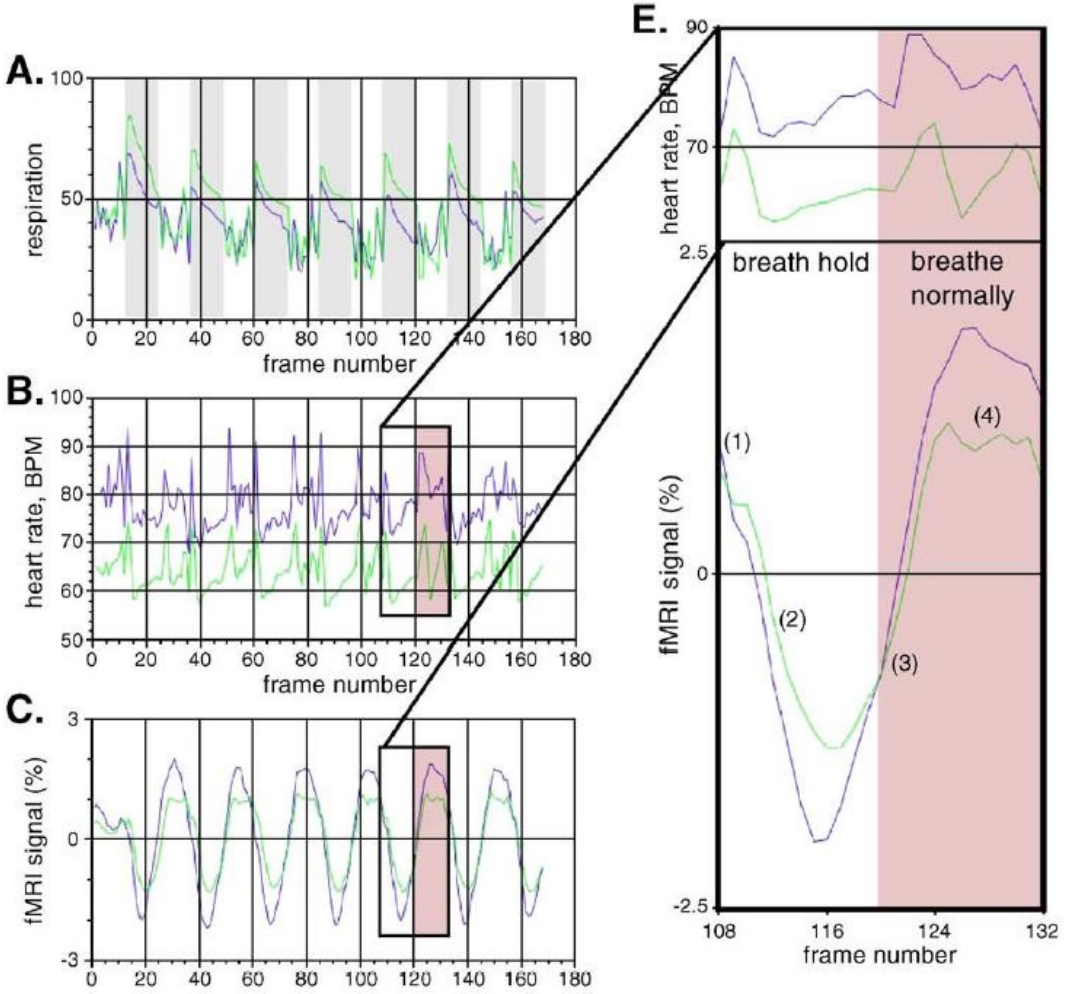
40s breath-hold after inspiration

30s breath-hold after expiration

18s breath-hold after expiration

A. Kastrup, et al. Stroke, 29, 1998

Breath-hold induced BOLD changes



1. Chest expansion → ↓intrathoracic pressure
2. Baroreceptor regulation → ↓Heart rate, ↓CBF
3. ↑CO2 → ↑CBF
4. Recovery of normal BF

(1) chest expansion --> decreased intrathoracic pressure --> reduced vascular resistance --> increased inflow of blood to heart.

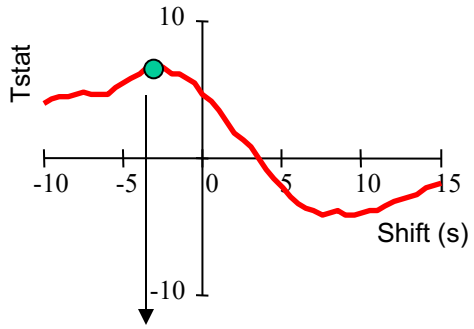
(2) autonomic regulation by baroreceptors --> reduced HR --> decreased blood flow to brain --> increased paramagnetic Hb --> reduced SI.

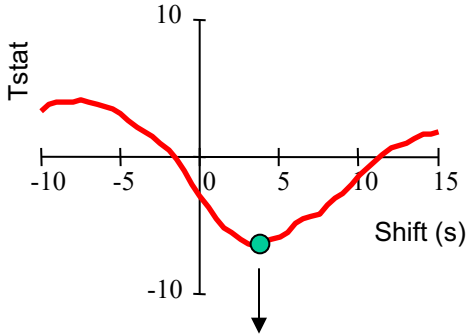
(3) Increase in CO2 --> increased CBF in brain --> drop in paramagnetic Hb --> rise in oxyHb and Si.

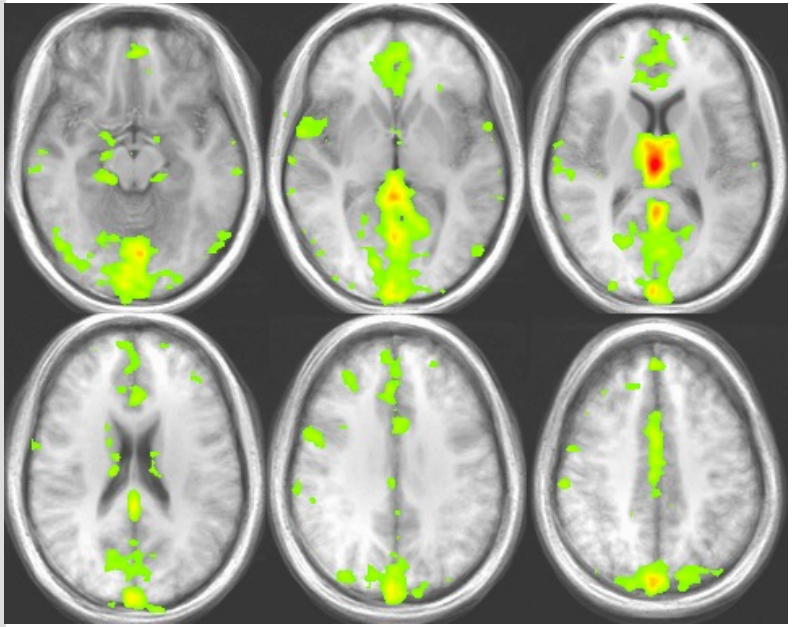
(4) Recovery of normal blood flow--> reduced CO2 --> vasoconstriction of arterials --> SI plateaus, return to normal rCBF, O2, Hb levels.

M.E. Thomason, et al. NeuroImage 25, 2005

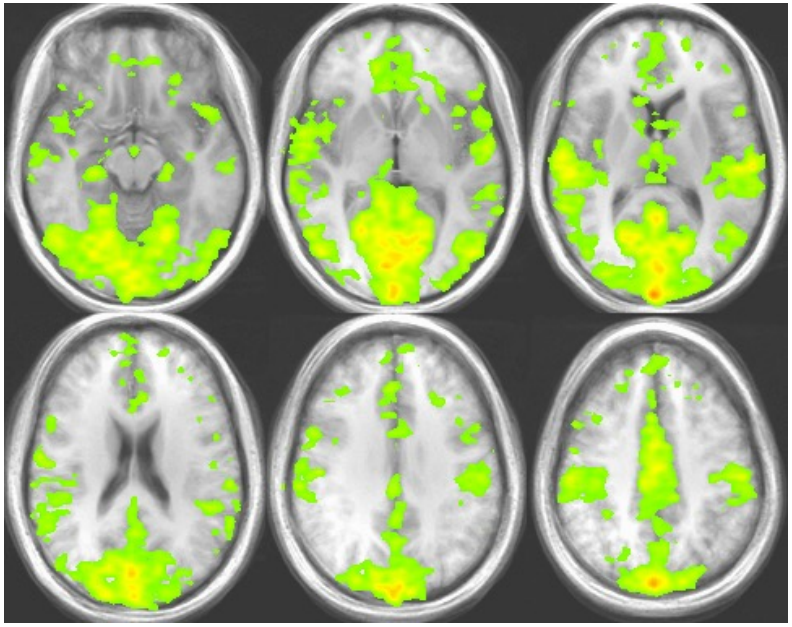
Latency – RVT vs. BOLD







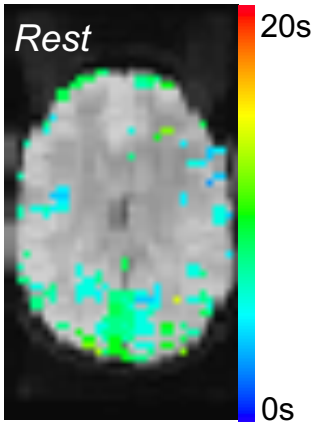
largest positive correlation (in each voxel)

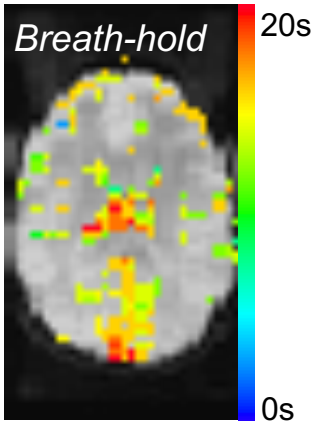


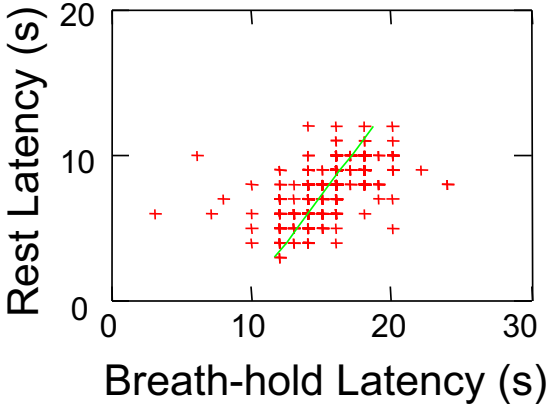
largest negative correlation (in each voxel)

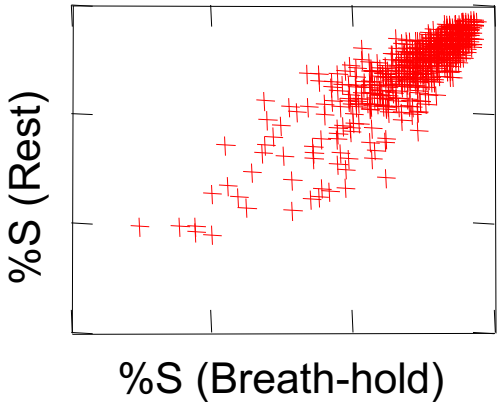
Resting changes in breathing vs. Breath-holding

M.A. Smith, P.A. Bandettini, R.M. Birn, ISMRM 2006







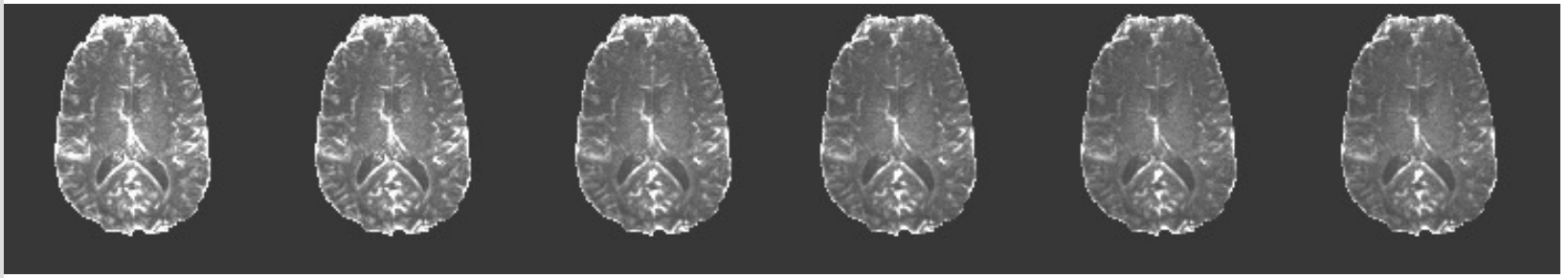


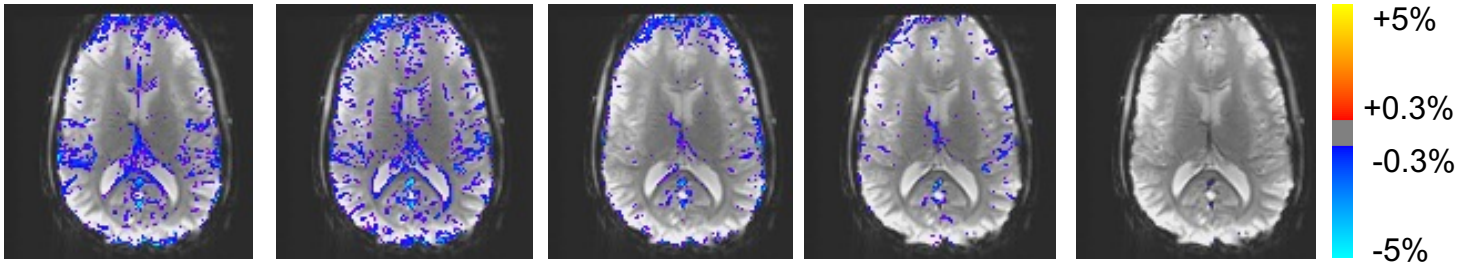
(each + represents one voxel signif. corr. With RVT)

End

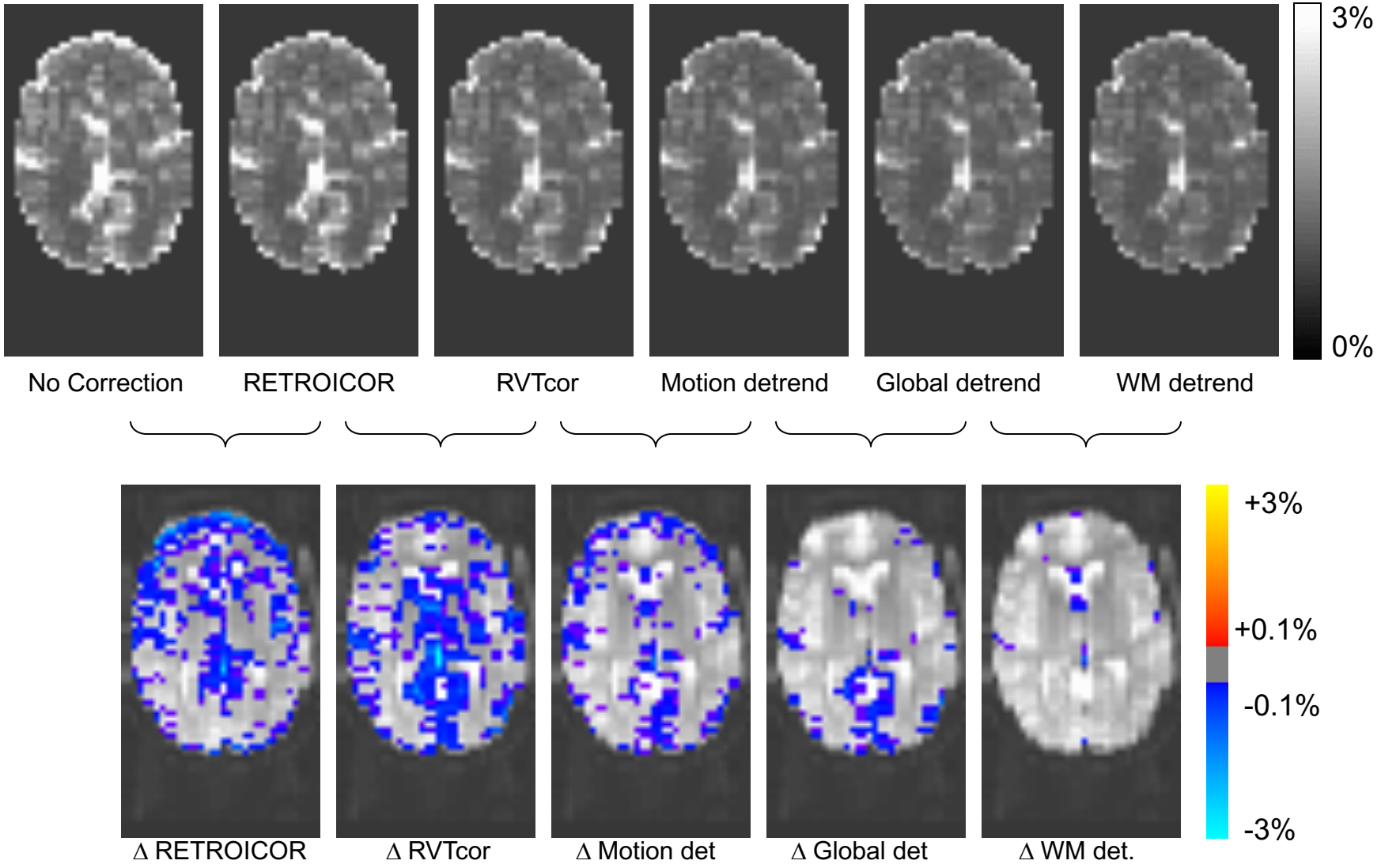
Multiple Physiological Regressors

Standard Deviation Maps (1 subject)

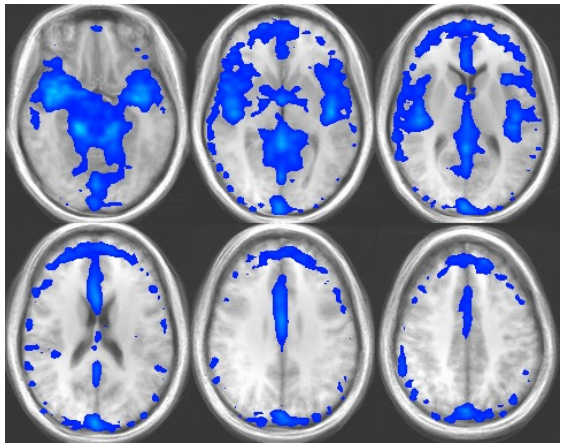




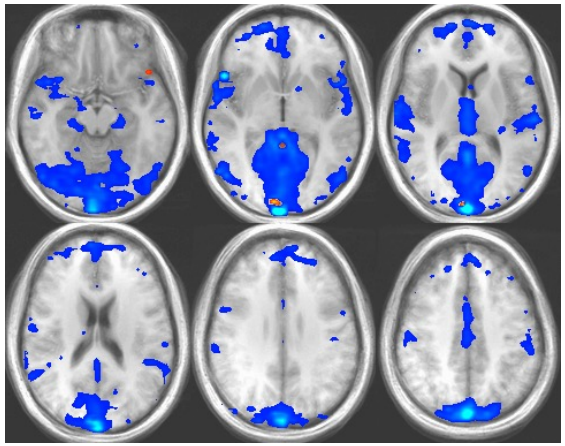
Standard Deviation Maps (1 subject)



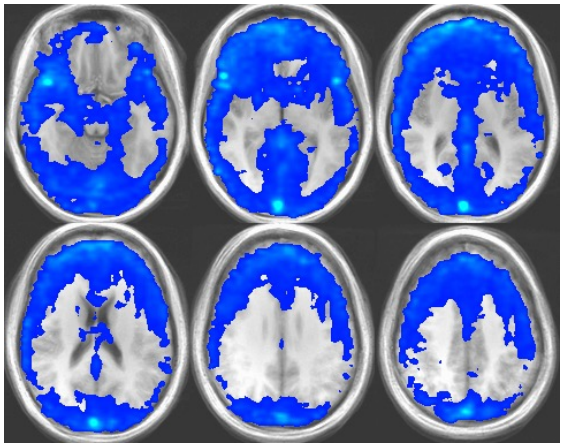
Change in StDev – Group data (n=10)



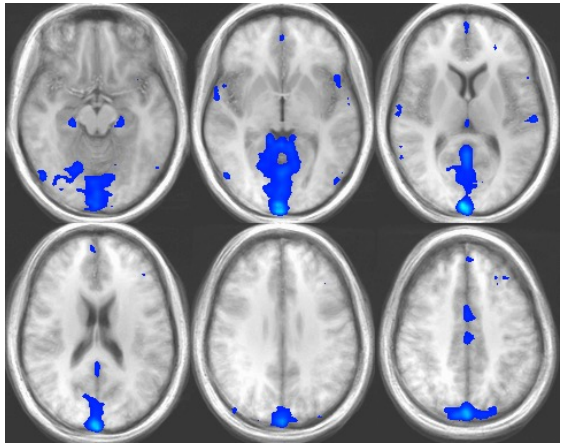
Δ RETROICOR



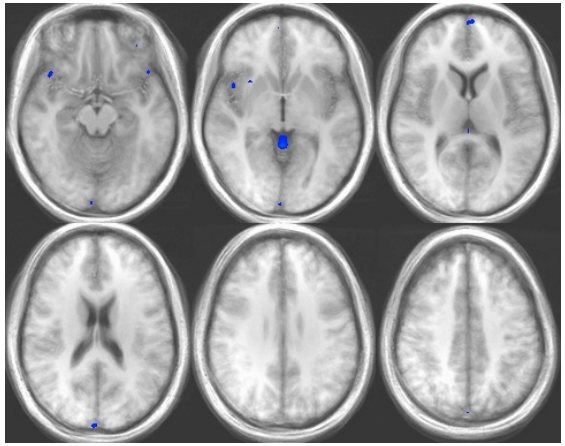
Δ RVTcor



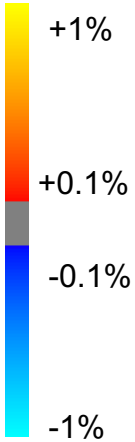
Δ Motion detrend



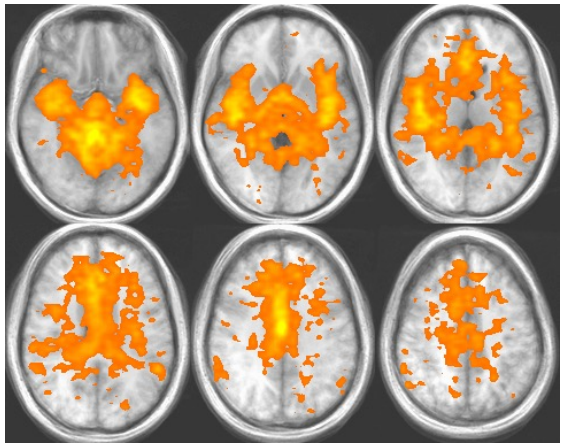
Δ Global detrend



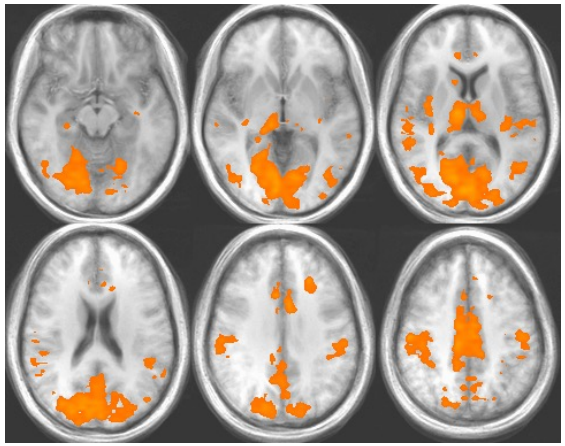
Δ WM detrend



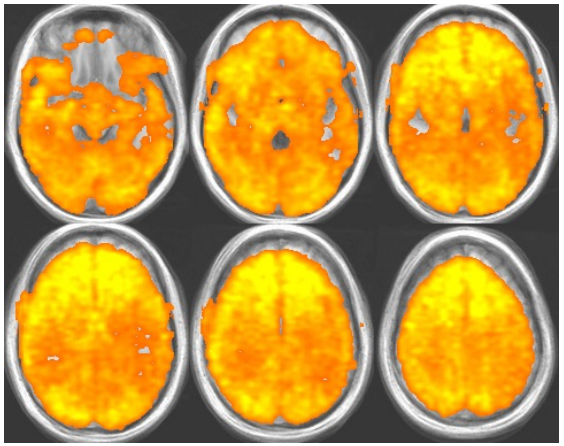
Change in TSNR – Group data (n=10)



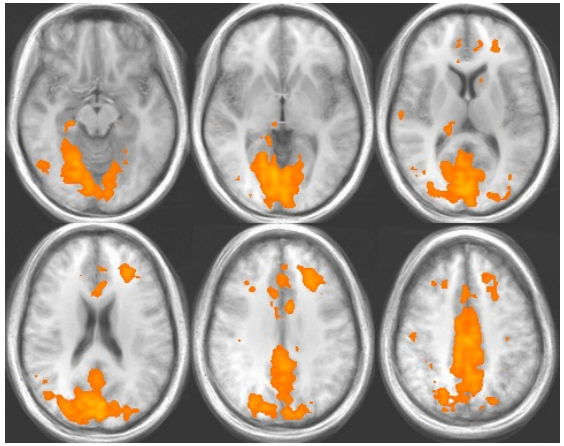
Δ RETROICOR



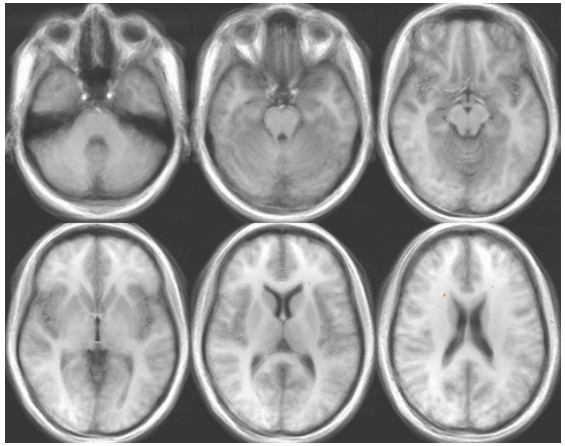
Δ RVTcor



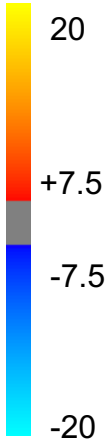
Δ Motion detrend



Δ Global detrend



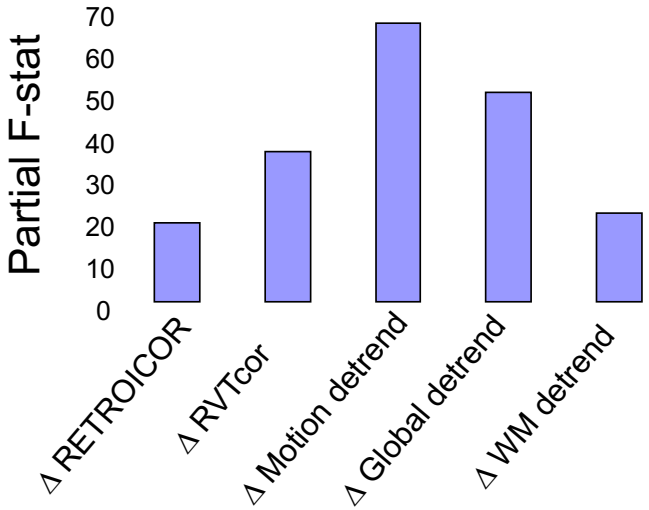
Δ WM detrend

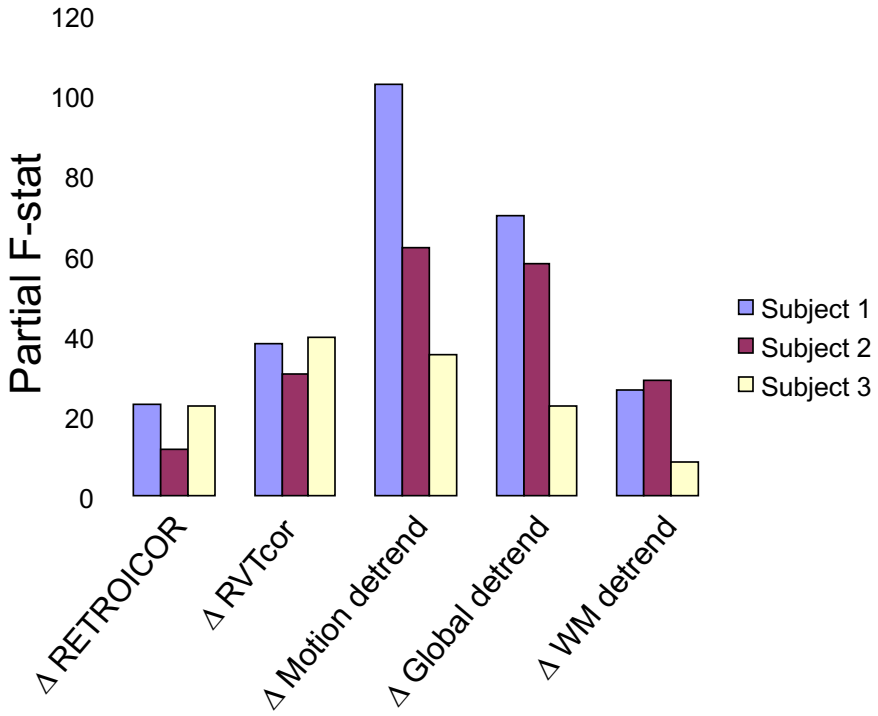


Relative contributions to noise

Averaged over Gray Matter

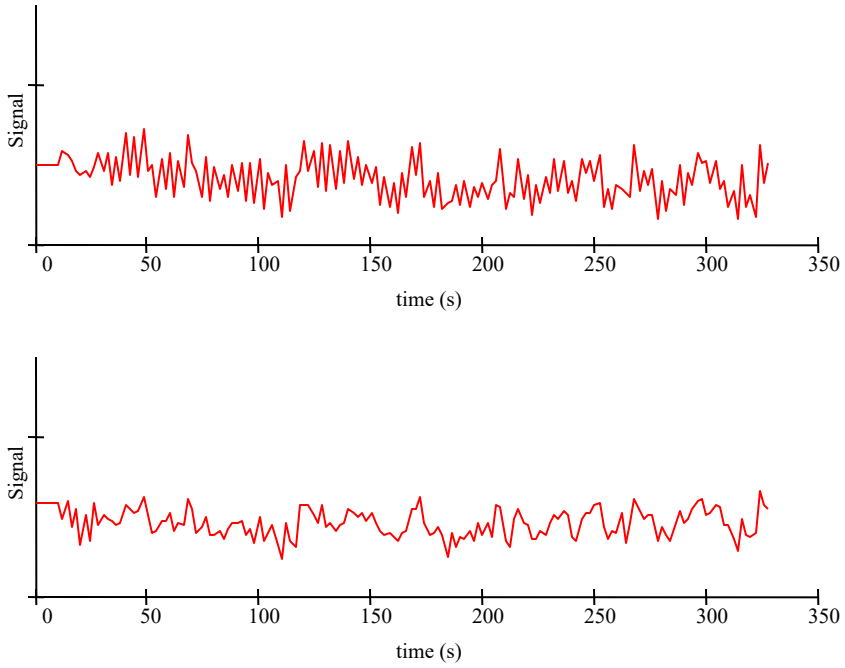
$$\text{Partial F} = \frac{\text{SSE(R)} - \text{SSE(F)}}{\text{SSE(F)}} \quad \frac{\text{dof(F)}}{\text{dof(R)-dof(F)}}$$





Example: regress out RVT

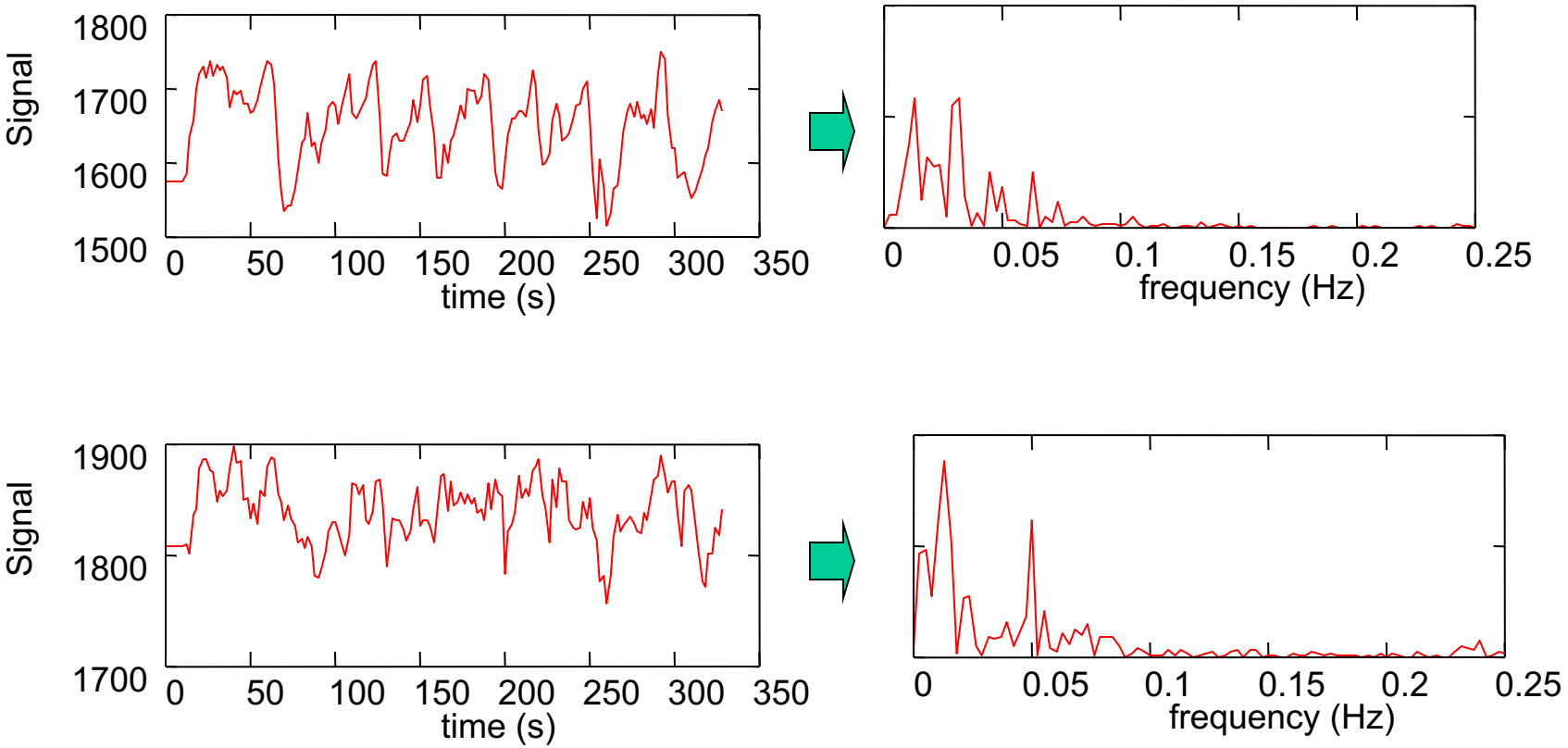
Regress out Card/Resp/RVT



Constant Respirations

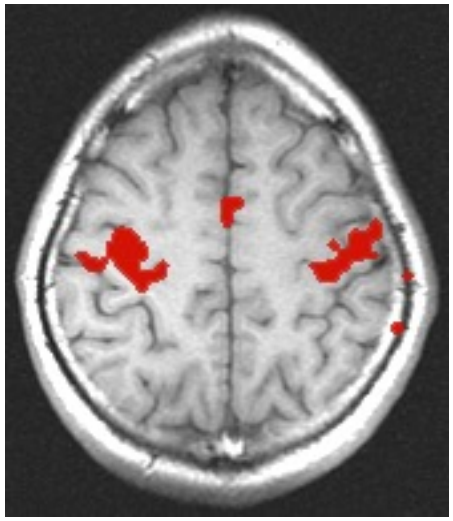
<END>

Sample time courses (& frequencies)

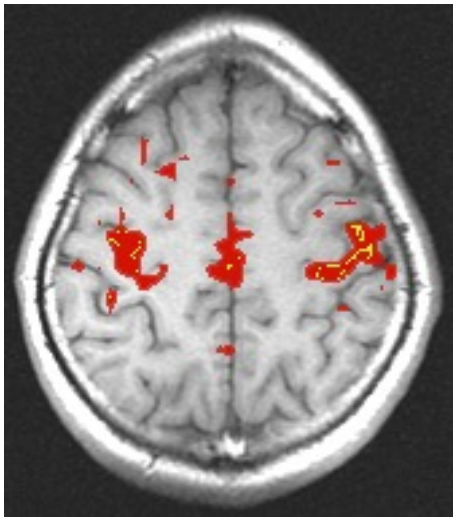


Resting-state functional connectivity

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



Activation during finger-tapping



Correlations with “seed voxel” in motor cortex at rest

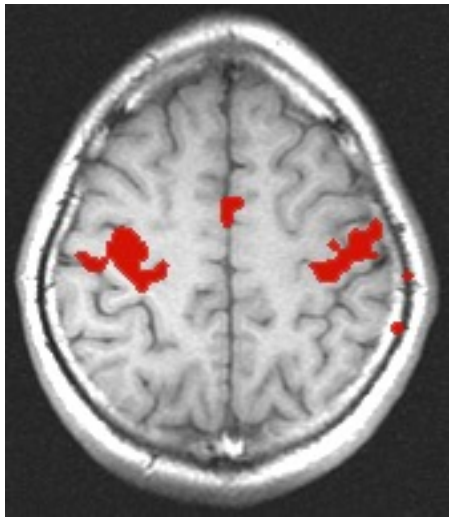
Further work:

M.J. Lowe, et al., NeuroImage 7(2), 1998.
D. Cordes, et al., AJNR 21(9), 2000.

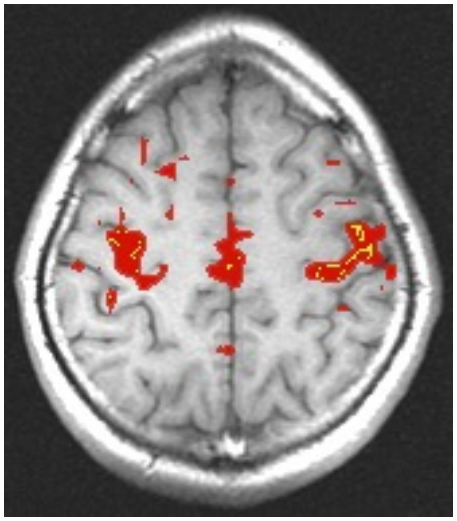
⋮

Resting-state functional connectivity

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



Activation during
finger-tapping

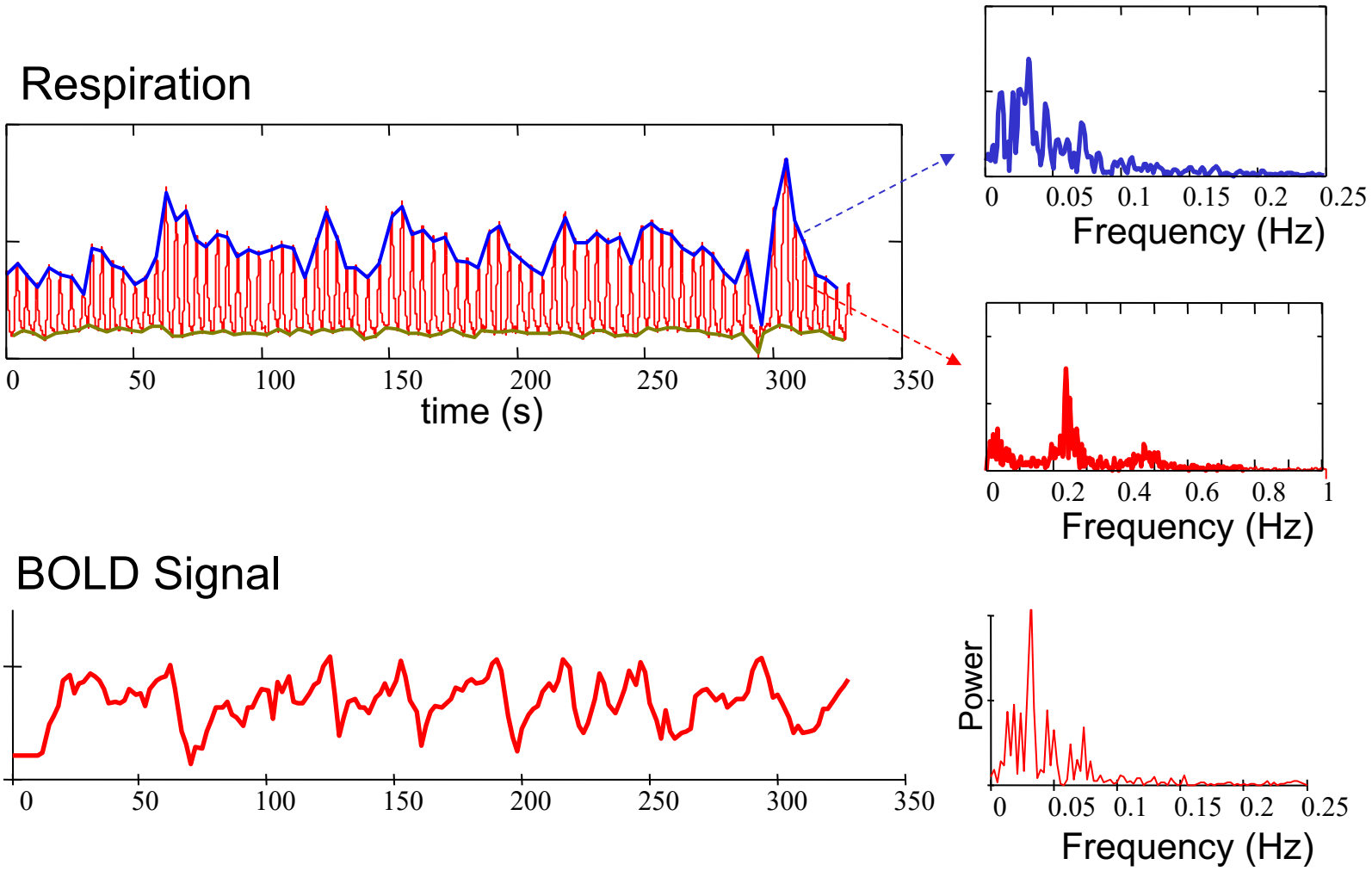


Correlations with “seed voxel”
in motor cortex at rest

M.J. Lowe, et al., NeuroImage 7(2), 1998.
D. Cordes, et al., AJNR 21(9), 2000.

⋮

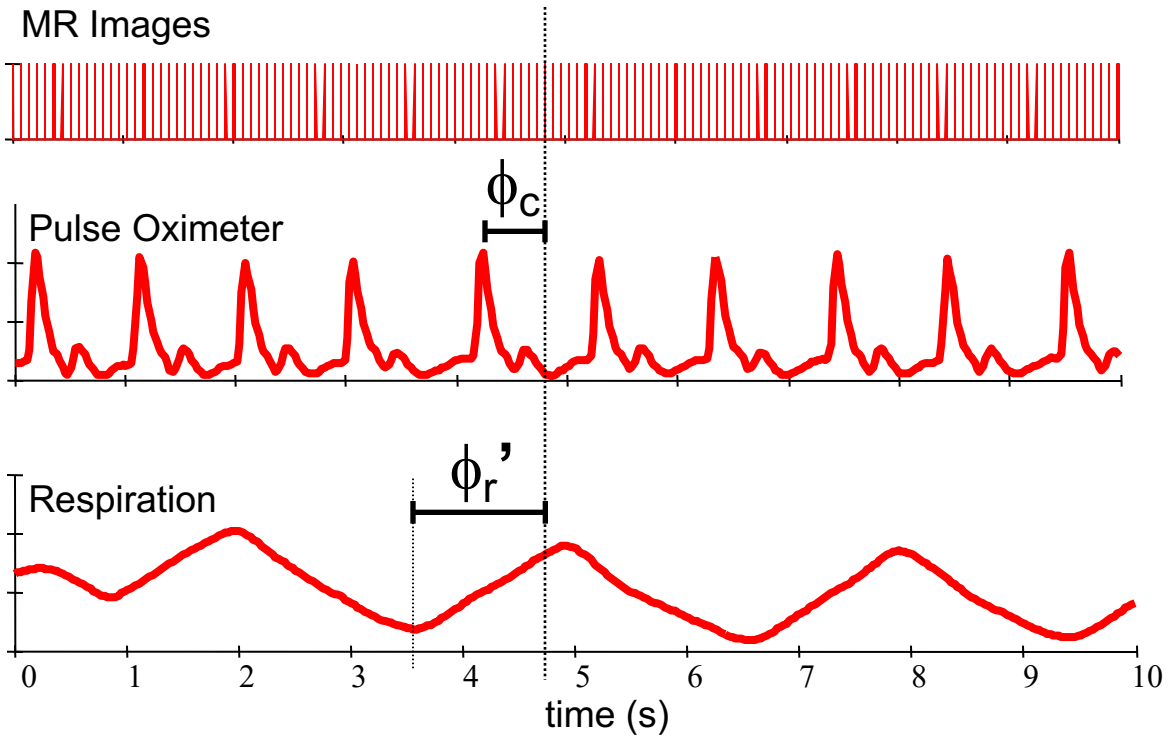
Resting fluctuations in respiration



Methods

Analysis

1. Image Registration
2. RETROICOR



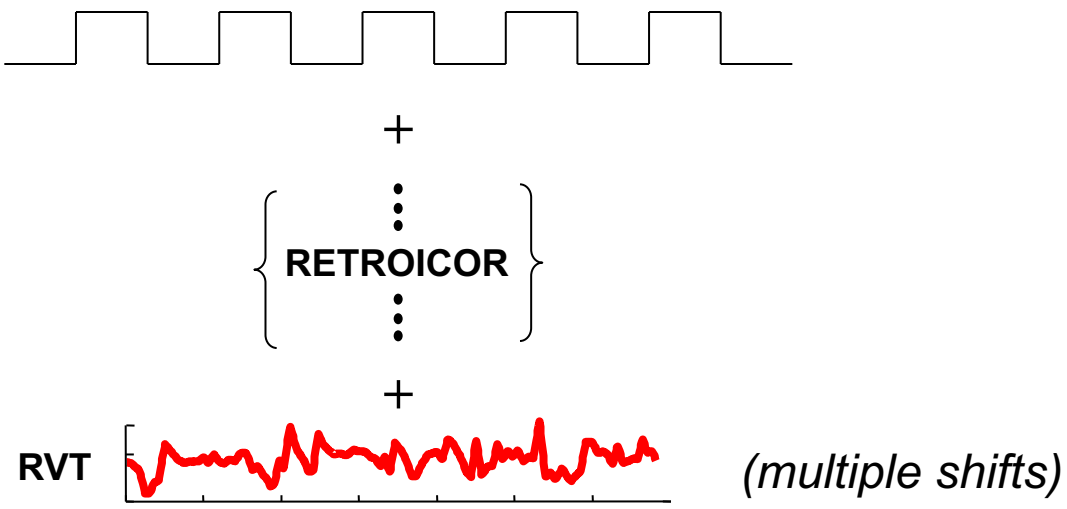
Additional Regressors:

$$\begin{Bmatrix} \sin(\phi_c) \\ \cos(\phi_c) \\ \sin(2\phi_c) \\ \cos(2\phi_c) \\ \sin(\phi_r) \\ \cos(\phi_r) \\ \sin(2\phi_r) \\ \cos(2\phi_r) \end{Bmatrix}$$

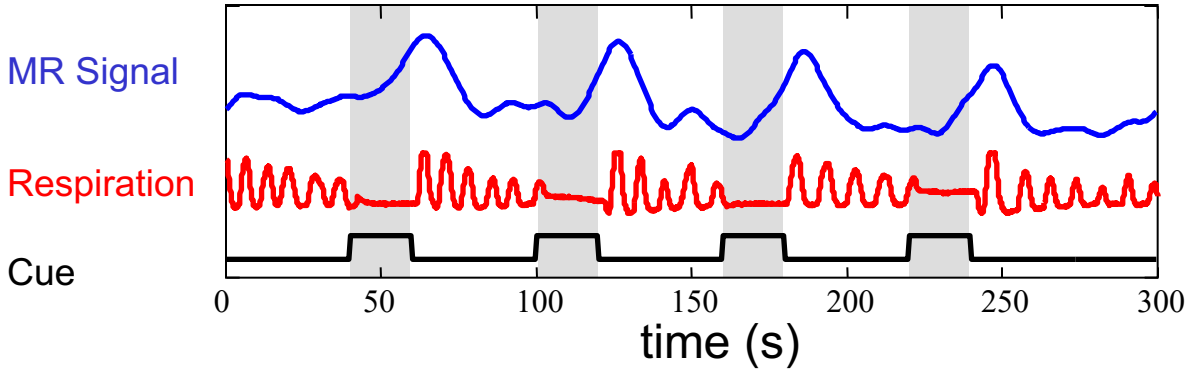
Methods

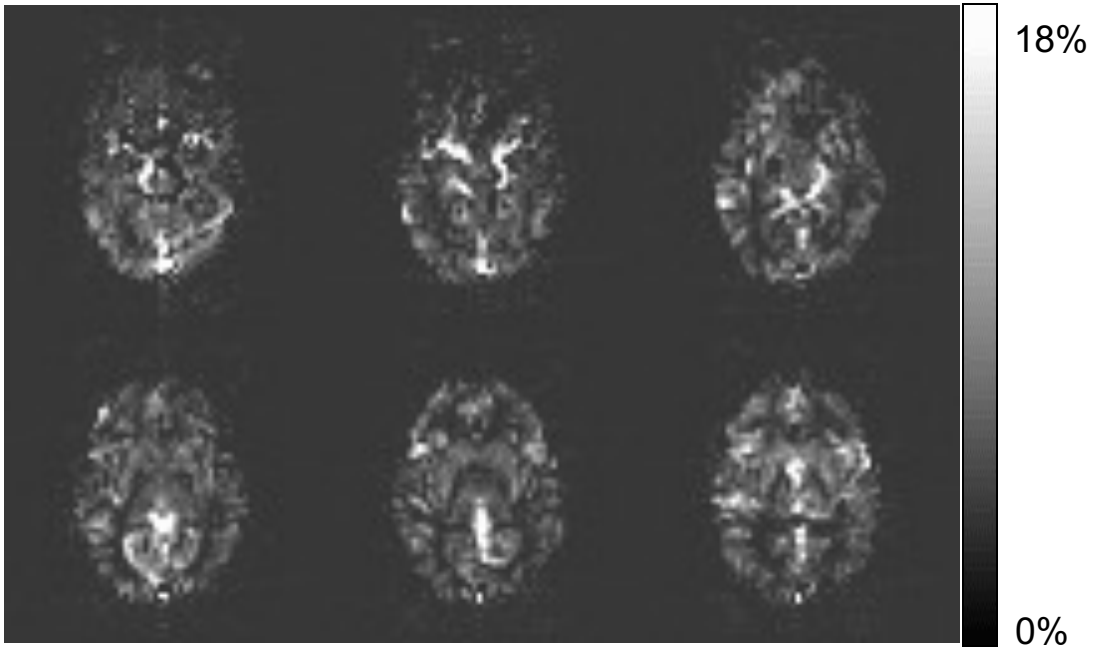
Analysis

1. Image Registration
2. RETROICOR
3. RVTcor
4. Regression Analysis

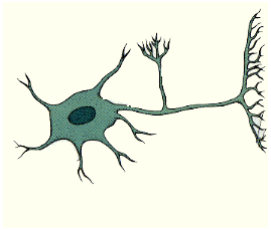


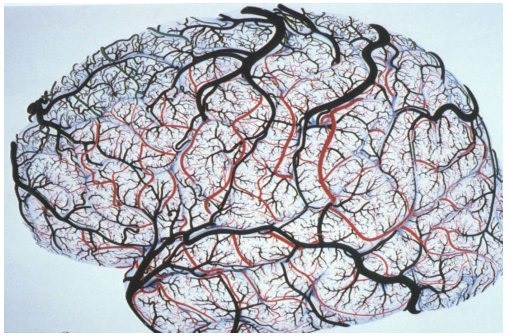
Breath-holding

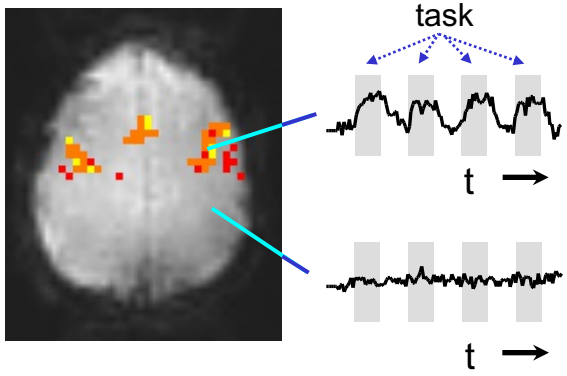




The fMRI Signal







Task-related Neuronal Activity

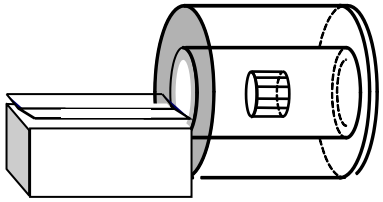
Spontaneous Neuronal Activity

Hemodynamics

fMRI signal

Thermal noise, Artifacts

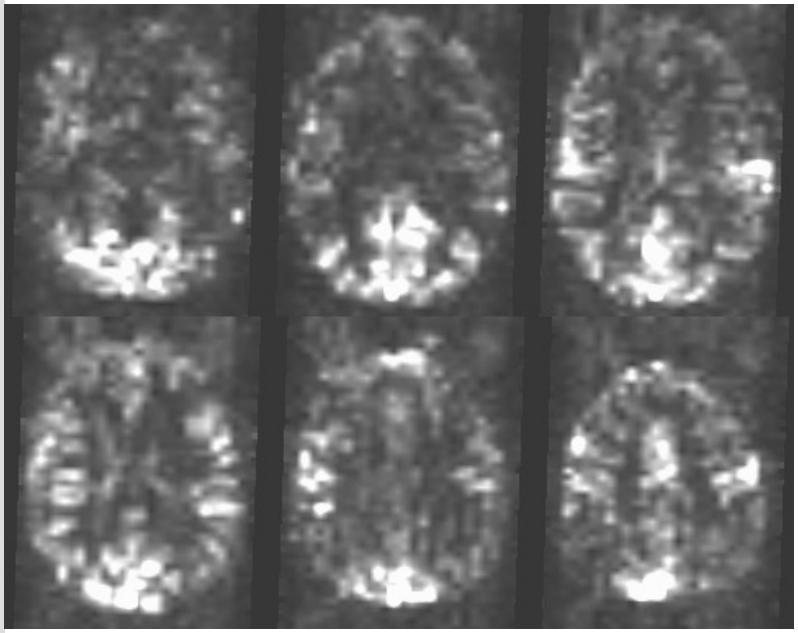
Physiologic noise (cardiac, respiration)



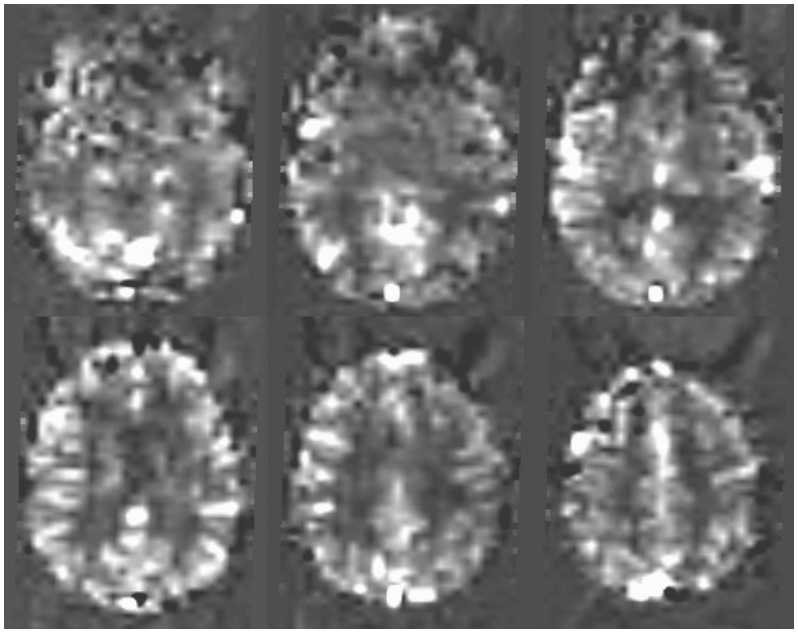
Resting changes in breathing vs. Breath-holding

Correlation with Respiration Volume / Time (RVT)

Rest



Breath-hold



General motivations for my research

- Improve image quality
  - Motion correction
  - Optimal paradigm design
  - Reducing sources of noise (e.g. physiological noise)

- Improve interpretability of BOLD fMRI

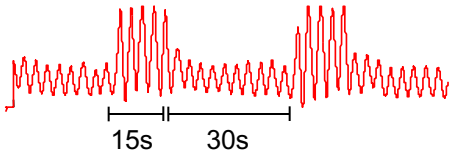
  How are BOLD changes related to neuronal activity?
  What does a certain % signal change really mean?

  - Temporal dynamics
  - Comparison to other vascular measures *(CBF, CO2, venogram, bolus contrast agent)*
  - Comparison of sequences with different contrast *(SE/ GE)*

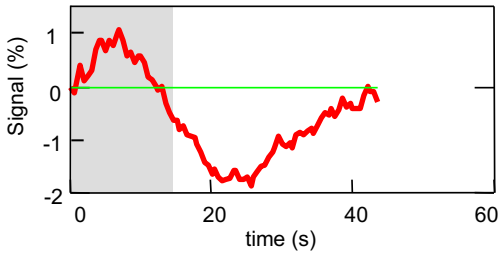
fMRI response to breathing modulations

Changes in Depth

Respiration

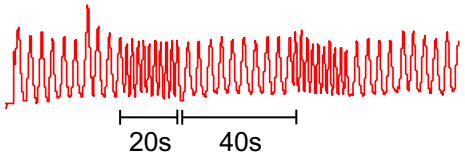


fMRI Signal

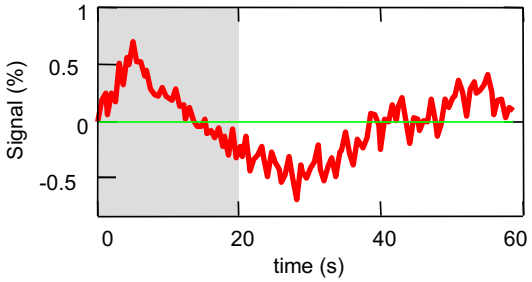


Changes in Rate

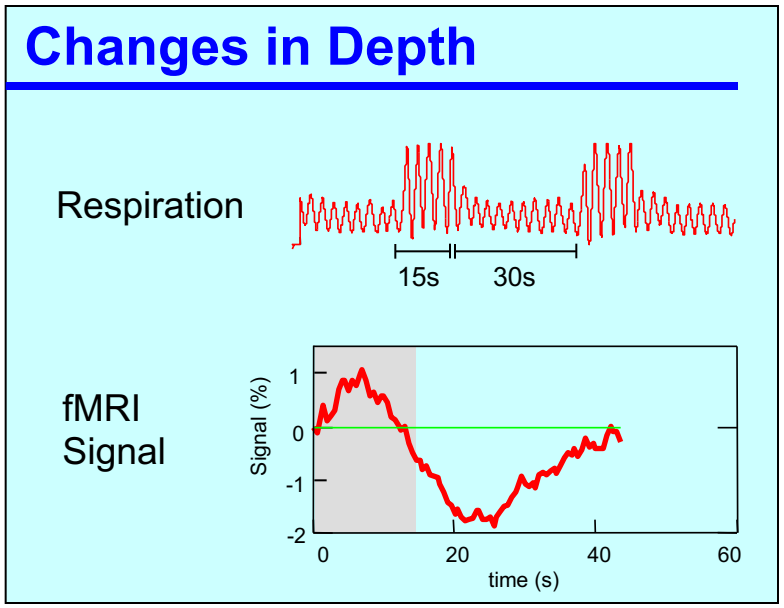
Respiration

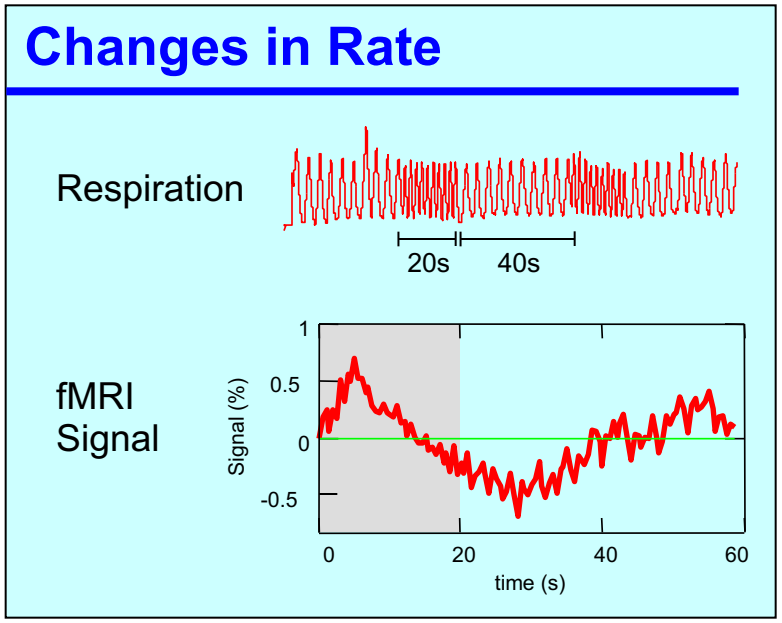


fMRI Signal

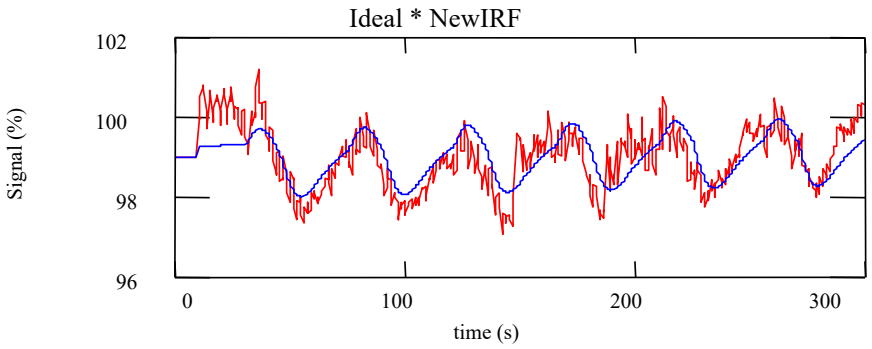


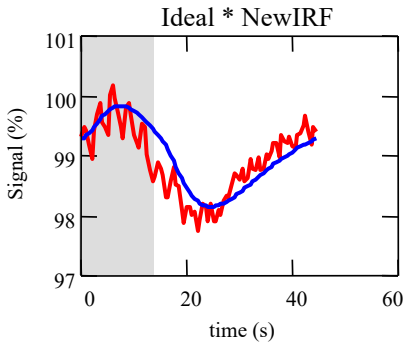
fMRI response to breathing modulations



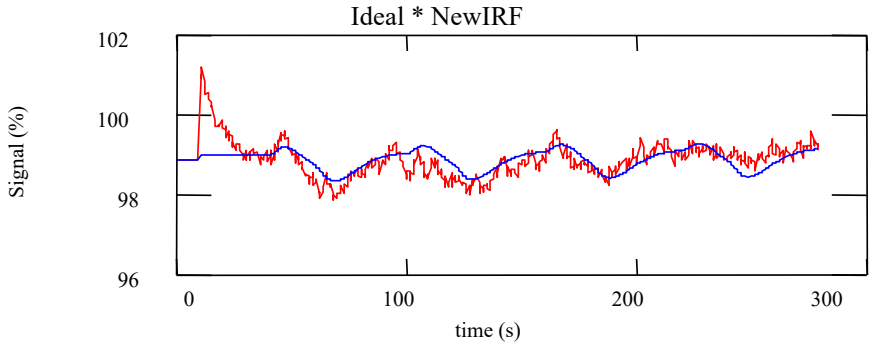


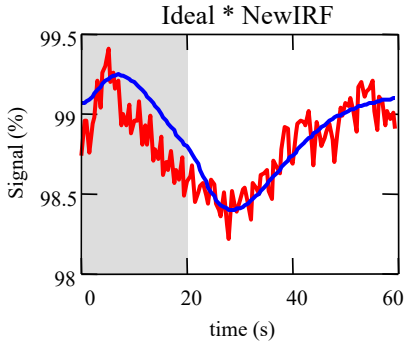
Depth


Ideal * NewIRF
Signal (%)
102
100
98
96
0
100
200
300
time (s)

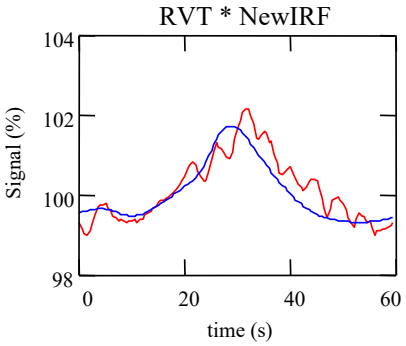

Ideal * NewIRF
Signal (%)
101
100
99
98
97
0
20
40
60
time (s)

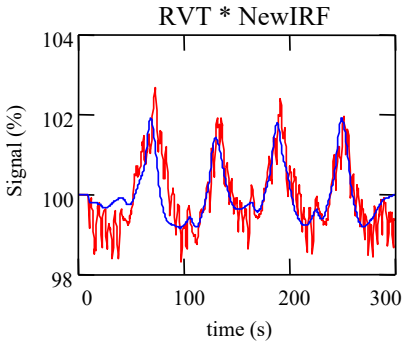
Rate

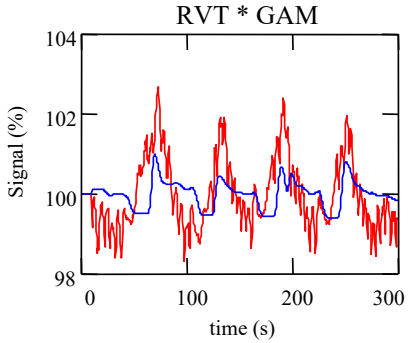

Ideal * NewIRF
Signal (%)
102
100
98
96
0
100
200
300
time (s)

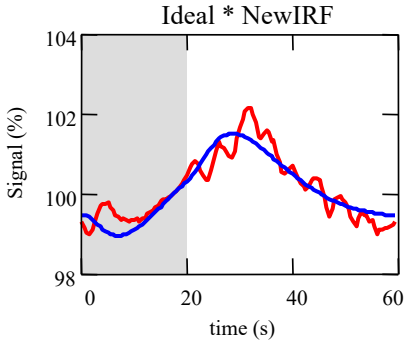

Ideal * NewIRF
Signal (%)
99.5
99
98.5
98
0
20
40
60
time (s)

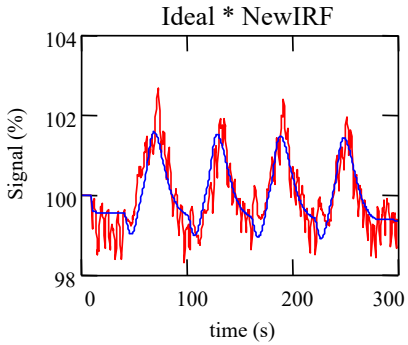
Breath-hold

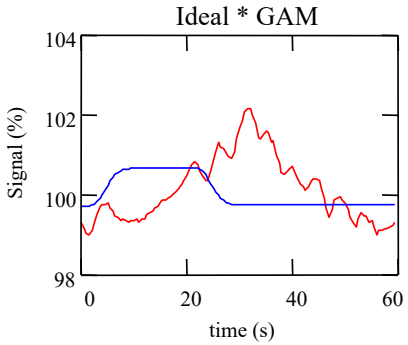

RVT * NewIRF
Signal (%)
104
102
100
98
0
20
40
60
time (s)


RVT * NewIRF
Signal (%)
104
102
100
98
0
100
200
300
time (s)

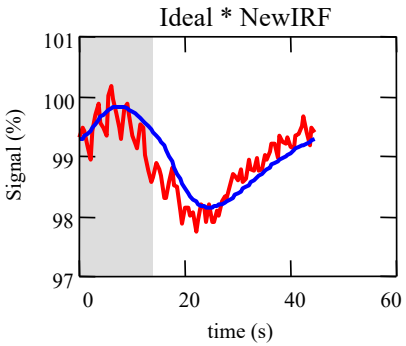

RVT * GAM
Signal (%)
104
102
100
98
0
100
200
300
time (s)

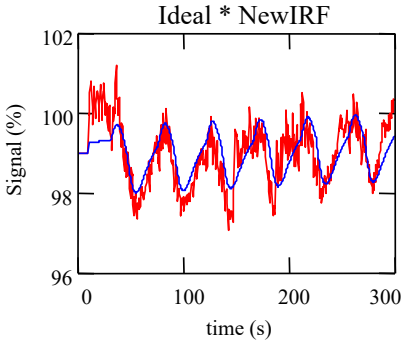

Ideal * NewIRF
Signal (%)
104
102
100
98
0
20
40
60
time (s)

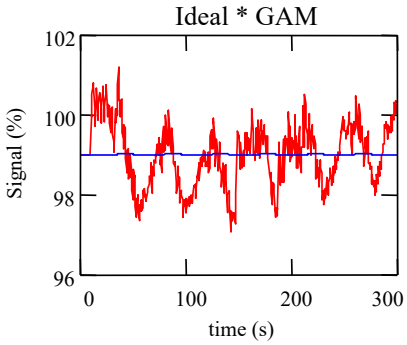

Ideal * NewIRF
Signal (%)
104
102
100
98
0
100
200
300
time (s)


Ideal * GAM
Signal (%)
104
102
100
98
0
20
40
60
time (s)

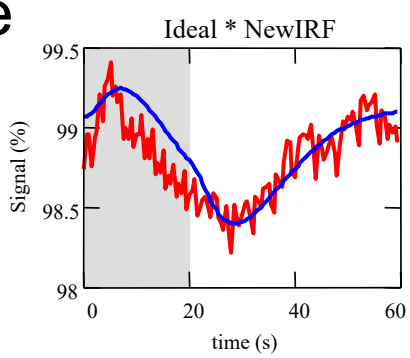
Depth

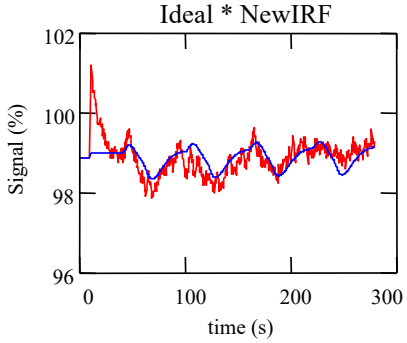

Ideal * NewIRF
Signal (%)
101
100
99
98
97
0
20
40
60
time (s)

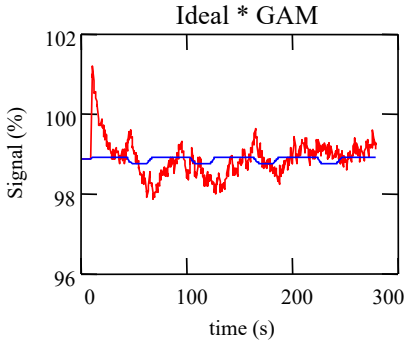

Ideal * NewIRF
Signal (%)
102
100
98
96
0
100
200
300
time (s)


Ideal * GAM
Signal (%)
102
100
98
96
0
100
200
300
time (s)

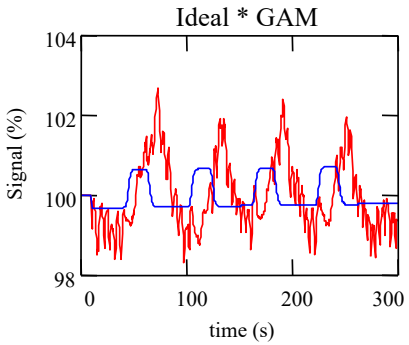
Rate


Ideal * NewIRF
Signal (%)
99.5
99
98.5
98
0
20
40
60
time (s)

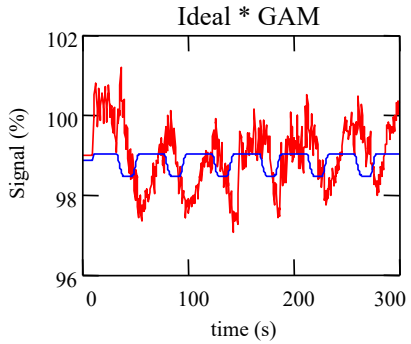

Ideal * NewIRF
Signal (%)
102
100
98
96
0
100
200
300
time (s)


Ideal * GAM
Signal (%)
102
100
98
96
0
100
200
300
time (s)

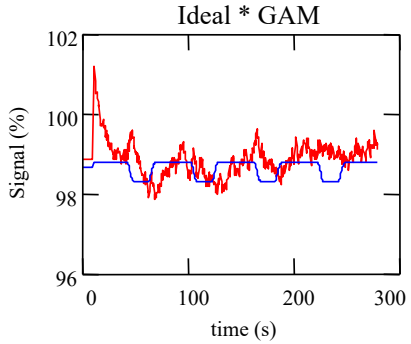
BH



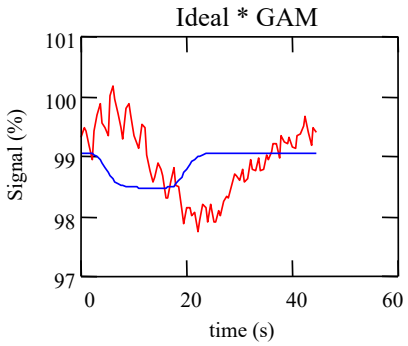
depth



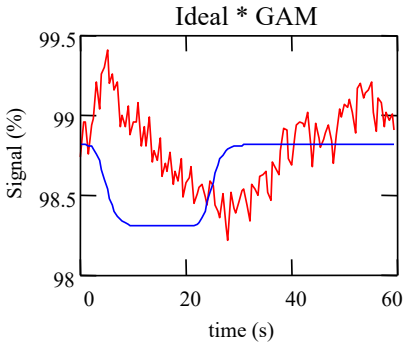
rate



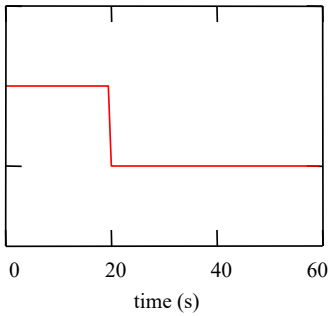
Depth

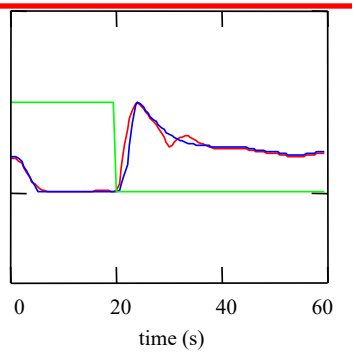

Ideal * GAM
101
100
99
98
97
Signal (%)
0
20
40
60
time (s)

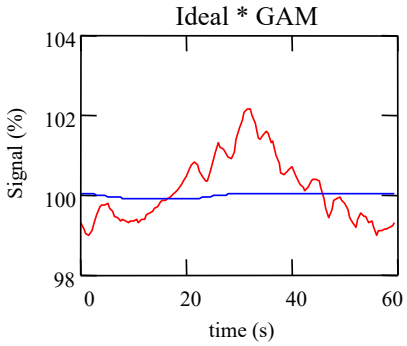
Rate

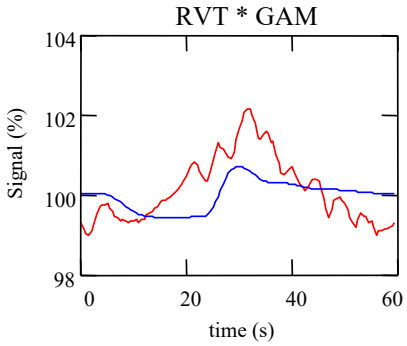

Ideal * GAM
99.5
99
98.5
98
Signal (%)
0
20
40
60
time (s)

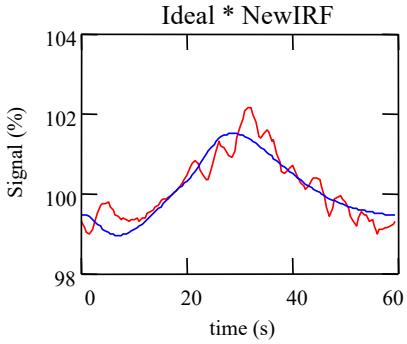
BH

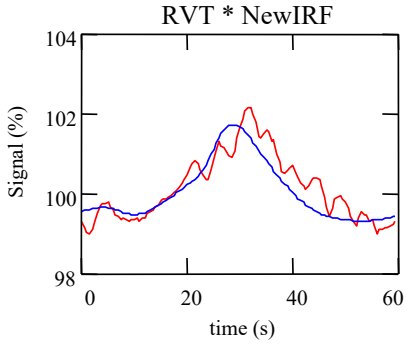

0
20
40
60
time (s)


0
20
40
60
time (s)

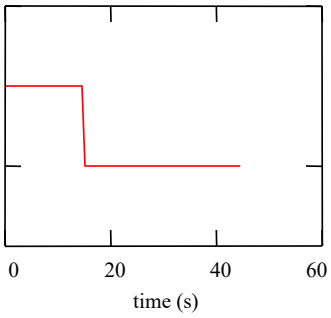

Ideal * GAM
104
102
100
98
Signal (%)
0
20
40
60
time (s)

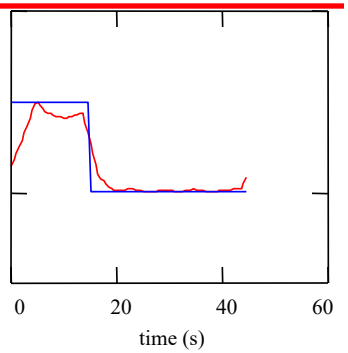

RVT * GAM
104
102
100
98
Signal (%)
0
20
40
60
time (s)

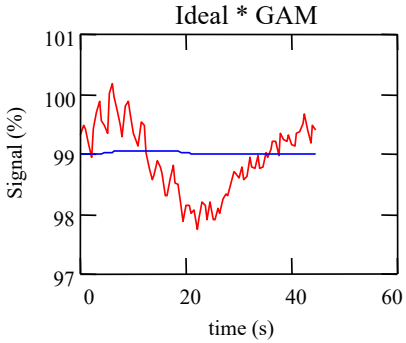

Ideal * NewIRF
104
102
100
98
Signal (%)
0
20
40
60
time (s)

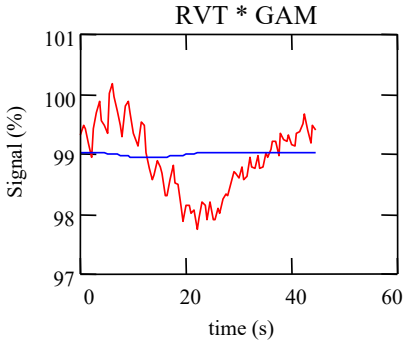

RVT * NewIRF
104
102
100
98
Signal (%)
0
20
40
60
time (s)

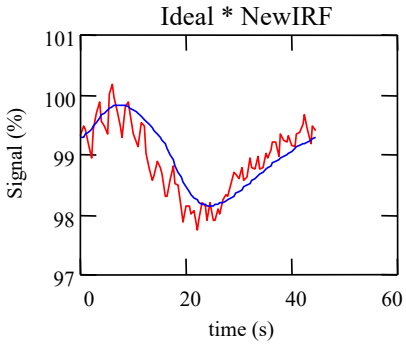
Depth

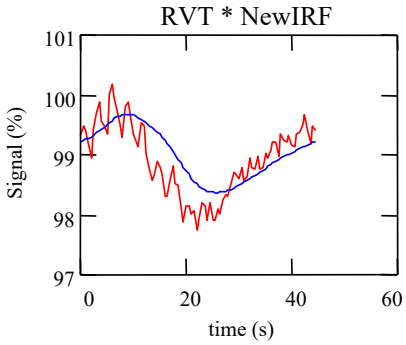

0
20
40
60
time (s)


0
20
40
60
time (s)

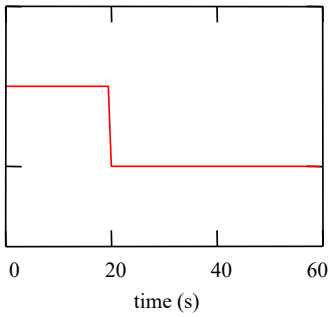

Ideal * GAM
101
100
99
98
97
Signal (%)
0
20
40
60
time (s)

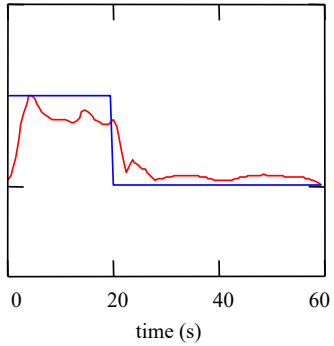

RVT * GAM
101
100
99
98
97
Signal (%)
0
20
40
60
time (s)

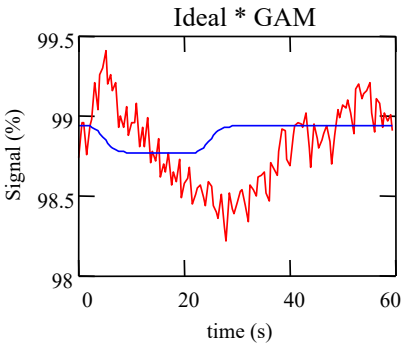

Ideal * NewIRF
101
100
99
98
97
Signal (%)
0
20
40
60
time (s)

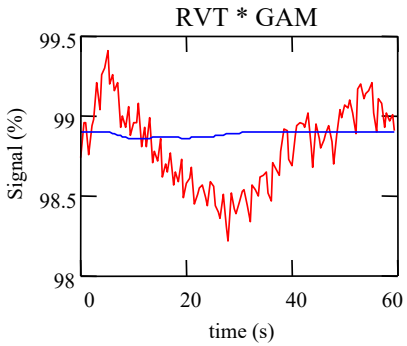

RVT * NewIRF
101
100
99
98
97
Signal (%)
0
20
40
60
time (s)

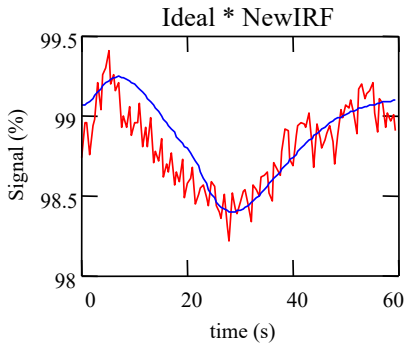
Rate

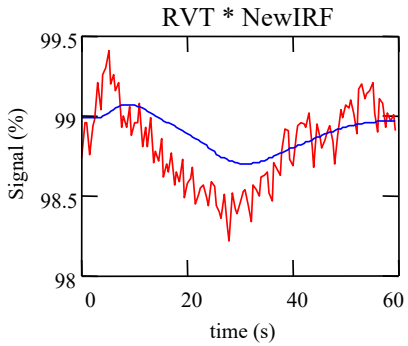

0
20
40
60
time (s)


0
20
40
60
time (s)

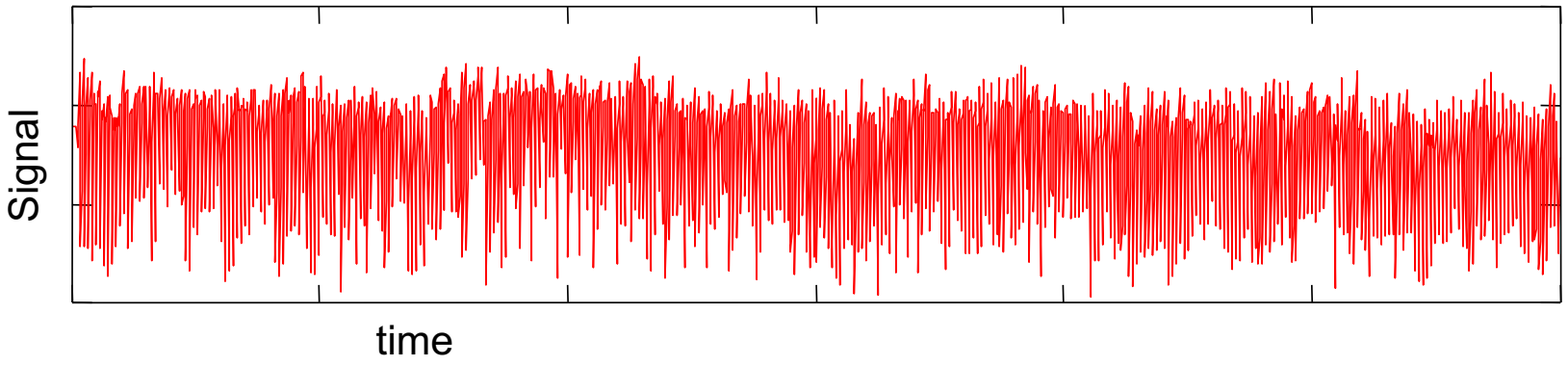

Ideal * GAM
99.5
99
98.5
98
Signal (%)
0
20
40
60
time (s)


RVT * GAM
99.5
99
98.5
98
Signal (%)
0
20
40
60
time (s)


Ideal * NewIRF
99.5
99
98.5
98
Signal (%)
0
20
40
60
time (s)


RVT * NewIRF
99.5
99
98.5
98
Signal (%)
0
20
40
60
time (s)

Correction of physiological noise



Reshuffle the data based on its cardiac or respiration phase