Basic physiology of fMRI: signal and noise
Overview

- Brief overview of fMRI
- Contrast mechanisms
  - Source of the fMRI signal
- Sources of Noise (& corrections)
  - Motion
  - Cardiac
  - Respiration
Brain activity during cued finger tapping
Measuring Brain Function with MRI

Task

Neuronal Activity

Red Blood Cells
How can we see brain function with MRI?

Oxygenated and deoxygenated red blood cells have different magnetic properties

Detecting “activation”

\[ \Delta S = M_{0a} e^{-t/T2^a} - M_{0r} e^{-t/T2^r} \]

\[ \frac{\Delta S}{S_0} = \frac{M_{0a}}{M_{0r}} e^{-t\Delta R^2} - 1 \]
Measuring Brain Function with MRI

BOLD = Blood Oxygenation Level Dependent

Task ➔ Neuronal Activity ➔ Hemodynamics ➔ MRI signal

Red Blood Cells

↑ Task ➔ ↑ Blood Flow ➔ ↓ deoxy-Hb ➔ ↑ MRI signal
The Blood Oxygenation Level Dependent Response

↑ Task
↓
↑ neuronal activity
↓
↑ BF
↓
deoxy-Hb
↓
↑ MR signal
The Blood Oxygenation Level Dependent Response

![Image of brain scan with blood flow visualization]

- ↑ Task
  - ↓ neuronal activity
    - ↑ BV ← ↑ BF ← ↑ CMRO$_2$
      - ↓ - ↓ + ↓ - ↓
    - ↑ HbO$_2$ ↓ deoxy-Hb
  - ↑ MR signal
Temporal dynamics of fMRI signal change

Activation amplitude

Delay
Functional Magnetic Resonance Imaging (fMRI)

Look for changes in MRI signal over time

Typical MRI

Task
Blood Flow
deoxy-Hb
MRI signal

Functional MRI
Brain activity during cued finger tapping

Map the changes in MRI signal over time
Functional MRI

- **Task-related Neuronal Activity**
- **Spontaneous Neuronal Activity**
- **Physiologic noise** (cardiac, respiration) Subject motion
- **Scanner instabilities** Image reconstruction errors

**Hemodynamics**

- **resting state**
Problem: Subject Motion

Signal changes occur at edges
Correcting for subject motion

- Prevent Motion
- Image registration

\[
\begin{align*}
  t = 0 & \quad \text{\textbf{head}} \\
  t = 1 & \quad \text{\textbf{head}}
\end{align*}
\]

- Regress out motion-related changes
Problem: motion during the volume
Problem: motion during the volume

expected acquisition: slices are actually acquired like this…
Problem: motion during the volume

Potential solution: Prospective motion correction

slice tracks with the motion

Physiological noise

Cardiac

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

Respiration

Field Map

Figure courtesy of J. Bodurka
Can filtering (<0.1 Hz) reduce cardiac noise?

- Not always: **Aliasing**
Correction of physiological noise


Additional Regressors:

\[
\begin{align*}
\sin(\phi_c) & \\
\cos(\phi_c) & \\
\sin(2\phi_c) & \\
\cos(2\phi_c) & \\
\sin(\phi_r) & \\
\cos(\phi_r) & \\
\sin(2\phi_r) & \\
\cos(2\phi_r) & 
\end{align*}
\]

MR Images

Pulse Oximeter

Respiration

Time (s)
Correction of physiological noise

Reshuffle the data based on its cardiac or respiration phase
Correction: Cardiac + Respiration

At what stage should physio correction be done?

- Preprocessing
  - Motion correction
  - Physiological noise correction
  - Slice time correction
  - Nuisance Regression
  - Spatial Smoothing
  - Convert to percent signal change
  - Temporal filter
- Define ROI (seed)
- Average EPI time course over ROI
- Regression

T.B. Jones et al., Neuroimage 42, 2008
Physio. fluctuations can occur at low frequencies

Variations in breathing during rest \( \rightarrow \Delta \text{BOLD signal} \)

\[ \Delta P_{\text{ET CO}_2} \text{ correlated w/ } \Delta \text{BOLD} \]

R.G. Wise et al., NeuroImage 21, 2004
Resting fluctuations in respiration

RVT-related changes

\[ RVT = \text{Respiration Volume per Time} \]

group (n=11)
RVHRcor (Respiration Volume + Heart Rate)

C. Chang et al., Neuroimage 2009
Nuisance Regression

H.J. Jo et al., NeuroImage 52, 2010
The effect of global signal regression

The global signal is highly correlated with RVT.

Connectivity maps (separate study, n = 18)

Without global regression

With global regression

CC: RVT ~ global signal
Global Signal Regression

Can introduce anti-correlations

K. Murphy, et al., Neuroimage, 2008
Global Signal Regression

Can alter group differences ...under certain conditions

Illustrative Model 3:
Contrast of correlations between groups A and B
‘long-range’ correlations in Group B only

Group A
Local Corr. Only

Group B
Local and Long Range Corr.

"local" correlations

"long-range" correlations

Pre-GSReg | Post-GSReg

Post-GSReg

$r^*_{B} - r^*_{A}$

Z.S. Saad, et al., Brain Connectivity, 2012
Nuisance Regression

H.J. Jo et al., NeuroImage 52, 2010
PSTCor (Phase-shifted Soft Tissue Corr.)

J.S. Anderson et al., HBM 32, 2011
“FIX” (FMRIB’s ICA-based X-noisifier)
ICA-AROMA: A robust ICA-based strategy for removing motion artifacts from fMRI data

Raimon H.R. Pruim a,b,*, Maarten Mennes a,b, Daan van Rooij b,c, Alberto Liera b, Jan K. Buitelaar a,b,d, Christian F. Beckmann a,b,e

* Radboudumc, Donders Institute for Brain, Cognition and Behaviour, Department of Cognitive Neuroscience, Nijmegen, The Netherlands
b Radboud University, Donders Institute for Brain, Cognition and Behaviour, Centre for Cognitive Neuroimaging, Nijmegen, The Netherlands
c University of Groningen, University Medical Center Groningen, Department of Psychiatry, Groningen, The Netherlands
d Karakter Child and Adolescent Psychiatry University Centre, Nijmegen, The Netherlands
ICA-AROMA

**Participant level**

- fMRI Preprocessing
  - Motion correction
  - 4D mean intensity normalization
  - Spatial smoothing (6mm FWHM)

**ICA-AROMA**

- ICA
  - Register IC spatial maps to MN152 2mm

- Motion Component Classification
  - Based on four features:
    - maximum RP correlation
    - Edge fraction
    - CSF fraction
    - High-frequency content

- fMRI data denoising
  - Removal of classified ICs from the fMRI data (fsi_regrfit)

- fMRI Preprocessing
  - Nuisance regression:
    - WM, CSF & linear trend
    - Highpass filtering

- Statistical analysis

**Graphs:**

- 24RP regression (1)
- 24RP regression (2)
- Spike regression
- ICA-AROMA

**Power Spectra:**

- Frequency (Hz)
- Power

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*R.H.R. Pruim et al., NeuroImage 112 (2015)*
Tools to correct for physiological noise

- Filtering - Works only if TR is short enough (< 400ms)
- IMPACT (Chuang et al., 2001) – if TR short enough
- Retrospective correction (k-space) (X. Hu et al., 1995)
- RETROICOR (Glover et al., 2000)
- CORSICA (V. Pelbarg, et al., 2007)
- PESTICA (E.B. Beall, et al., 2007)
- RVTcor (R.M. Birn, et al., 2006)
- RVHRcor (C. Chang, et al., 2009)
- ANATICOR (H-J. Jo, et al., )
- APPLECOR, PEARCOR (M Marx, et al., 2013)
- PSTCor (J.S. Anderson, et al., 2011)
- CompCor (Y. Behzadi, et al., 2007)
- FIX (L. Griffanti, et al., 2014)
- ICA-AROMA (###, et al., 2015)
Should we perform physio corrections?

- Reduces fluctuations related to heart beat and respiration
  - Reduce false positives
  - Reduce false negatives

- Some physiological fluctuations are associated with neuronal activity
  - E.g. Heart rate variability

This is still an open question in the field
TSNR vs SNR

Signal / Thermal Noise

Signal / Physiologic Noise

Temporal Signal to Noise Ratio

Signal-to-Noise Ratio
TSNR vs SNR

TSNR

Limits:
GM = 87
WM = 155
CSF = 53
Vessels = 68

#voxels:
GM=9472
WM=14844
CSF=9443
Vasculature=8666

Voxel Volume:
1.7 x 1.7 x 4 mm$^3$

SNR

J. Bodurka