MRC | Cognition and Brain Sciences Unit

MRI Physics II: the BOLD signal and common image artefacts

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Overview

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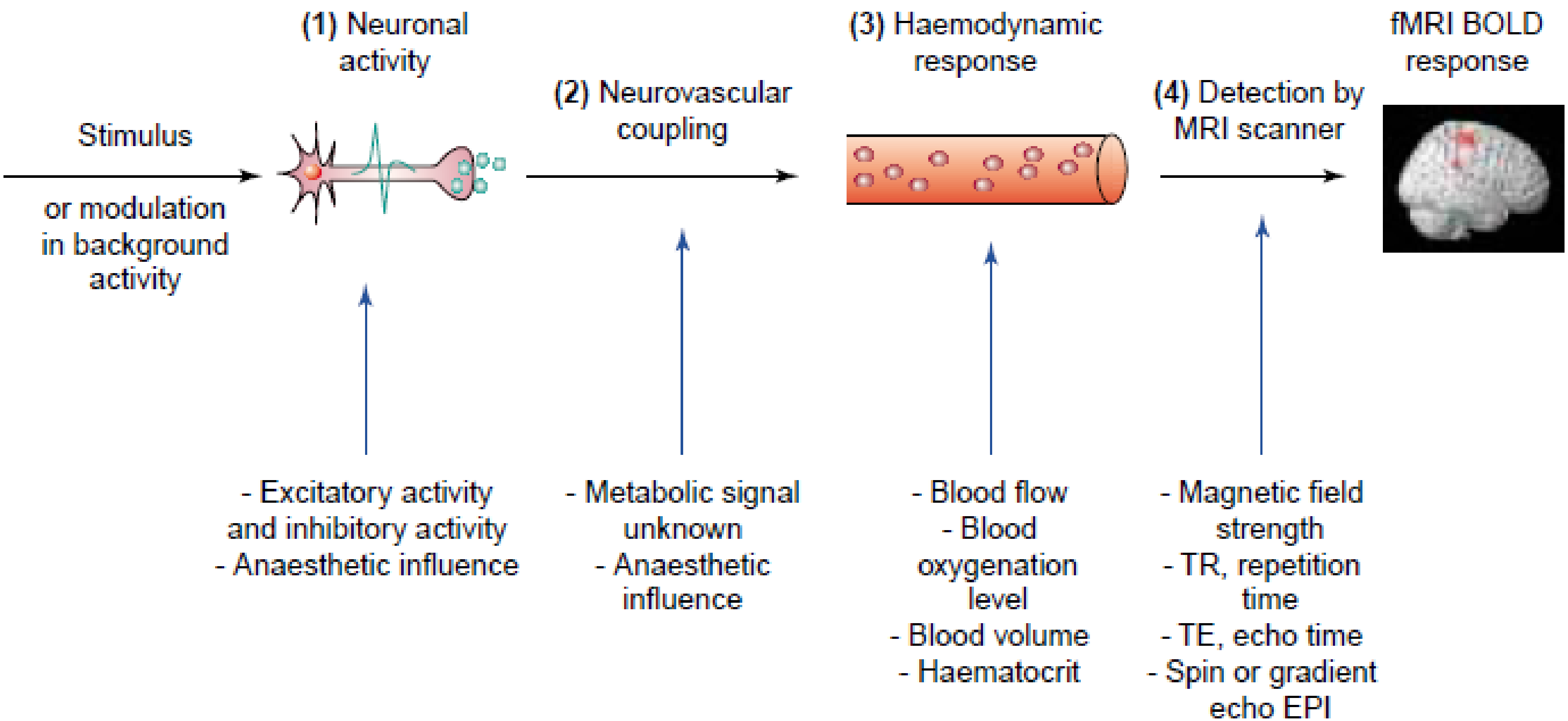
- Biophysics of functional MRI
  - Haemodynamic response
  - Haemodynamic – MRI coupling
  - Measuring the BOLD signal

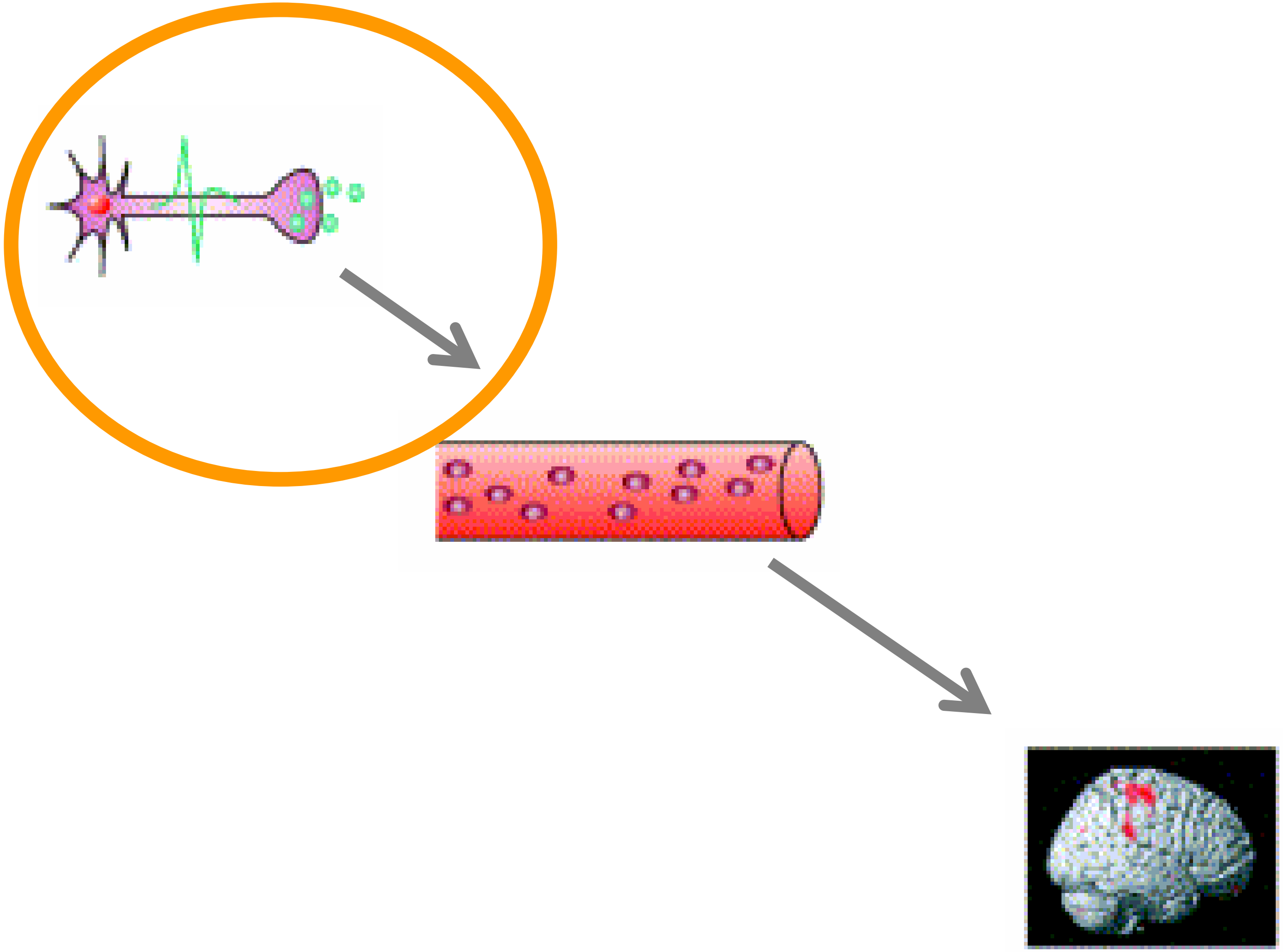
- Common Image artefacts
  - EPI distortion
  - Movement artefacts
  - Signal dropout

Biophysics of functional MRI

Key determinants of fMRI BOLD response



Arthurs & Boniface (2002)

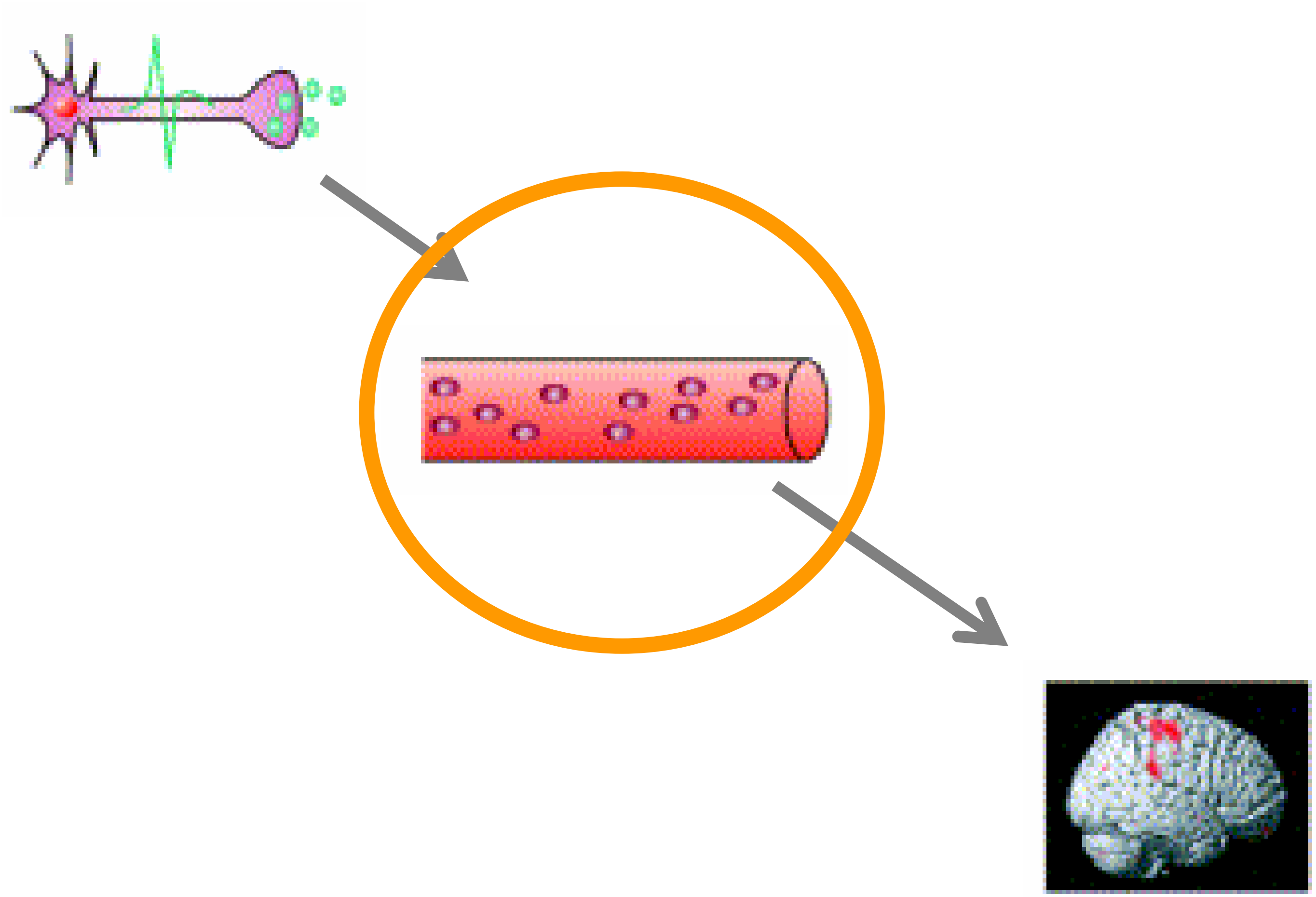


What aspects of neuronal activity determines BOLD response?

- **LFP (Logothetis et al, 2001)**
  - Simultaneous BOLD FMRI & electrophysiological recording
  - Measured **Local Field Potentials** (pre-synaptic, input) and Multi Unit Activity (spiking, output)
  - Both provided reasonable fit to BOLD activity, but LFPs better

- **Oxygen consumption (Hoge et al, 1999)**
  - Used MRI to measure CBF & oxygenation
  - Found linear relationship

- **Energy use/Neurotransmitter (Attwell & Iadecola, 2002)**
  - Assessment of energy use by different processes
    - Spiking very energy expensive
    - Most used by postsynaptic currents & action potentials
  - Argue hemodynamic response is driven by neurotransmitter signalling and not local energy use

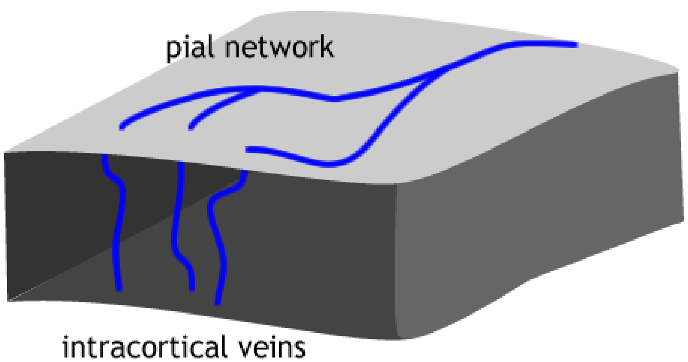


Hemodynamic response (HDR)

- **Increase in blood volume**
  - Increase in volume throughout system, from arterioles to capillaries, venules & veins
  - Fastest and greatest response in arterioles (Vanzetta, Hildenshen & Grinwald, 2005)
- **Large increase in blood flow**
- **Oxygenation**
  - Initial de-oxygenation in capillaries (Vanzetta et al, 2005)
  - Then, flow increase leads to a increase in oxygenation relative to the baseline state (Ogawa et al, 1990; Bandettini et al, 1997)

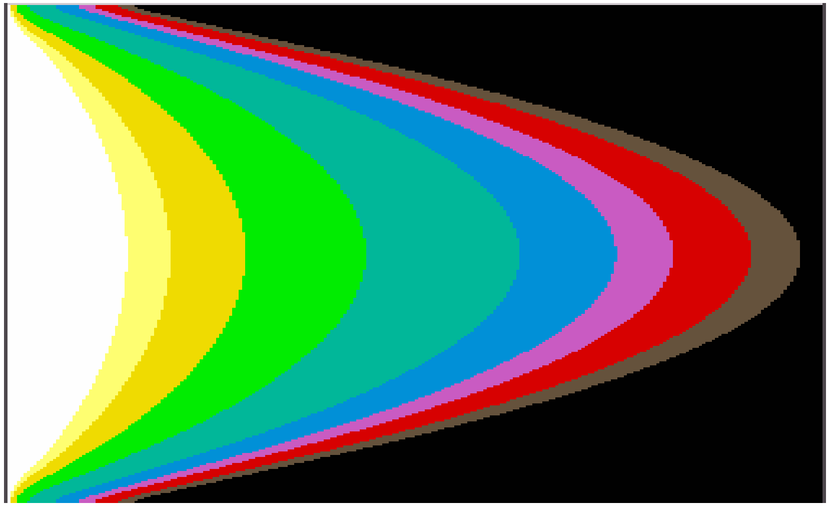
Influences on spatial distribution of HDR

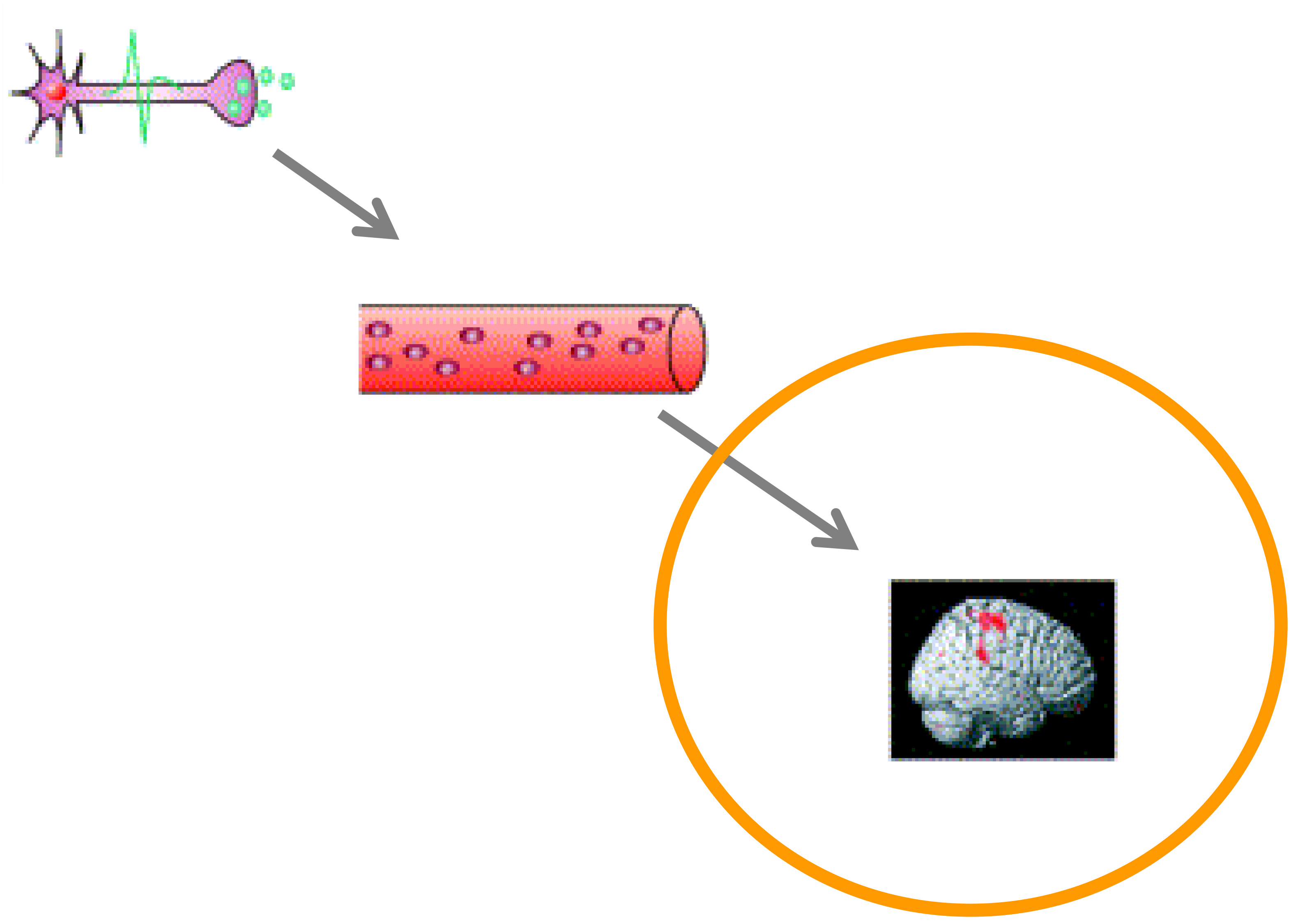
- Spatial characteristics influenced by
  - Vascular plumbing & structure
    - Intracortical vessels
    - Pial network
    - Larger vessels
  - Size of region activated (Turner, 2002)



Influences on temporal profile of HDR

- Temporal characteristics influenced by
  - By neurovascular coupling in arterioles/capillaries
  - Flow times
    - Function of vessel size
    - Blood velocity proportional to radius – much of delay in small vessels
  - Mixing due to laminar flow within vessels (de Zwart, 2005)
  - Other effects (e.g., vessel size dependence of post-stimulus adaptation – Mandeville et al, 1999; Yacoub et al, 2006)





Hemodynamic-MRI coupling

- HDR affects MRI signal through several mechanisms:
  - Extravascular: reduced field gradients around venules & veins
  - Intravascular change in T2*
  - Reduced phase mismatch between signal from inside and outside venules & veins
  - Change in blood volume

Hemodynamic-MRI coupling

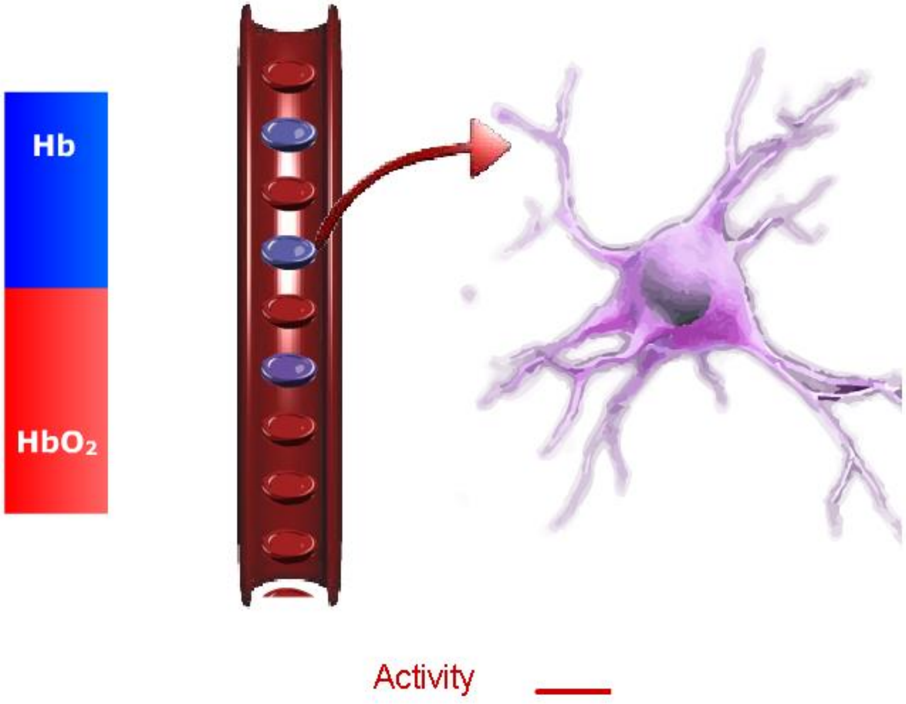
- Affected by parameters of MR acqusition
  - Field strength (higher field – more sensitivity, particularly to smaller vessels/capillaries) (Haacke, 1994; Yacoub et al, 2003)
  - Gradient echo vs. spin echo
    - latter insensitive to large vessels
    - less signal, but more spatially specific (Lee et al, 1999; Zhao et al, 2006)

Detecting HDR with MRI – BOLD signal

- BOLD – Blood Oxygenation Level Dependent
- BOLD fMRI employs haemoglobin as a convenient contrast agent
- It relies on the magnetization difference between oxy- and deoxyhaemoglobin to create the MRI signal.

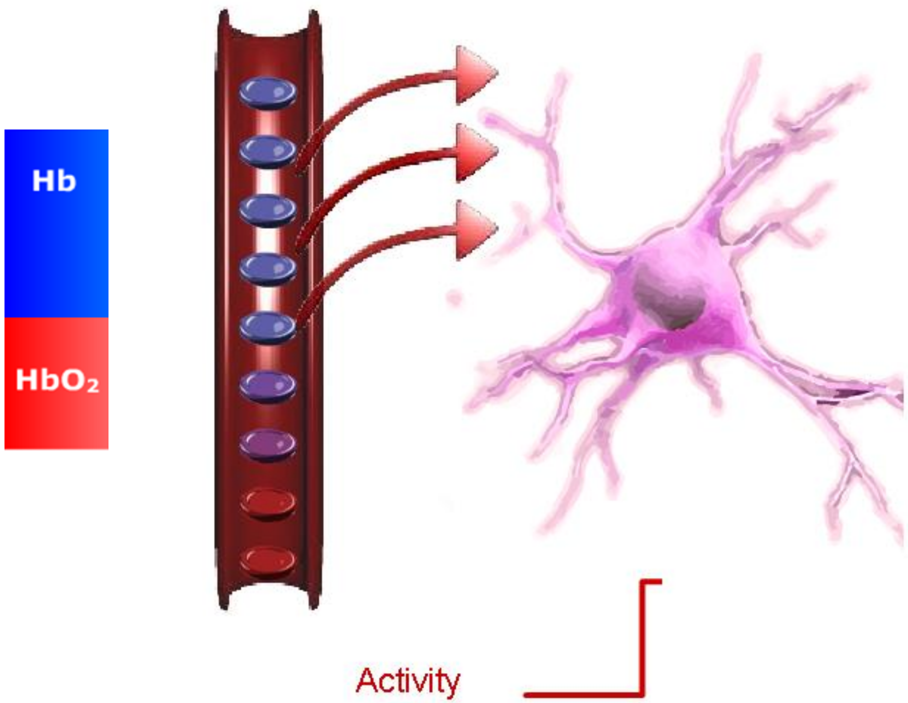
BOLD contrast step-by-step (1)

- The neuronal metabolism is dependent on blood oxygen supply, as the production of energy from glucose is mainly of the aerobic type.



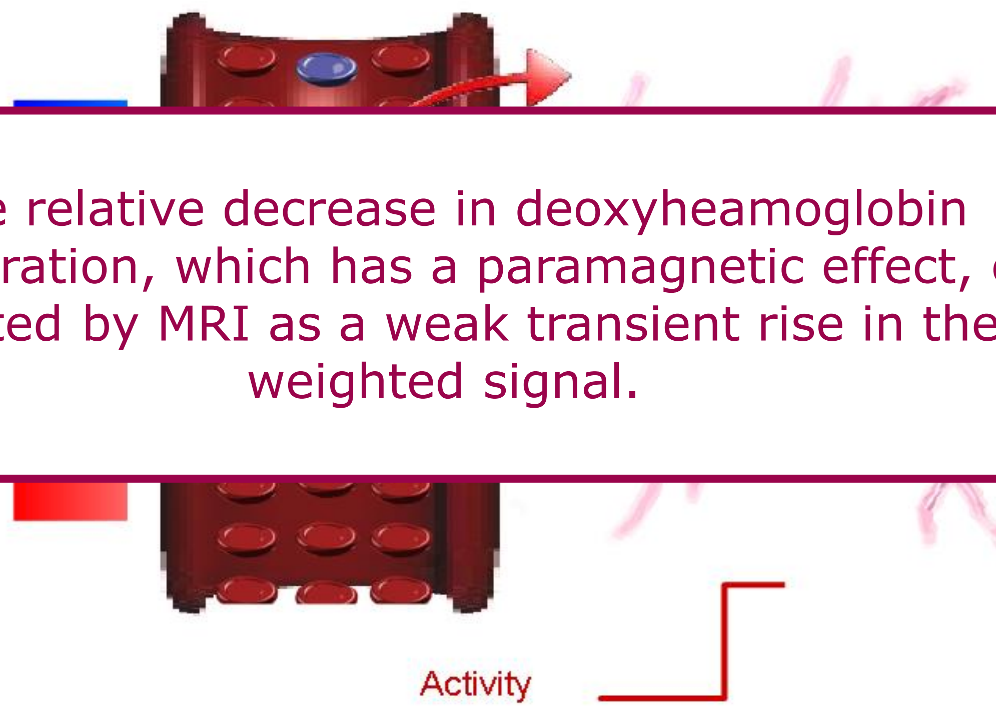
BOLD contrast step-by-step (2)

- Neuronal activity provokes an increase in oxygen consumption and an even higher increase in local blood flow (neurovascular coupling).



BOLD contrast step-by-step (3)

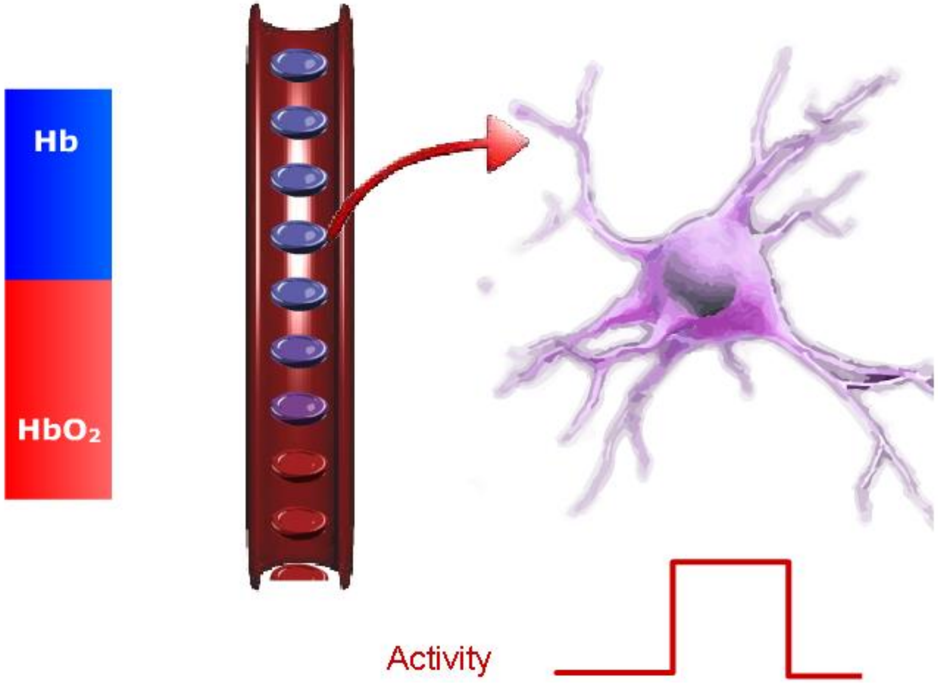
- As the increase in flow exceeds the increase in oxygen consumption, neuronal activity is expressed as a relative increase in oxyheamoglobin compared to deoxyheamoglobin in the activated zones.



The relative decrease in deoxyheamoglobin concentration, which has a paramagnetic effect, can be detected by MRI as a weak transient rise in the T2* weighted signal.

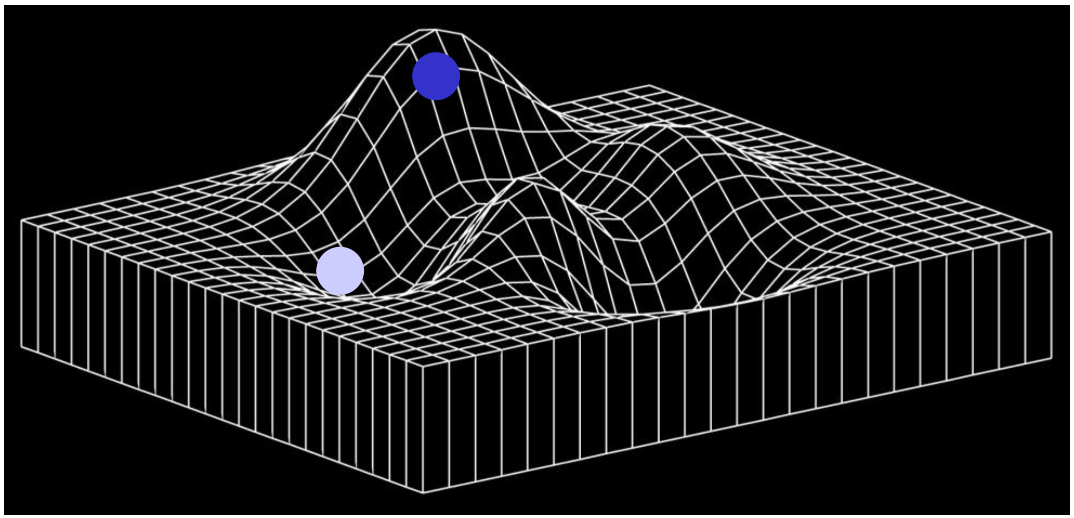
BOLD contrast step-by-step (4)

- As the neural activity goes back to baseline so does the oxy:deoxyhaemoglobin ratio and consequently the MRI signal



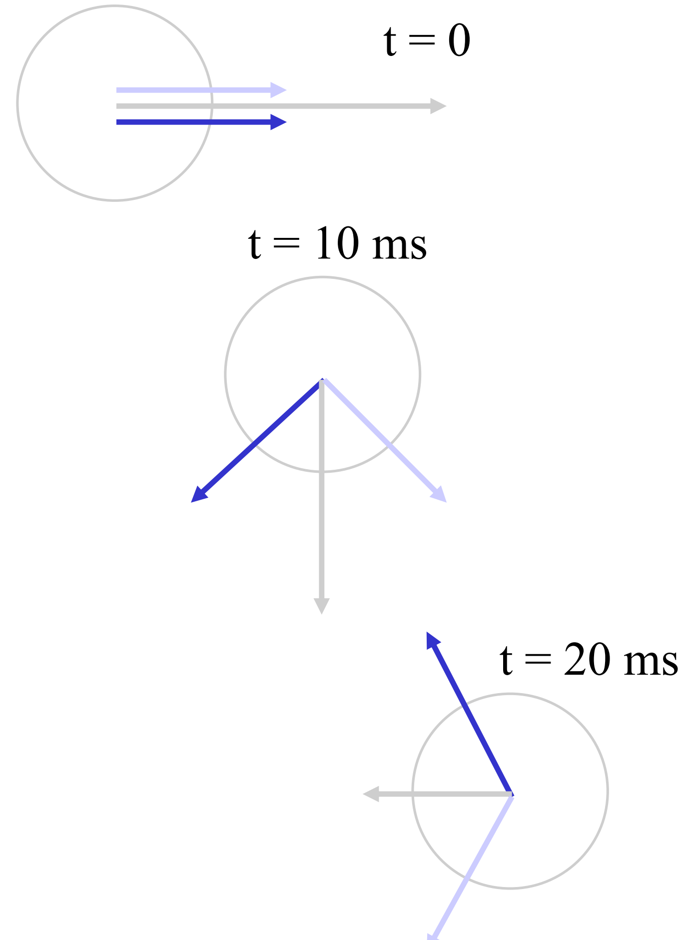
How does haemoglobin change T2*?

From last week: Signal loss due to B_0 inhomogeneity



$$\omega = \gamma B_0$$

● has higher frequency than ●

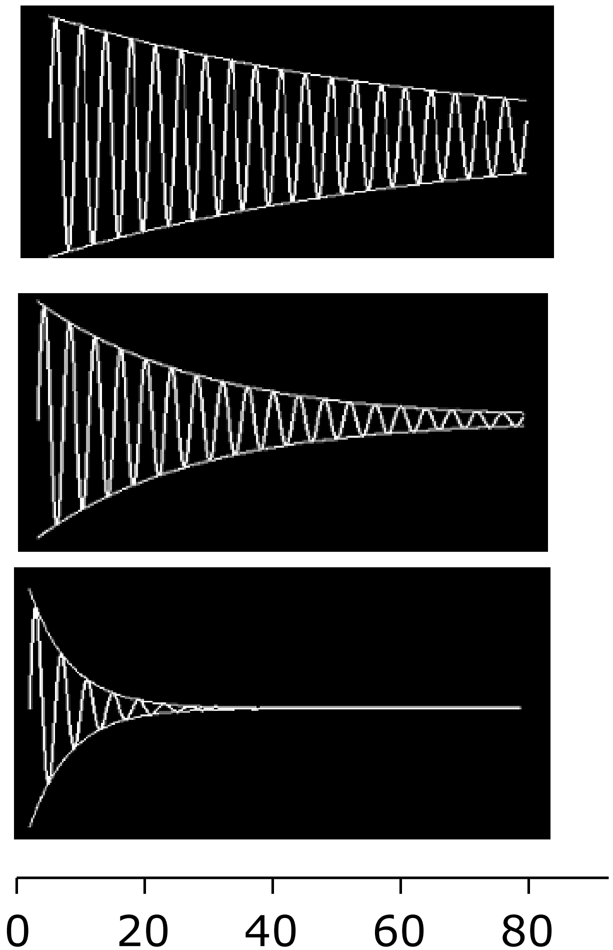


From last week: Effective transverse relaxation

No inhomogeneities
($T_2^* = T_2$ = 100 ms)

Moderate inhomogeneities
(T_2^* = 40 ms)

Strong inhomogeneities
(T_2^* = 10 ms)



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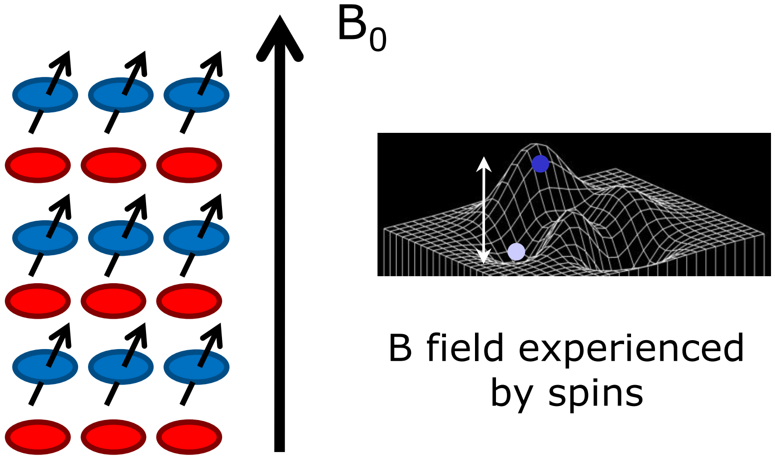
How does haemoglobin change T2*?

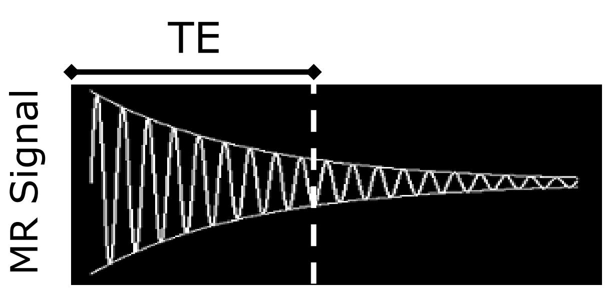
- Since oxygen is not very soluble in blood, it is transported bound to the large iron-containing molecule, **haemoglobin**.
- The presence of iron atoms in the molecule mean that haemoglobin has **magnetic properties**.
- The location of the oxygen binding sites determines that deoxyhaemeglobin is **paramagnetic** (having a significant effect on its environment) while oxyhaemoglobin is **diamagnetic** (having a neglectable effect).

How does haemoglobin change T2*?

Baseline

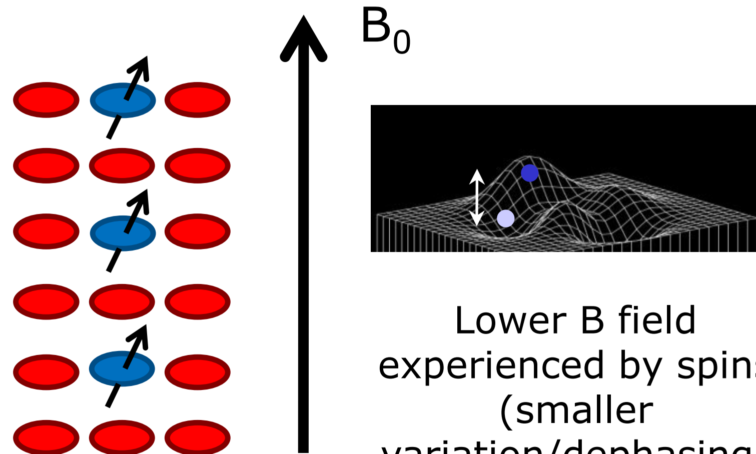


B field experienced by spins

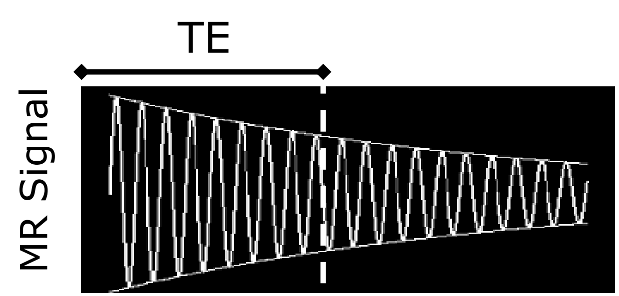


T_2*_{rest}

Neural Activity



Lower B field experienced by spins (smaller variation/dephasing)

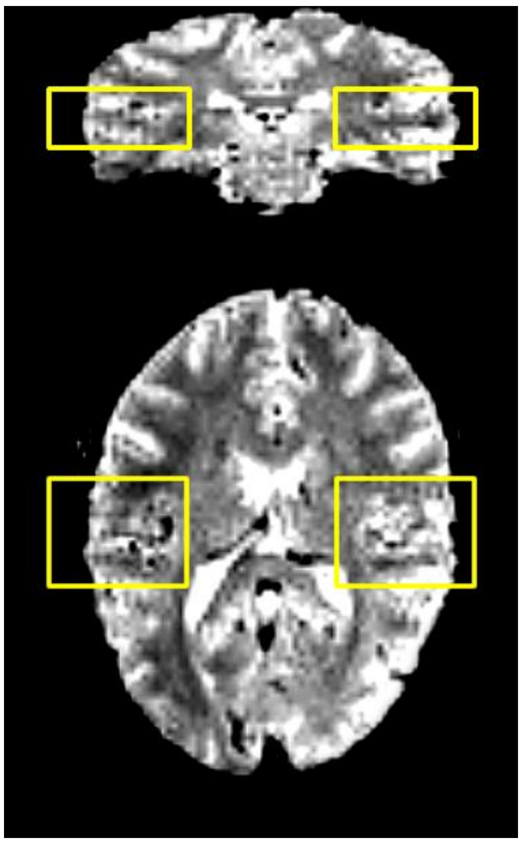


$T_2*_{active} > T_2*_{rest}$

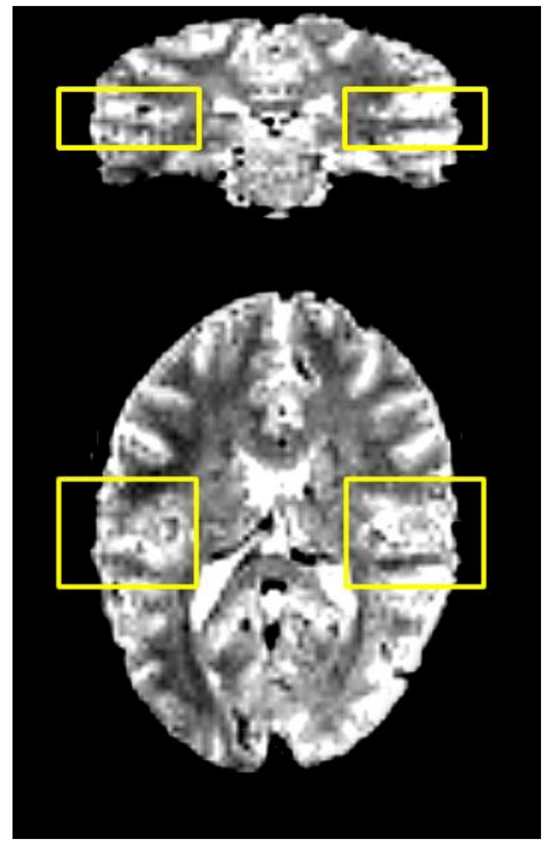
MRI signal increases

Example: auditory cortex activation

Baseline

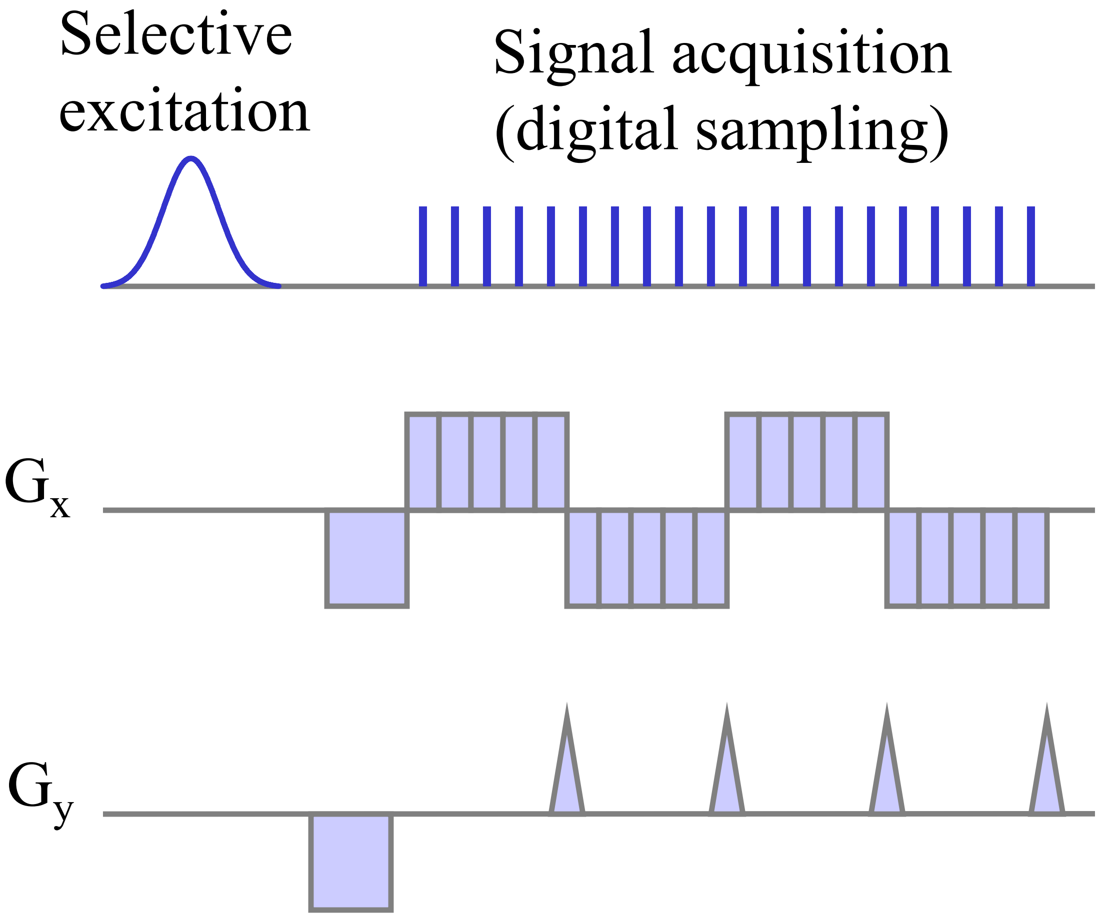


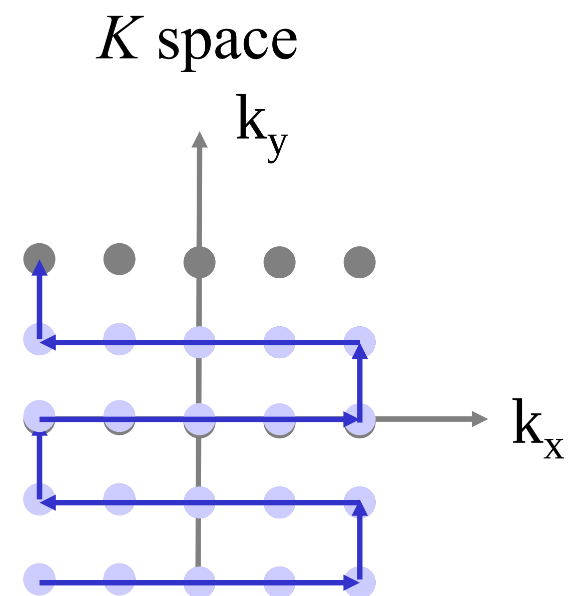
Neural Activity



Common Image artefacts

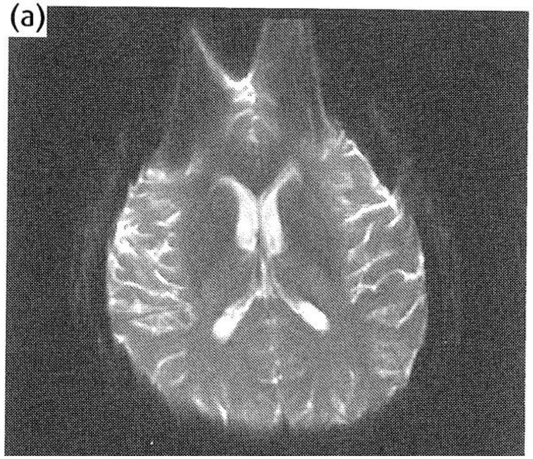
From last week: Echo Planar Imaging (EPI)





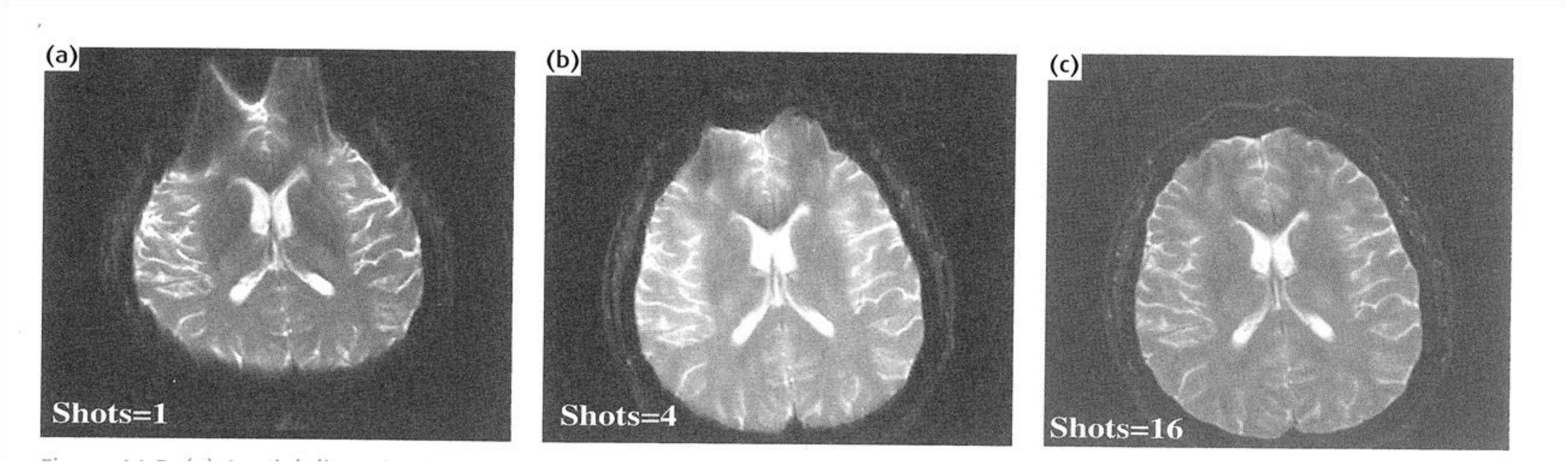
EPI distortion: the price we pay for fast imaging

- **Bandwidth** is a measure of frequency range (the range between the highest and lowest frequency allowed in the signal).
- The echo planar technique suffers from a very low bandwidth in the phase encode direction.
- Typically, the bandwidth per pixel is <20 Hz.
- A local shim inhomogeneity of 100 Hz (as is quite typical close to the frontal sinuses at 3.0 Tesla) can lead to a mis-location of the signal in that region by 5 pixels.



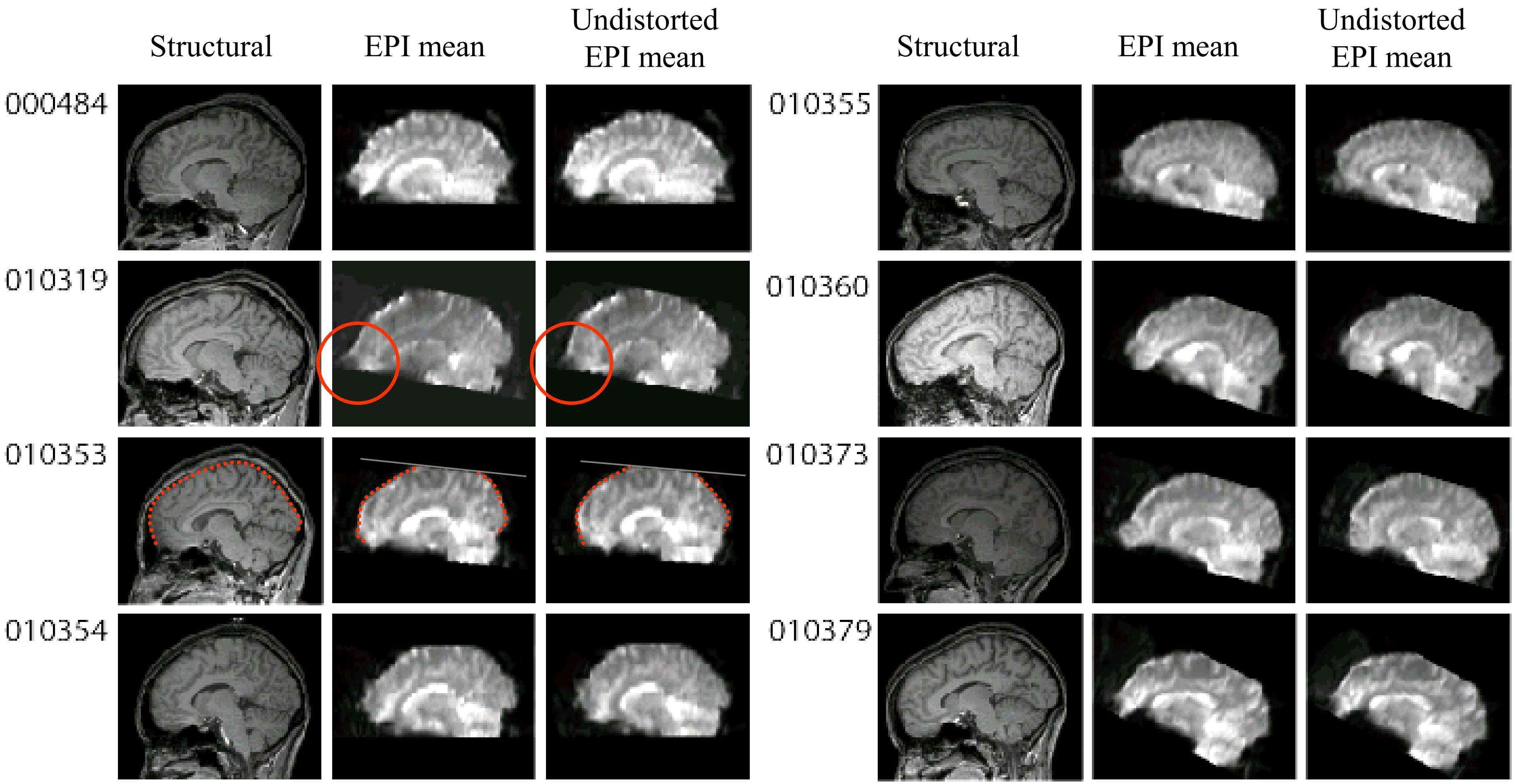
Tackling artefacts I

- **Distortion**
  - Optimise acquisition
    - Parallel acquisition (GRAPPA, SENSE)
    - Multi-shot EPI



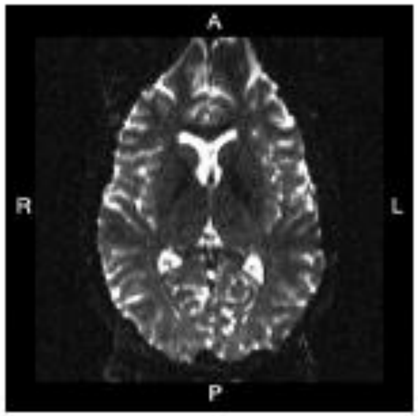
  - Acquire fieldmaps & undistort

Fieldmap undistortion: evaluation by eye



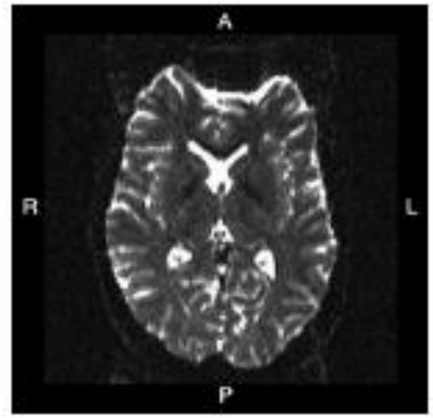
Cusack, Brett & Osswald (2004)

EPI distortion correction - TOPUP

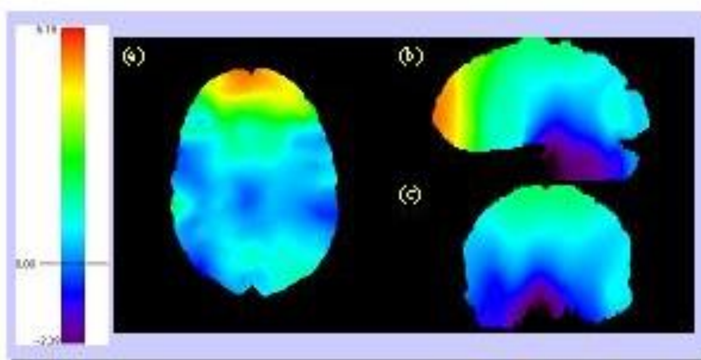


Phase encode direction P>>A

+



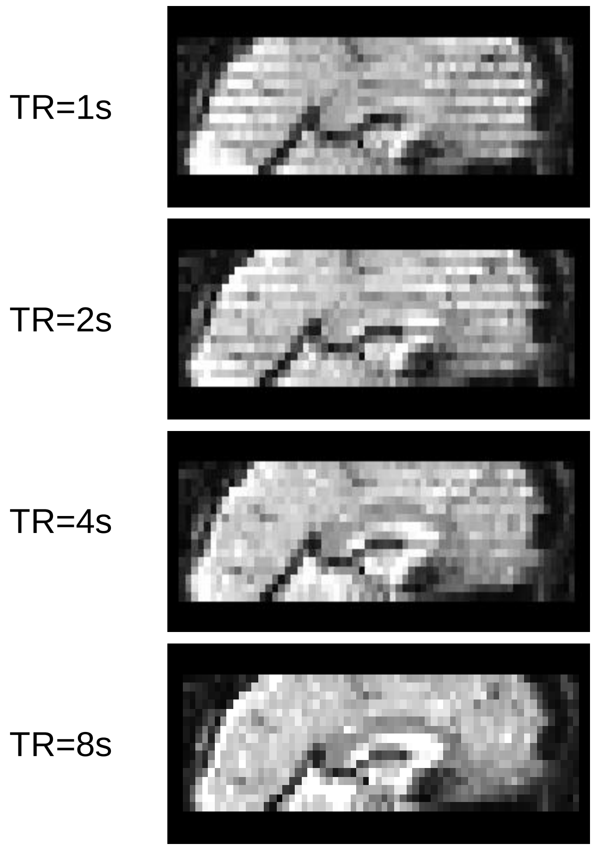
Phase encode direction A>>P



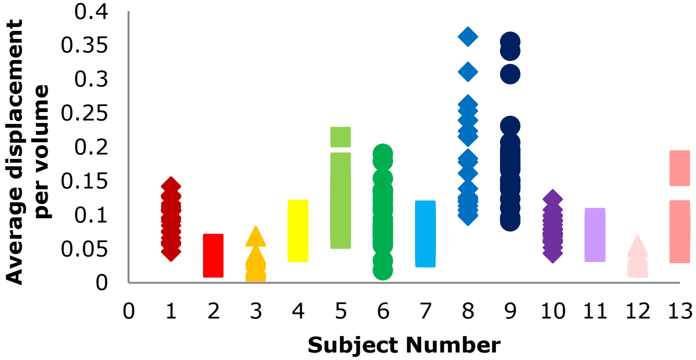
EPI distortion map. The colour coding shows the amount of displacement in pixel units.

Tackling artefacts II

- **Distortion by movement**



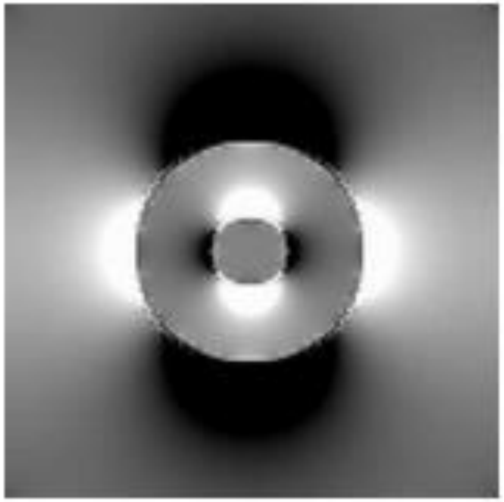
- Maximise subject comfort in the scanner
- Apply post-acquisition motion correction
- Include movement parameters into model
- Choose the right subjects!



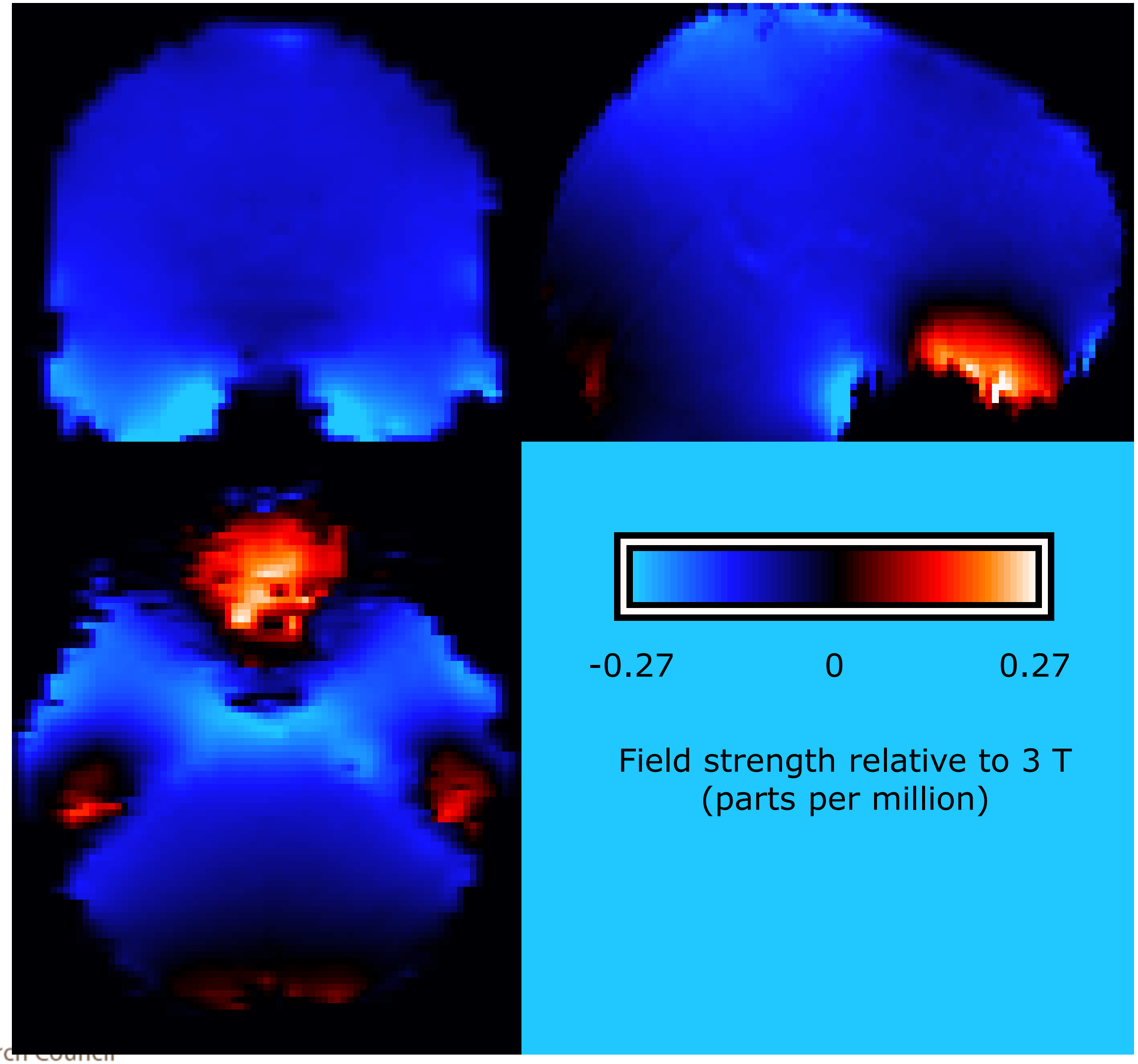
The B_0 field should be homogeneous, but…

- MRI scanners apply a strong magnetic field (3T at CBU)
- Ideally, field should be homogeneous
  - Easy to do when the scanner is empty, but ruined as soon as a head is put in
- Different materials interact differently with external magnetic fields and act to strengthen or weaken them

Free space	1.00000000
Air	1.00000040
Water	0.99999096
Fat	0.99999221
Bone	0.99999156
Blood	0.99999153
Grey matter	0.99999103
White matter	0.99999120
Iron	150-5000



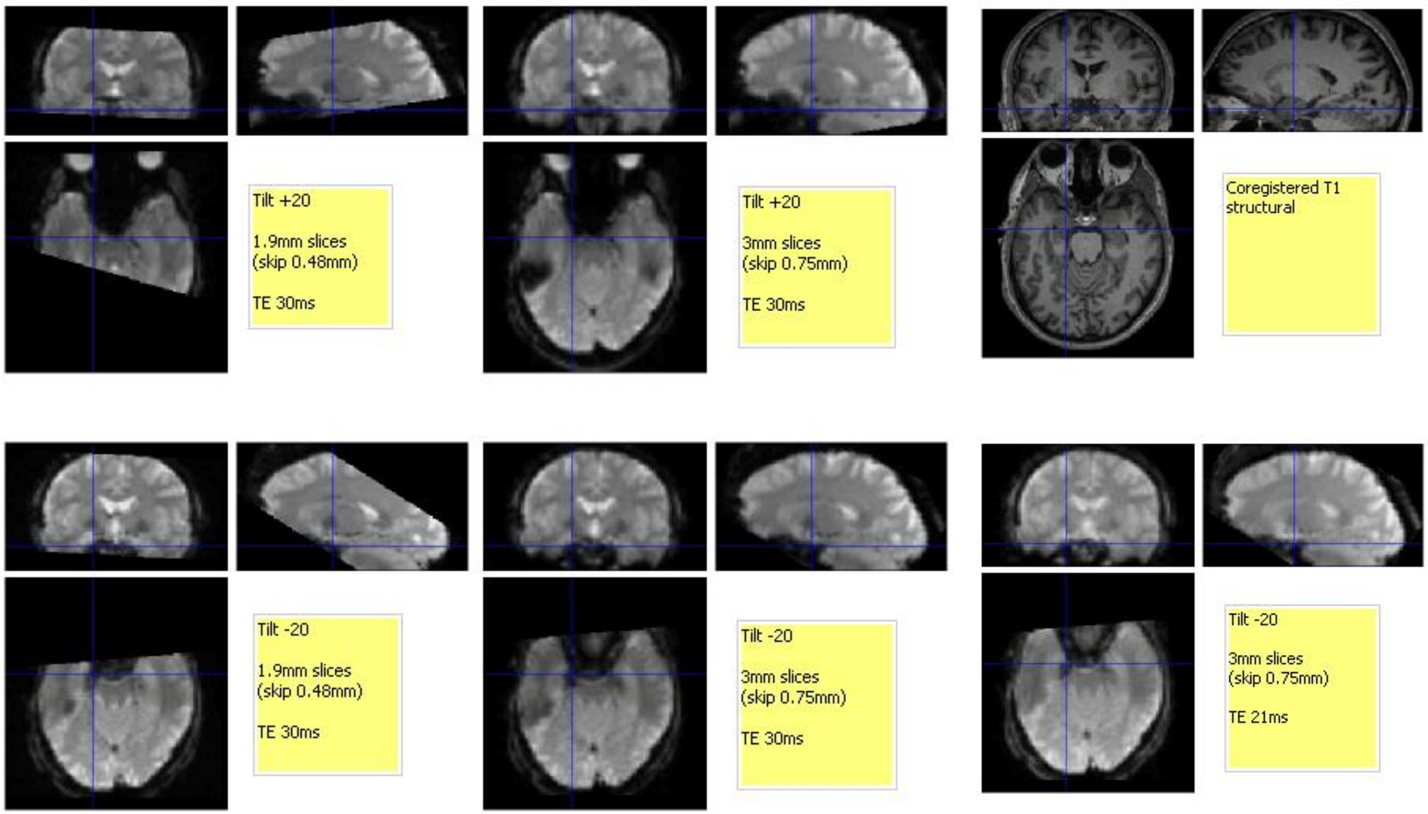
The B_0 field should be homogeneous, but…



Tackling artefacts III

- **Dropout**
  - Optimise acquisition parameters (e.g., TE, slice orientation, voxel size and slice thickness)
  - Z-shimming
  - Use spin-echo/ multi-echo
  - Passive shimming (Wilson, Jezzard and colleagues; Cusack et al, 2004)
  - Choose the right subjects!

Optimising parameters to reduce dropout



From Rik Henson

Summary

- BOLD FMRI involves a complicated set of couplings
  - Be careful when interpreting effects, or comparing fMRI with other imaging modalities
- It can fail in many ways
  - Optimise acquisition and analysis
  - Perform proper quality control

Coming up in February…

- 13th Feb
  fMRI Analysis 1: fMRI Pre-Processing
- 13th Feb
  fMRI Analysis 2: Single-subject analysis and GLM
- 14th Feb
  fMRI Analysis 3: Group Statistics
- 14th Feb
  FMRI/EEG/MEG connectivity

Questions?