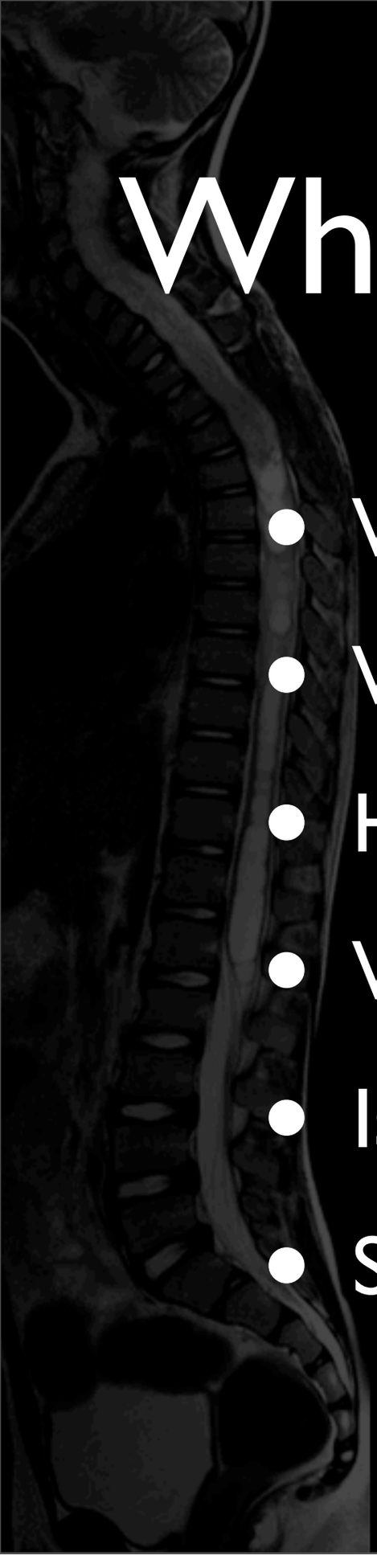
Spinal FMRI and Physiological Noise Correction

Jonathan Brooks

CRiCBristol, University of Bristol



What's covered in this talk

- What is physiological noise?
- Why does it matter?
- How do I measure it?
- What to do with the data....
- Is it worth the hassle?
- Spinal FMRI

What's covered in this talk

- **What is physiological noise?**
- Why does it matter?
- How do I measure it?
- What to do with the data....
- Is it worth the hassle?
- Spinal FMRI

What is physiological noise?

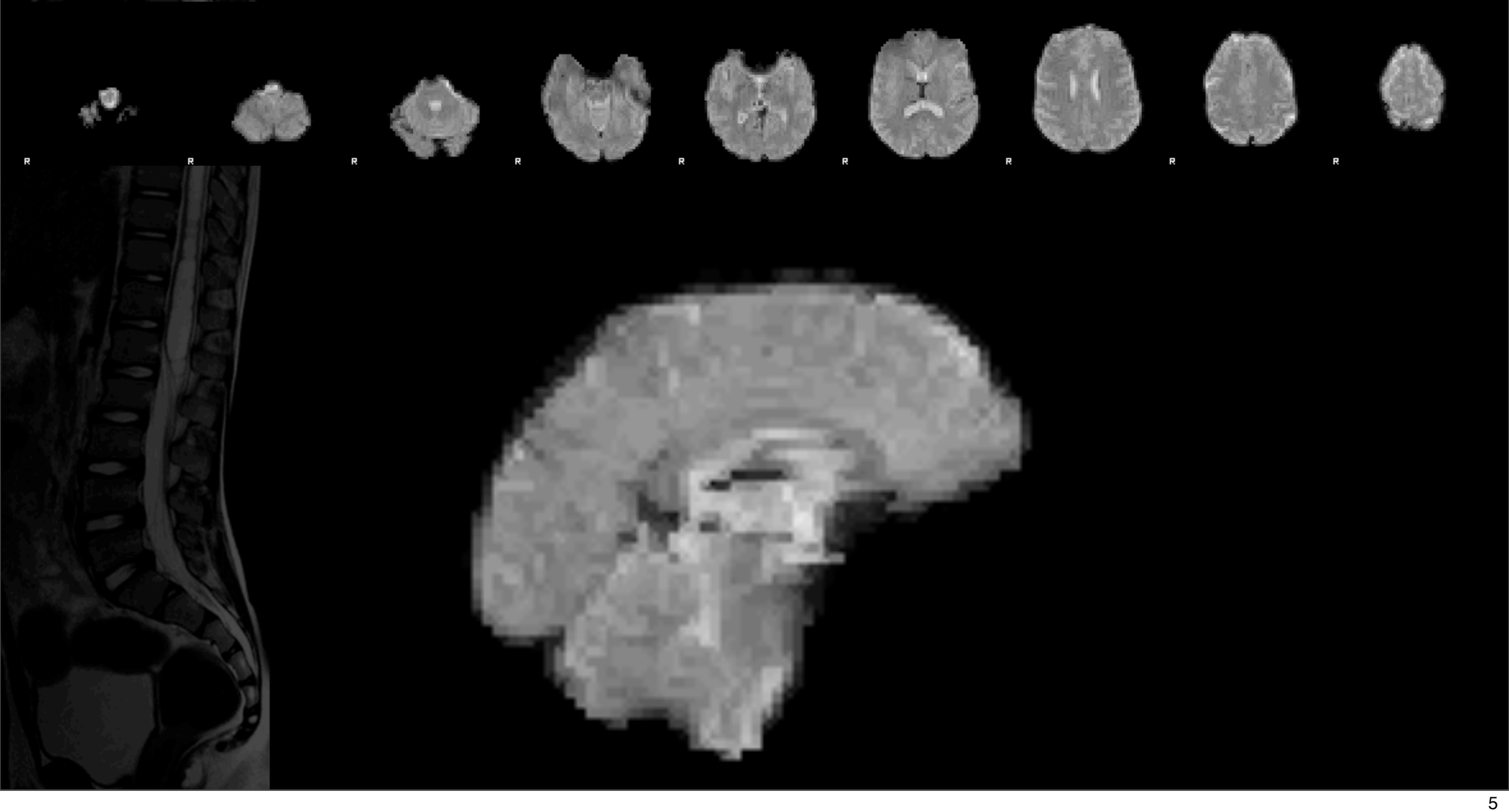
- Sources: cardiac, respiratory, movement
- Importance: at higher field strength, dominant source of noise (σ_{physio} α field strength)
- Effects: additive, will confound signal detection particularly areas of low SNR, or regions with large CSF spaces, near large vessels etc.

Glover et al. MRM (2000)
Kruger & Glover, MRM (2001)
Triantafyllou et al. NeuroImage (2005/2006/2011)

What does it look like

What does it look like

What does it look like



Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

- Thermal/scanner
- Cardiac
- Respiratory
- Autonomic

Kruger & Glover, MRM (2008)

Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

- Thermal/scanner
- Cardiac
- Respiratory
- Autonomic

Kruger & Glover, MRM (2008)

Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

Kruger & Glover, MRM (2008)

- Thermal/scanner
- **Cardiac**
- Respiratory
- Autonomic

Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

Kruger & Glover, MRM (2008)

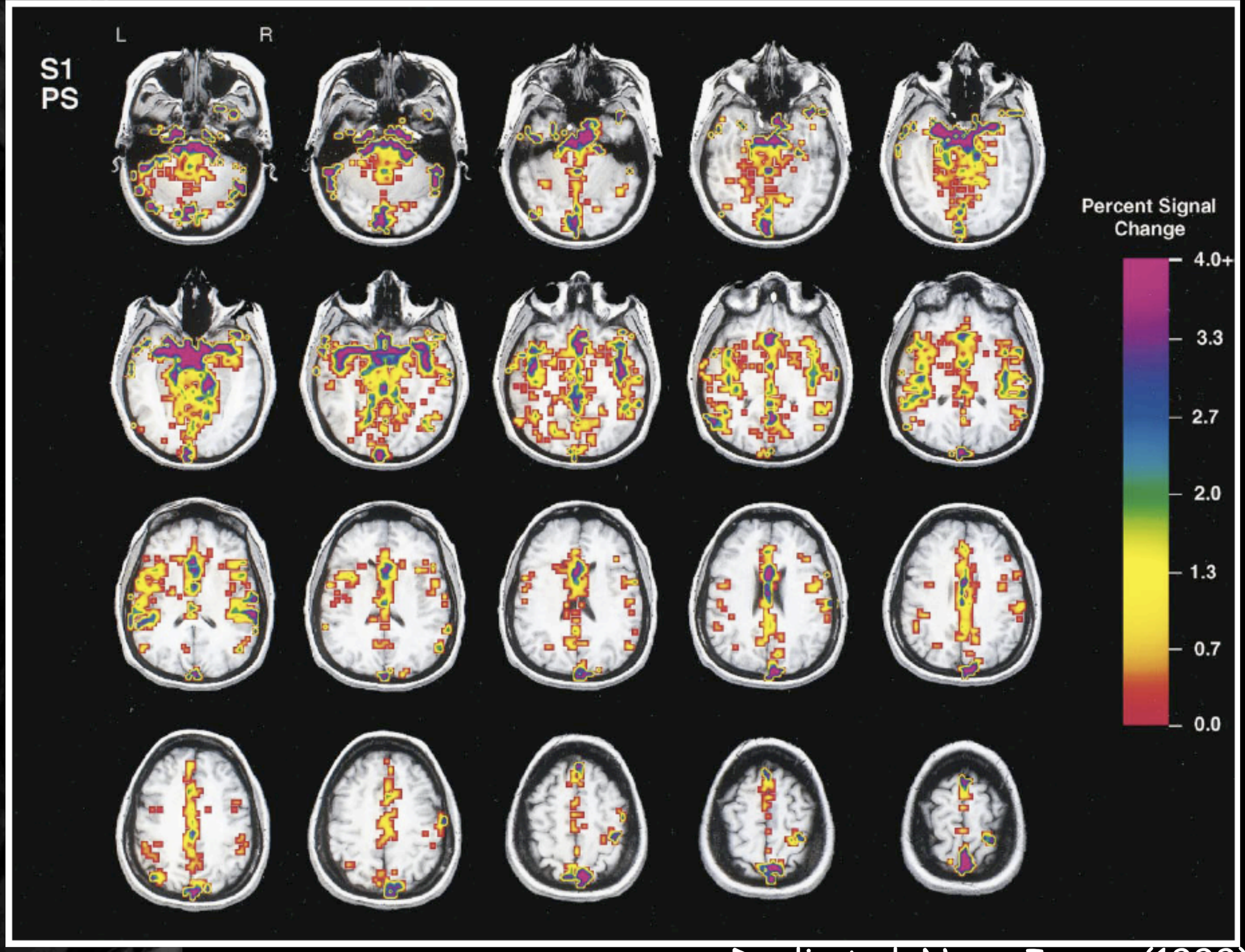
- Thermal/scanner
- **Cardiac**
- Respiratory
- Autonomic

CARDIAC

- Pulsatile movement (arteries, capillaries, brain tissue)
- BOLD-like effects?
- Increased CBV, but fixed cranial capacity

  ⇒ movement of CSF

Dagli et al, NeuroImage (1999)

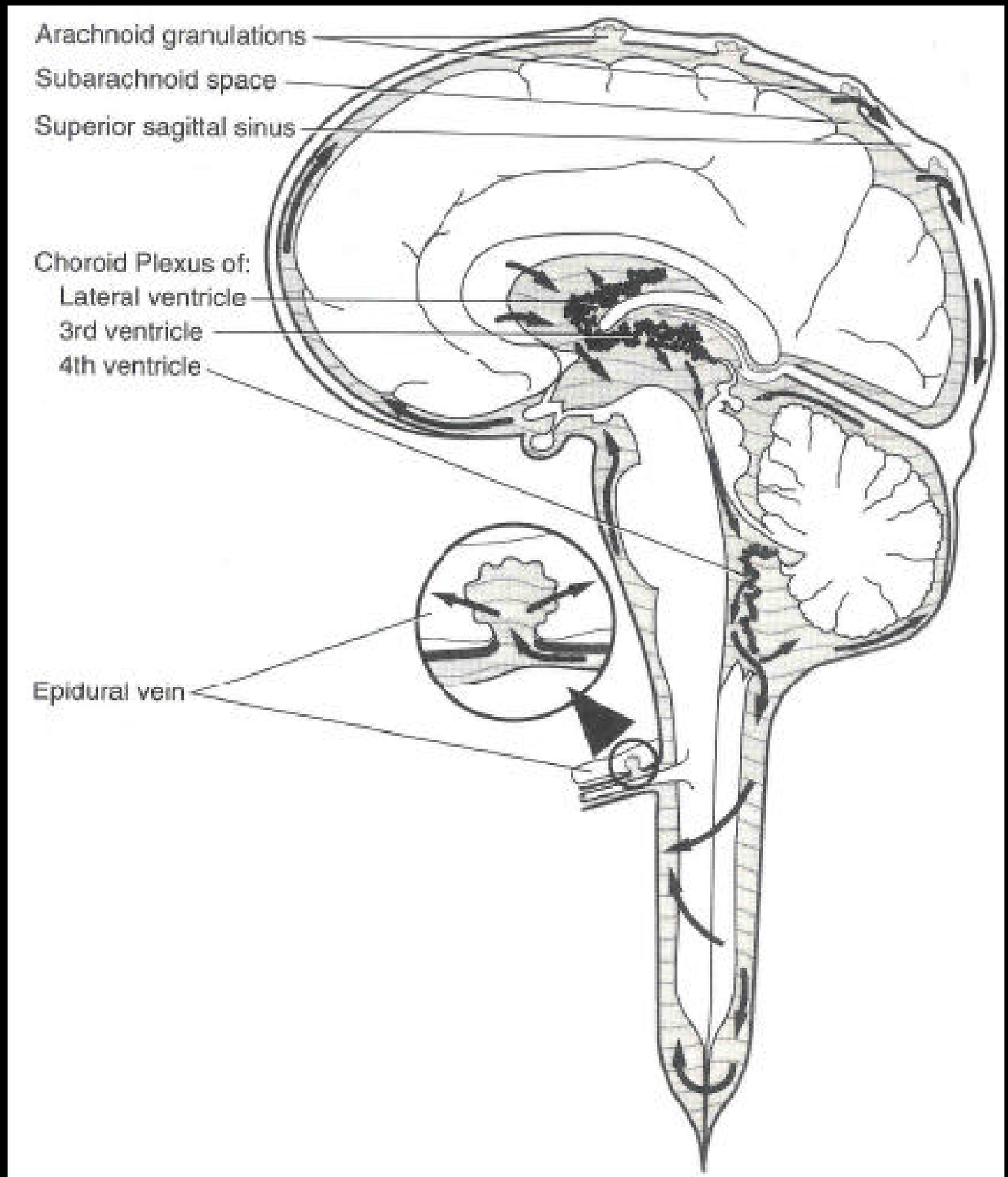


Dagli et al, NeuroImage (1999)

CARDIAC

- Pulsatile movement
- Increased CBV, but fixed cranial capacity

  ⇒ movement of CSF


Arachnoid granulations
Subarachnoid space
Superior sagittal sinus
Choroid Plexus of:
Lateral ventricle
3rd ventricle
4th ventricle
Epidural vein

Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

Kruger & Glover, MRM (2008)

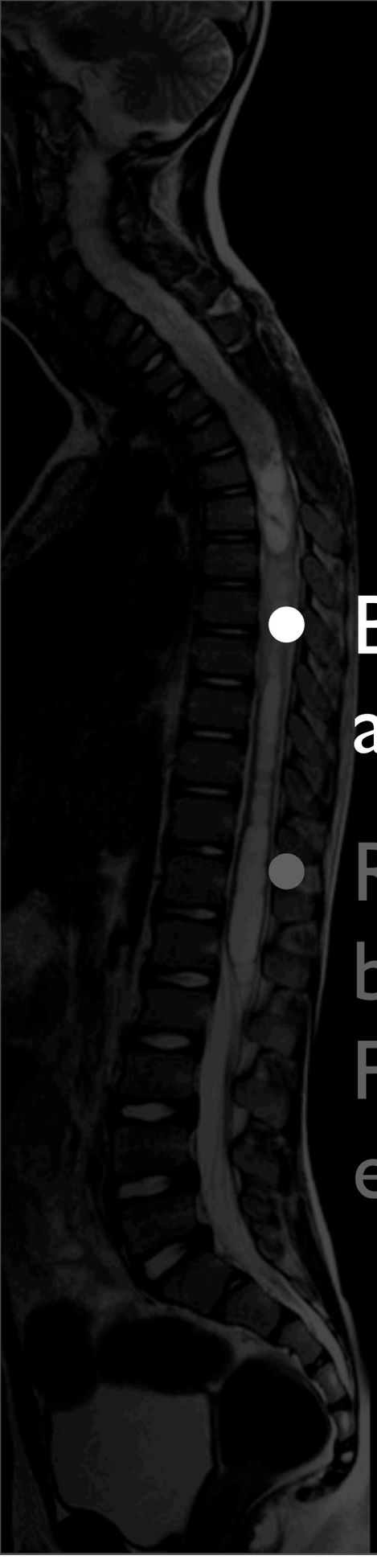
- Thermal/scanner
- Cardiac
- **Respiratory**
- Autonomic

Sources of noise

$$\sigma = \sqrt{\sigma_S^2 + \sigma_T^2 + \sigma_P^2}$$

Kruger & Glover, MRM (2008)

- Thermal/scanner
- Cardiac
- **Respiratory**
- Autonomic



RESPIRATORY

- B_0 susceptibility - changing volume of air and position of chest
- Resting fluctuations in rate and depth of breathing can produce systemic change in PaCO2, producing vasodilatory (BOLD-like effects)

RESPIRATORY

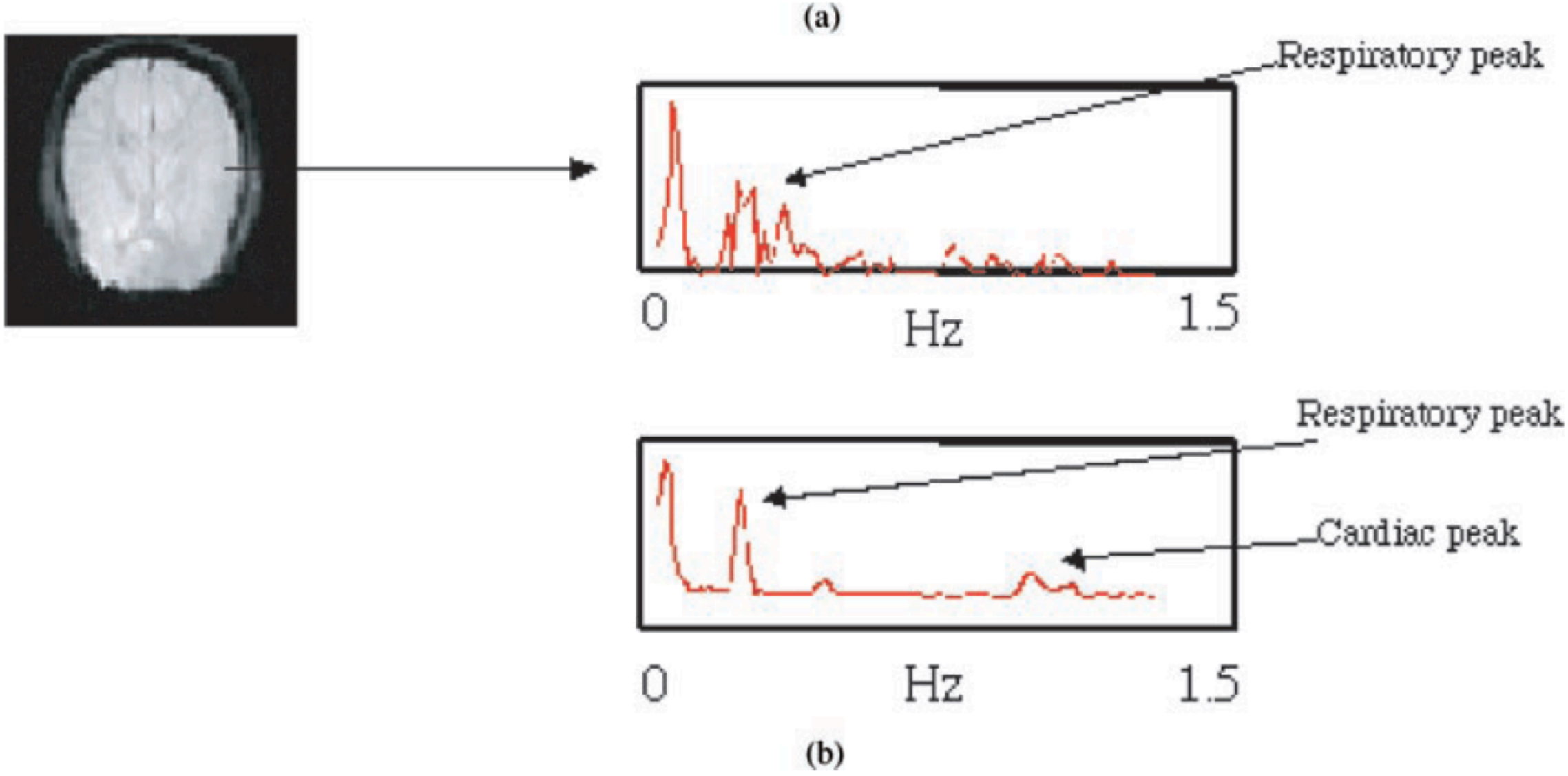
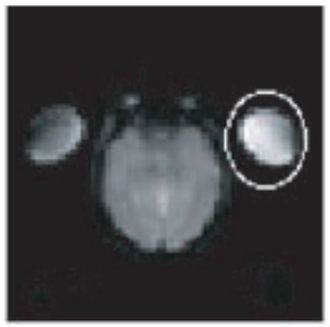


Figure 1. (a) The power spectrum of the signal from a single pixel in grey matter. (b) Averaged power spectrum for pixels across the whole brain.

Raj et al, Phys Med Biol (2001)

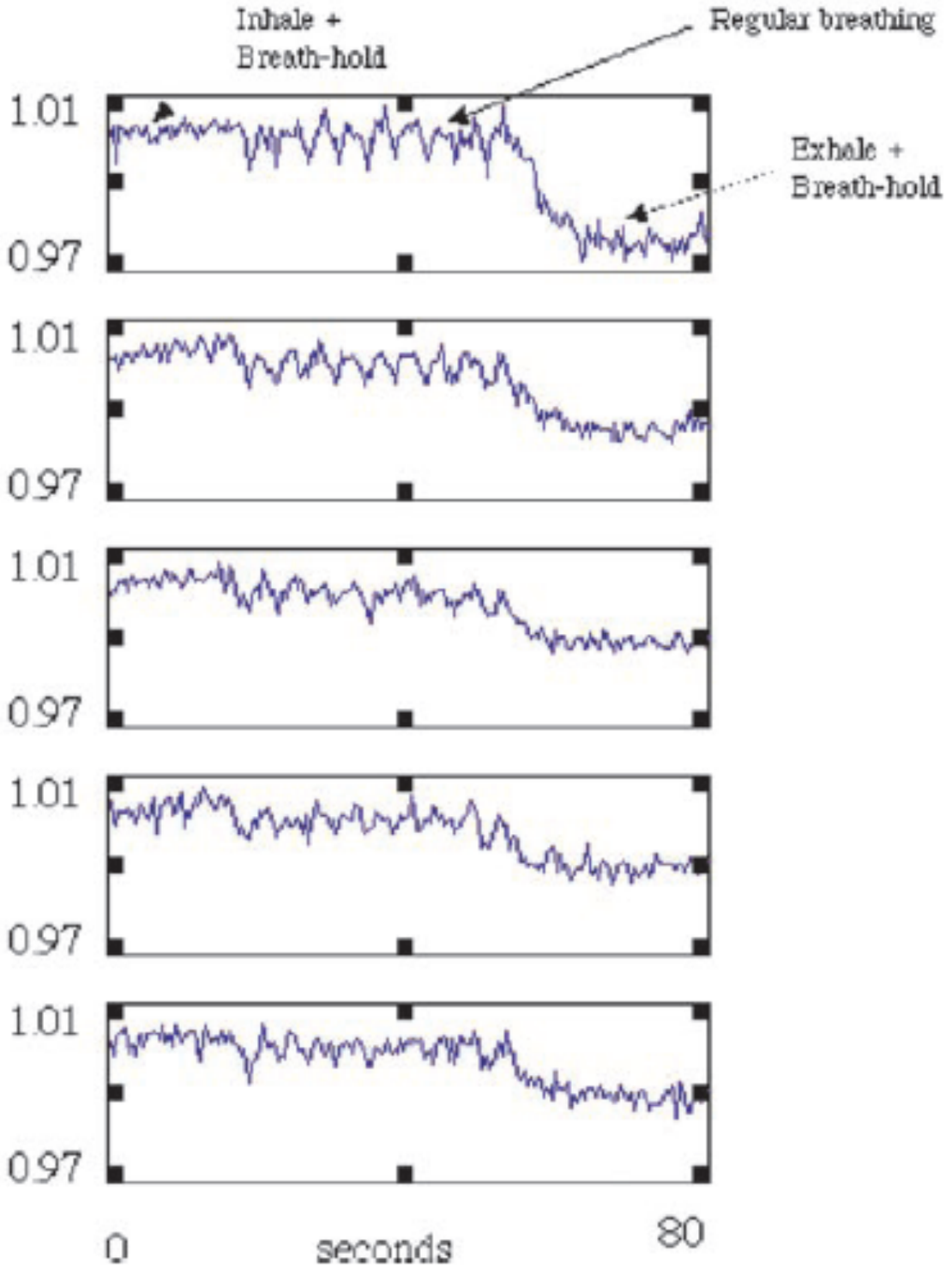
RESPIRATORY



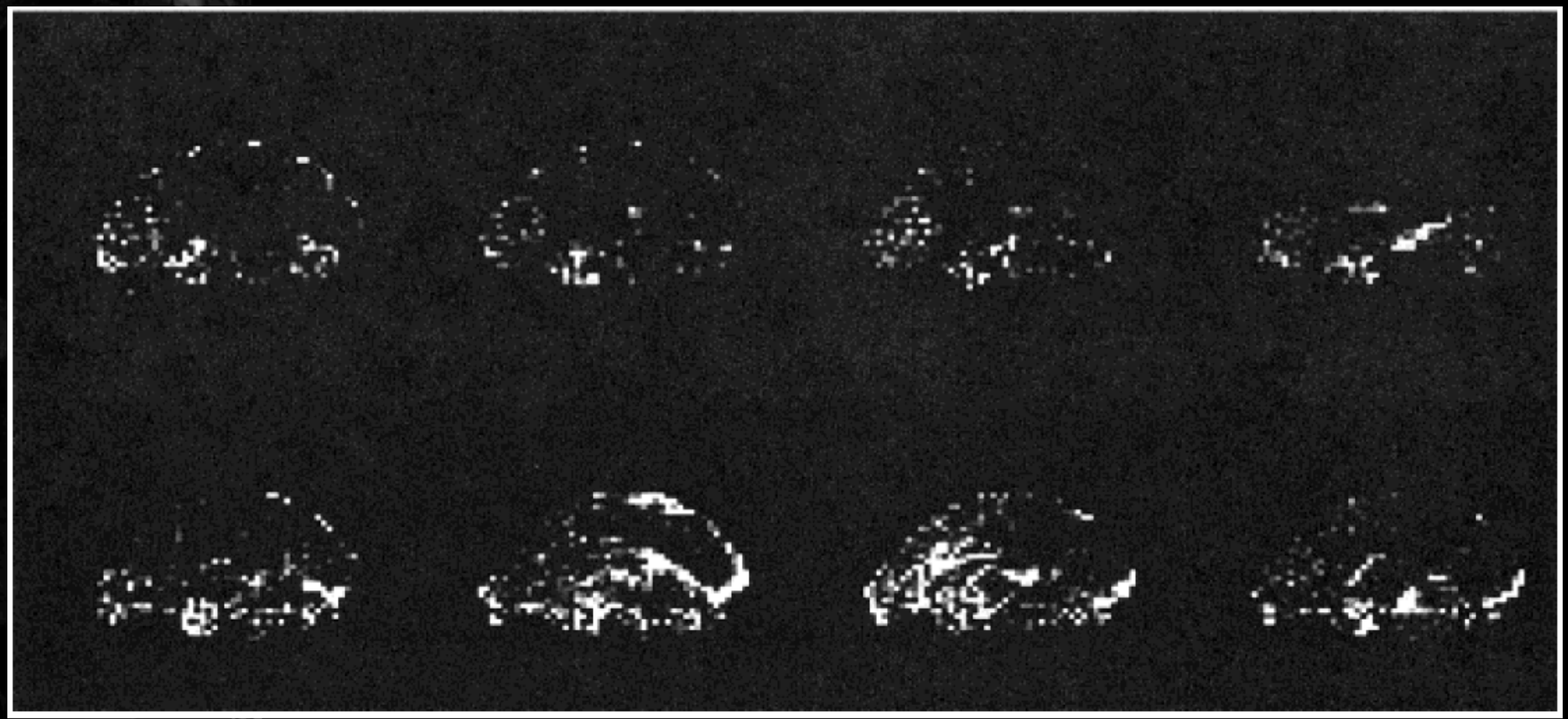
(a)

Figure 2. (a) Axial echo-planar brain image acquired with two bottles containing 0.01 mM copper sulfate attached to the head coil. (b) MR signal from a region of interest (10 pixels) in the bottle shown in figure 2(a). During images 1–40, the subject held his breath after exhaling completely, during images 40–140 normal breathing was resumed and during images 140–200 the subject held his breath at full inspiration.

Raj et al, Phys Med Biol (2001)



RESPIRATORY

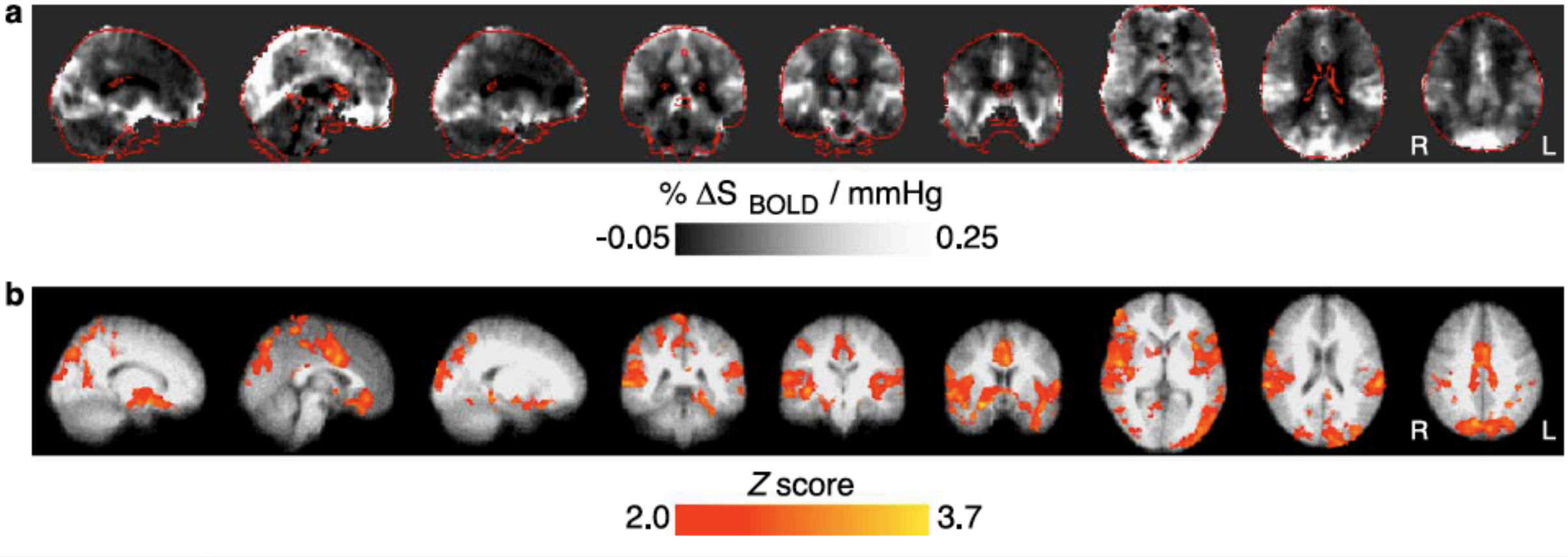


Frank et al, MRM (2001)

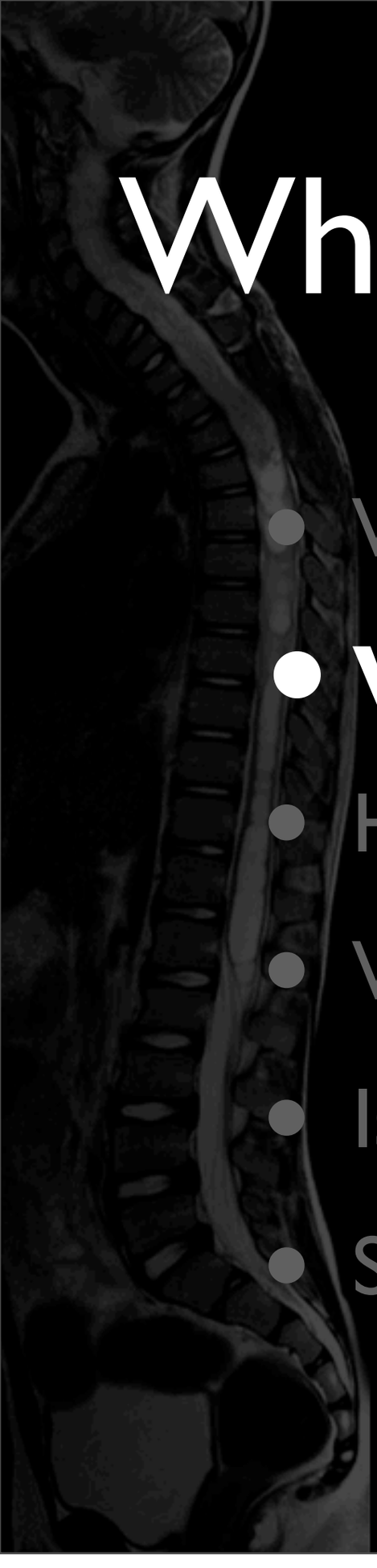
RESPIRATORY

- B_0 susceptibility - changing volume of air and position of chest
- Resting fluctuations in rate and depth of breathing can produce systemic change in PaCO2, producing vasodilatory (BOLD-like effects)

RESPIRATORY



Wise et al, NeuroImage (2004)



What's covered in this talk

- What is physiological noise?
- **Why does it matter?**
- How do I measure it?
- What to do with the data....
- Is it worth the hassle?
- Spinal FMRI

Why does it matter?

- fMRI relies on principle of pure insertion
- Physiological noise creates time varying signals unrelated to stimulation
- I.e. model does not fit data properly:
  - reduced accuracy of parameter estimates
  - decreases significance
  - increased numbers required to show effect at group level

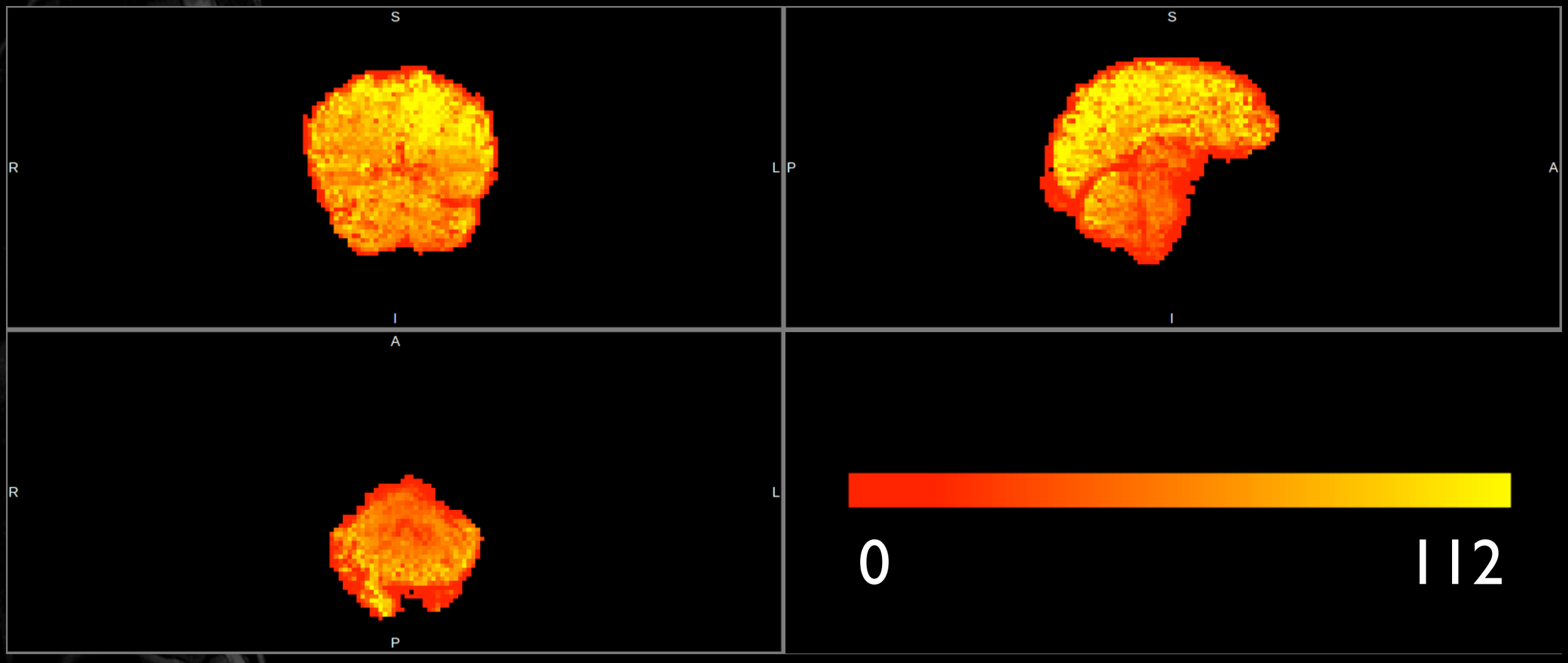
Temporal Signal to Noise Ratio (TSNR)

- Quantity measures intrinsic quality of data
- High signal, and low variability
- Need resting data

$$TSNR = \frac{\text{temporal mean } (T_{mean})}{\text{temporal standard deviation } (T_{std})}$$

Parrish et al (2000) Impact of signal-to-noise on functional MRI. Magn Reson Med 44:925-932.

TSNR



Murphy et al (2007) How long to scan? The relationship between fMRI temporal signal to noise ratio and necessary scan duration. NeuroImage 34:565-574

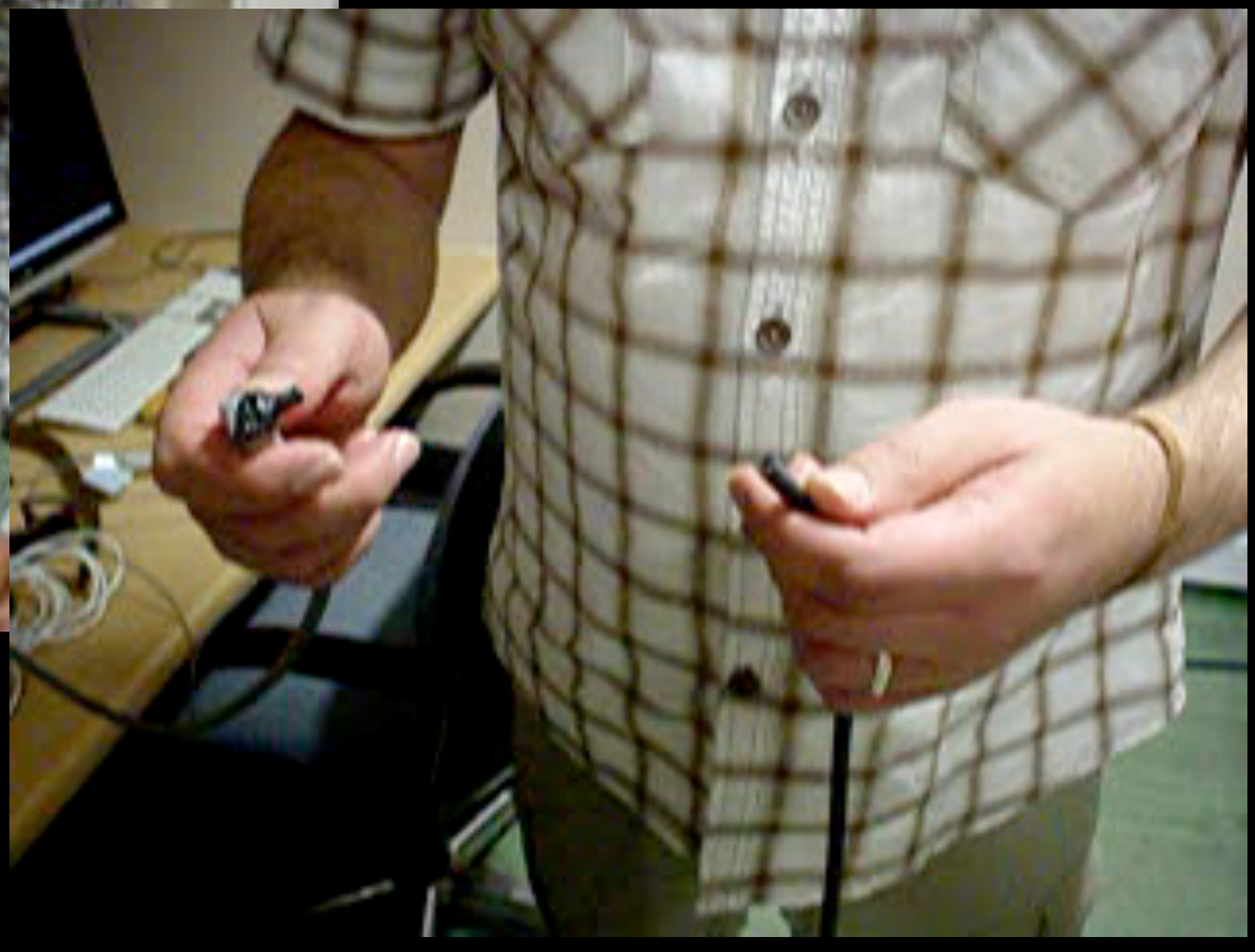
What's covered in this talk

- What is physiological noise?
- Why does it matter?
- **How do I measure it?**
- What to do with the data....
- Is it worth the hassle?
- Spinal FMRI

SETUP

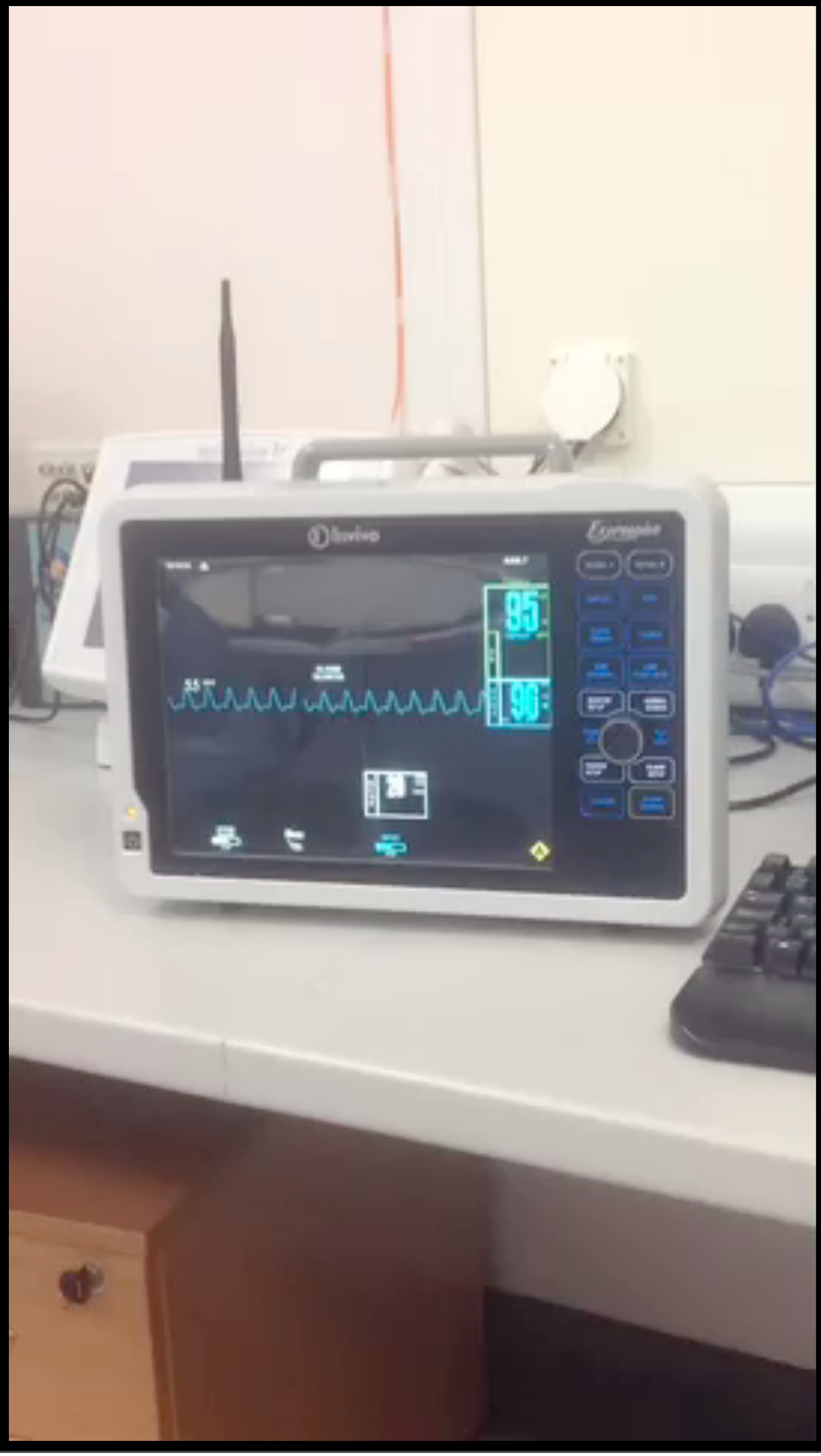
SETUP

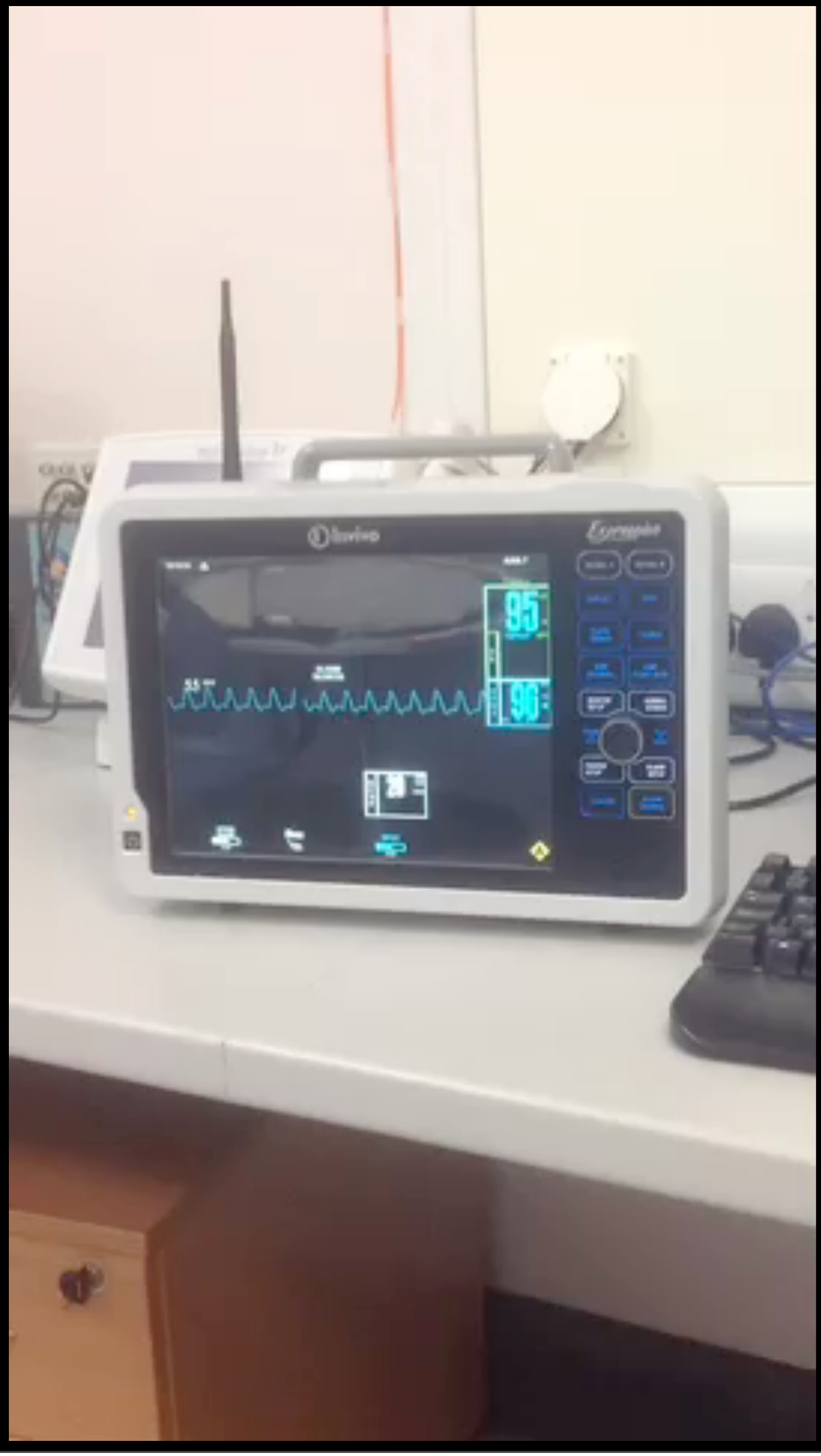
SETUP



SETUP

SETUP


Esprimo
95
96


Esprimo
95
96

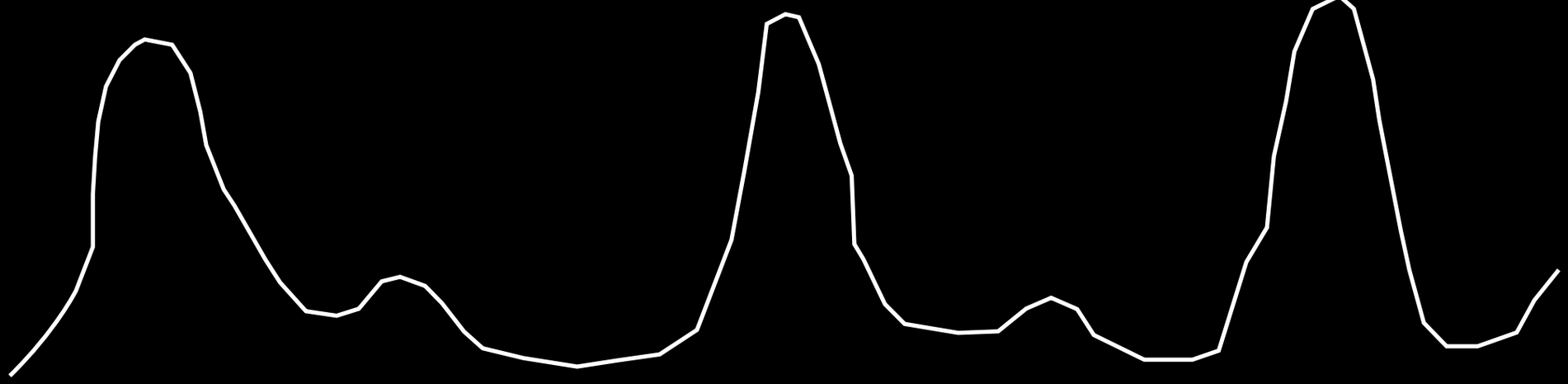
What's covered in this talk

- What is physiological noise?
- Why does it matter?
- How do I measure it?
- **What to do with the data....**
- Is it worth the hassle?
- Spinal FMRI

CARDIAC PHASE

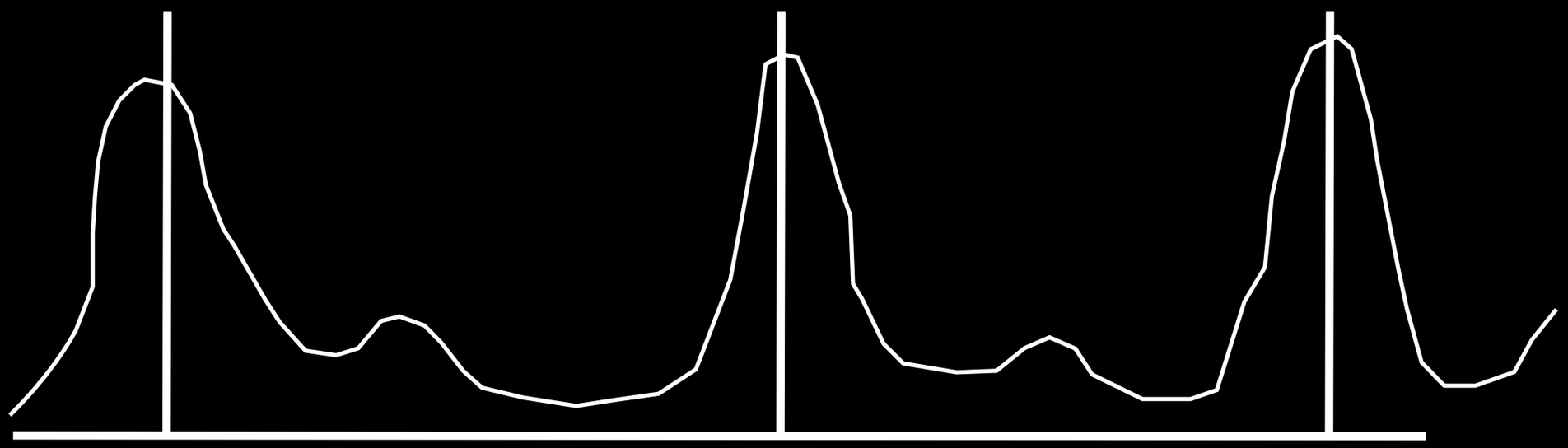
Glover et al, MRM (2000)
Brooks et al, NeuroImage (2008)

CARDIAC PHASE



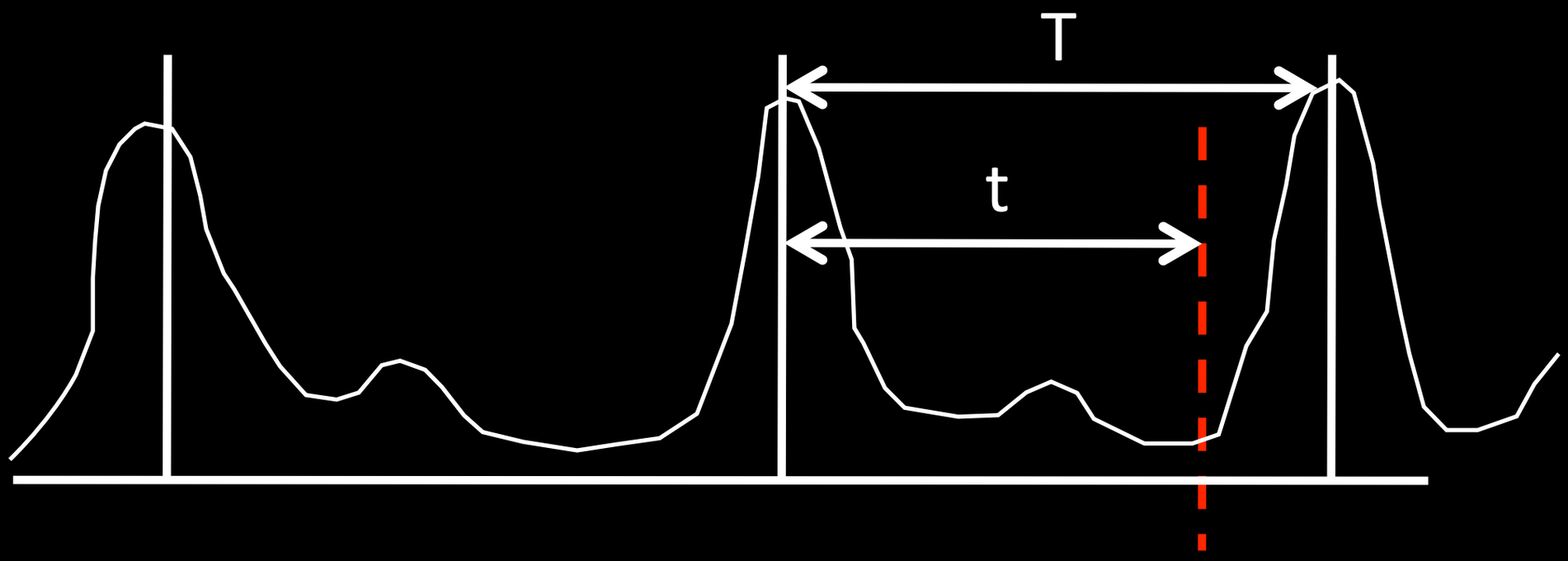
Glover et al, MRM (2000)
Brooks et al, NeuroImage (2008)

CARDIAC PHASE



Glover et al, MRM (2000)
Brooks et al, NeuroImage (2008)

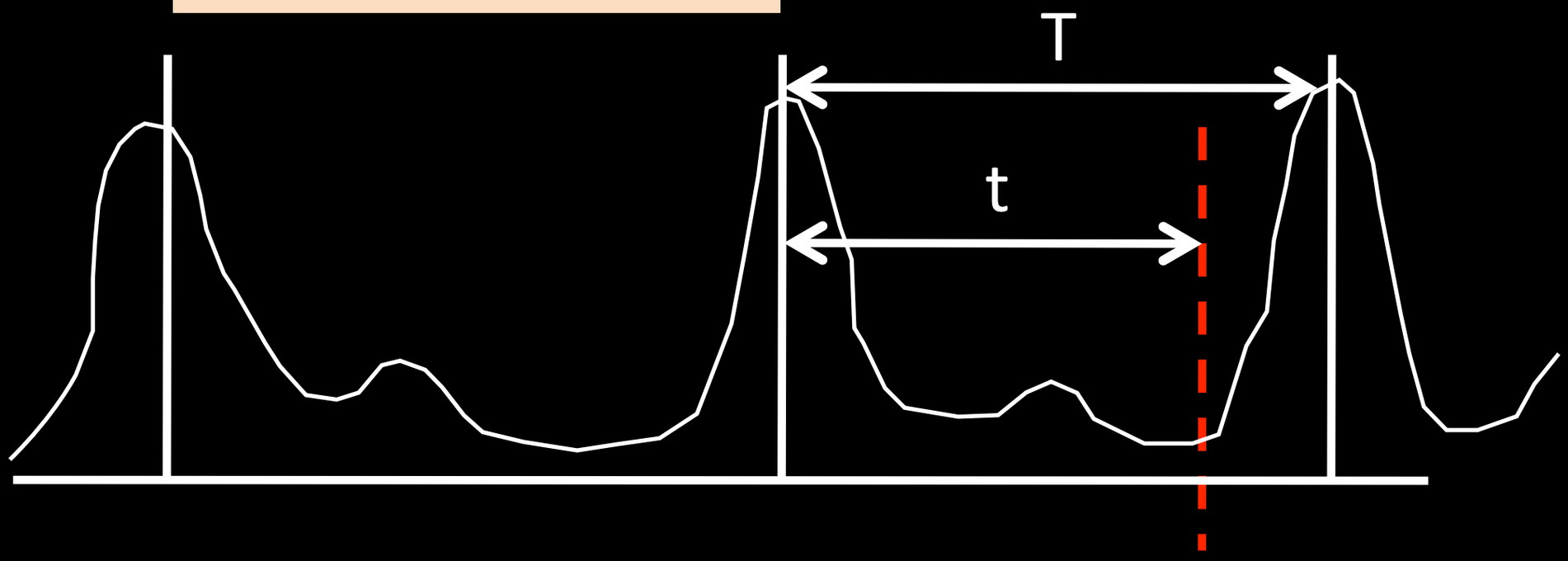
CARDIAC PHASE



Glover et al, MRM (2000)
Brooks et al, NeuroImage (2008)

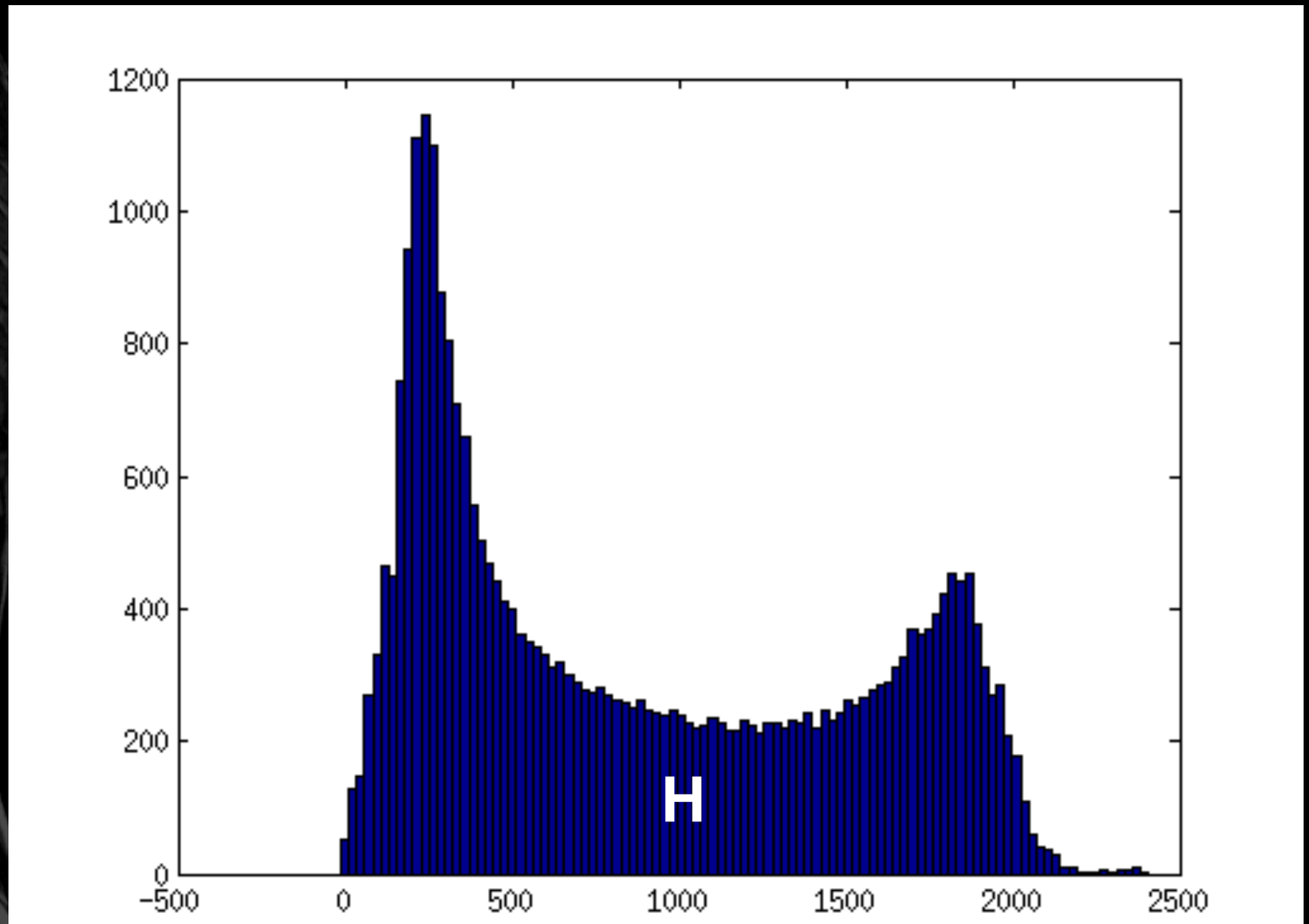
CARDIAC PHASE

$$\theta_C = 2\pi * (t/T)$$

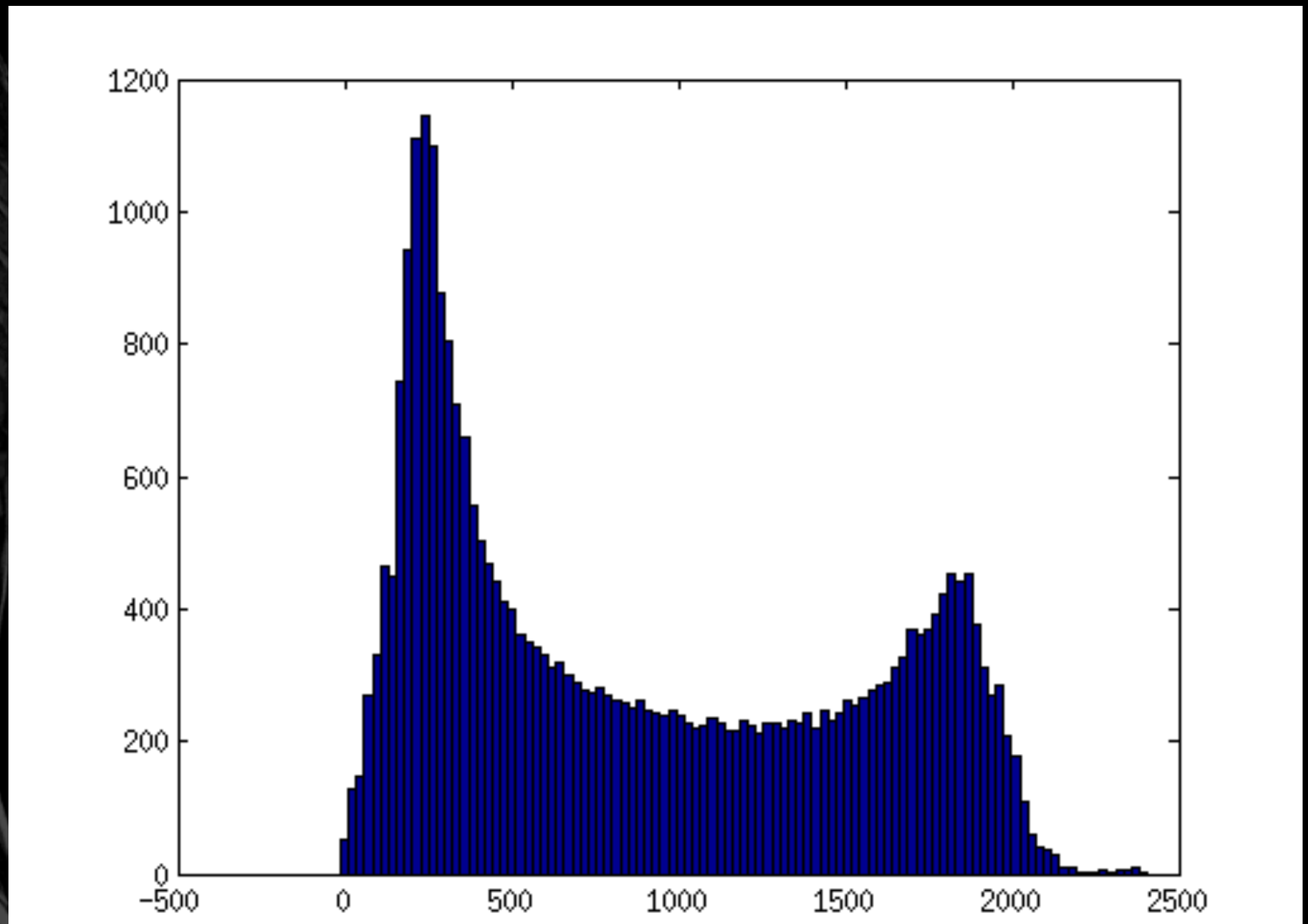


Glover et al, MRM (2000)
Brooks et al, NeuroImage (2008)

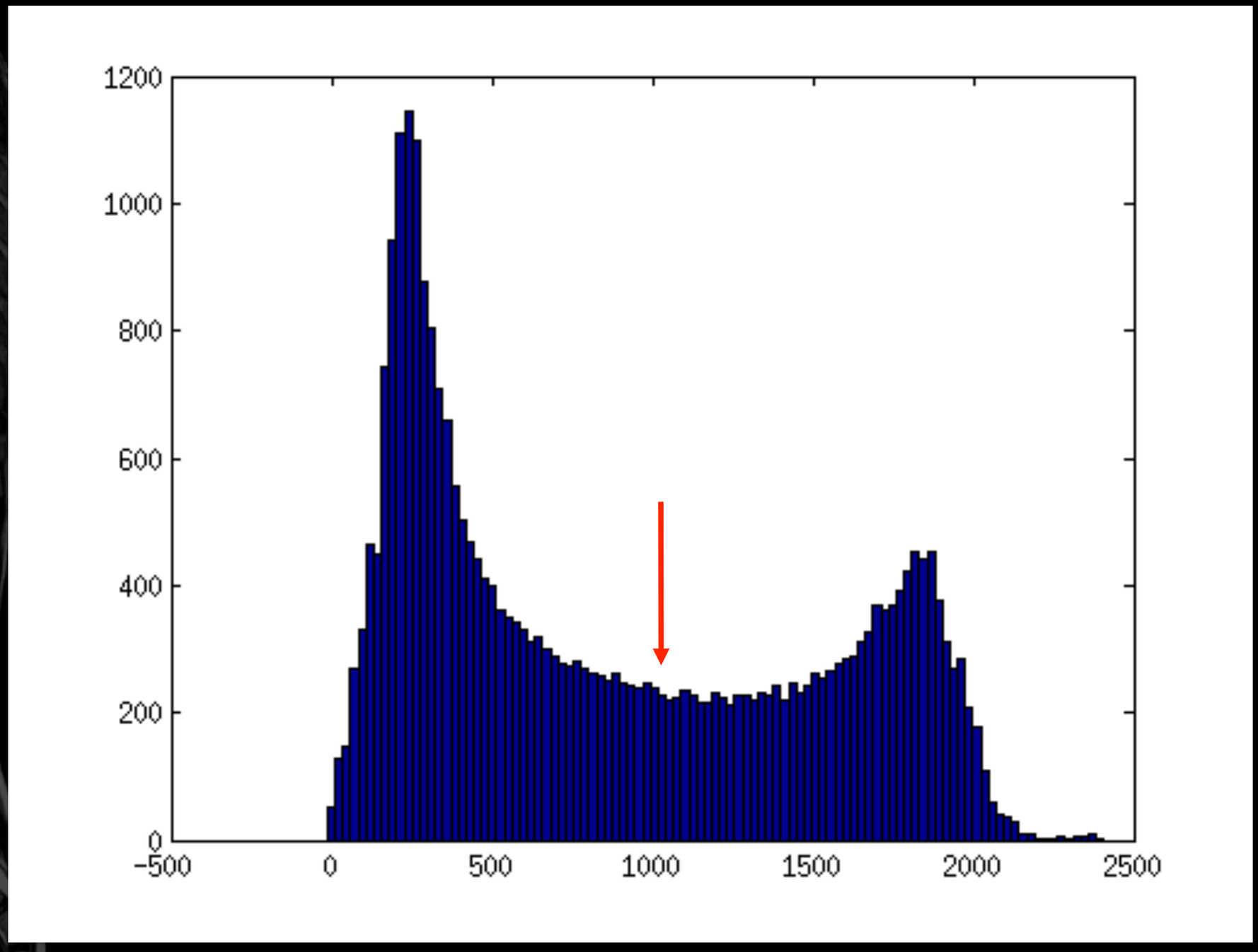
RETROICOR - RESPIRATORY PHASE



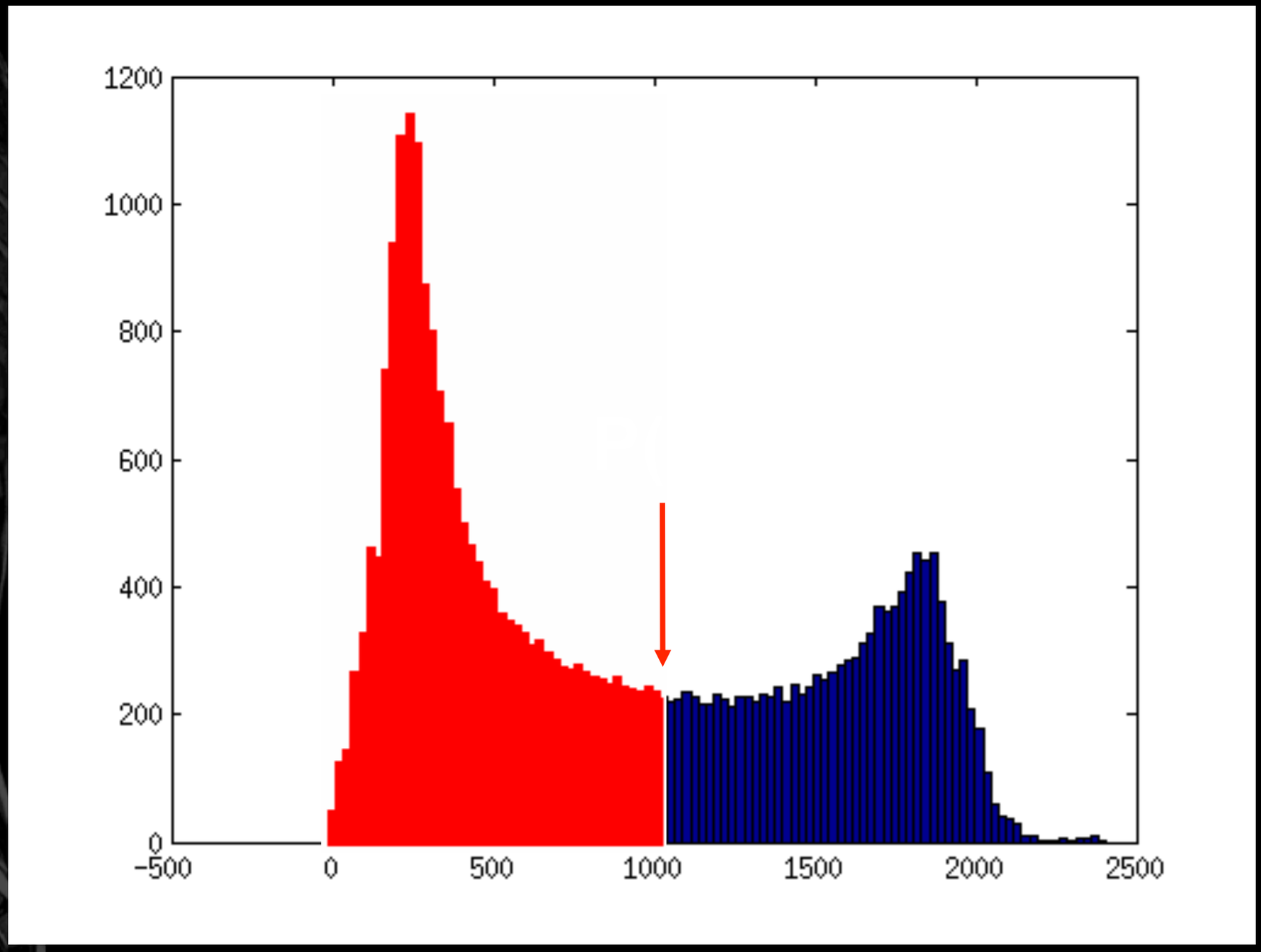
RETROICOR - RESPIRATORY PHASE



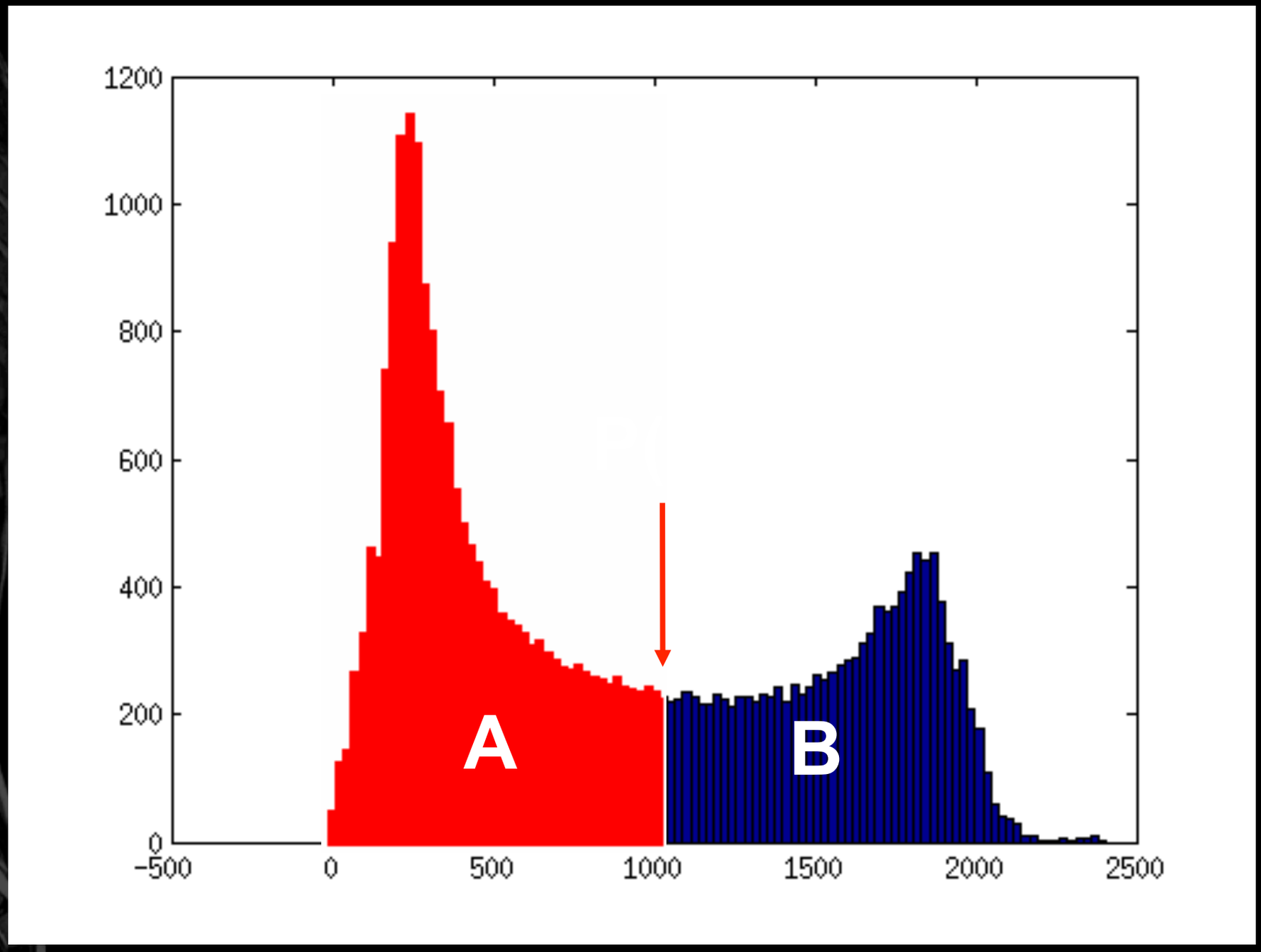
RETROICOR - RESPIRATORY PHASE



RETROICOR - RESPIRATORY PHASE

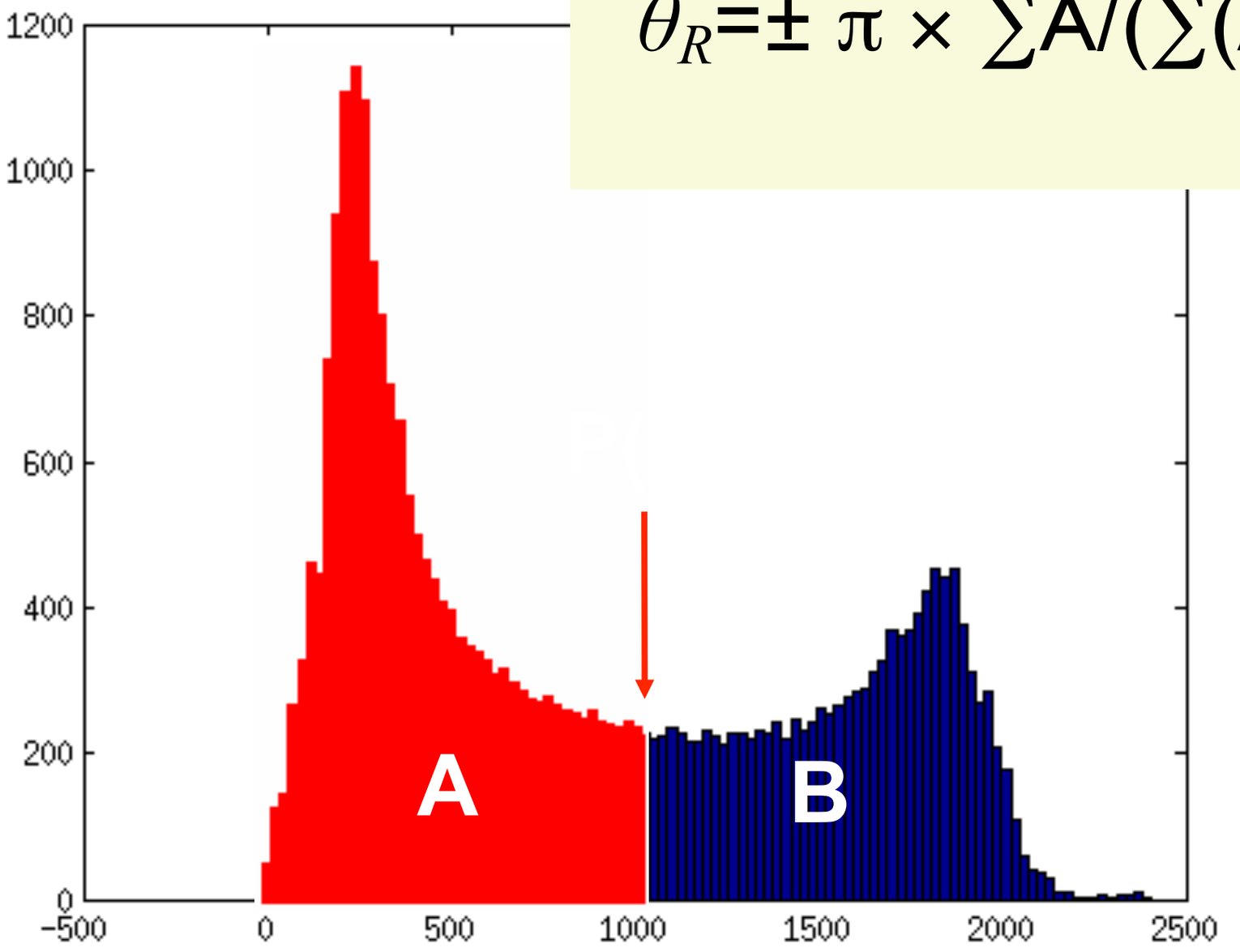


RETROICOR - RESPIRATORY PHASE



RETROICOR - RESPIRATORY PHASE

$$\theta_R = \pm \pi \times \sum A / (\sum (A+B))$$



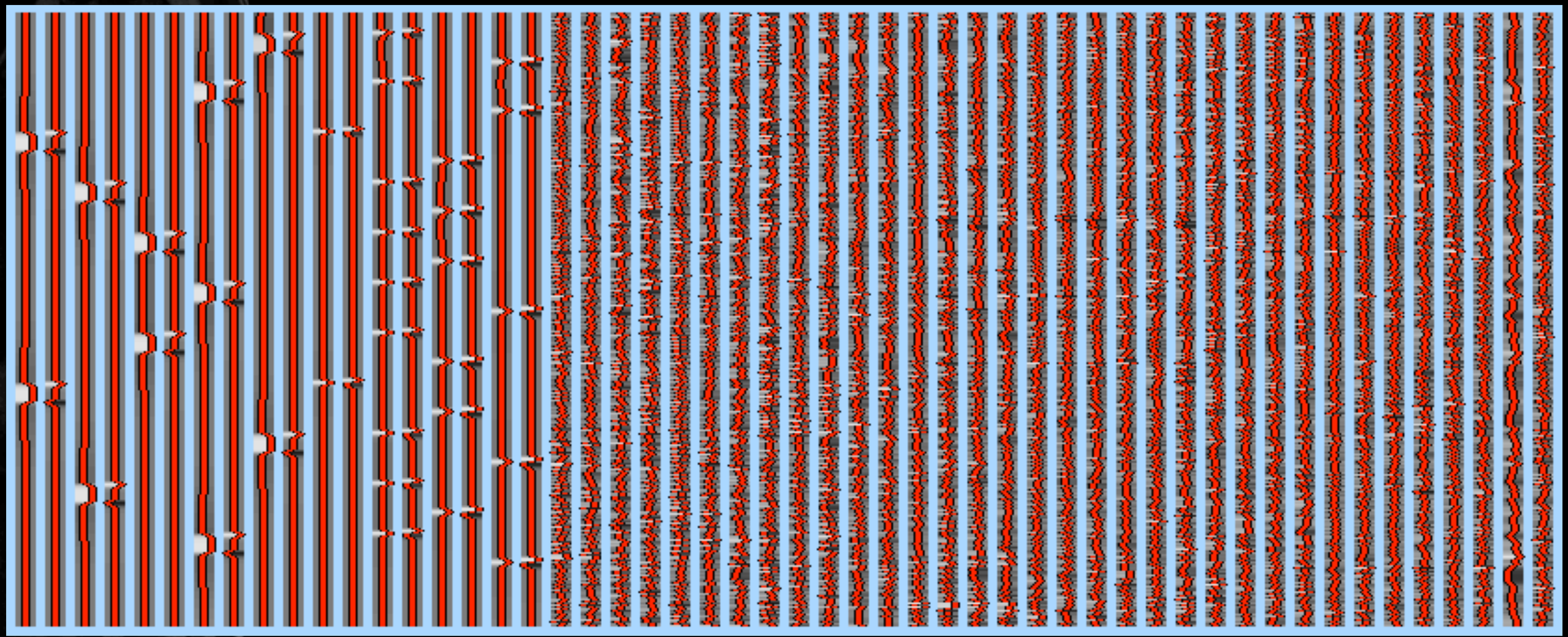
RETROICOR

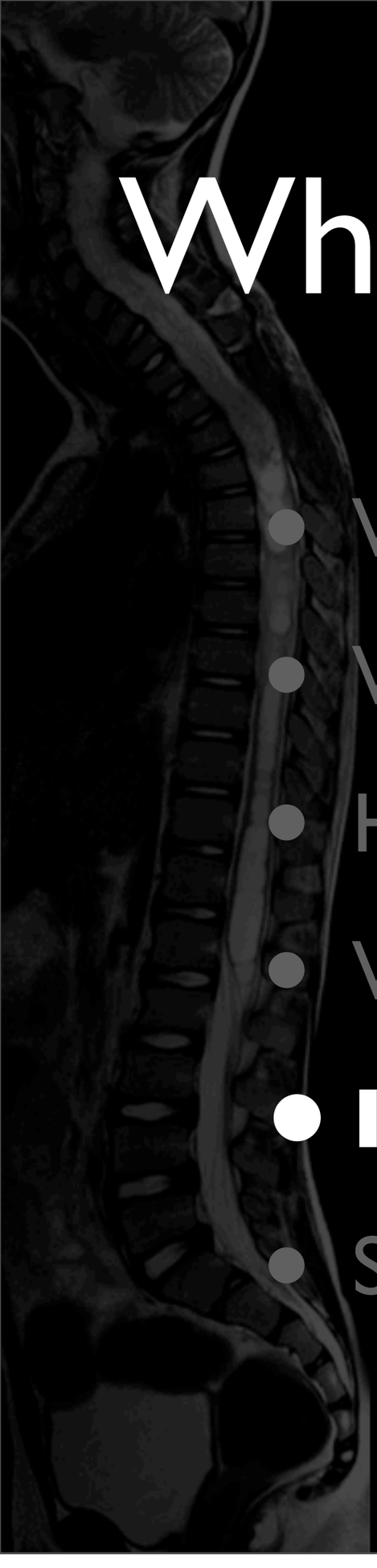
- Fourier analysis (RETROICOR) can be used to model noise (*Glover et al. MRM, 2000*)
- Use 4 terms for cardiac (sine/cosine)
- Use 4 terms for respiratory (sine/cosine)
- Use 2 terms for interaction:

$$sin/cos(\alpha\theta_C \pm \beta\theta_R) \qquad (\alpha,\beta = 1, 2)$$

- These are fed into Feat along with the experimental design and should (hopefully) explain most of the physiological noise in the images

Model





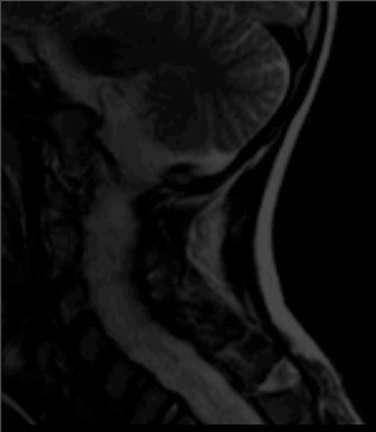
What's covered in this talk

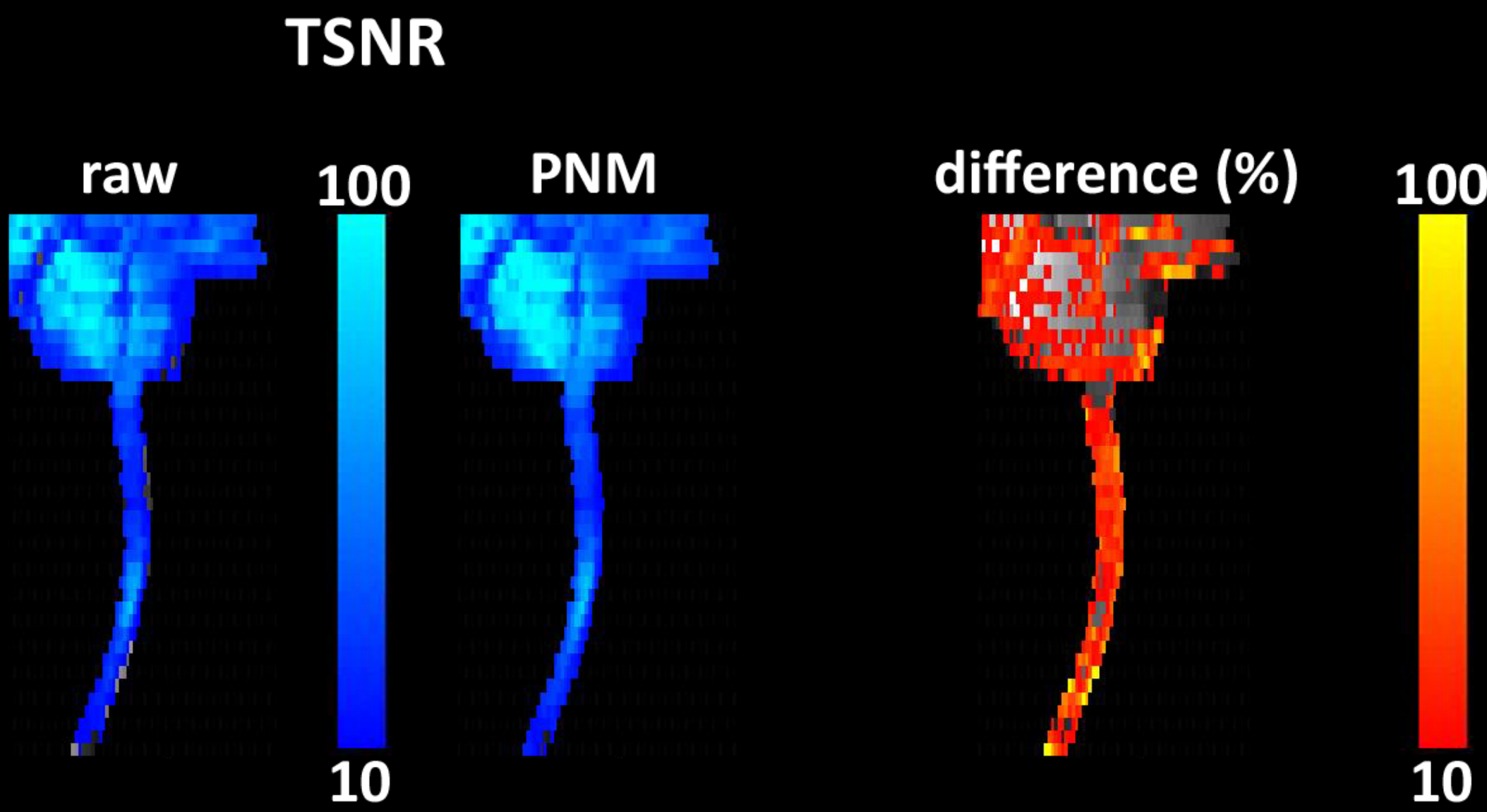
- What is physiological noise?
- Why does it matter?
- How do I measure it?
- What to do with the data....
- **Is it worth the hassle?**
- Spinal FMRI

What's the POINT?!!!

- Reduced number of subjects required to detect group effect
- Possibility to draw conclusions from N=1 expts?
- Greater accuracy of parameter estimates
- Ability to extract meaningful signal from difficult regions e.g. brainstem, spinal cord, areas near Circle of Willis: VTA, hippocampus, amygdala

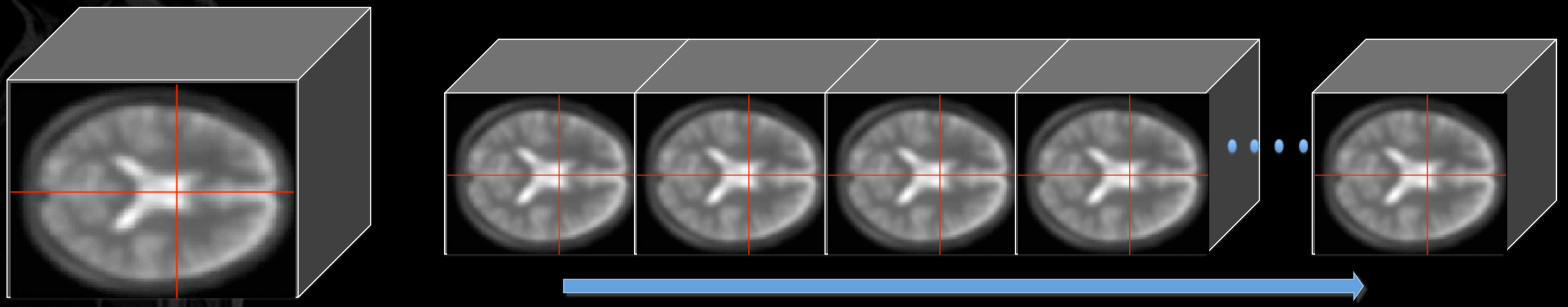
Increased TSNR





The fMRI-adapted version of the Placing Test

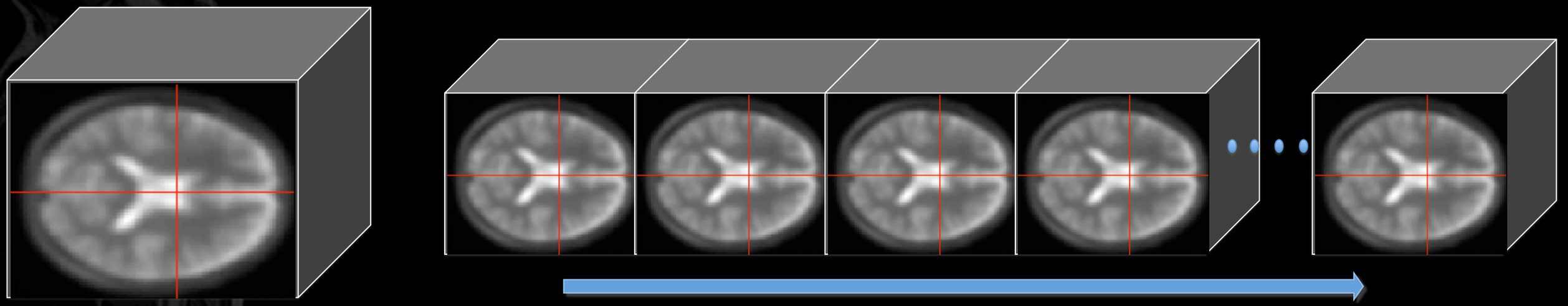
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

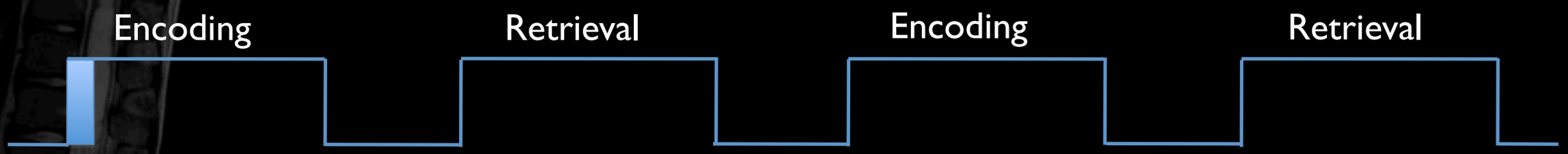


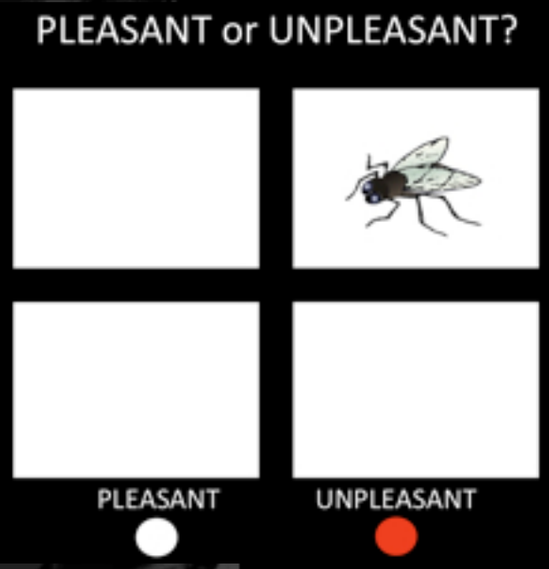
Encoding Retrieval Encoding Retrieval

The fMRI-adapted version of the Placing Test

During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

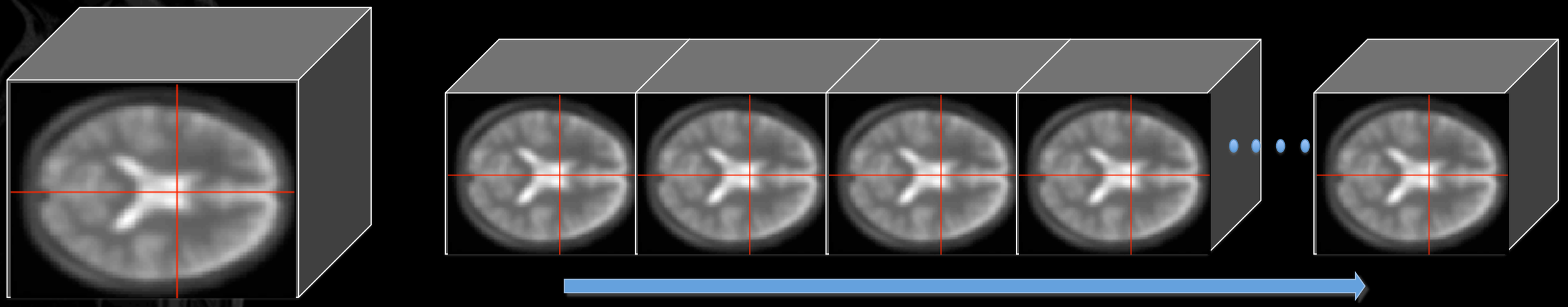


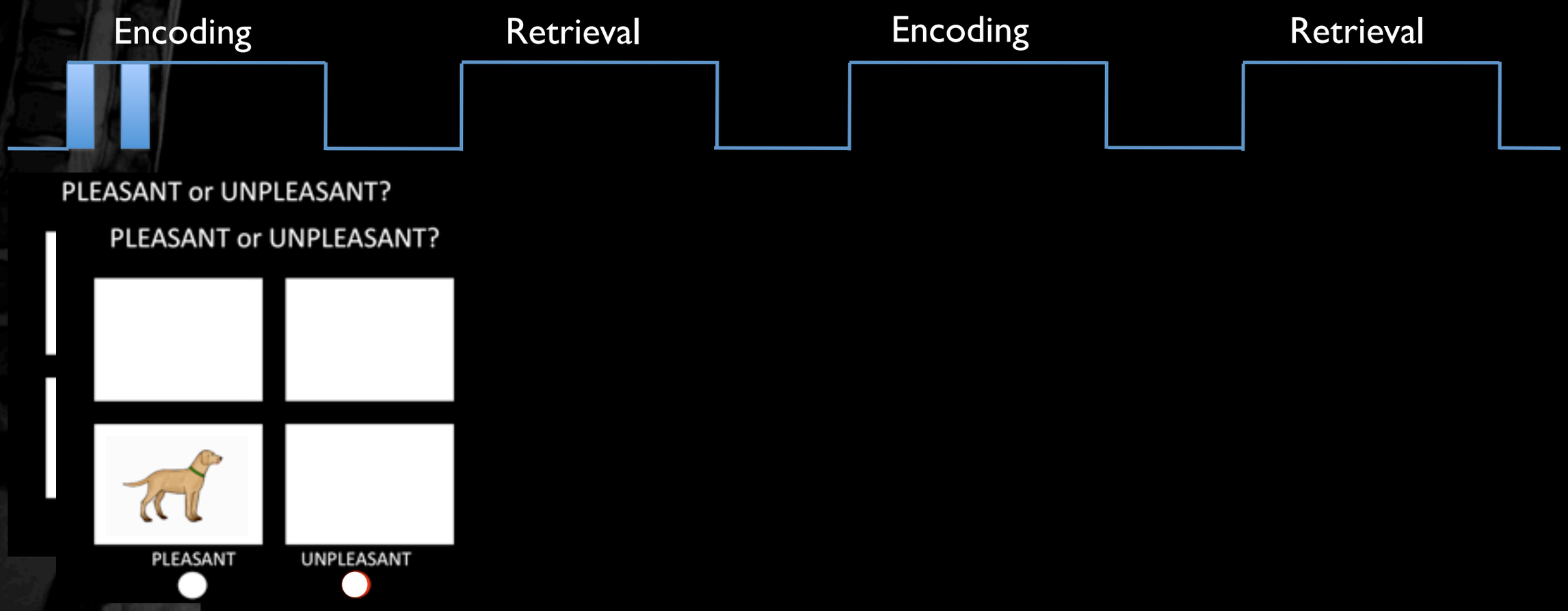




The fMRI-adapted version of the Placing Test

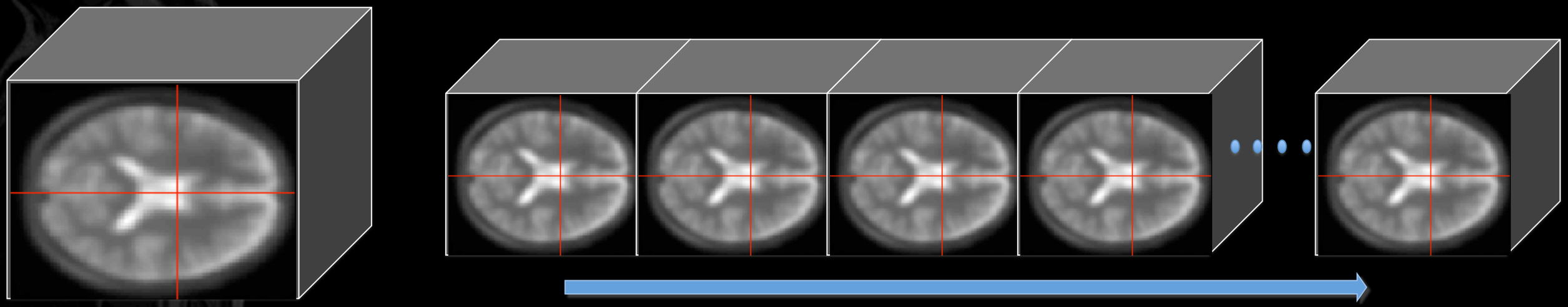
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

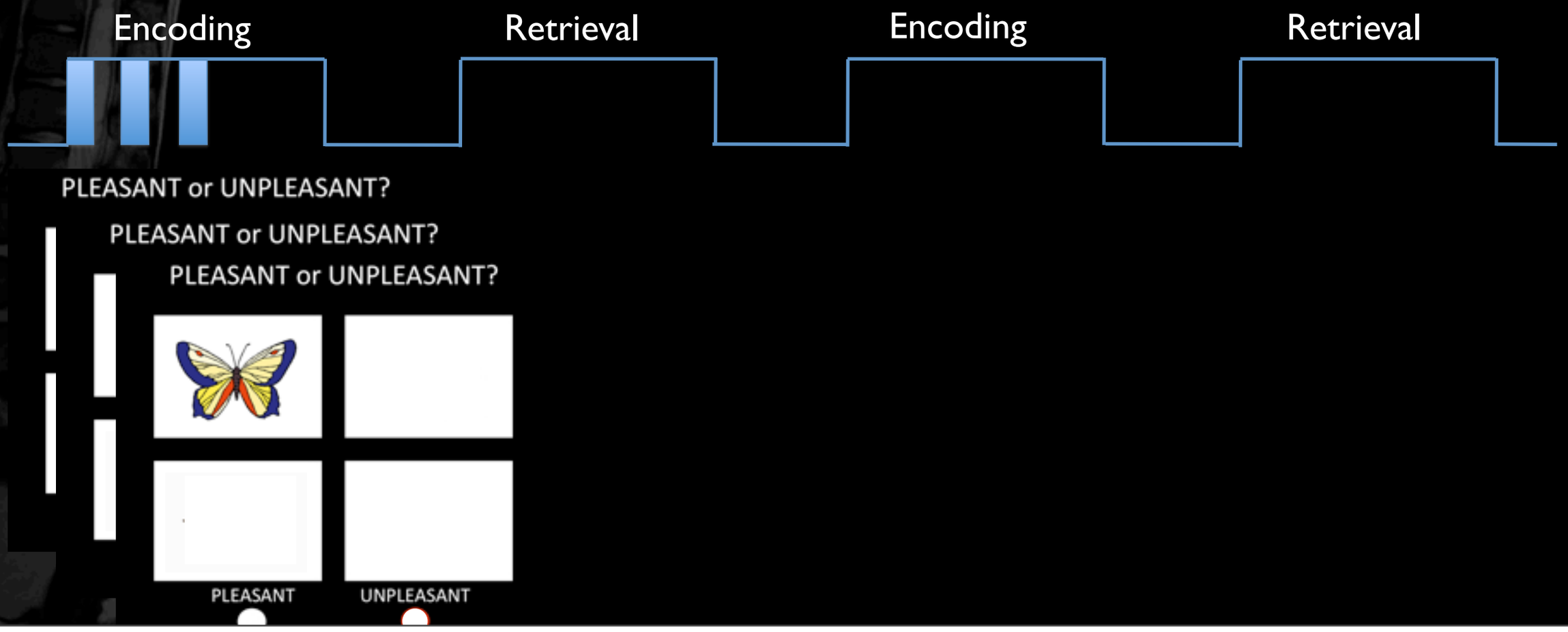




The fMRI-adapted version of the Placing Test

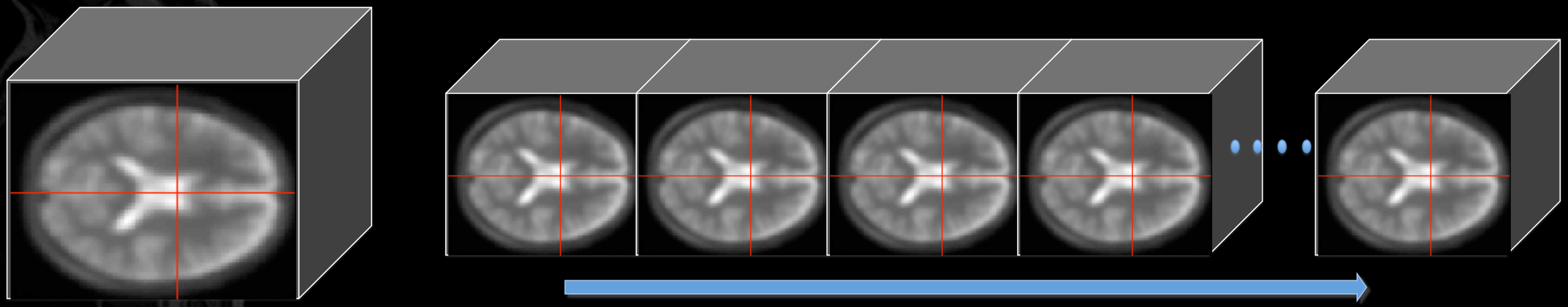
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

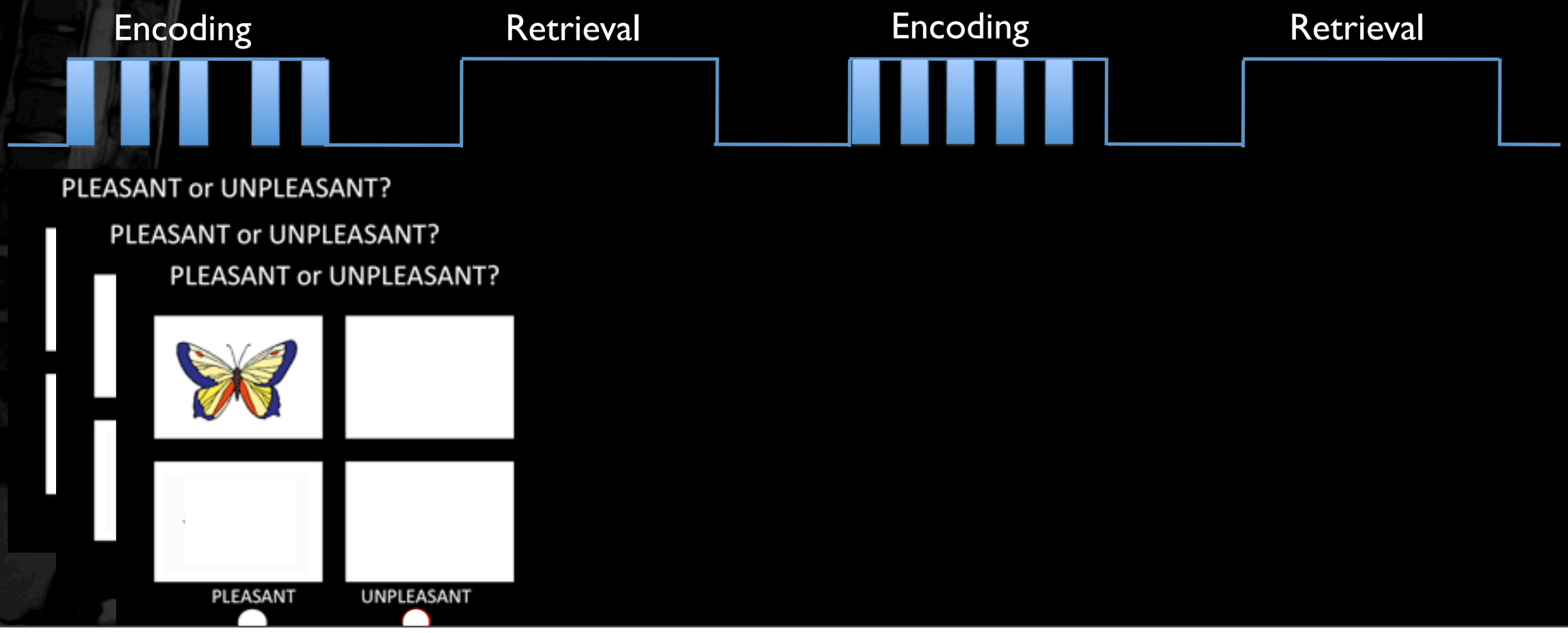




The fMRI-adapted version of the Placing Test

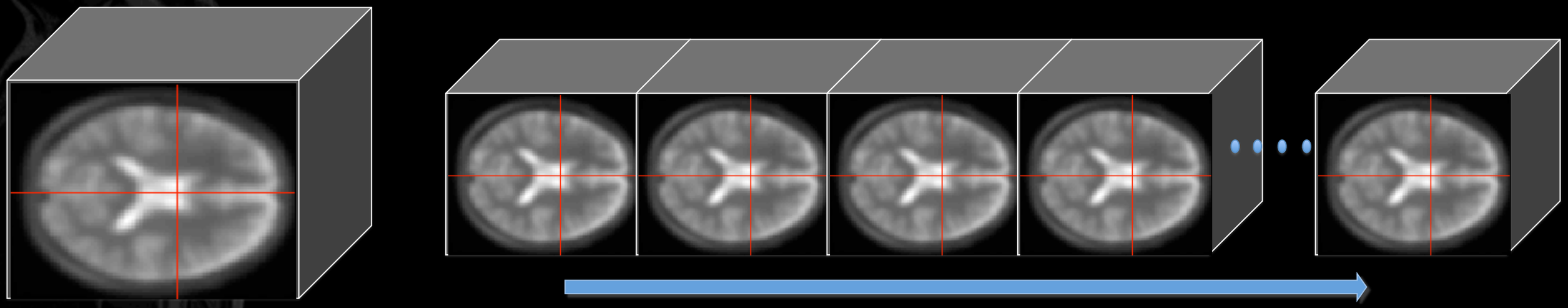
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

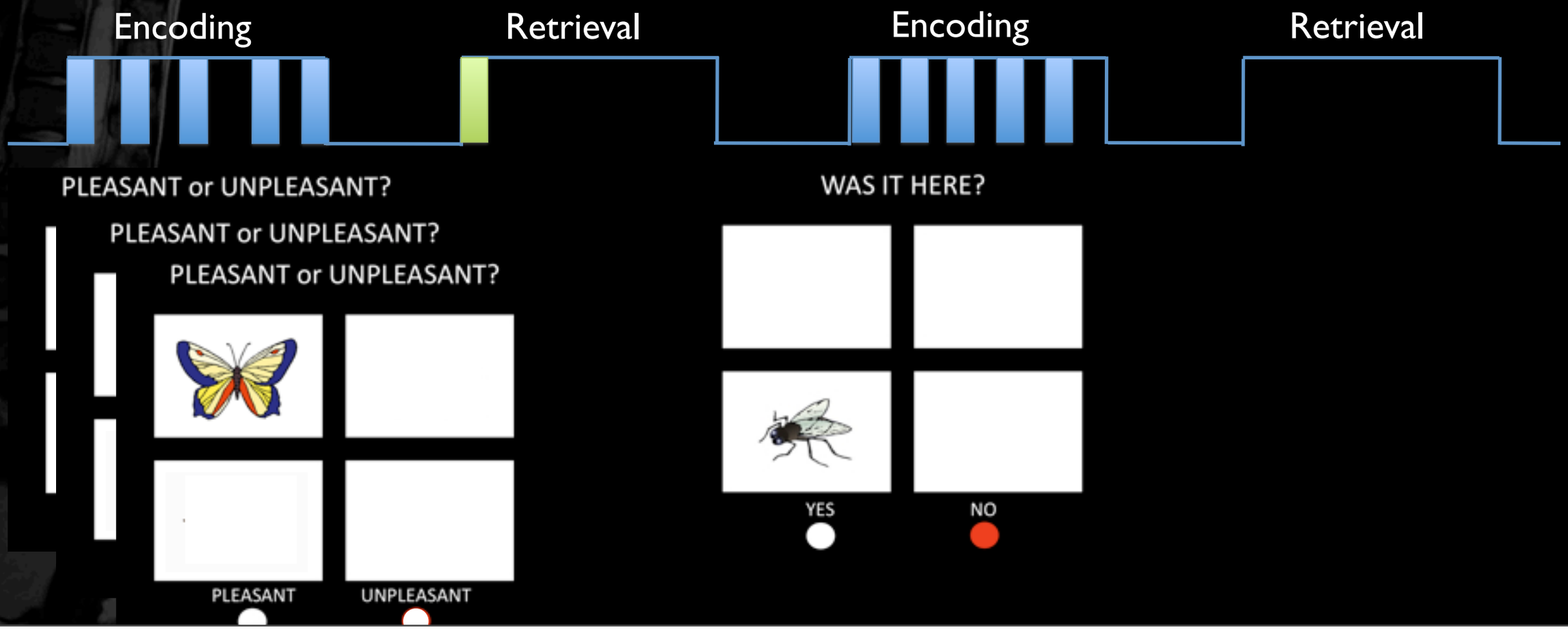




The fMRI-adapted version of the Placing Test

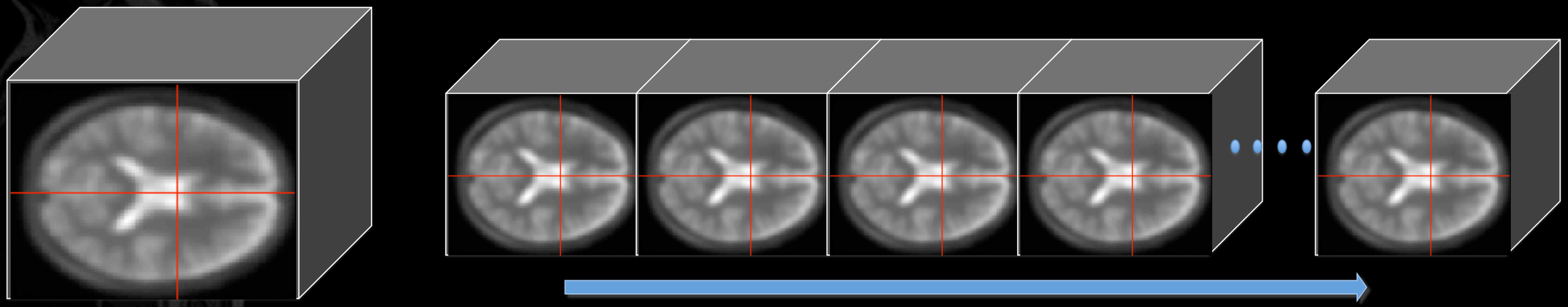
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

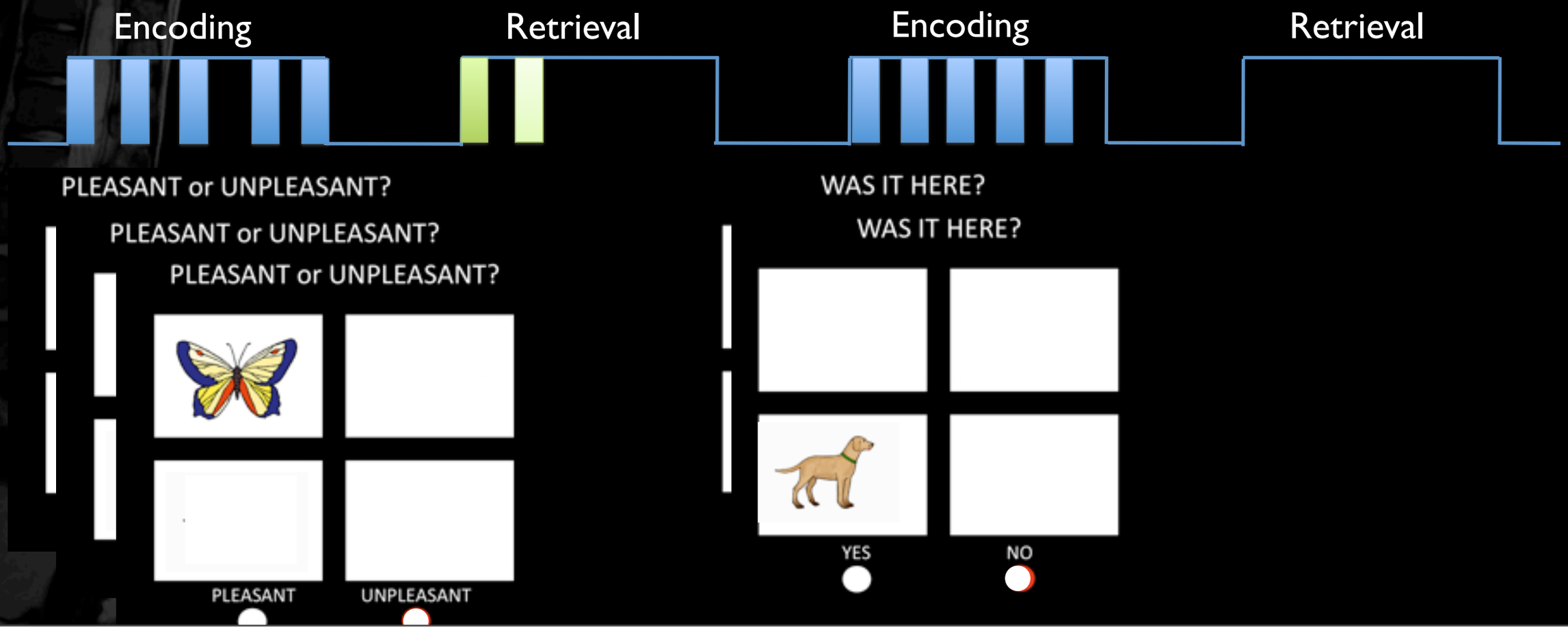




The fMRI-adapted version of the Placing Test

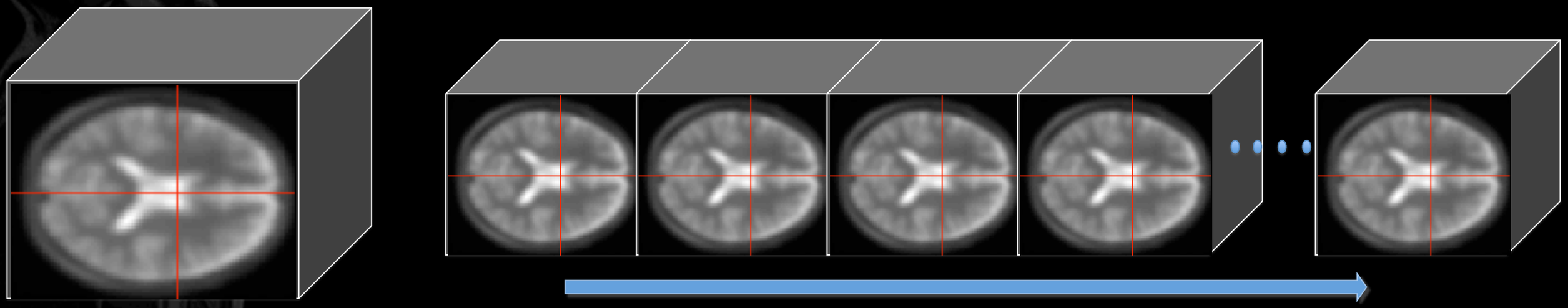
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

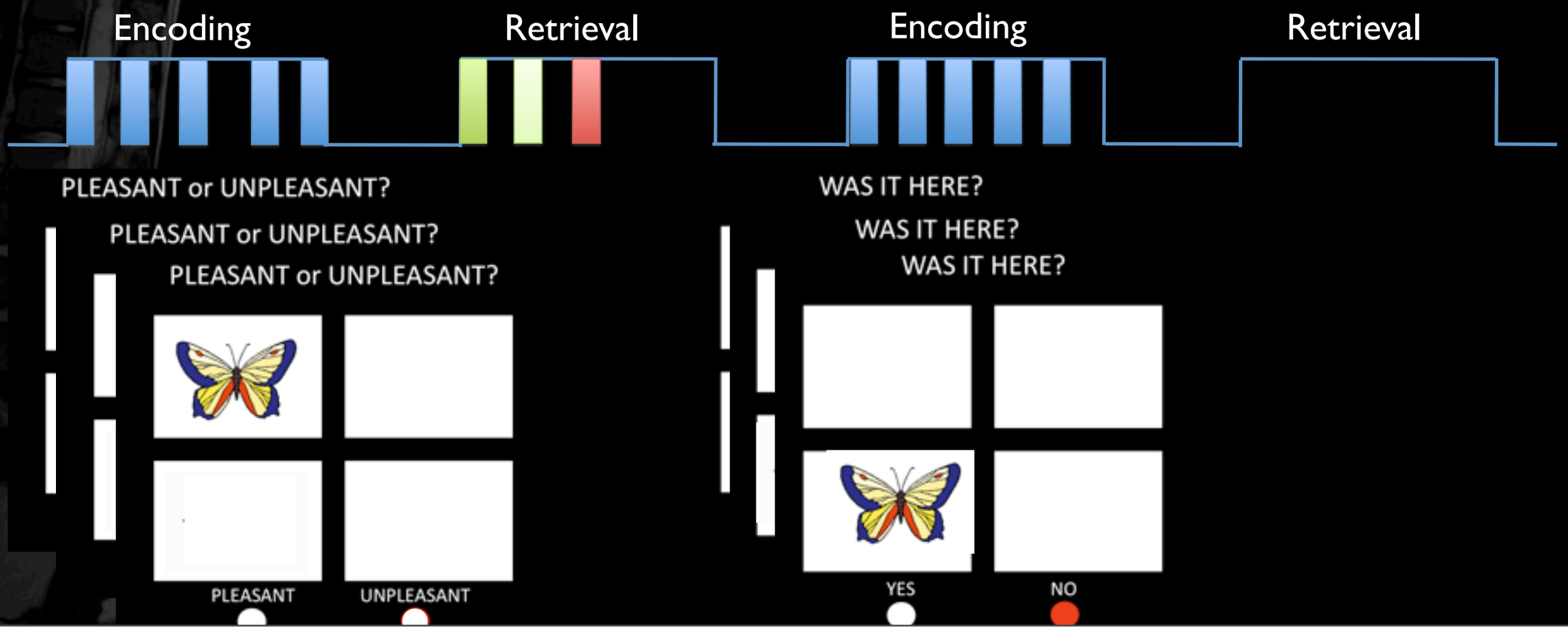




The fMRI-adapted version of the Placing Test

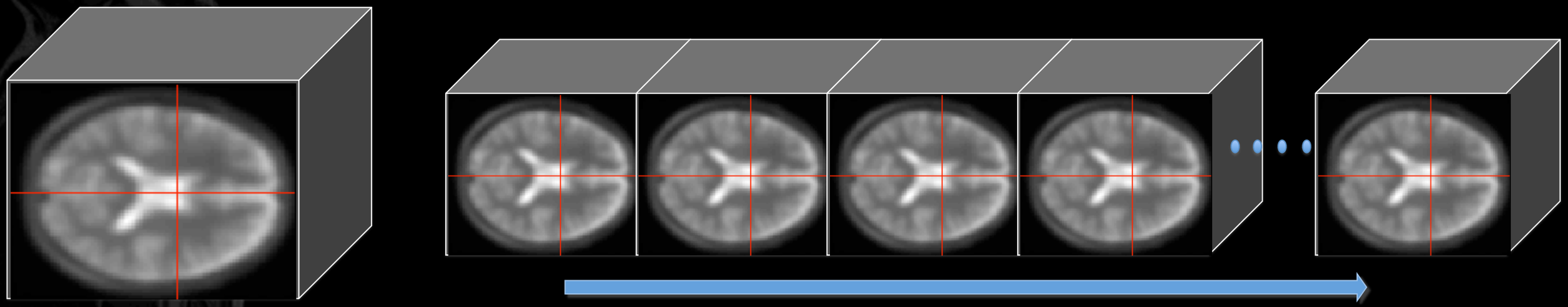
During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)

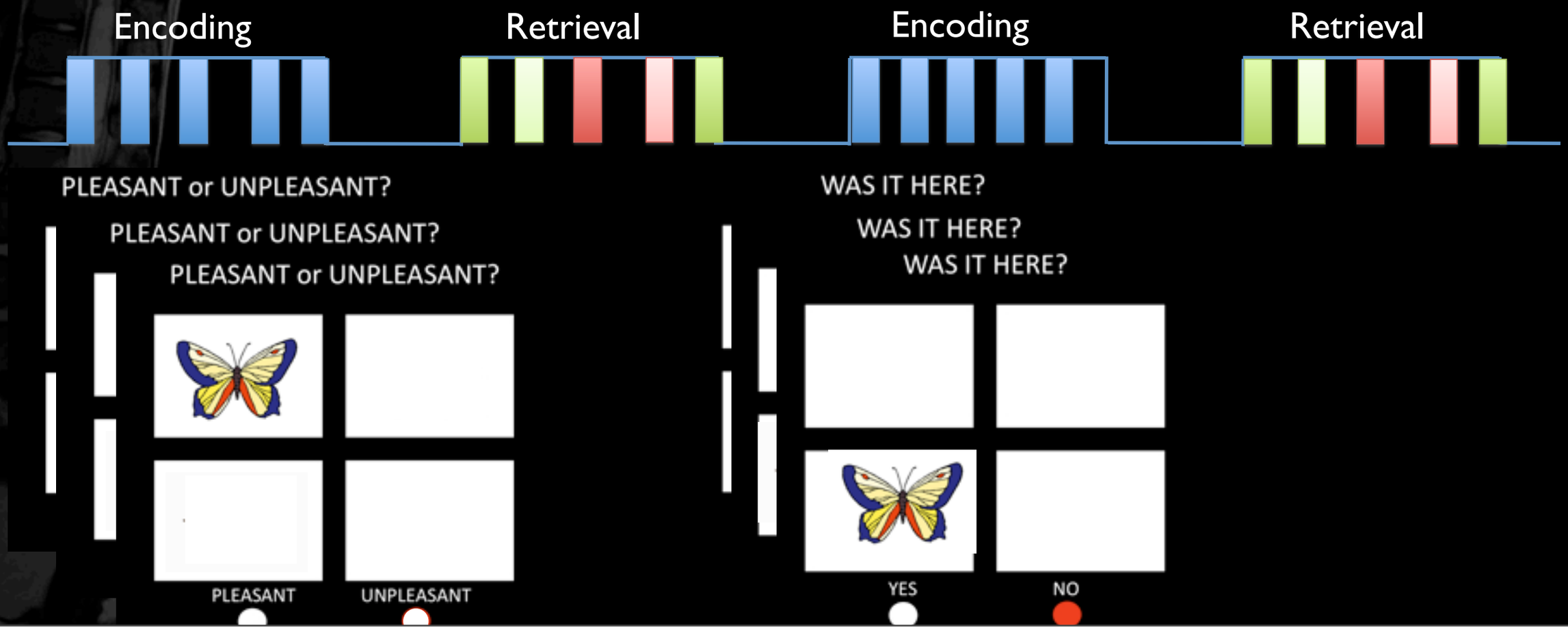


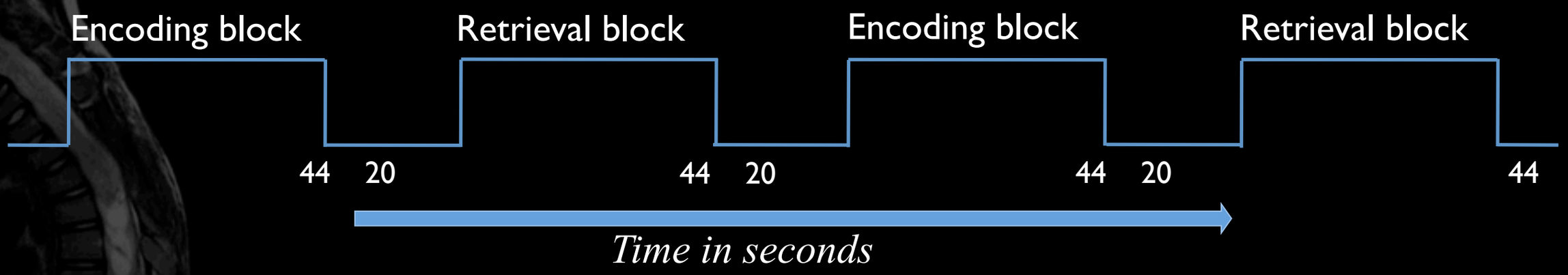


The fMRI-adapted version of the Placing Test

During the fMRI experiment subjects are asked to perform a visuo-spatial pair associates learning test ("fMRI adapted" Placing Test)







Encoding block

PLEASANT or UNPLEASANT?

PLEASANT or UNPLEASANT?

PLEASANT or UNPLEASANT?

PLEASANT or UNPLEASANT?

PLEASANT or UNPLEASANT?

PLEASANT

UNPLEASANT

Retrieval block

WAS IT HERE?

WAS IT HERE?

WAS IT HERE?

WAS IT HERE?

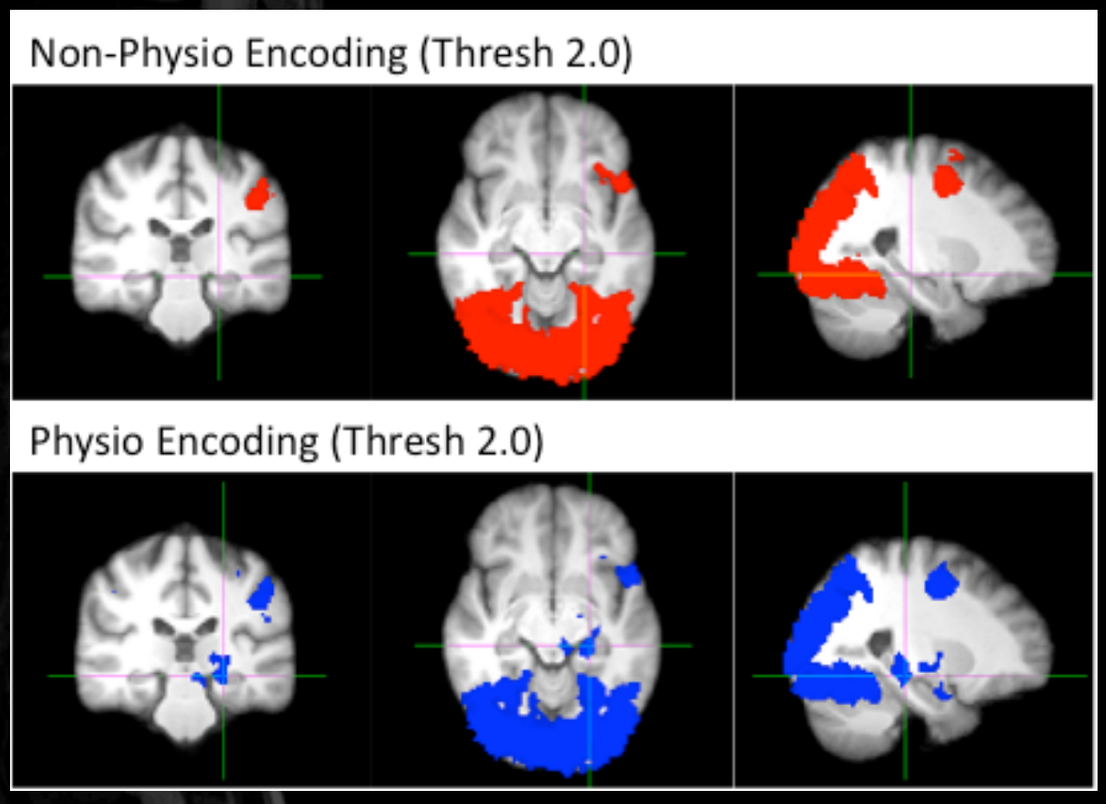
WAS IT HERE?

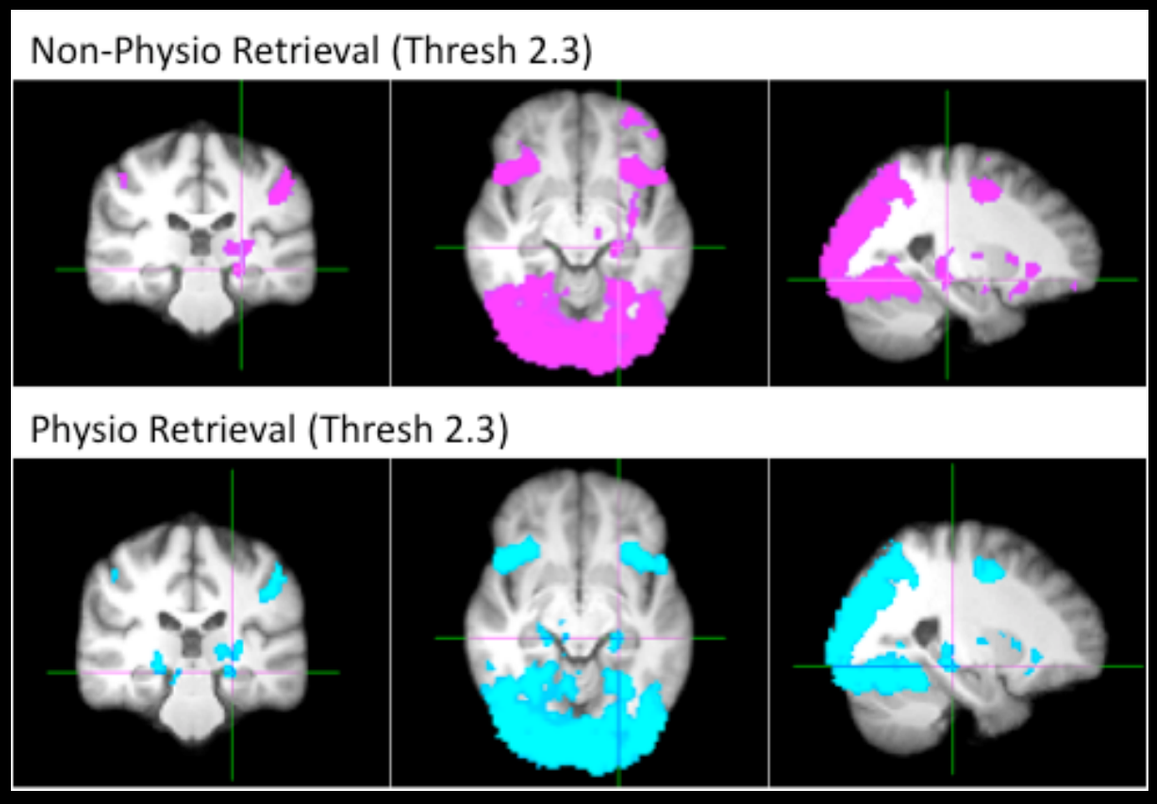
YES

NO

5 associates per block 6 secs each

Hippocampal activity





encoding, cluster corrected p<0.05

retrieval, cluster corrected p<0.05

Brainstem experiments

METHODS

Subjects: To date, six right-handed healthy volunteers (3 male, 3 female; age: 26 ± 2.17).

Physiological monitoring: *R*espiratory bellows, pulse oximeter and CO2 sampling via a BIOPAC device.

Paradigm: 2 runs of pain stimuli and 2 runs of vibrotactile stimuli, each run testing either a coronal 2x2x2 mm^3 or an axial 1.5x1.5x3 mm^3 resolution acquisition.

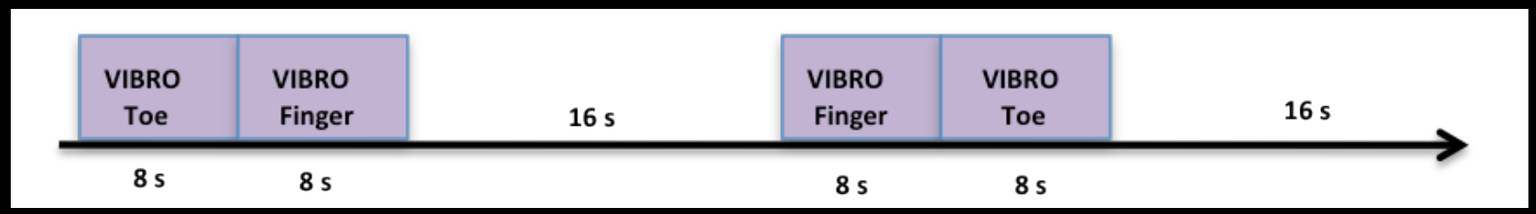
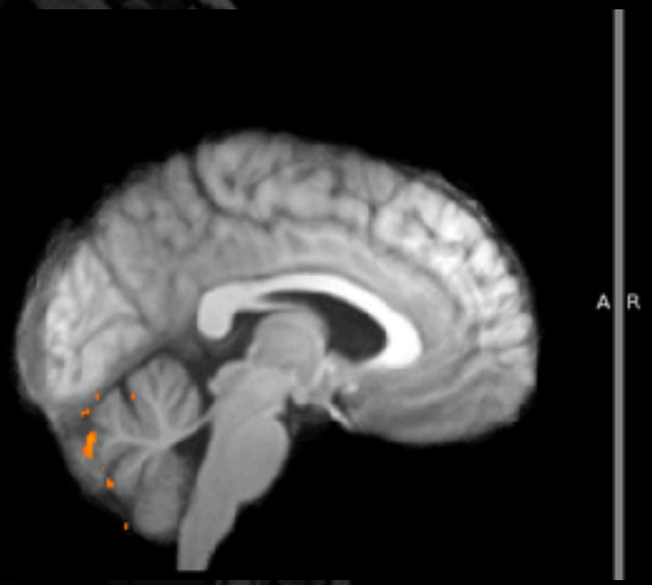


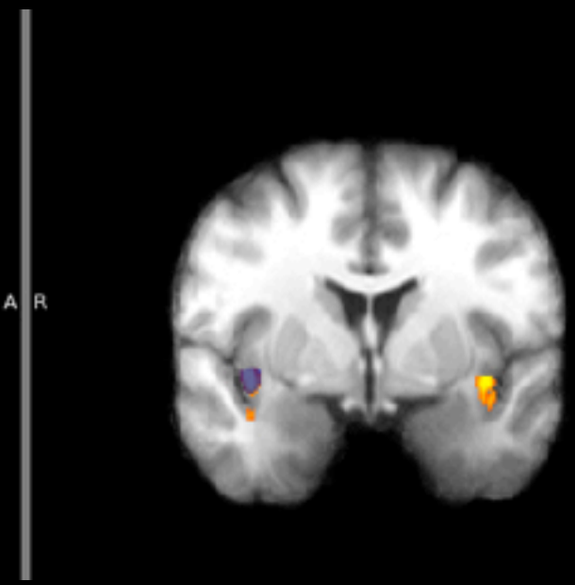
Figure 1A. Vibrotactile paradigm- subjects received 20 blocks of vibrotactile stimuli to the right index finger and the right hallux delivered pseudorandomly at 30Hz via a Piezo-electric vibrotactile device.

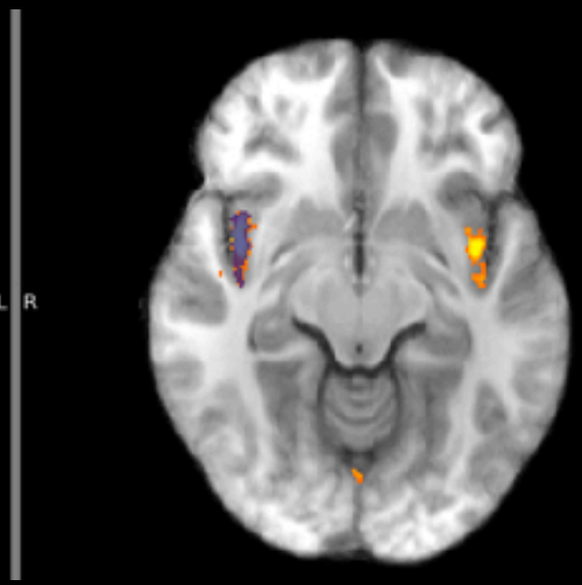
Figure 1B. Pain paradigm- subjects received 15 thermal stimuli to the right volar forearm, delivered with a MEDOC Pathway CHEPS device and thresholded at 6/10 on an 11-point pain rating scale. The thermal stimuli were separated by two punctate stimuli delivered pseudorandomly between the right arm and right leg using a 512mN punctate probe.

Analysis: Data was processed using FMRIB software library (FSL) tools. Physiological data was processed in MATLAB.

Pain- thermal

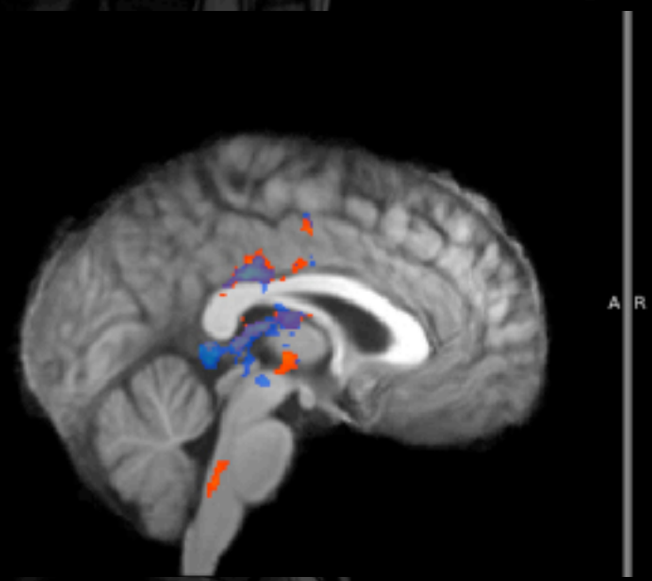


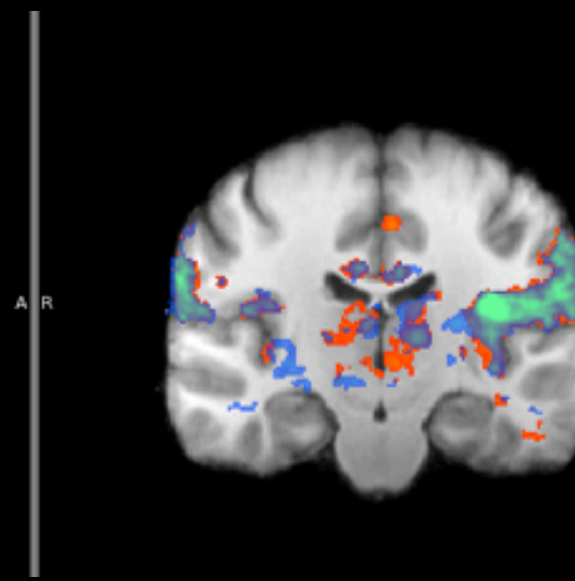


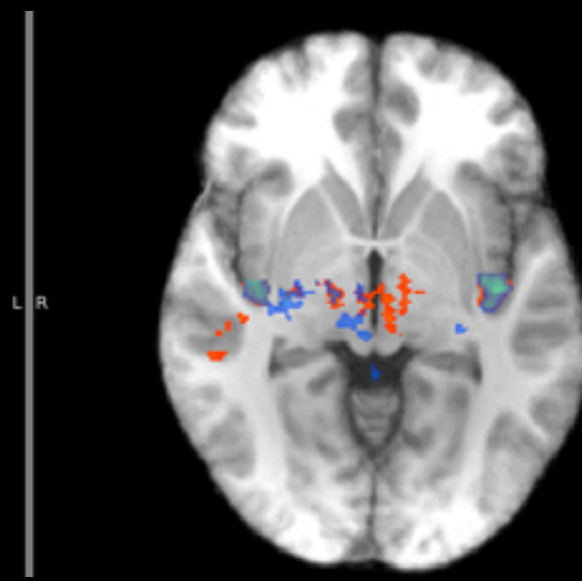


AXIAL

N=6, Group mean (Fixed effects) Z=1.8 p<0.05





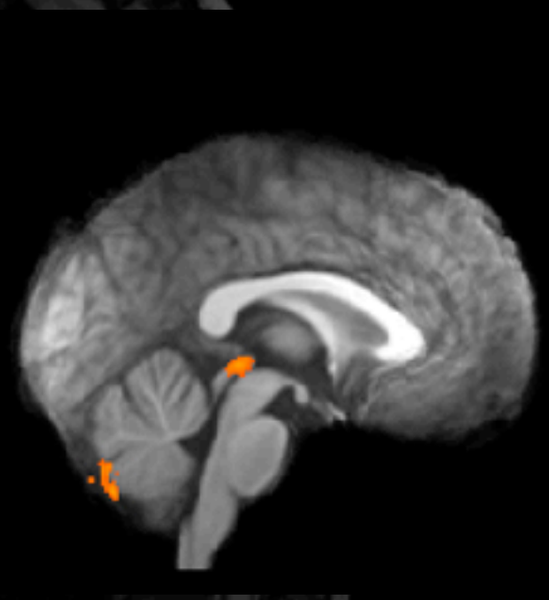


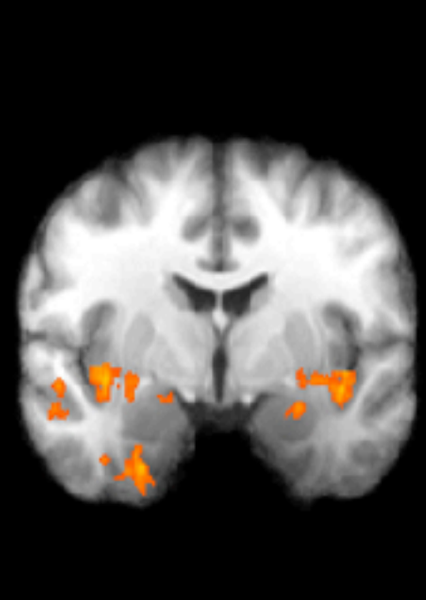
CORONAL

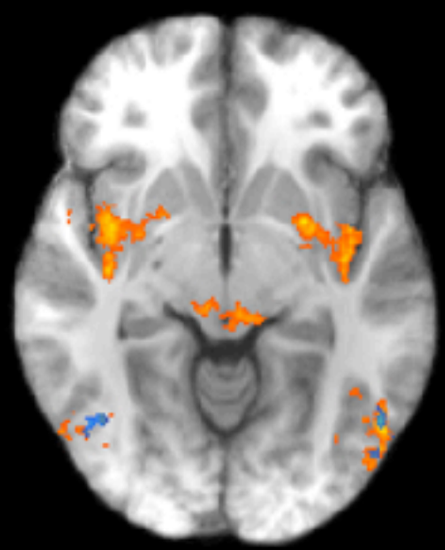
With PNM

Without PNM

Pain- punctate arm

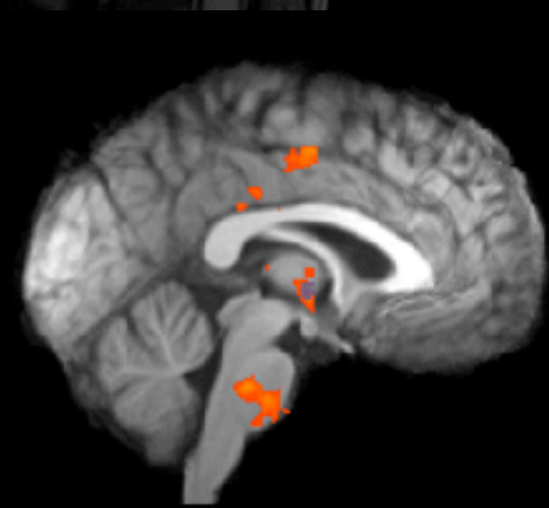


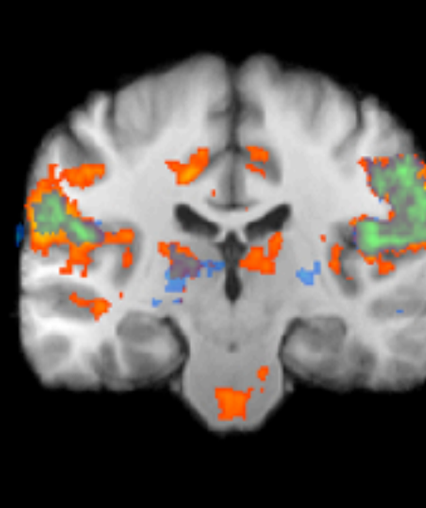


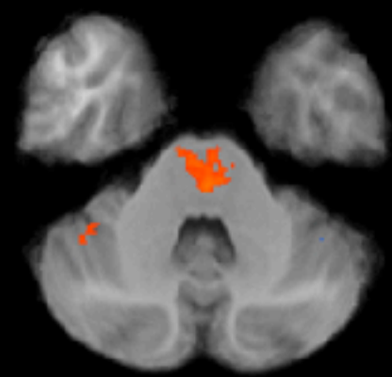


AXIAL

N=6, Group mean (Fixed effects), Z=1.8 p<0.05







CORONAL

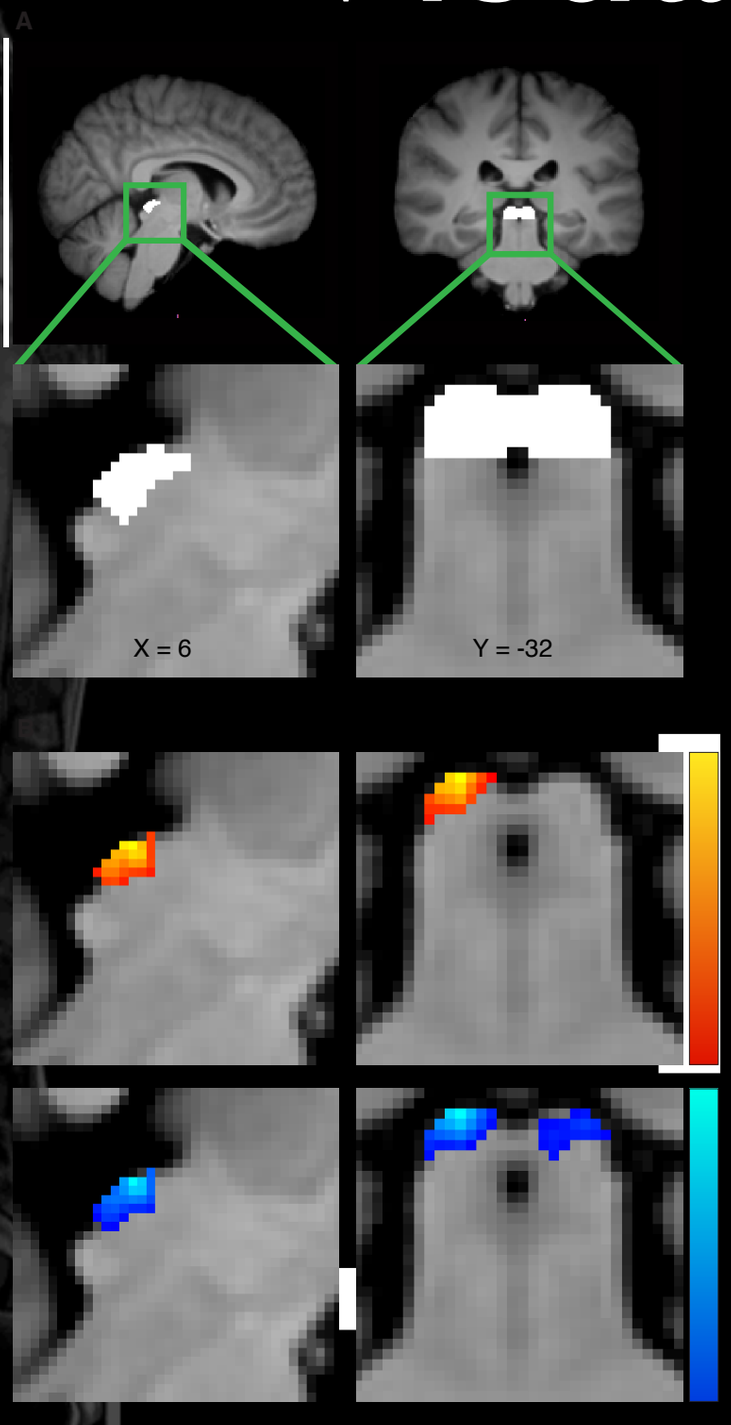
With PNM

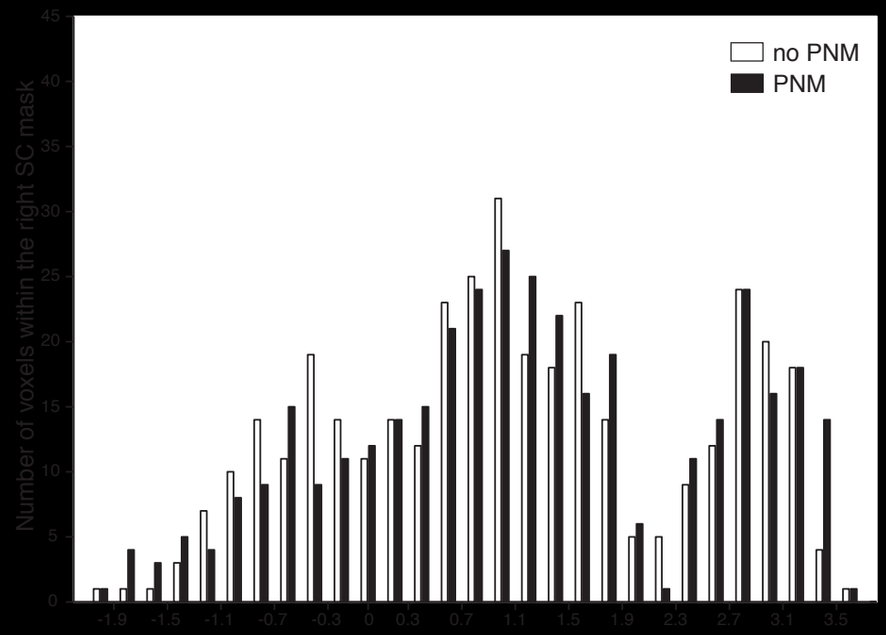
Without PNM

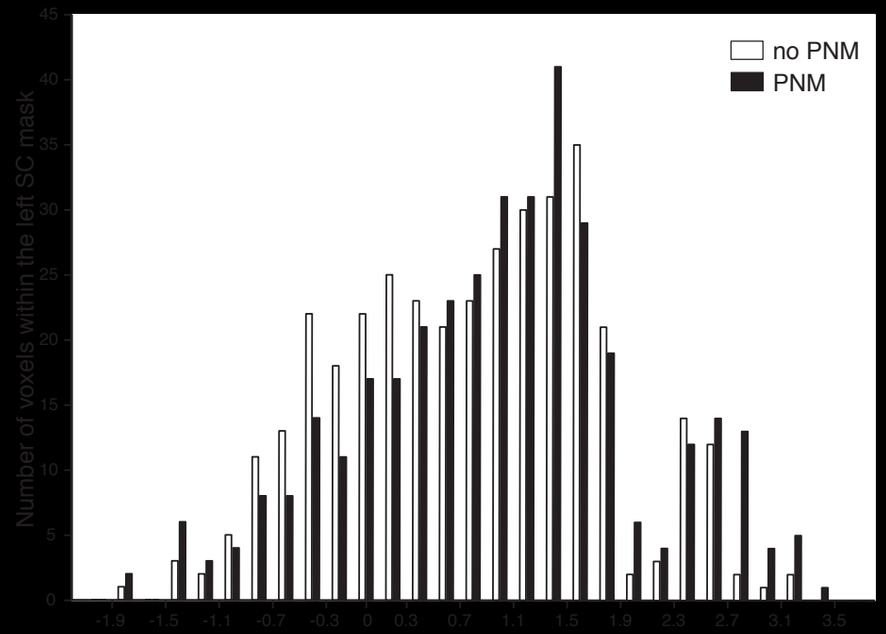
Visual paradigm

- 10 healthy controls
- Coronal oblique acquisition through brainstem (superior colliculi)
- Philips 3T scanner, ECG and respiratory bellows
- Smoothly rotating semi circle made of alternating black and white checks that scaled linearly with eccentricity
- Checks reversed contrast at 8Hz and the semi-circle rotated at 1Hz. Each presentation lasted for two seconds, random ITI, jittered
- Data analysis MATLAB script, and 4D regressors in FSL

Visual paradigm



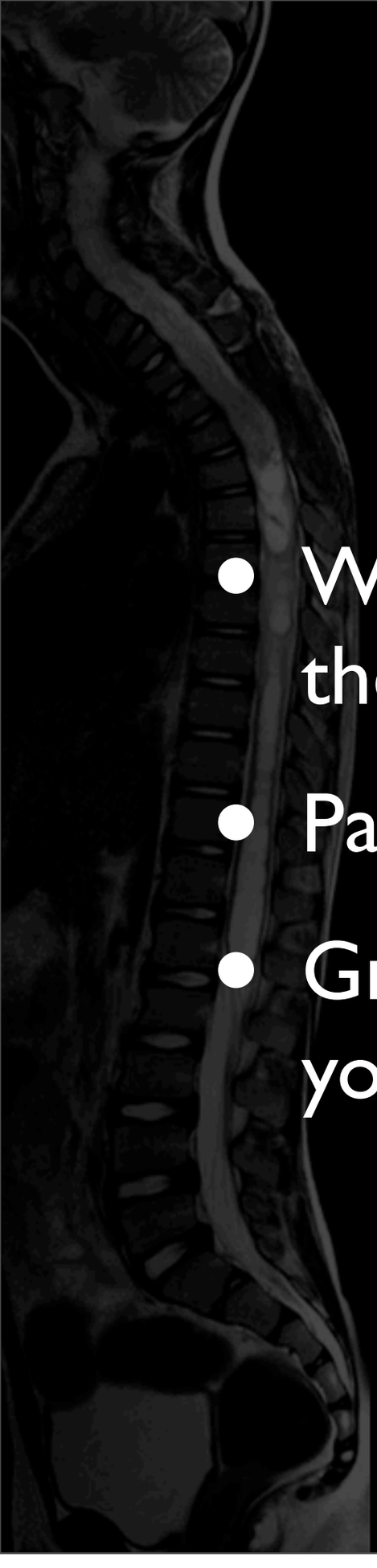




Limbrick-Oldfield et al (2012). NeuroImage 59:1230–1238.

What's covered in this talk

- What is physiological noise?
- Why does it matter?
- How do I measure it?
- What to do with the data....
- Is it worth the hassle?
- **Spinal FMRI**



Spinal fMRI

- Why? Understanding processes occurring at the spinal level (e.g. sensorimotor)
- Pain - central sensitisation, also brainstem
- Greater influence of physiological noise as you move down the neuraxis:

brain << (brainstem < spinal cord)

Physiological Noise Model (PNM)

- Uses a sum of sine and cosine terms
- Empirically defined regressor (CSF)
- Modelled using the GLM in Feat
- Available in FSL5

Brooks et al (2008) Physiological noise modelling for spinal functional magnetic resonance imaging studies. NeuroImage 39:680-692.

RIGHT HAND STIMULATION

LEFT HAND STIMULATION

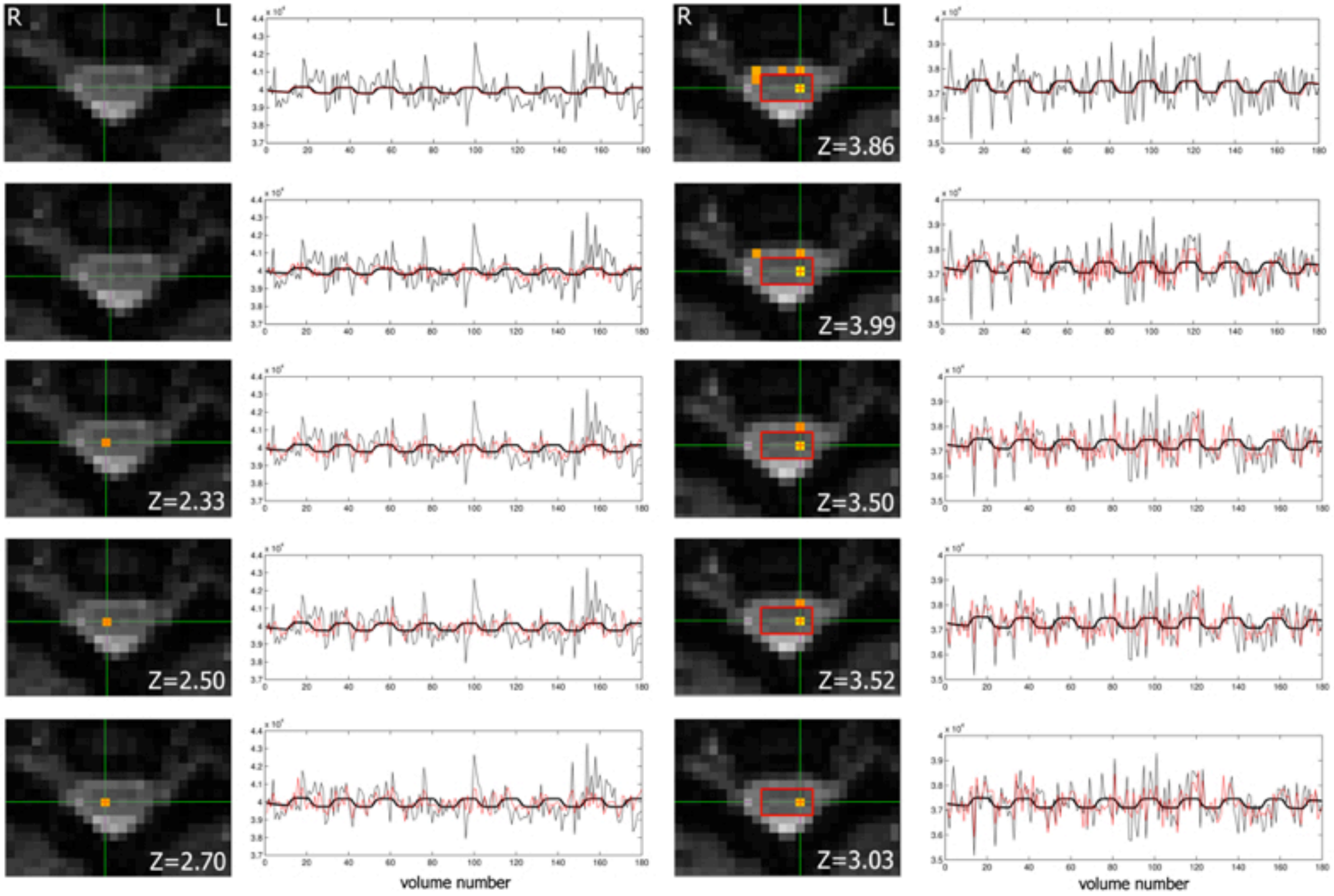
BASIC

RETRO10

RETRO15

RETRO21

RETRO37



Useful info

- http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/PNM
- http://www.fmrib.ox.ac.uk/Members/jon/physiological-noise-correction

jon.brooks@bristol.ac.uk

Acknowledgments

- Mark Jenkinson, Matthew Webster, Karla Miller, Jesper Anderson, Christian Beckmann, Irene Tracey (FMRIB)
- Yazhuo Kong (FMRIB)
- Eve Limbrick-Oldfield (Imperial College)