EEG/fMRI correlation analysis. A data and model driven approach.

JC de Munck (V)
SI Goncalves
PJW Pouwels
JPA Kuijer
P Andersen

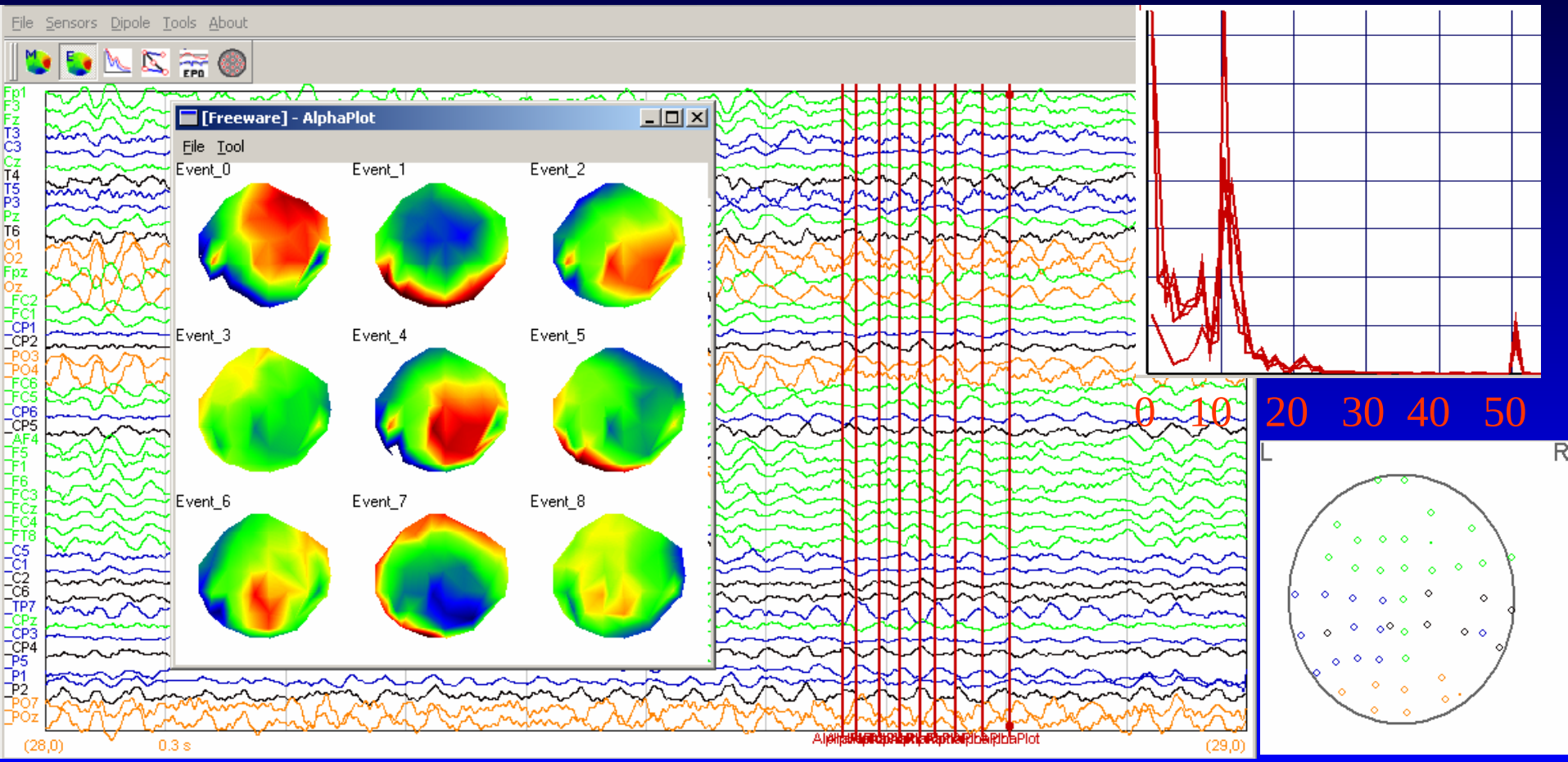
P Ossenblok
L Huijboom

FH Lopes da Silva

Introduction

- Why EEG/fMRI?
- Determination of the HRF.
- The HRF of the occipital alpha rhythm.
- A data driven approach.
- Discussion

Introduction



3 s

The alpha rhythm consists of 10 Hz oscillations that vary in strength.

Introduction

Source localisation:

specify

specify

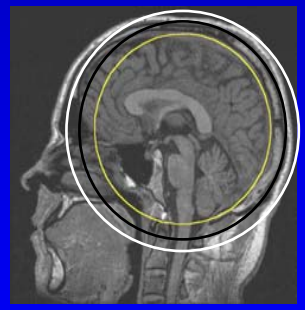
specify

Noise model

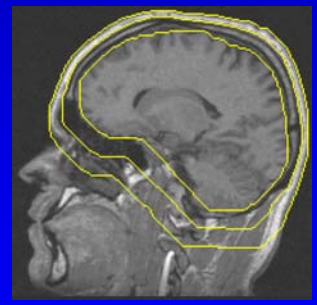
Source Model:

Current Dipole

Volume Conductor:



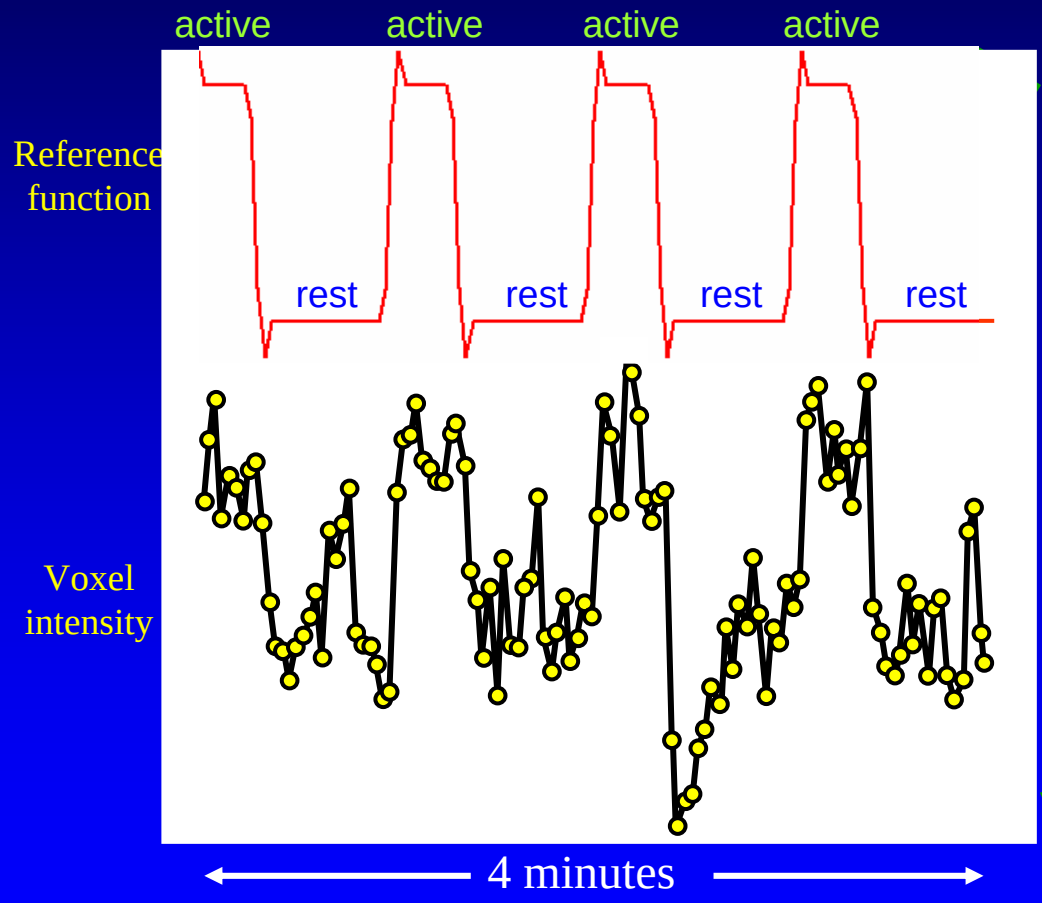
Spherical

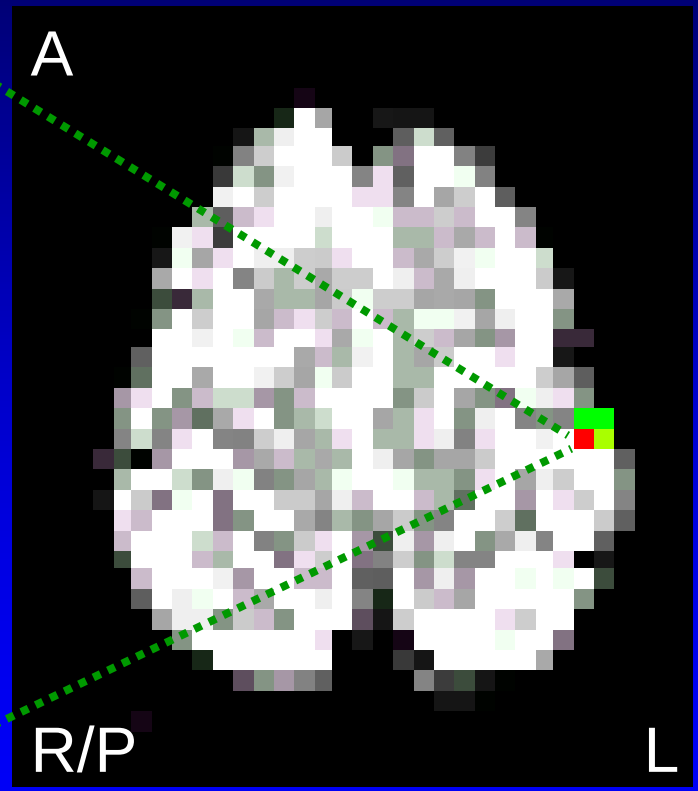


Realistic

The generators of the alpha rhythm can be found by analyzing its spatio-temporal patterns with mathematical models.

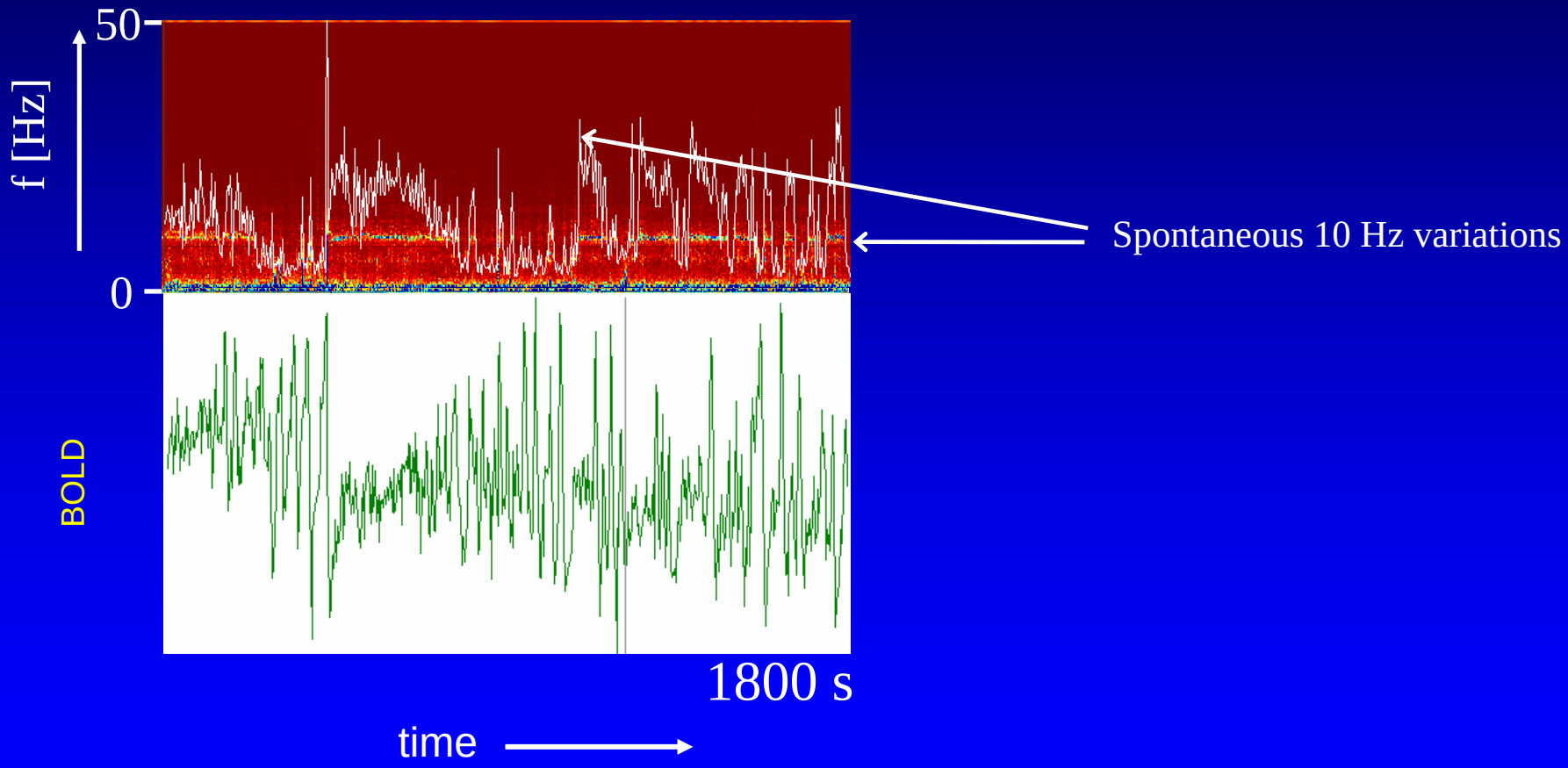
Introduction





With fMRI localization is obtained by correlating BOLD signals to a reference function.

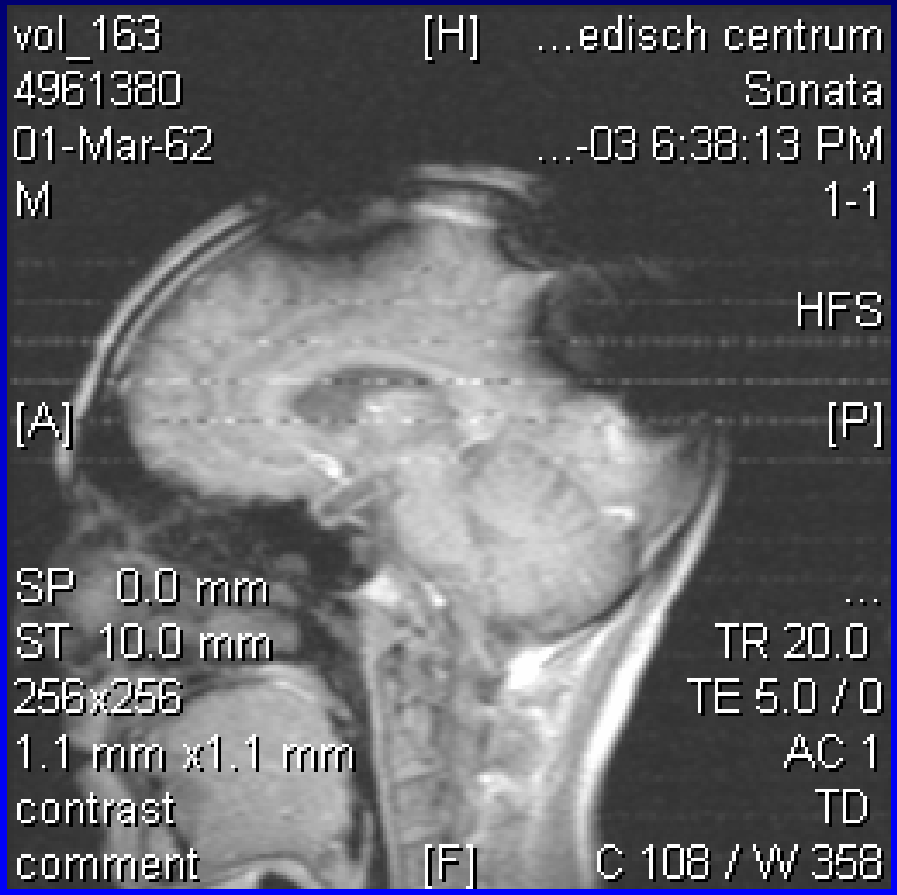
Introduction



One of the challenges of simultaneous EEG/fMRI is to derive this reference function from the EEG.

Methodology

Artifacts on the MR



Degradation of the MR signal by the presence of ferromagnetic materials.

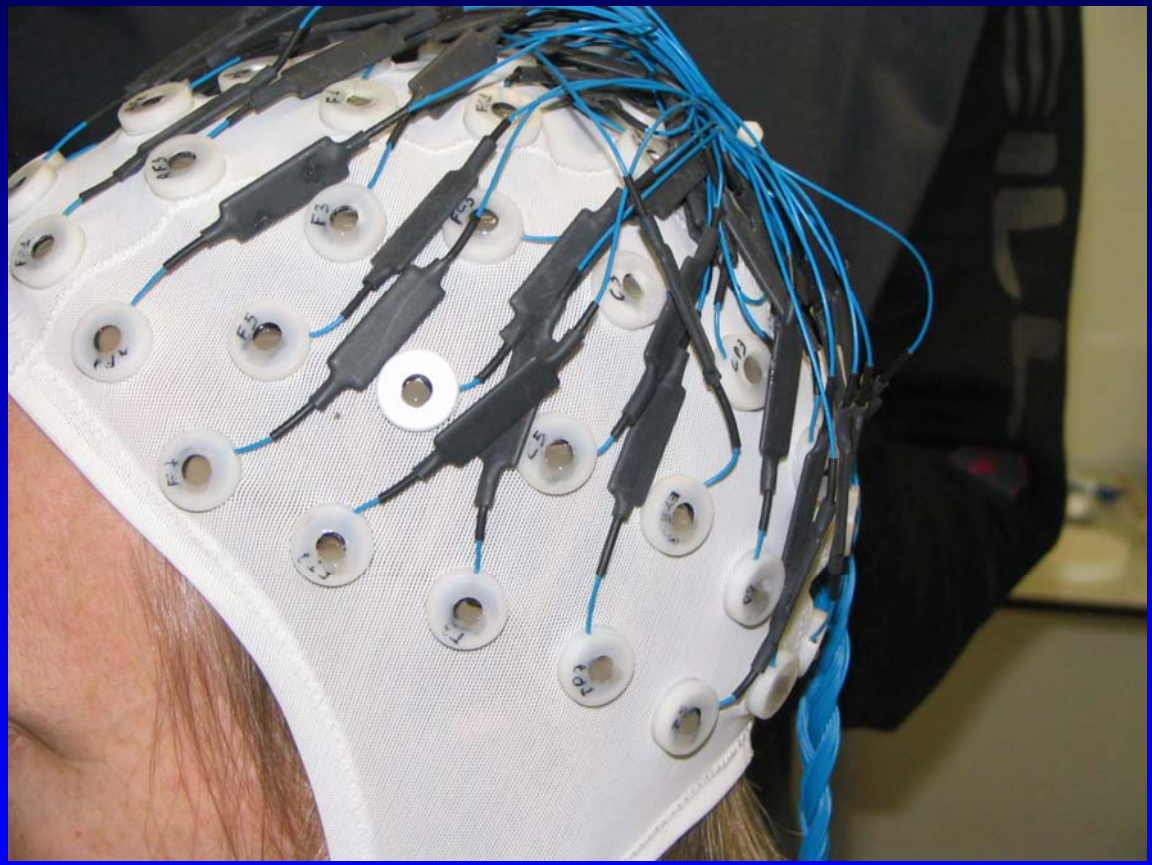
Methodology

Artifacts on the MR

RF contamination of the MR signal by the EEG hardware.

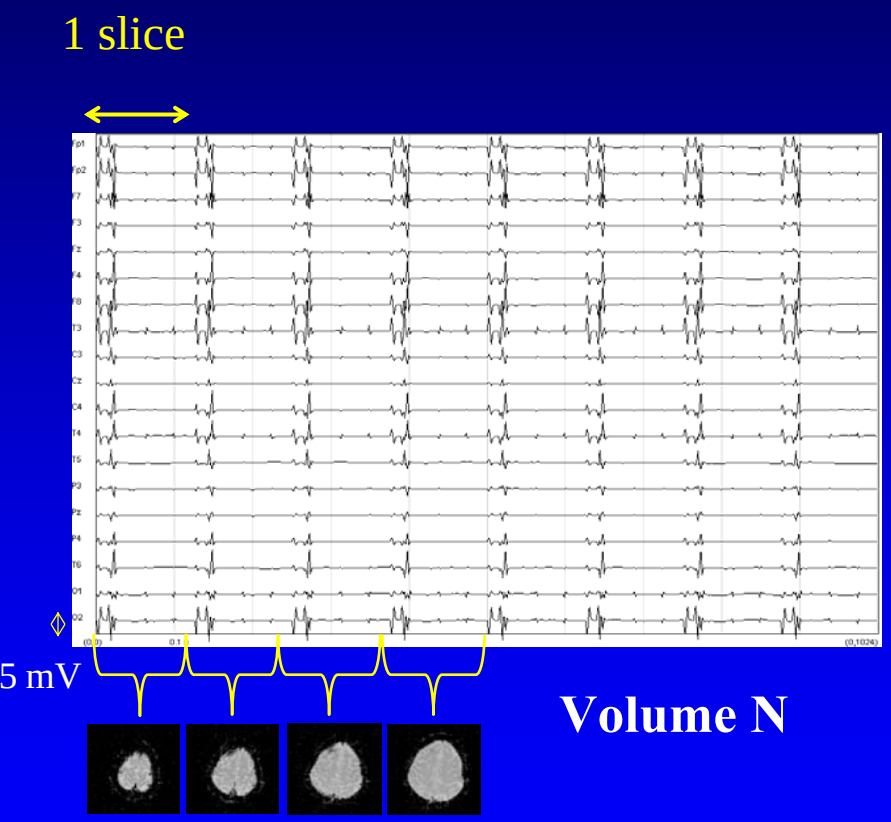
Methodology

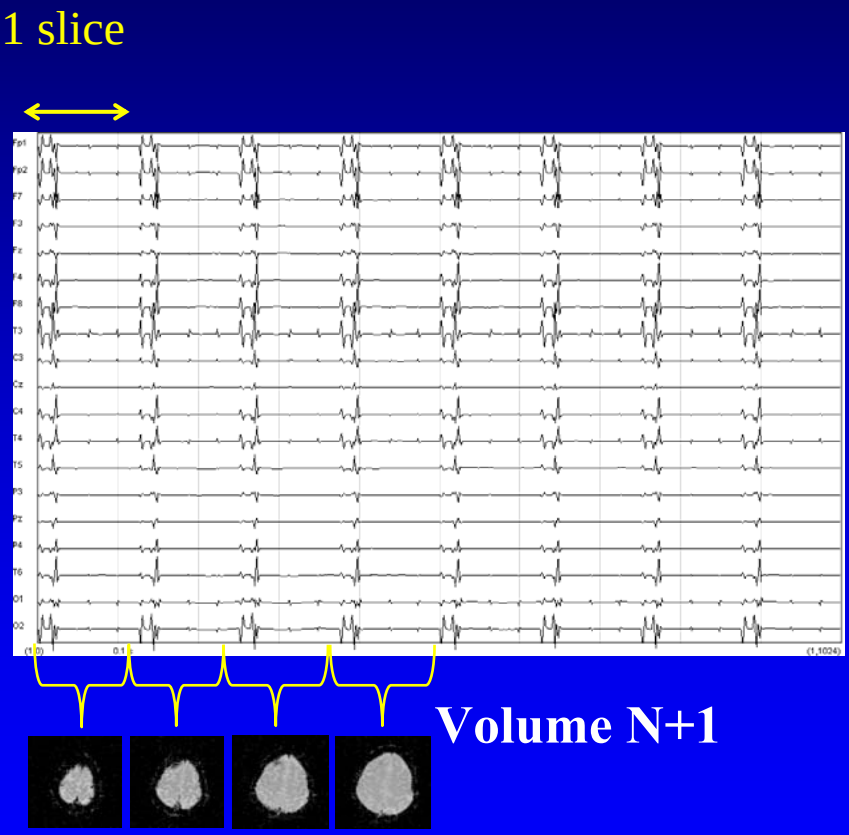
Safety aspects



The EEG equipment should be well chosen, for the safety of the subject.

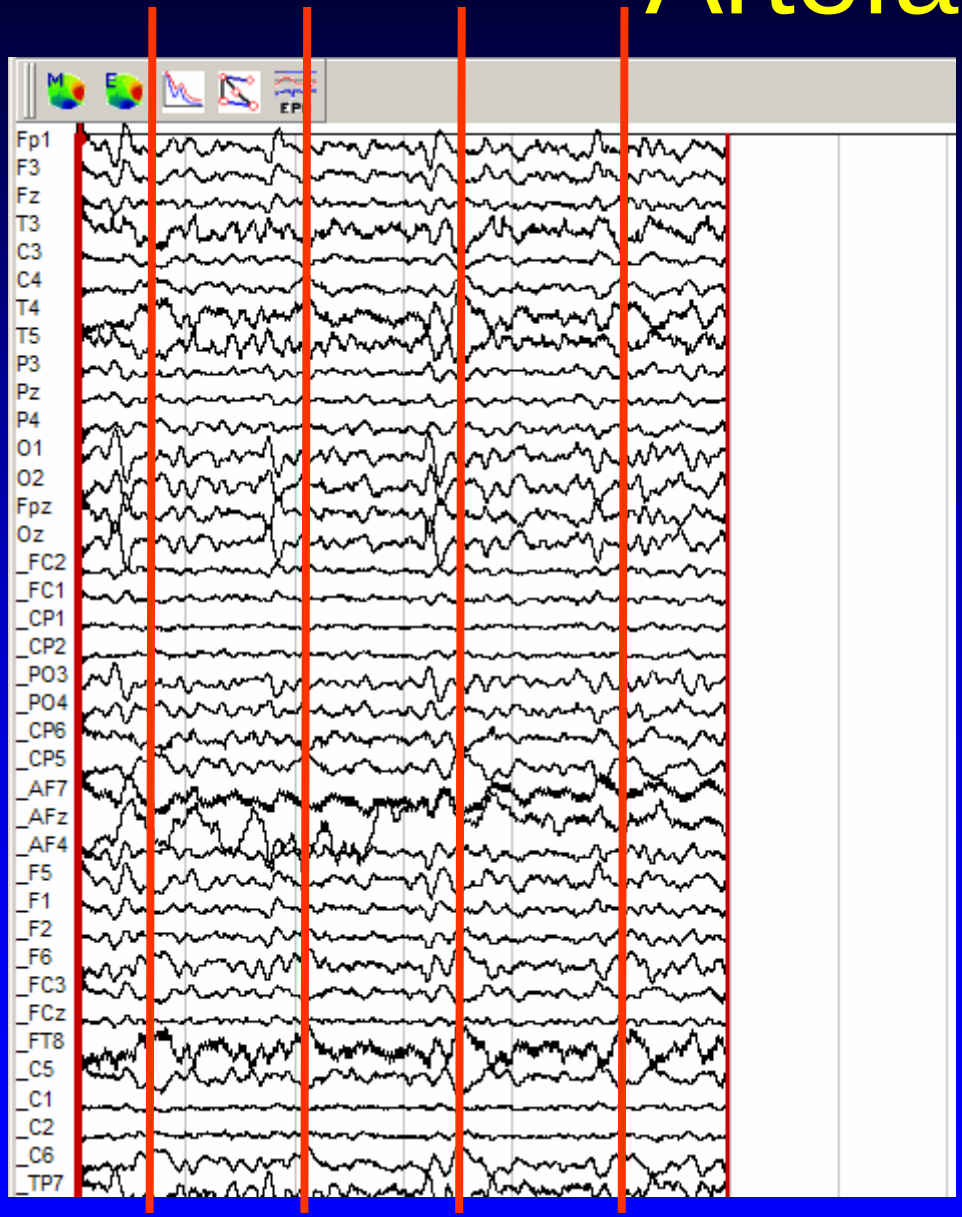
Artefacts in the EEG





The EEG is largely disturbed by the MR scanner, but in a very regular way.

Artefacts in the EEG



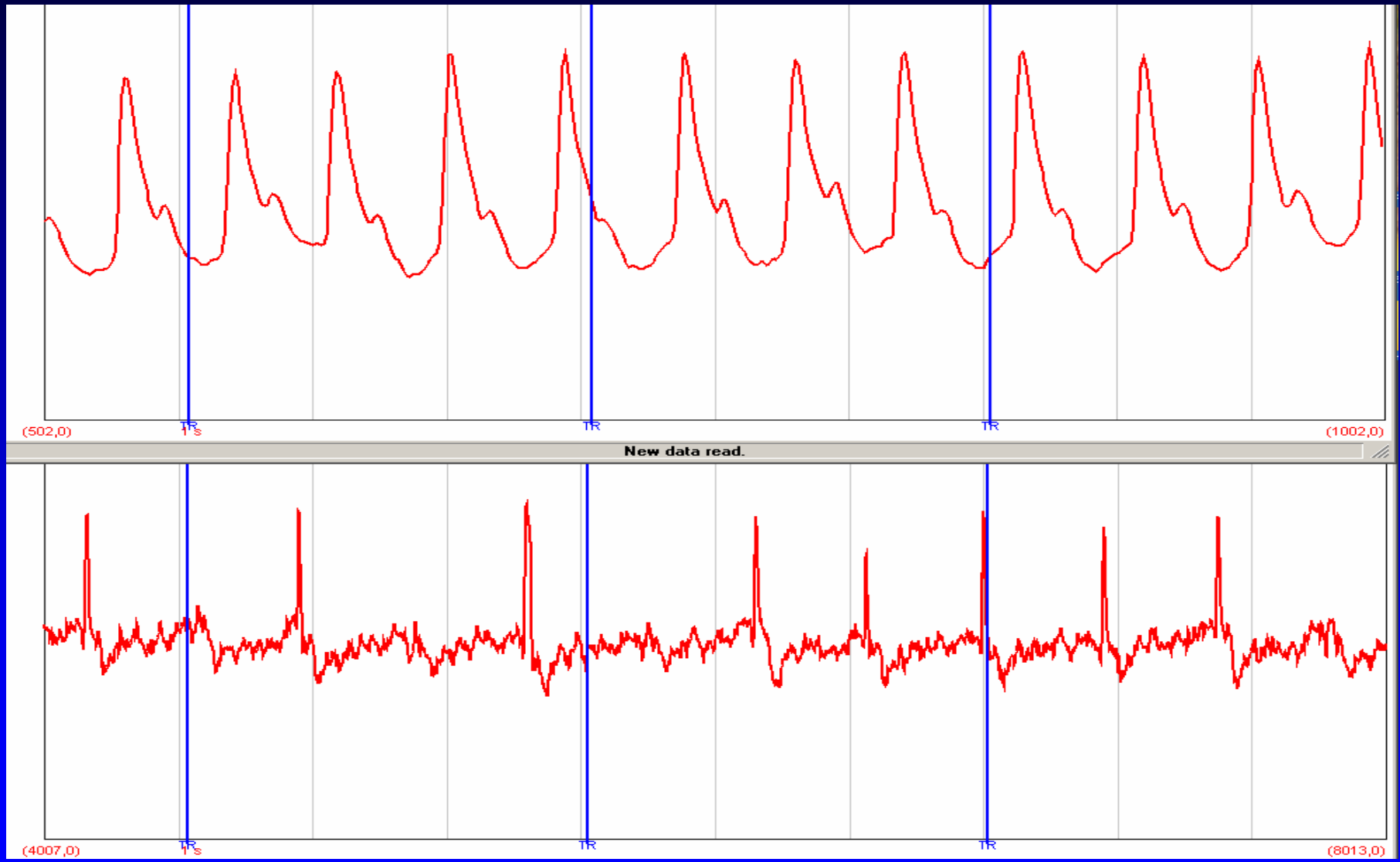
After removing gradient artefacts, the pulse artefacts remain.

Artefacts in the EEG

EKG cable of Sonata

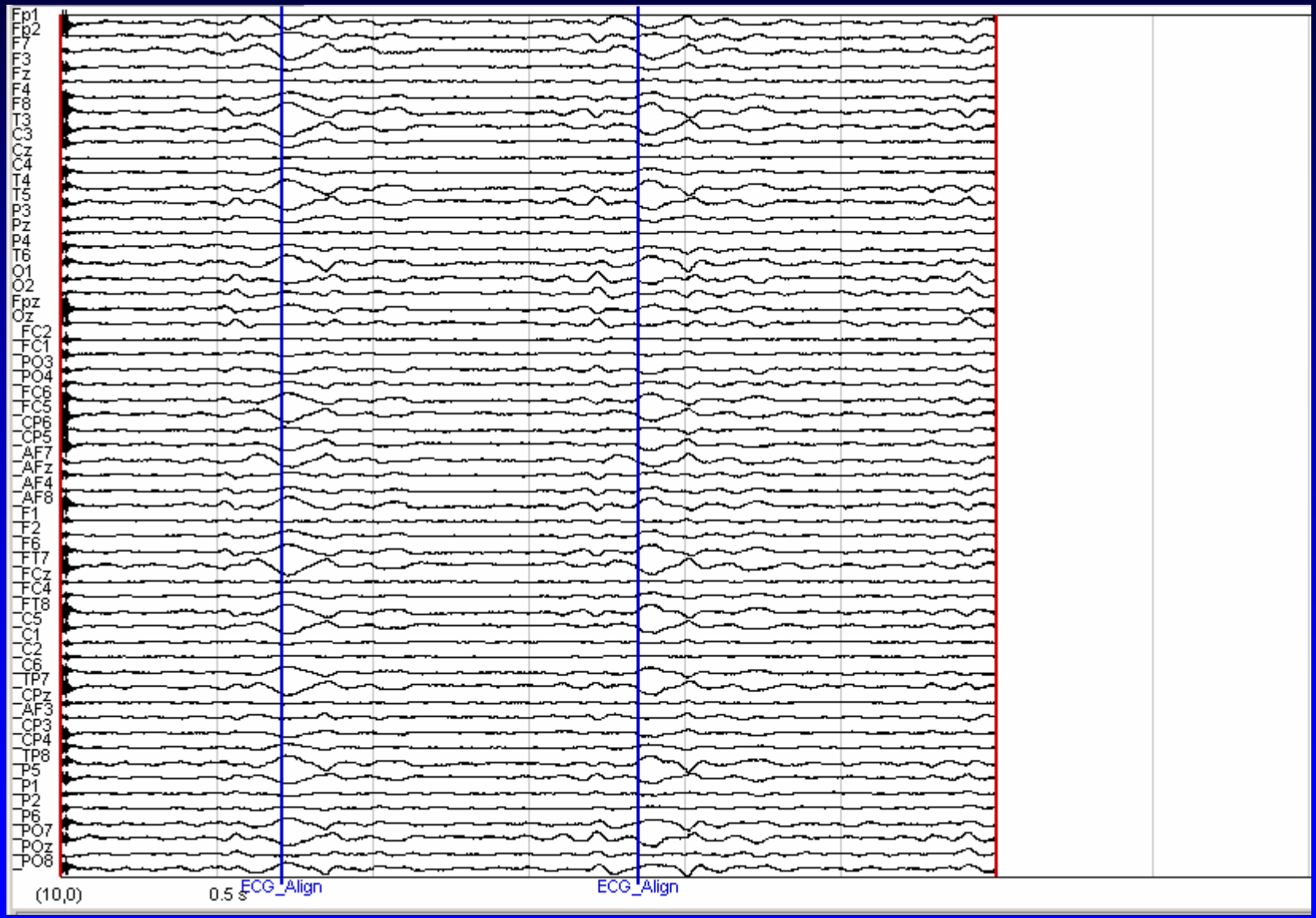
We record ECG and pulse using MR supplied ECG and Pulse system. This avoids gradient artefacts in these signals, and is better for subject/patient safety.

Artefacts in the EEG



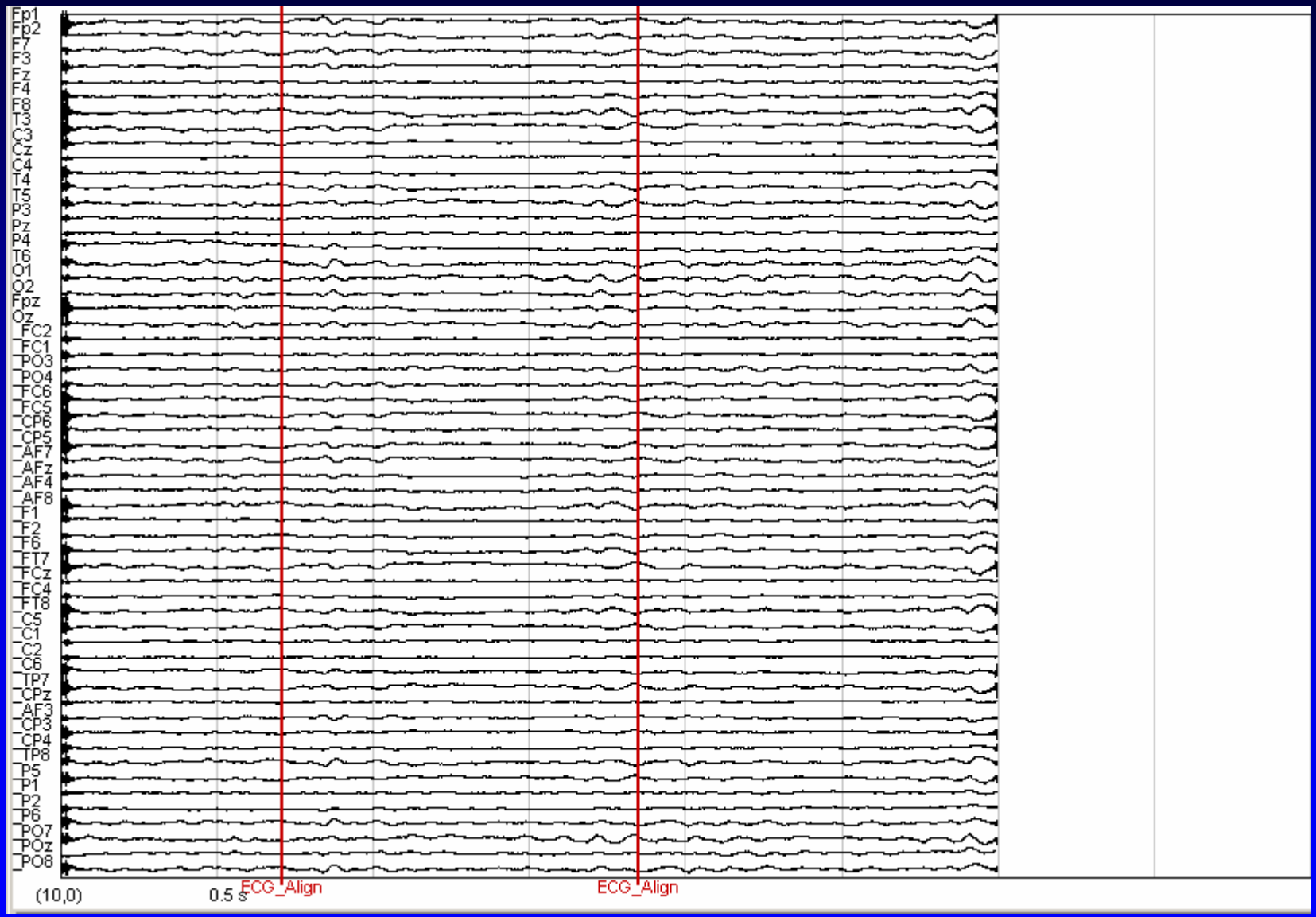
The pulse signal is much more appropriate to record heart beat than the ECG.

Artefacts in the EEG



Heart beat artefacts can also be removed by an averaging procedure.

Artefacts in the EEG



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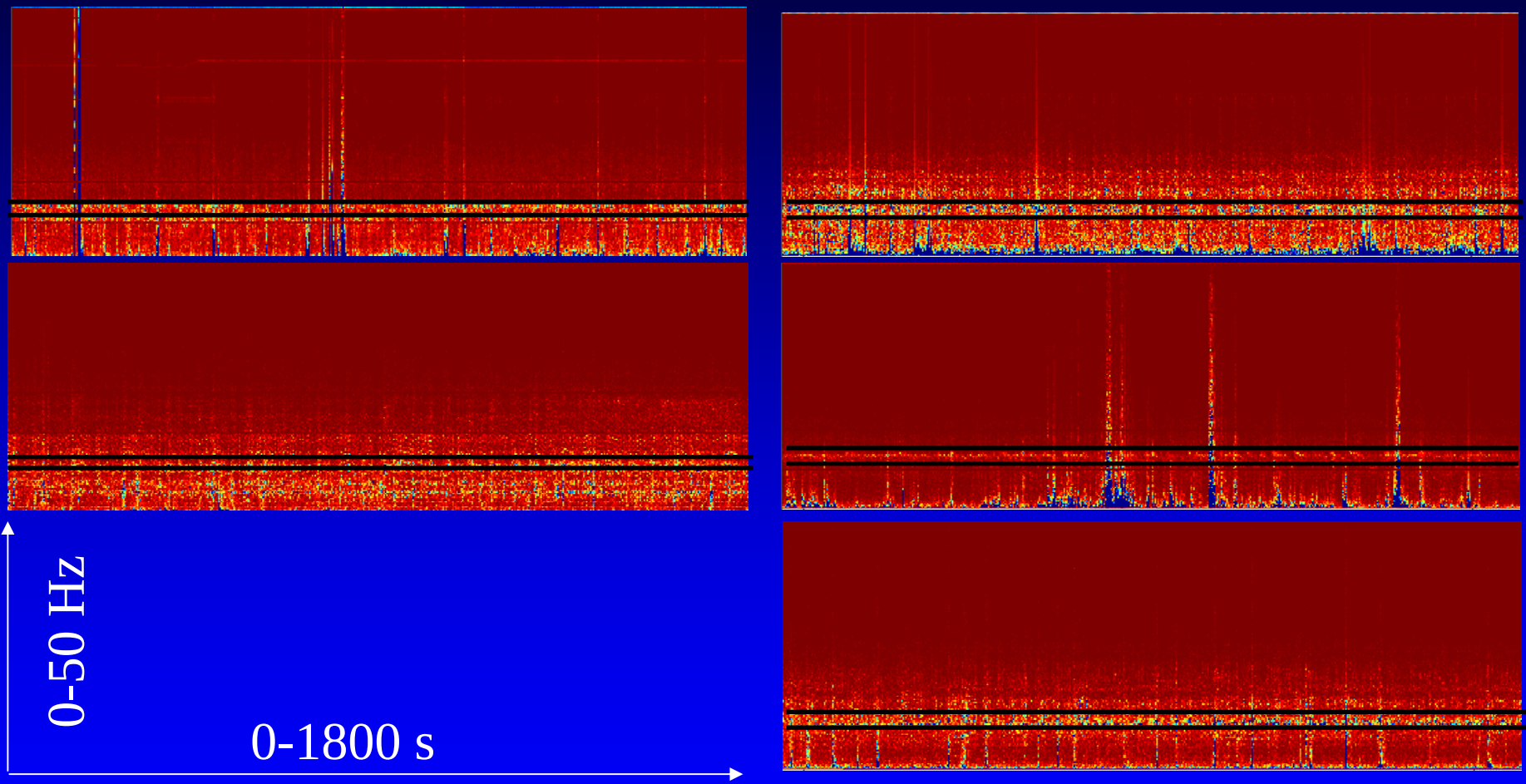


Spectrograms of five subjects, average of occipital channels.
Alpha signal is averaged over a 2 Hz band.

The hemodynamic response

Hemodynamic response function

(Averaged) alpha band profile

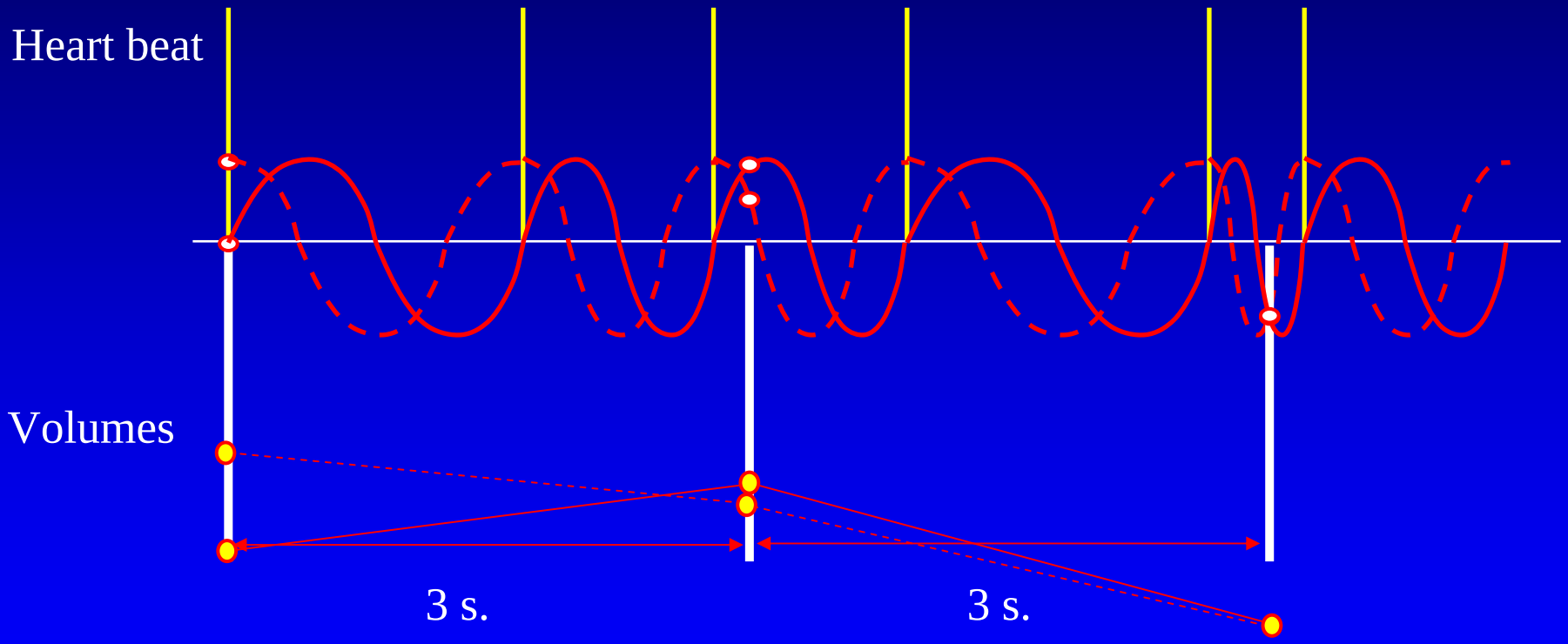
$$\mathrm{BOLD}_n = \sum_{m=0}^{M-1} h_m EEG_{n-m} + \sum_{l=0}^{L-1} \varphi_l DIST_{l,n} + \eta_n$$

Negative?

Confounders:
Motion, heart beat, trends

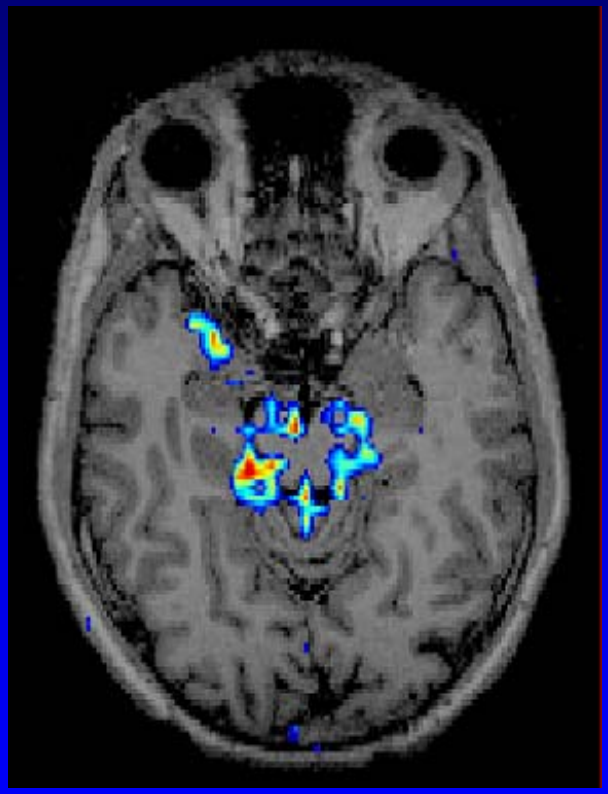
Gaussian noise

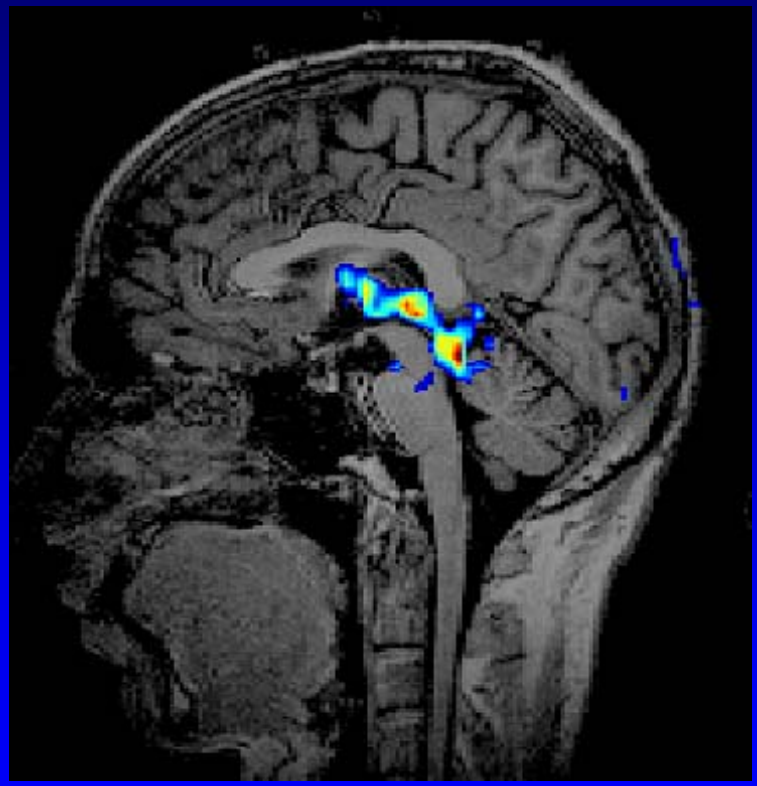
The heart beat artefact in fMRI



There is a correlation between BOLD and the heartbeat signal...

The heart beat artefact in fMRI

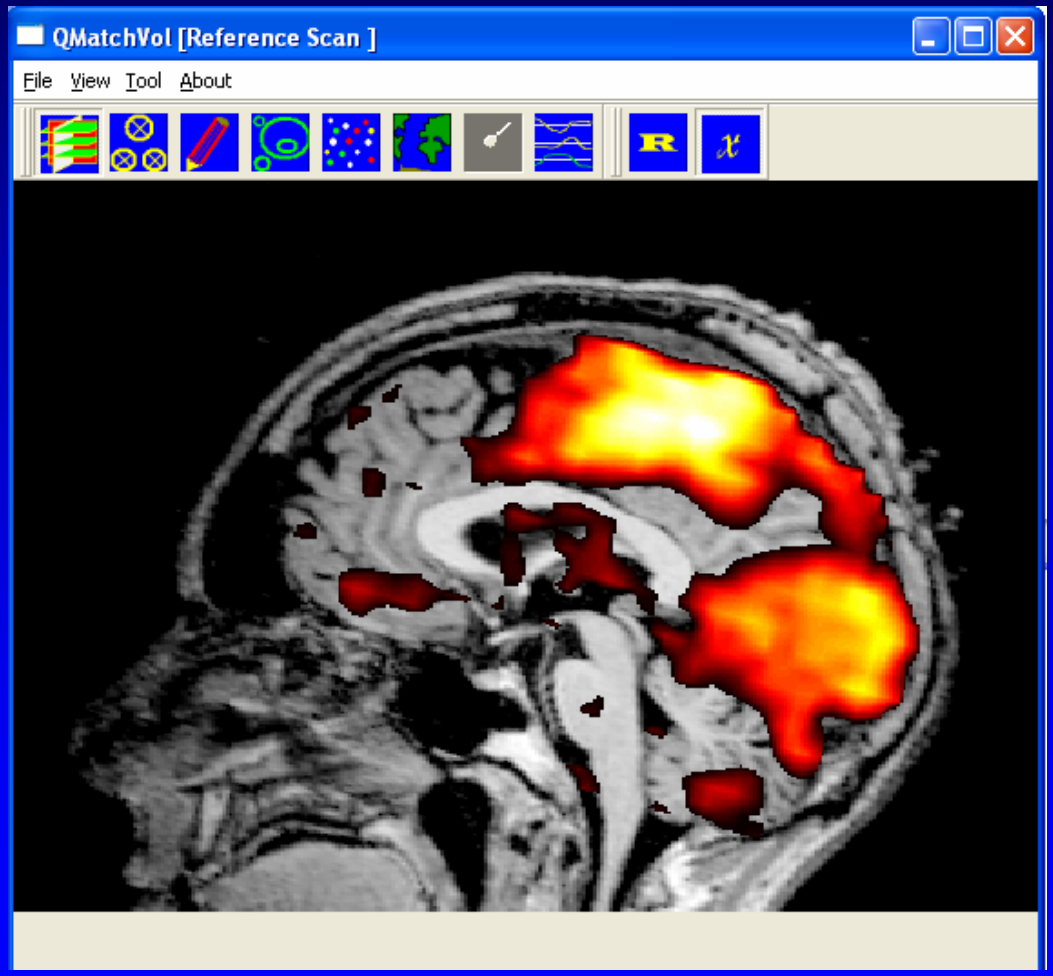




Correlation between heart beat and BOLD

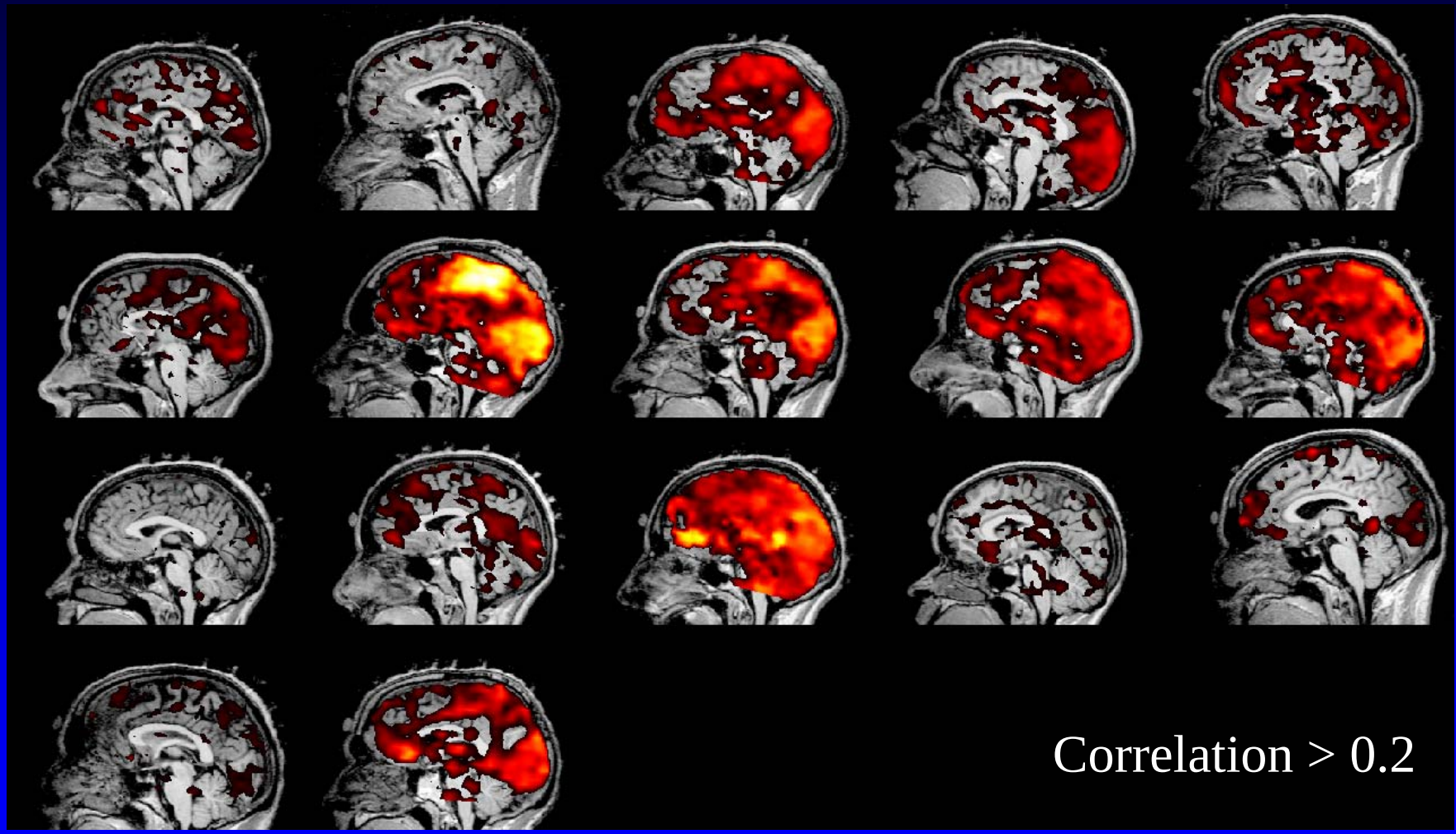
There are many fMRI points that correlate well with the heart beats. Therefore the heart beat should be accounted for in the correlation analysis.

The generators of the alpha band



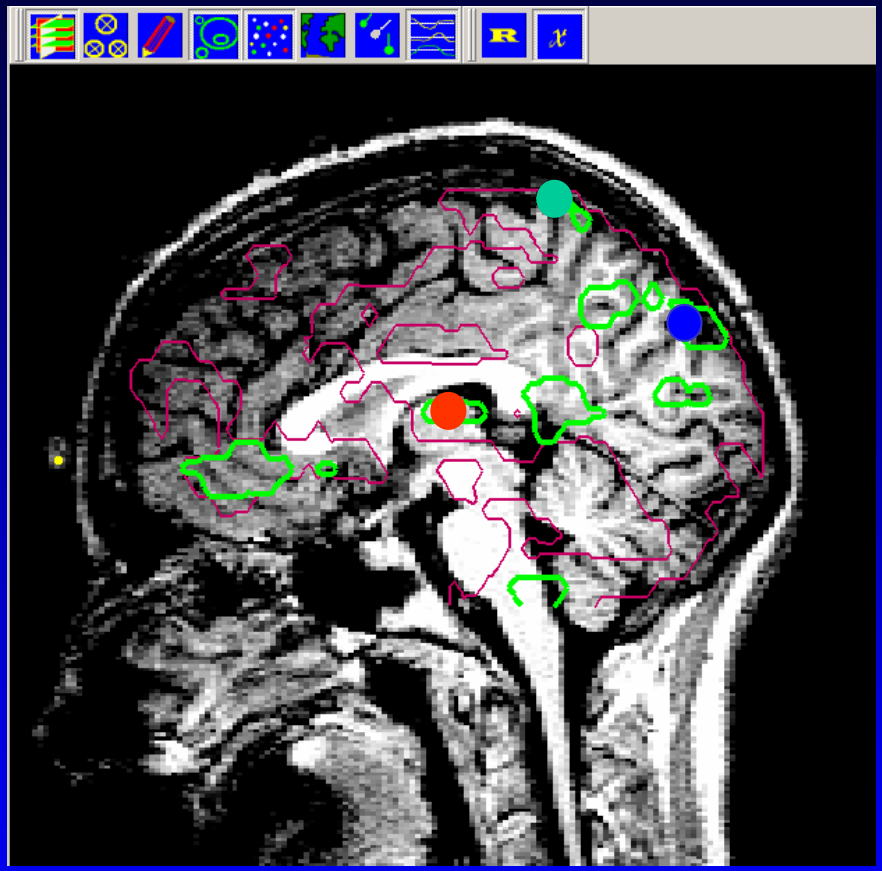
Correlation > 0.3

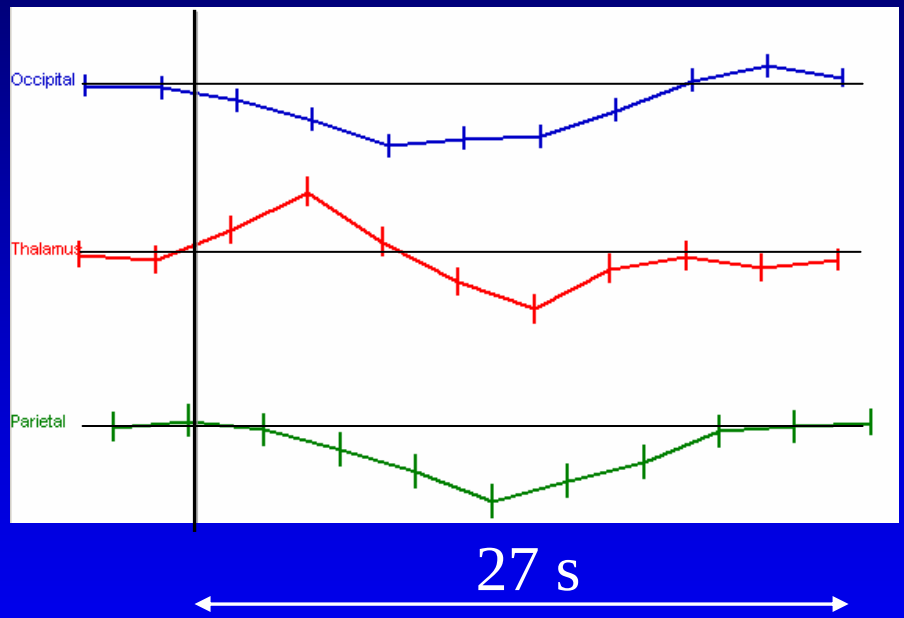
The generators of the alpha band



There is a large inter-subject variability regarding the amount of alpha-BOLD correlation.

The hemodynamic response





Correlation>0.38 FDR < 10^{-12}

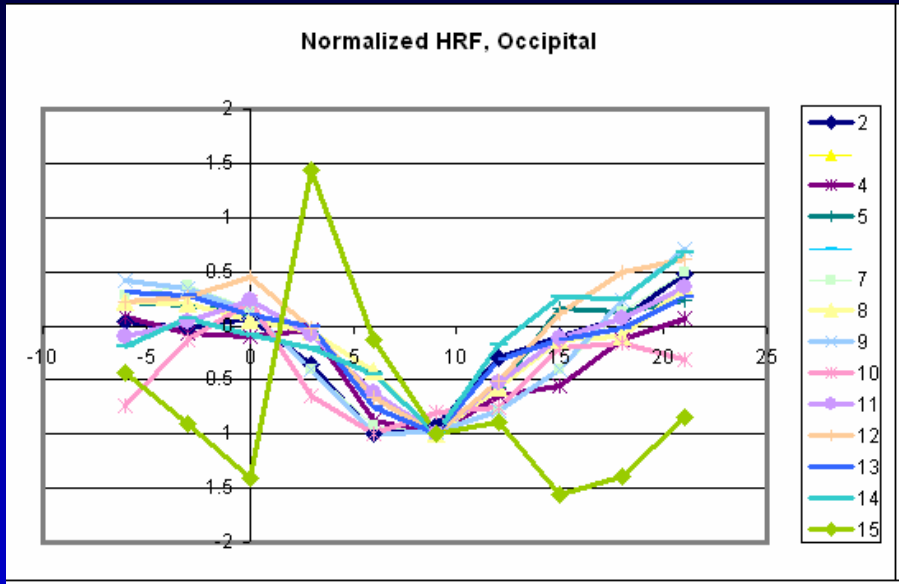
Correlation>0.5 FDR << 10^{-12}

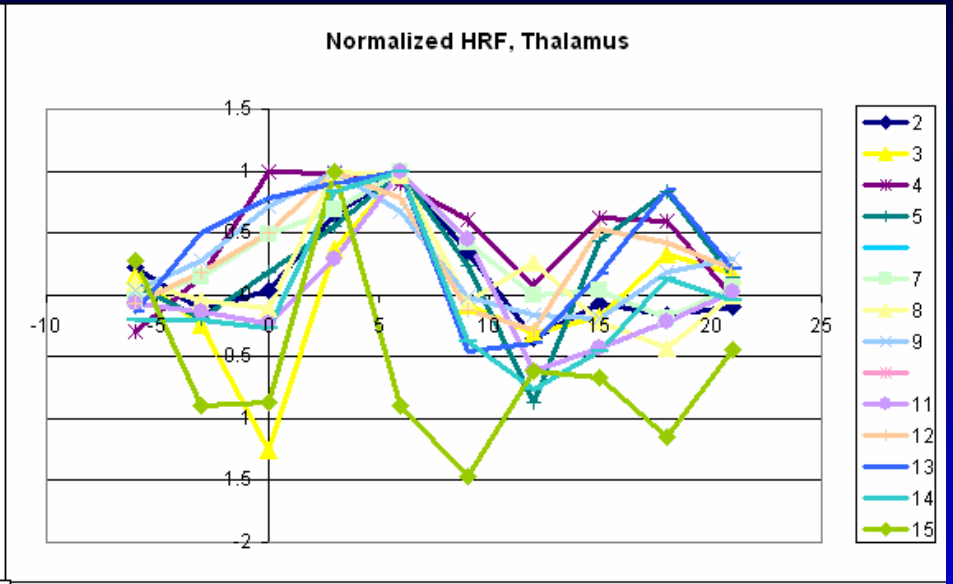
The hemodynamic response to the alpha rhythm varies over brain area.

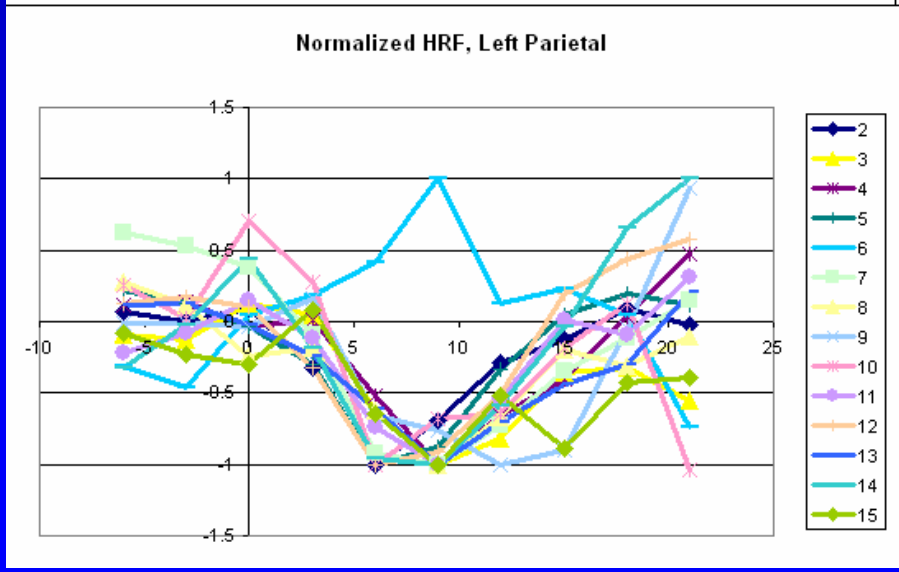
Significant areas at FDR=0.01

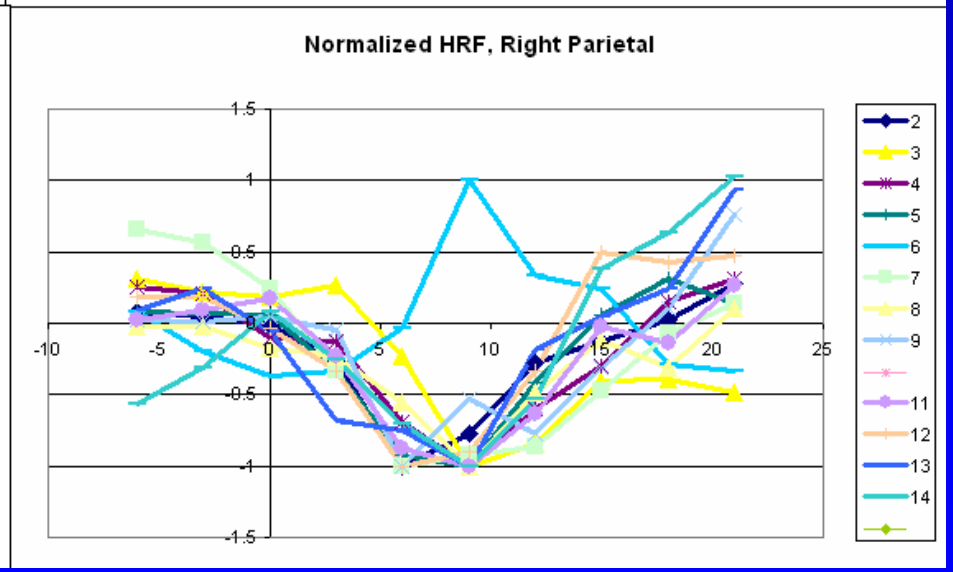
Subject	*Alpha Power*	*Occi*	*Thal*	*Lpar*	*Rpar*	*Eye ball*	*Back of eye*	*BOLD prior to EEG*
1	1,90	N	N	N	N	+	0	No
2	10,25	Y	Y	Y	Y	+	-	No
3	2,38	N	Y	Y	Y	+	-	No
4	4,53	Y	Y	Y	Y	+	0	No
5	30,80	Y	Y	Y	Y	+	-	Eyes, L+R Lat. Part CS
6	2,42	N	N	Y	Y	0	0	No
7	1,69	Y	Y	Y	Y	+	-	R eye, areas in visual cortex
8	30,38	Y	Y	Y	Y	0	-	No
9	5,20	Y	Y	Y	Y	+	-	Eyes
10	10,04	Y	N	Y	N	0	-	No
11	20,53	Y	Y	Y	Y	+	-	No
12	5,80	Y	Y	Y	Y	+	-	No
13	10,47	Y	Y	Y	Y	+	-	No
14	9,35	Y	Y	Y	Y	+	-	No
15	10,13	Y	Y	Y	N	+	-	No
16	30,01	N	N	N	N	+	0	Rlat part CS
	$10^3\ \mu V^2/Hz$	12	12	14	12			

The hemodynamic response









There are subject dependent differences in alpha band HRF.

The hemodynamic response

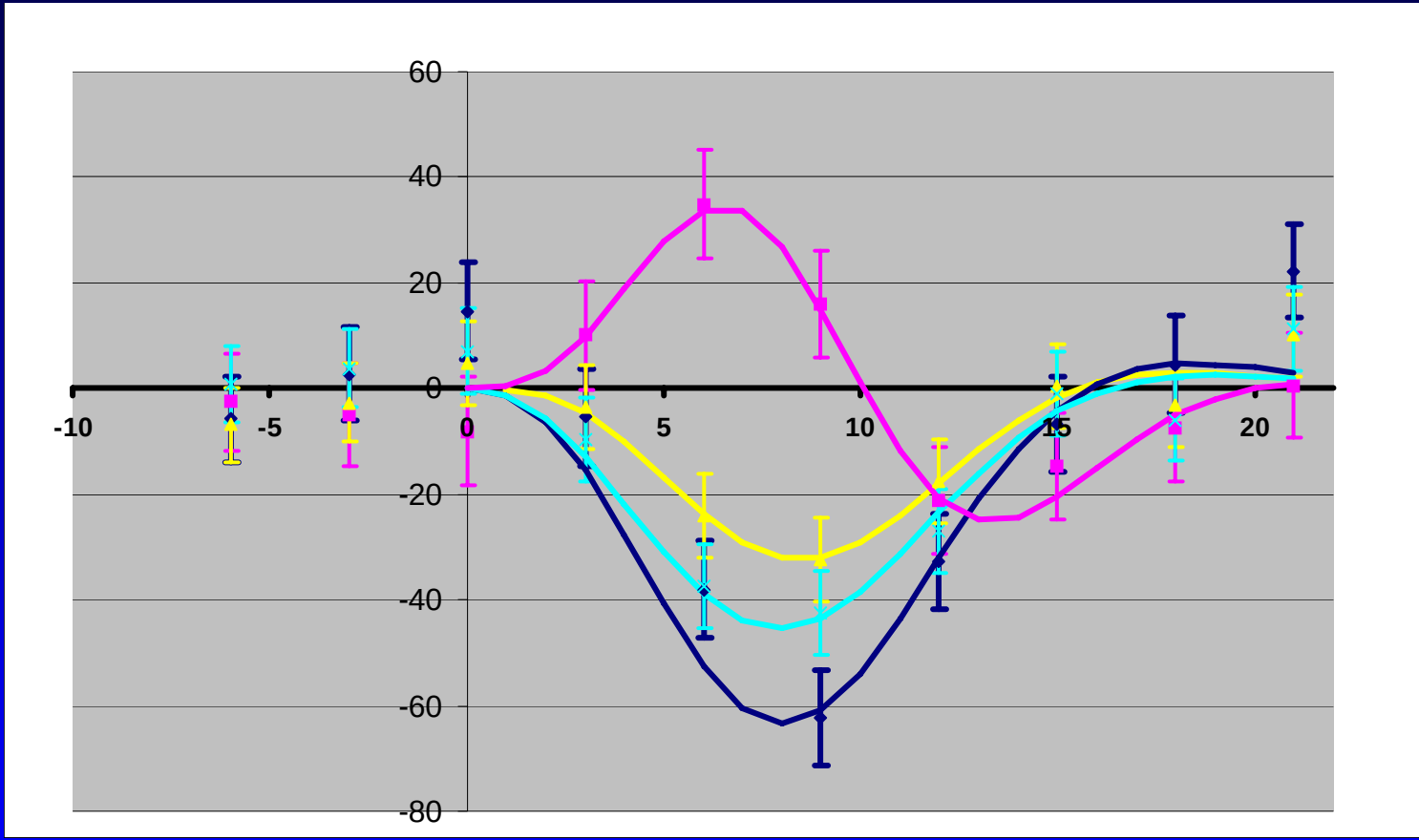
New HRF parameterisation:

$$h(t_n) = \begin{cases} t < 0: & 0 \\ t > 0: & p_1\, t^2\, \mathrm{e}^{-p_2 t} \sin\, p_3 (t - p_4) \end{cases}$$

Envelop function

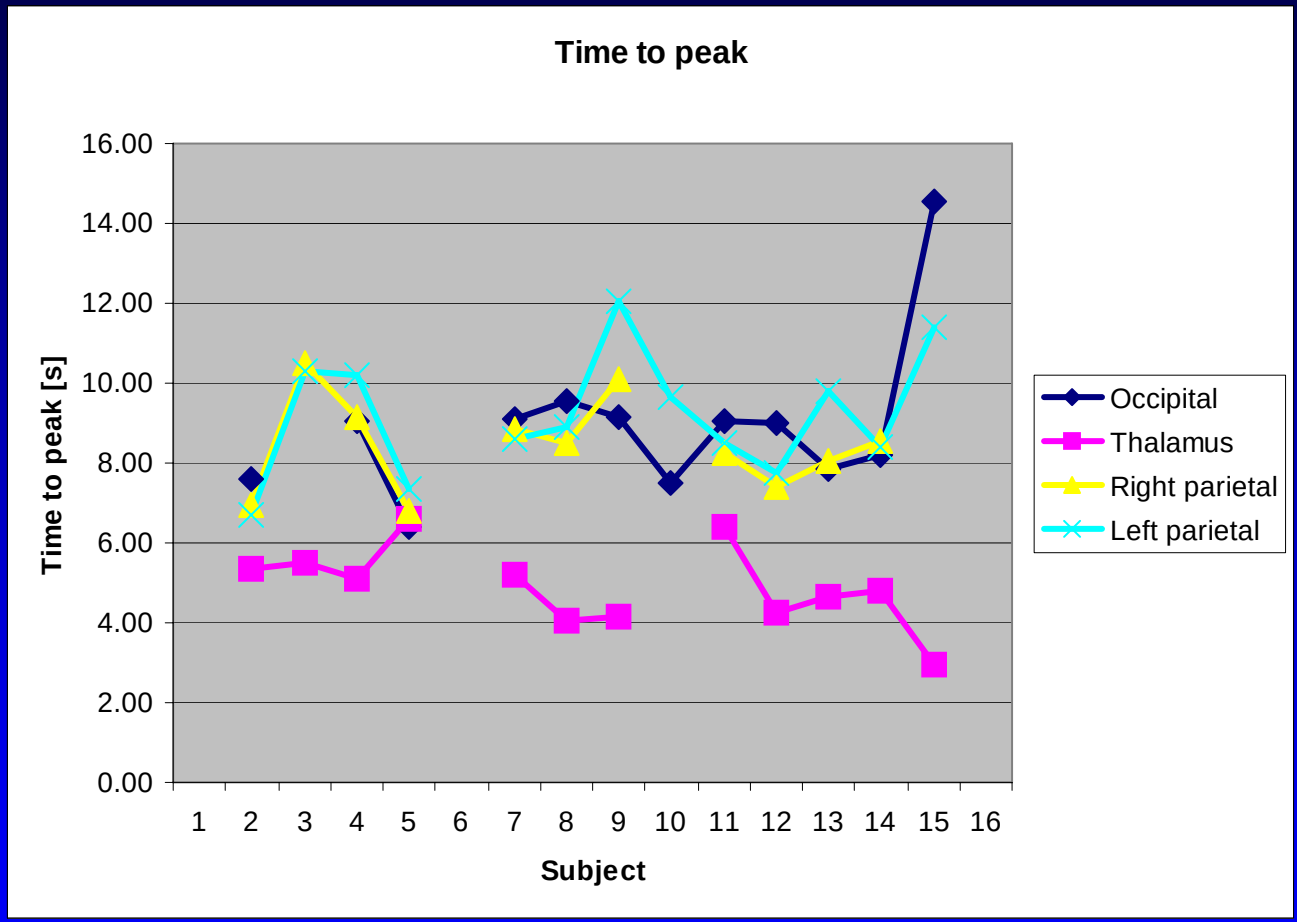
Sine “wave”

The hemodynamic response



Residual fit errors are typically 10 %. Here it is about 3 %.

The hemodynamic response



The thalamus always peaks earlier than the occipital and parietal cortex.

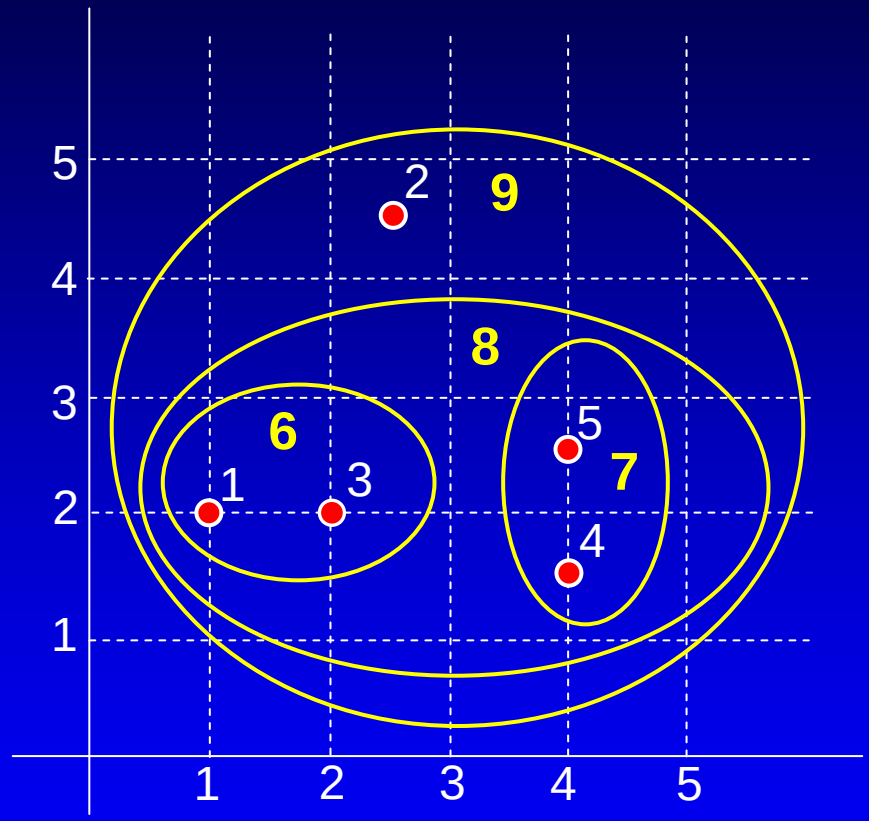
The hemodynamic response

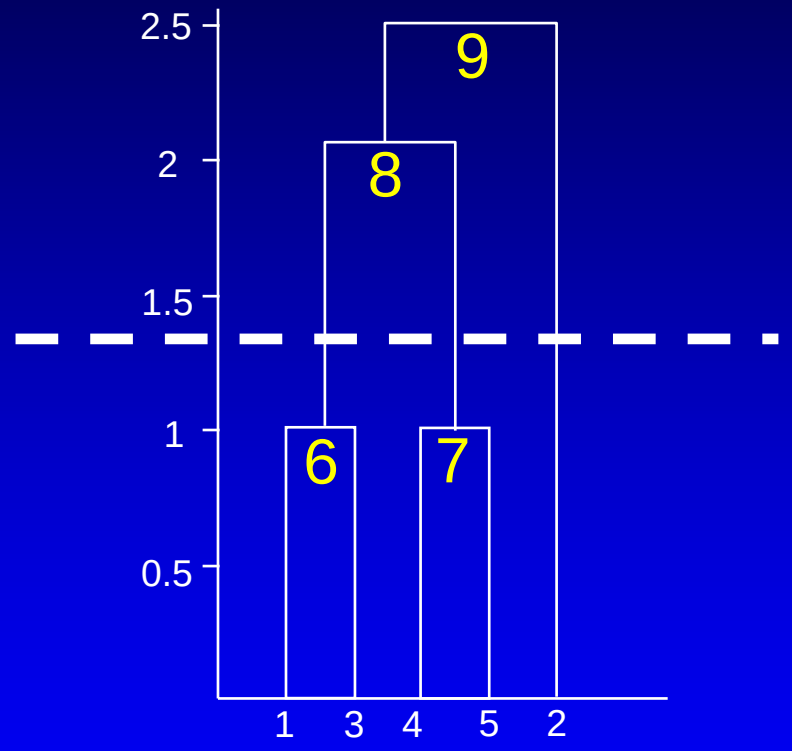
How can 10.000 HRF within one subject be visualized?

Apply hierarchic clustering.

The hemodynamic response

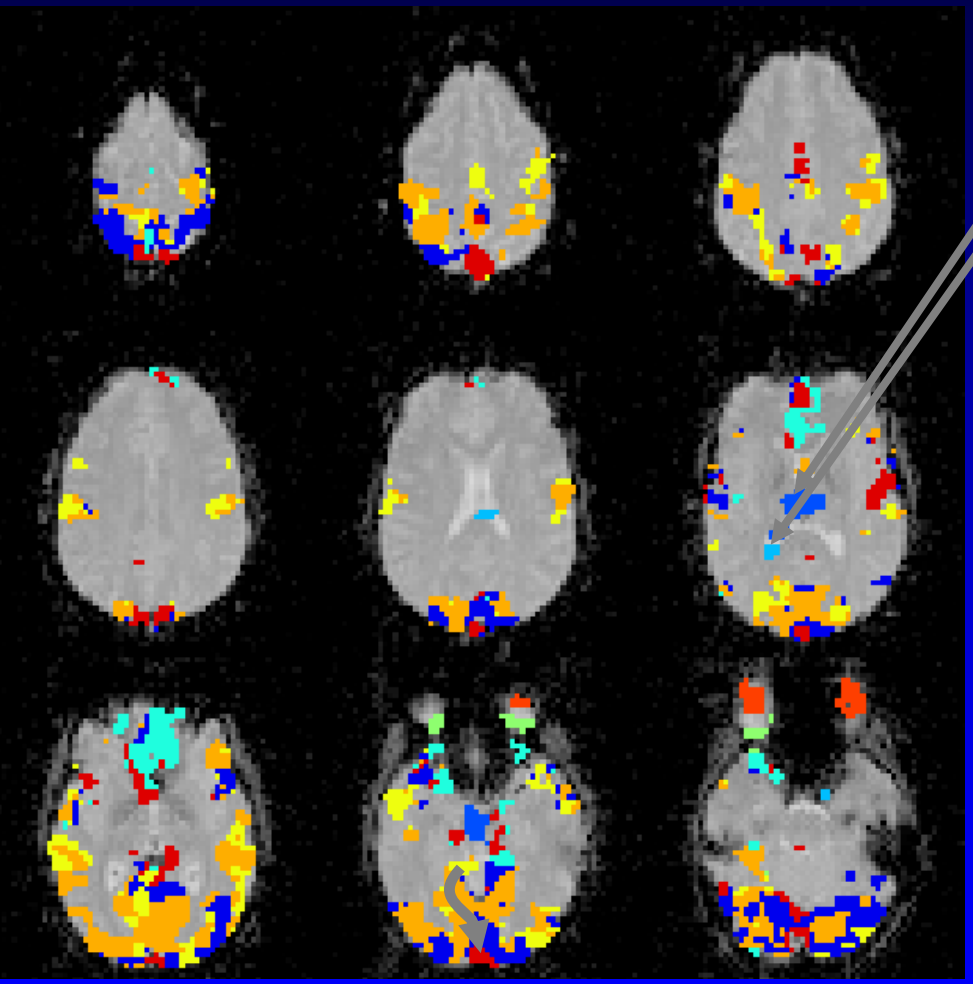
construct dendrogram

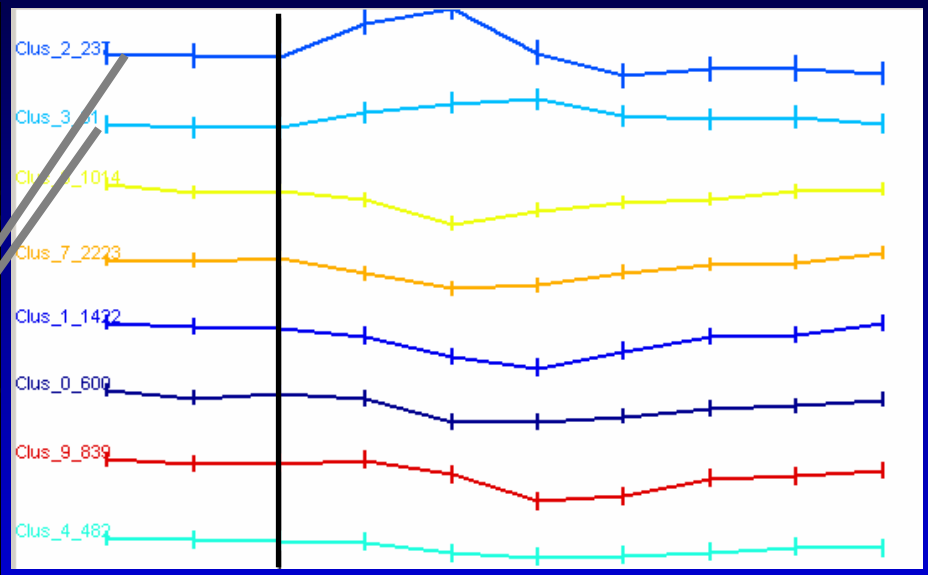


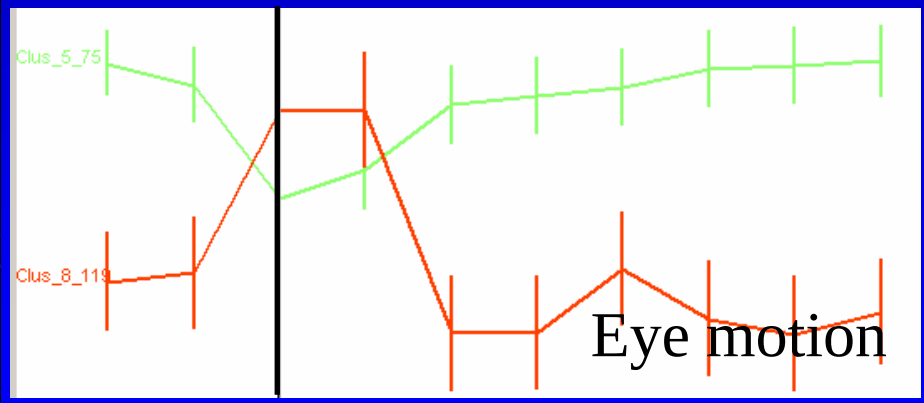


Compute “distances” between significant HRF’s at different voxels using the Euclidian distance.

Clustering of HRF

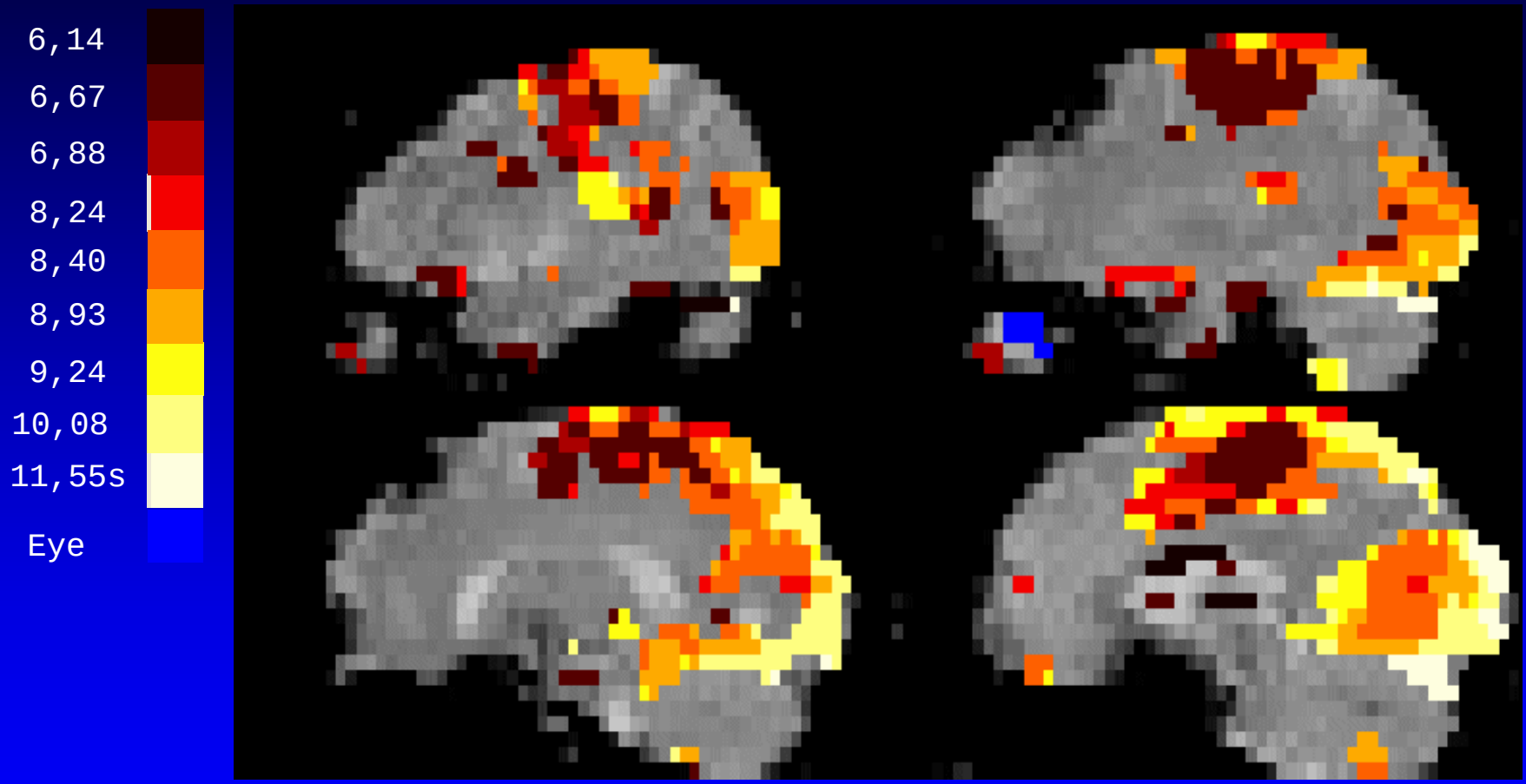






Part of the response of the alpha rhythm appears as a wave phenomenon.

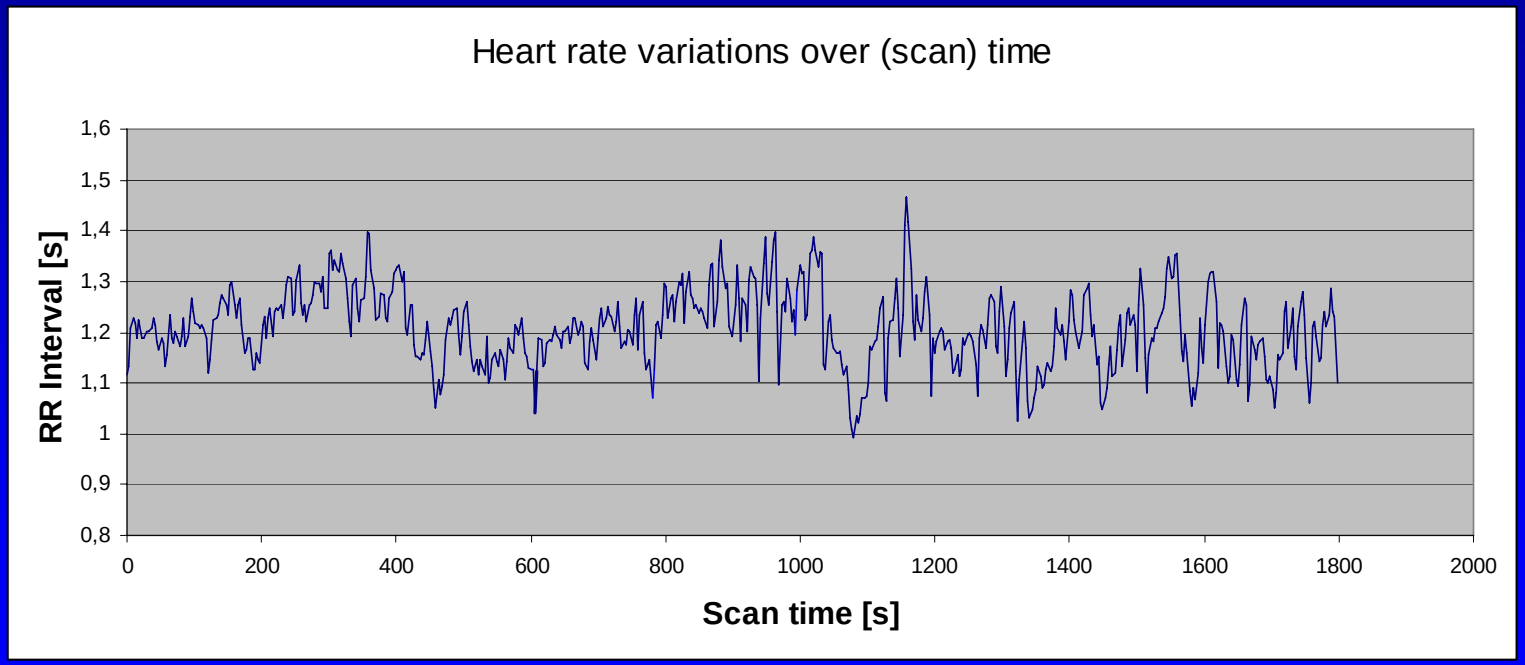
Clustering of HRF



De Munck et al., NeuroImage, 2007

Part of the response of the alpha rhythm appears as a wave phenomenon.

Relation alpha, heart rate and fMRI



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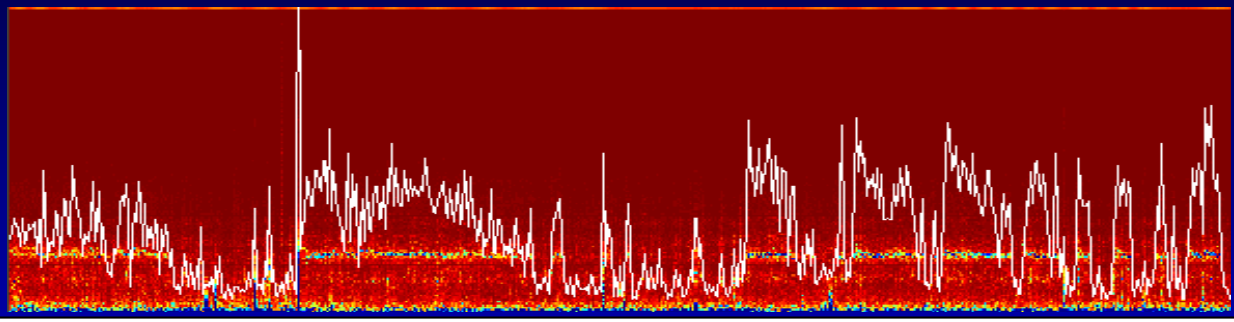

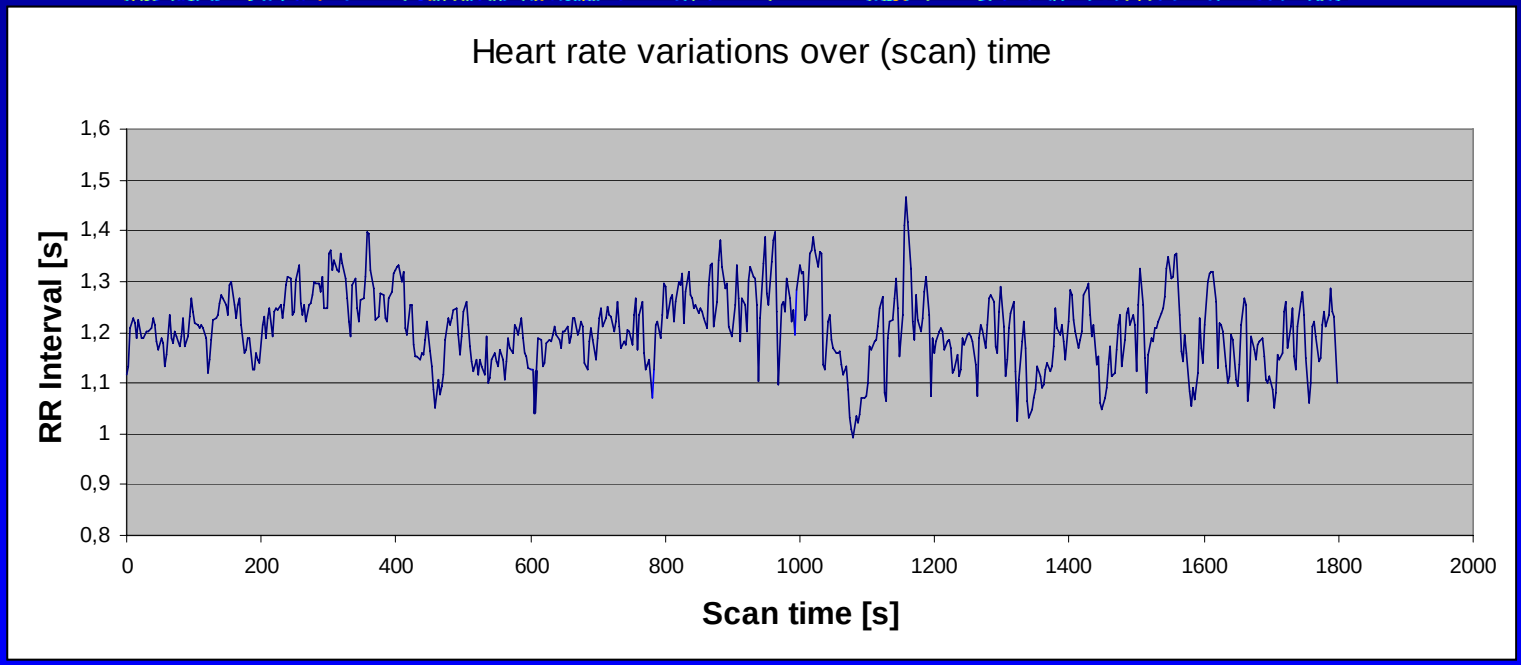

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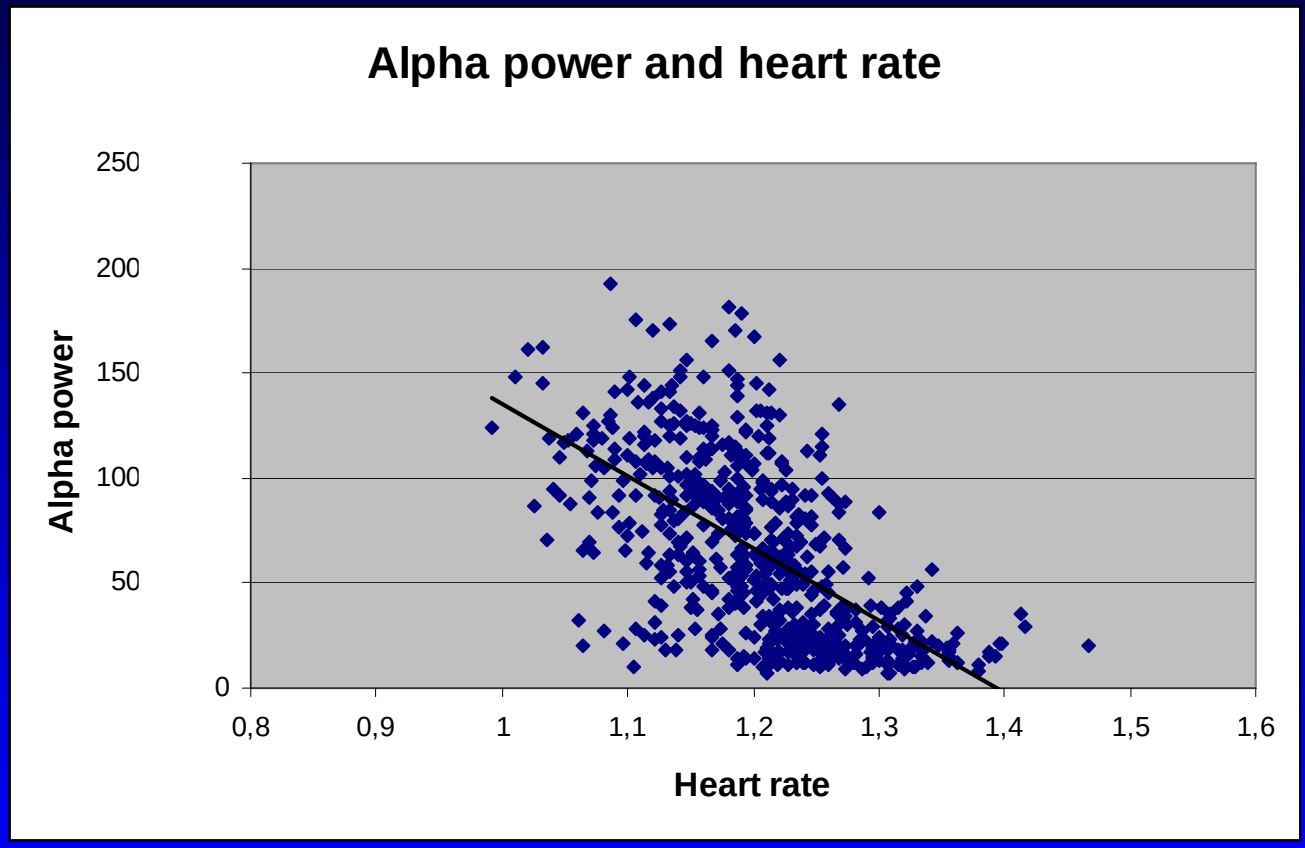
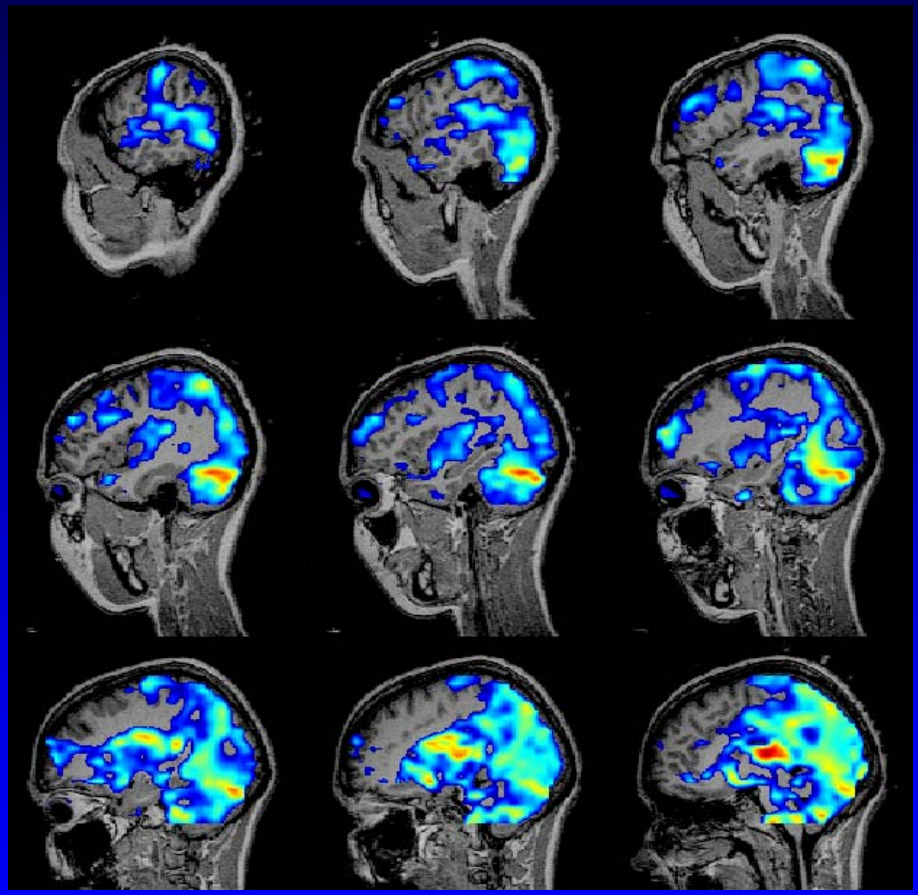
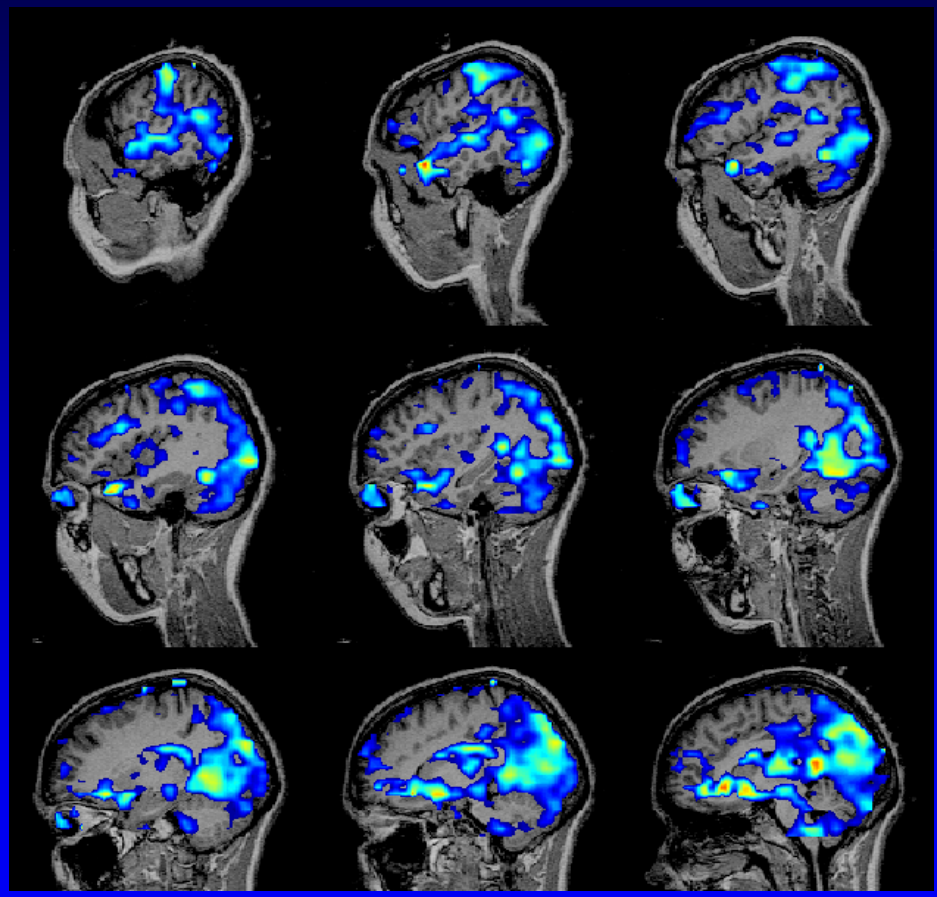


The correlation between heart beat interval and alpha power amounts to -0.6

Relation alpha, heart rate and fMRI



Heart rate, corr >0.4



Alpha power, corr >0.3

Relation alpha, heart rate and fMRI

Subject	Alpha HB	Alpha		HBeat	
		Active points	Variation	Active points	Variation
1	-0.18	0.31	0.81	0.09	0.040
2	-0.24	0.44	1.17	0.10	0.024
3	-0.18	0.08	0.46	0.48	0.056
4	-0.10	0.35	0.72	0.03	0.273
5	-0.39	0.74	0.85	0.43	0.059
6	0.01	0.04	0.54	0.30	0.036
7	-0.30	0.49	0.50	0.05	0.038
8	-0.19	0.29	0.42	0.35	0.056
9	-0.61	0.86	0.66	0.74	0.062
10	0.04	0.04	0.45	0.23	0.054
11	-0.22	0.68	0.48	0.87	0.117
12	-0.50	0.47	0.63	0.54	0.070
13	-0.36	0.64	0.59	0.81	0.064
14	-0.22	0.21	0.37	0.51	0.058
15	-0.02	0.04	0.52	0.23	0.095
16	-0.07	0.01	0.29	0.08	0.139
17	0.30	0.01	0.57	0.03	0.032

Data driven analysis

Limitations of model driven approach:

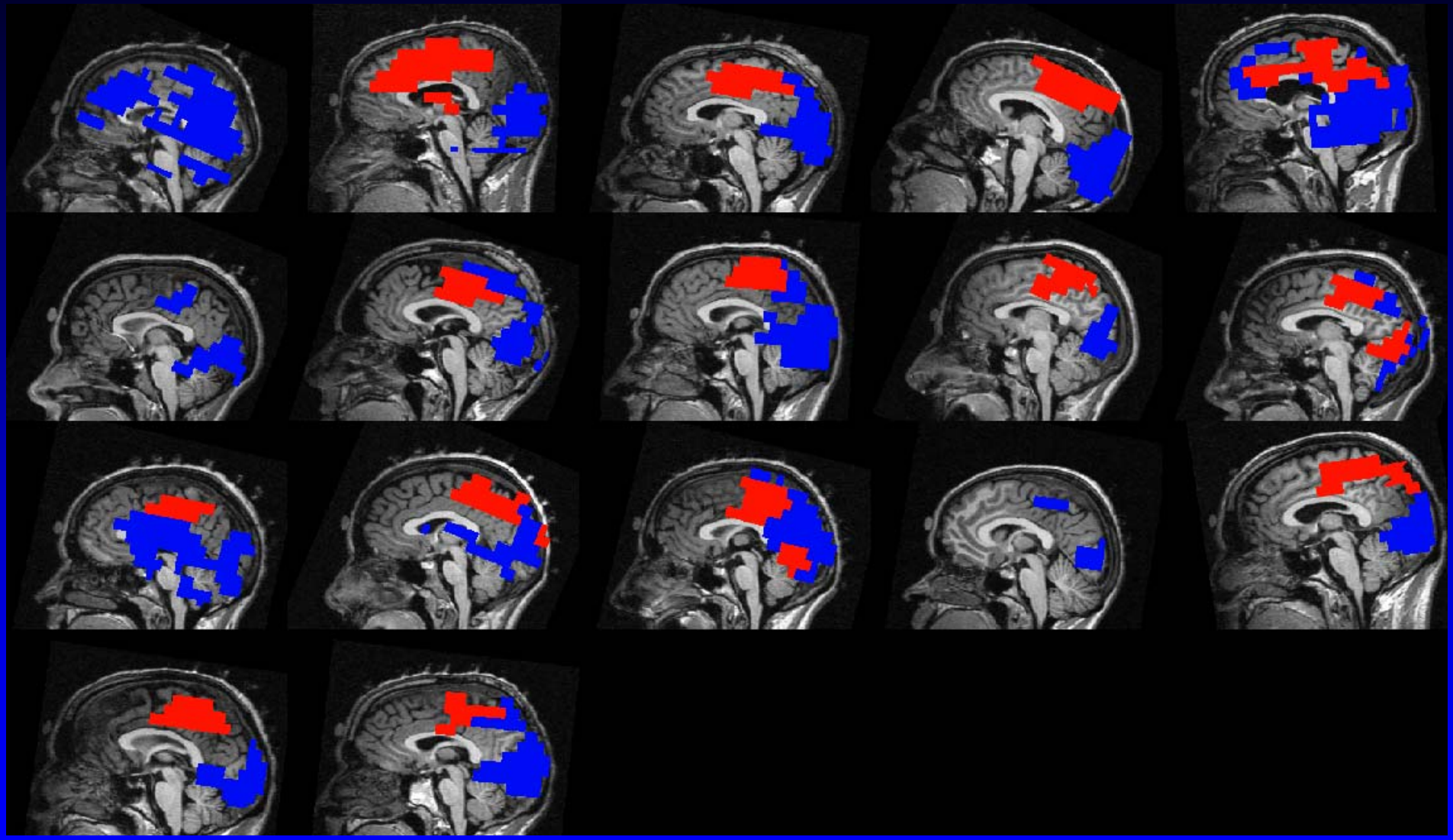
- Methods
  - All alpha frequencies are averaged
  - No use is made of spatial distribution of alpha frequency maps
- Results
  - Amount of correlation varies greatly over subjects
  - Shape of significant HRF is similar over subjects

Data driven analysis

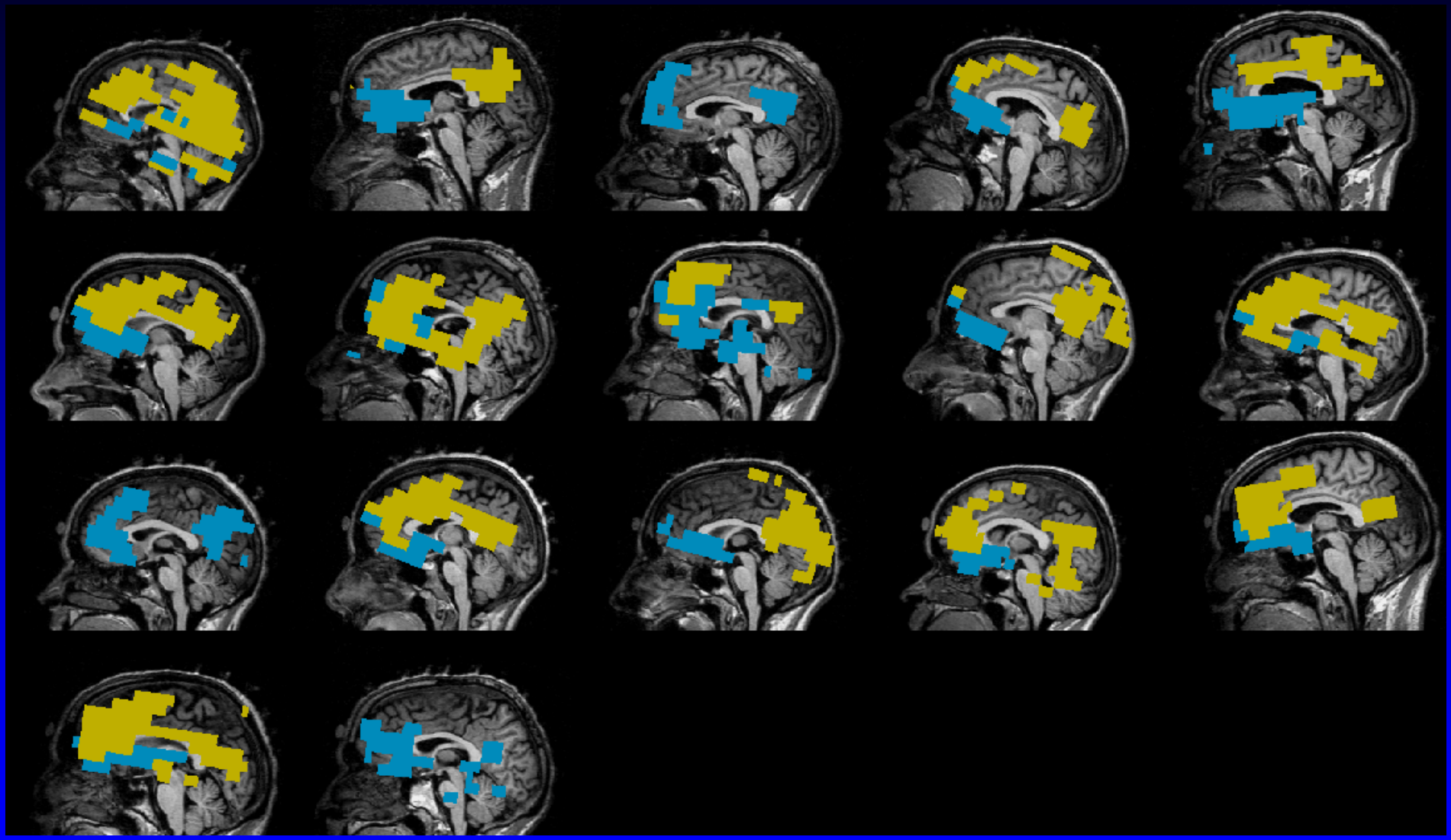
Apply hierarchical clustering on de-confounded fMRI signals.

$$D^2_{n,m} = \left| Ps_n - Ps_m \right|^2$$

Down sample fMRI data before clustering.



In most subjects, there is a clear distinction between occipital and parietal regions. The cluster-averaged fMRI signals all correlate well to the alpha band.



In most subjects, also the default mode network shows up in separate clusters.

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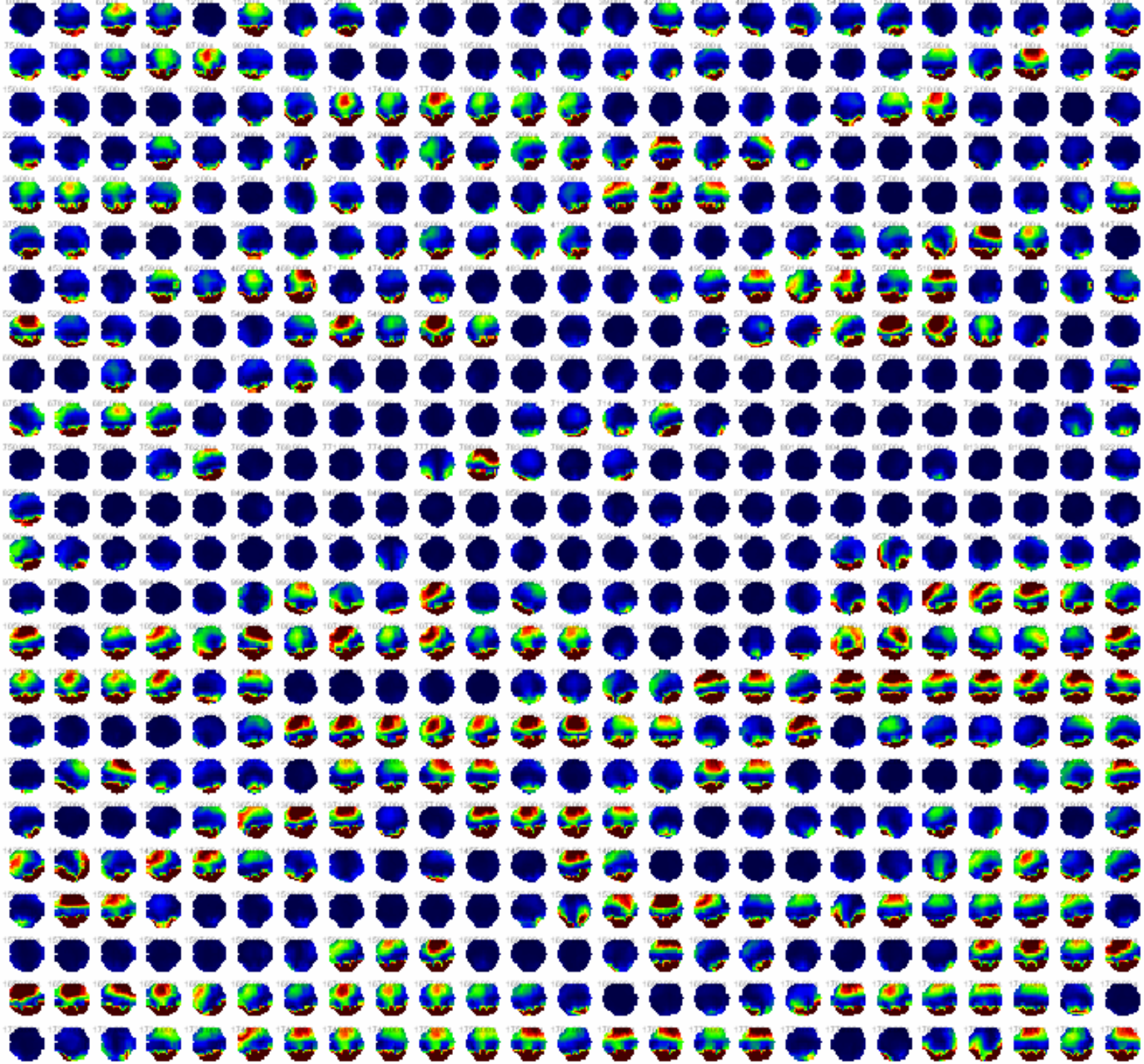
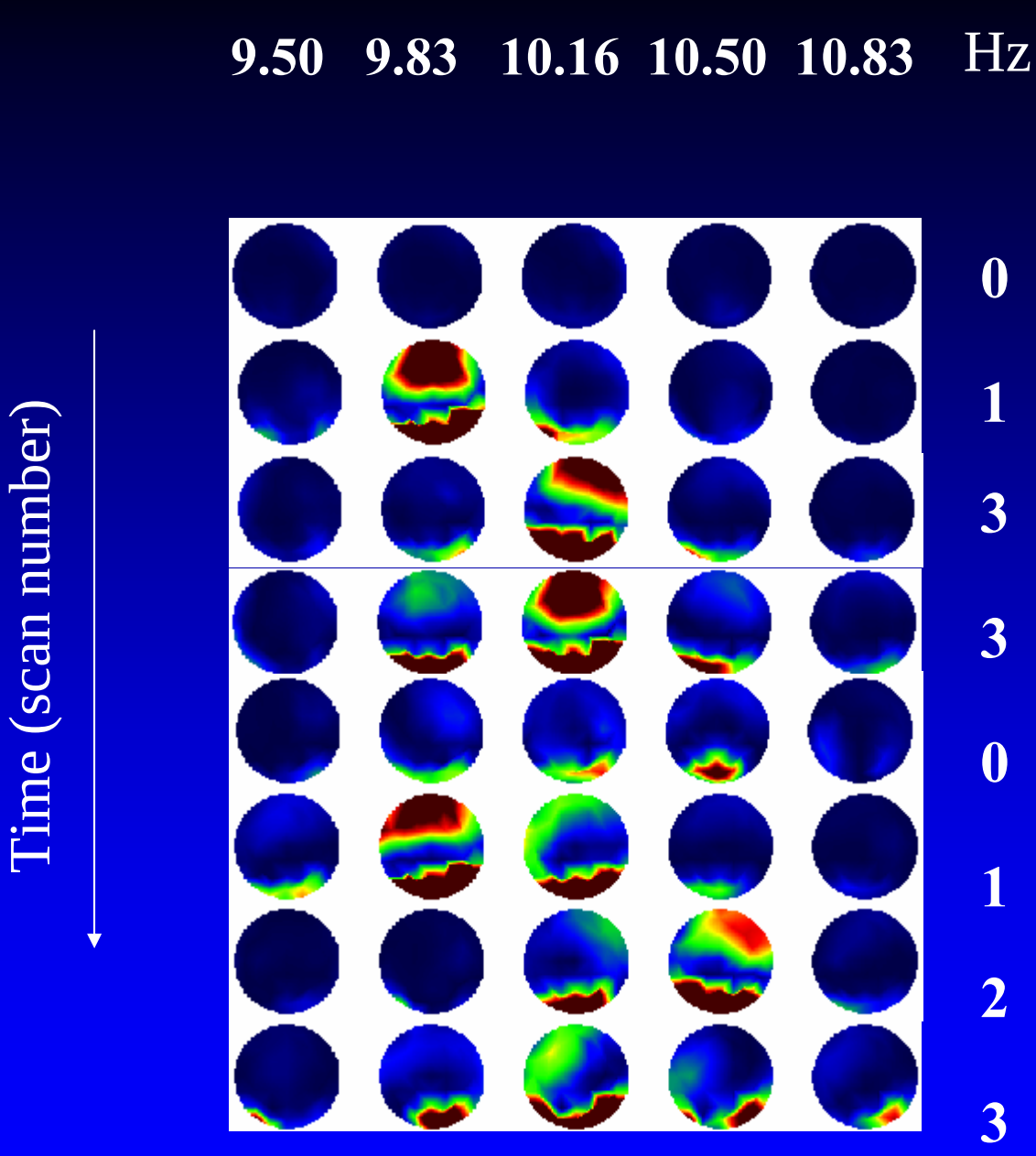
  - Amount of correlation varies greatly over subjects
  - Shape of significant HRF is similar over subjects



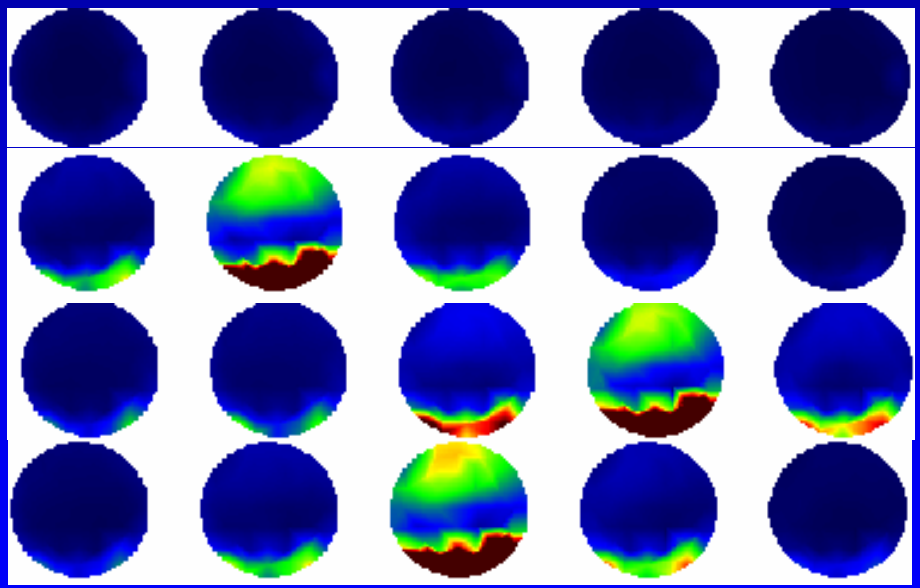
10.16Hz


9.50
9.83
10.16
10.50
10.83
Hz
Time (scan number)
0
1
3
3
0
1
2
3

Data driven analysis

Clustering Averages

9.50 9.83 10.16 10.50 10.83 Hz



Cluster 0 Non-Spec

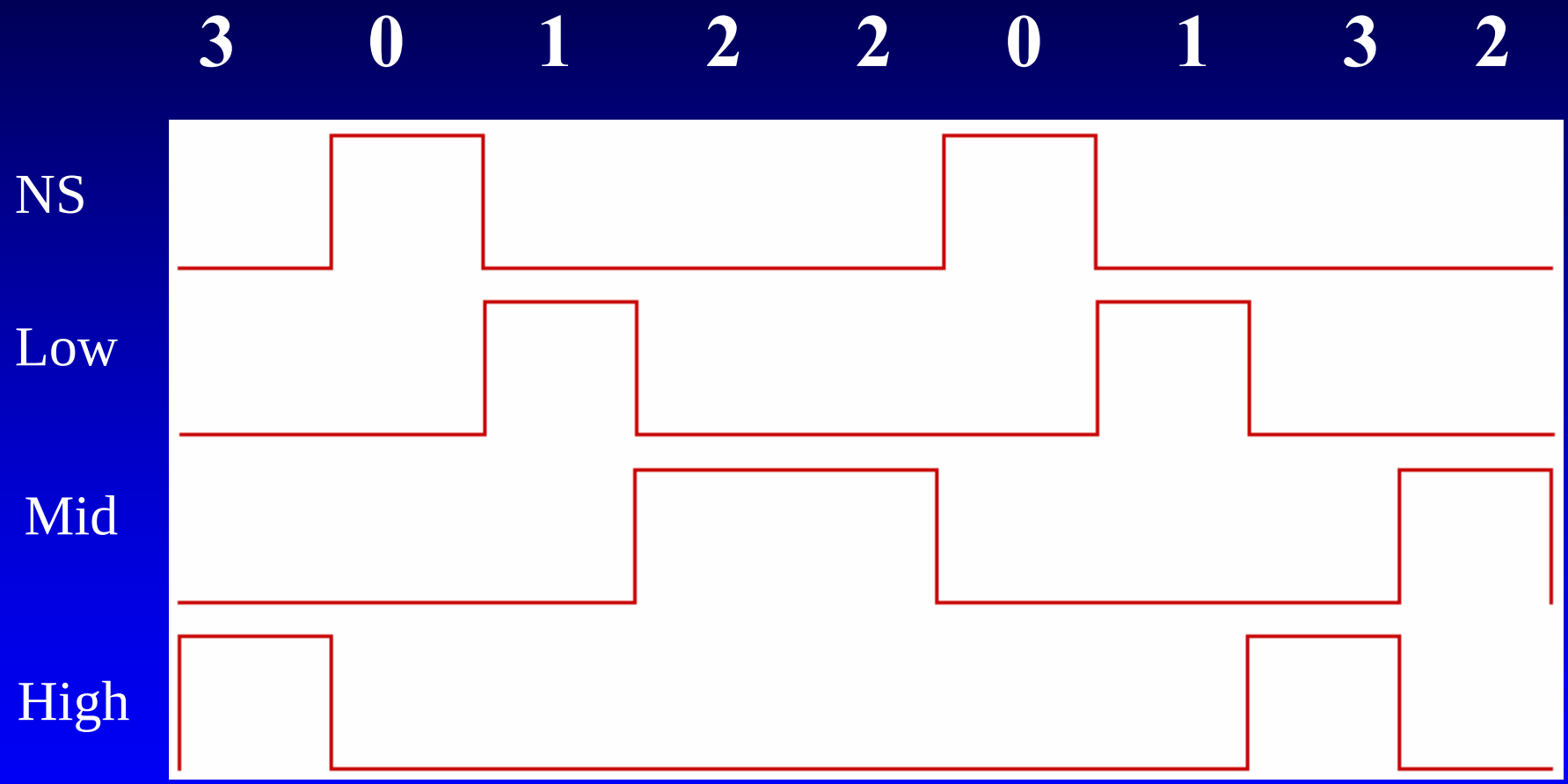
Cluster 1 Low

Cluster 2 High

Cluster 3 Middle

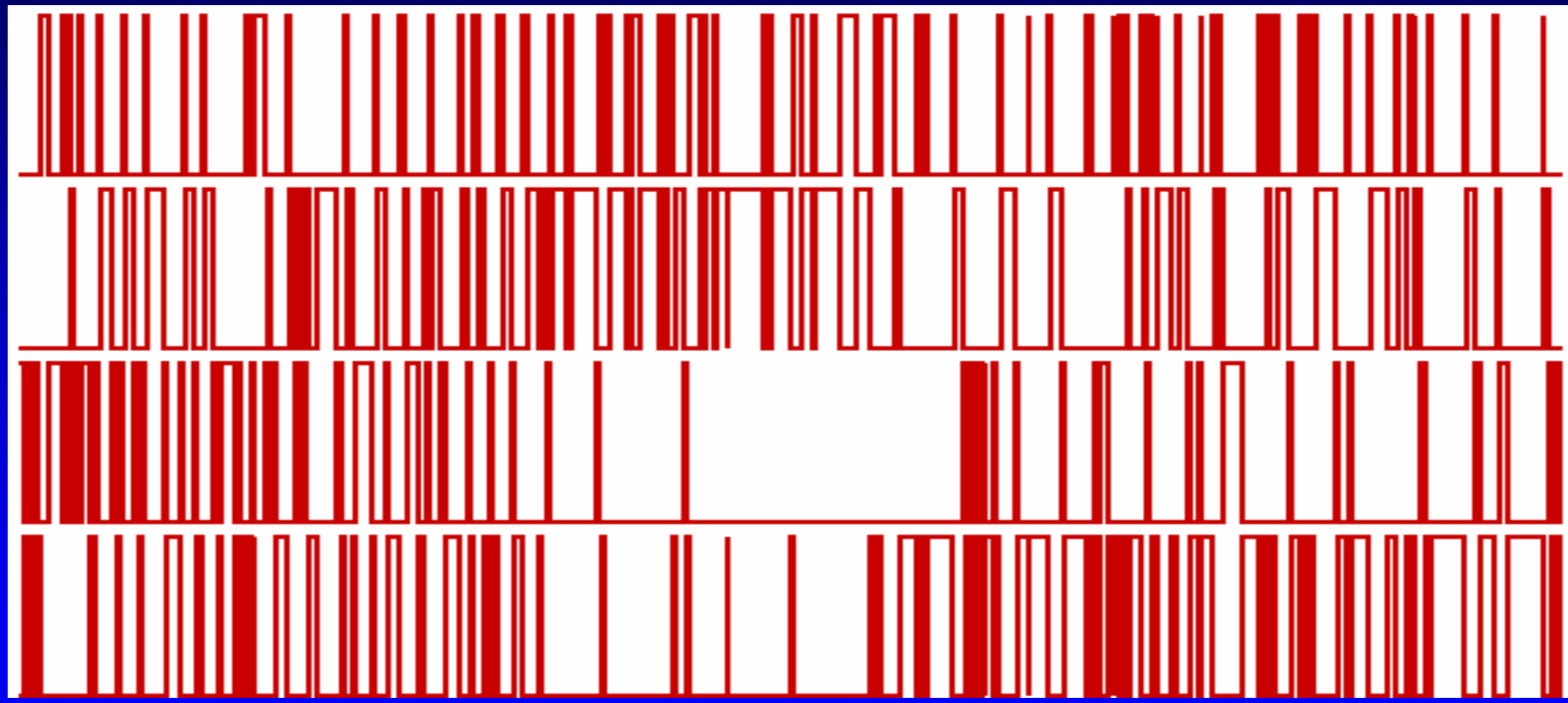
Automatic clustering analysis yielded three frequency specific groups.

Data driven analysis



The group memberships can be converted to time functions, which may be related to fMRI.

Data driven analysis

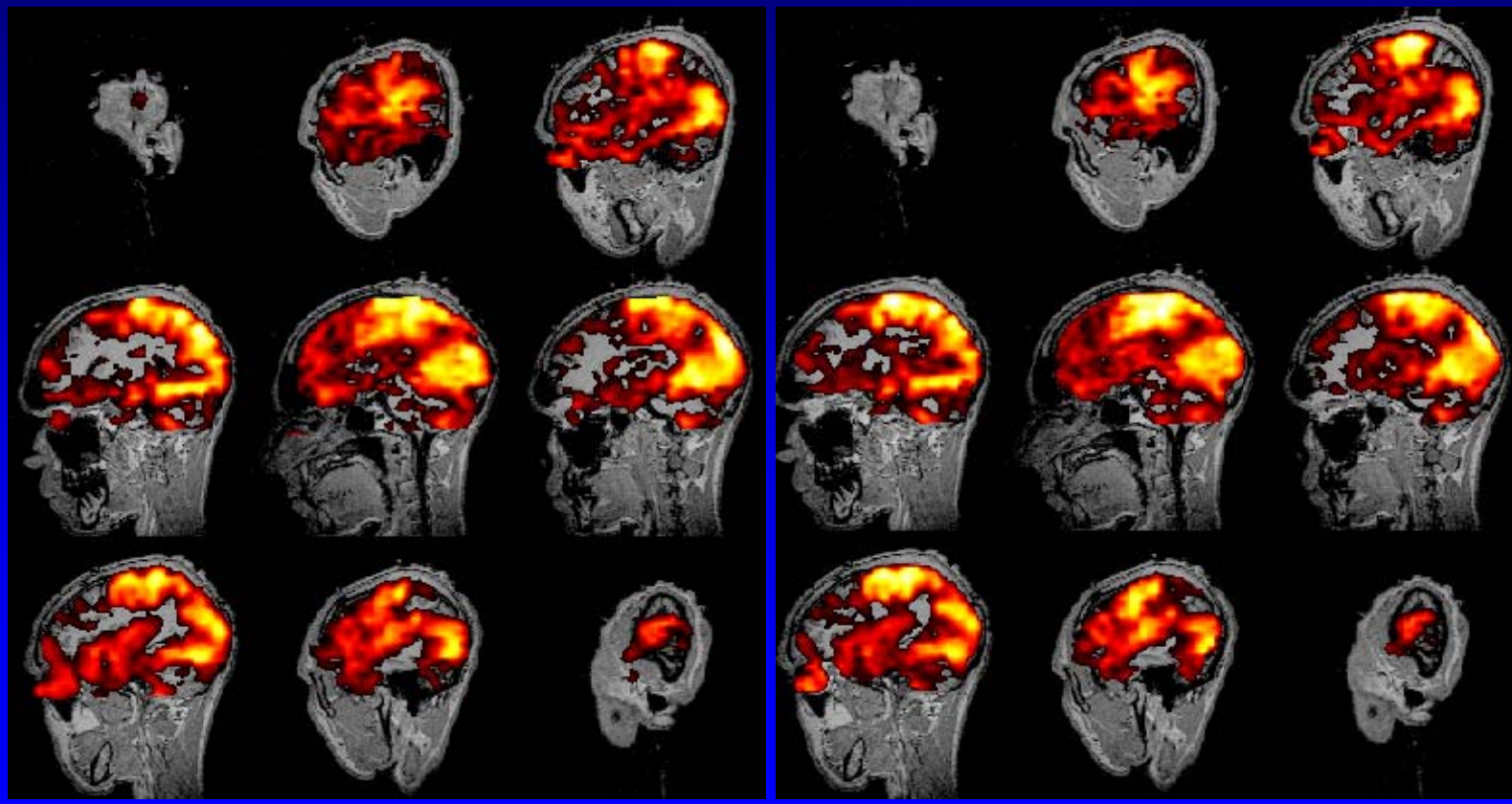


The group memberships can be converted to time functions, which may be related to fMRI.

Data driven analysis

Data driven results

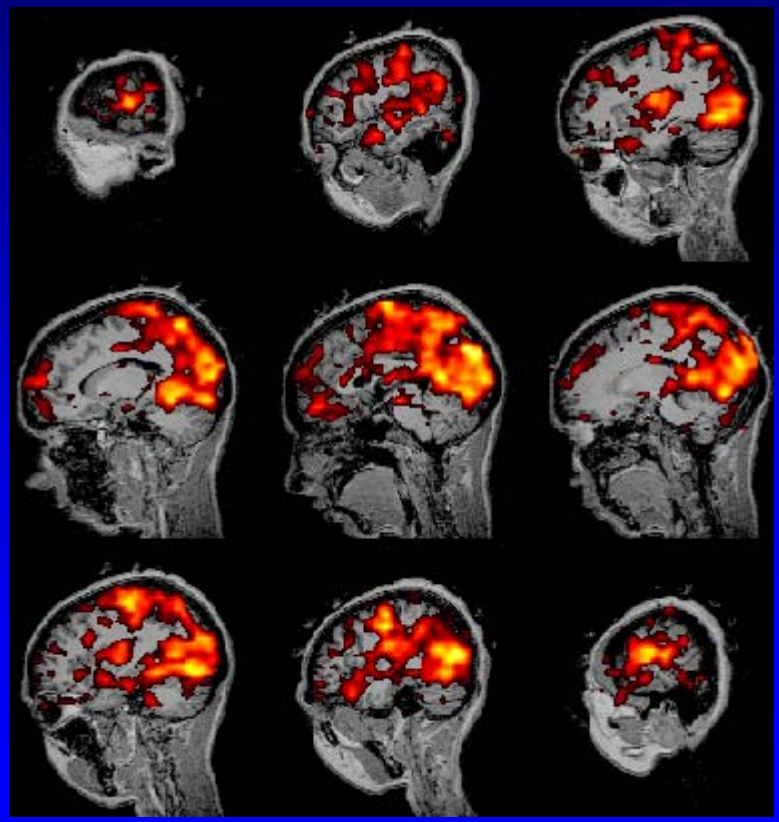
Model driven results



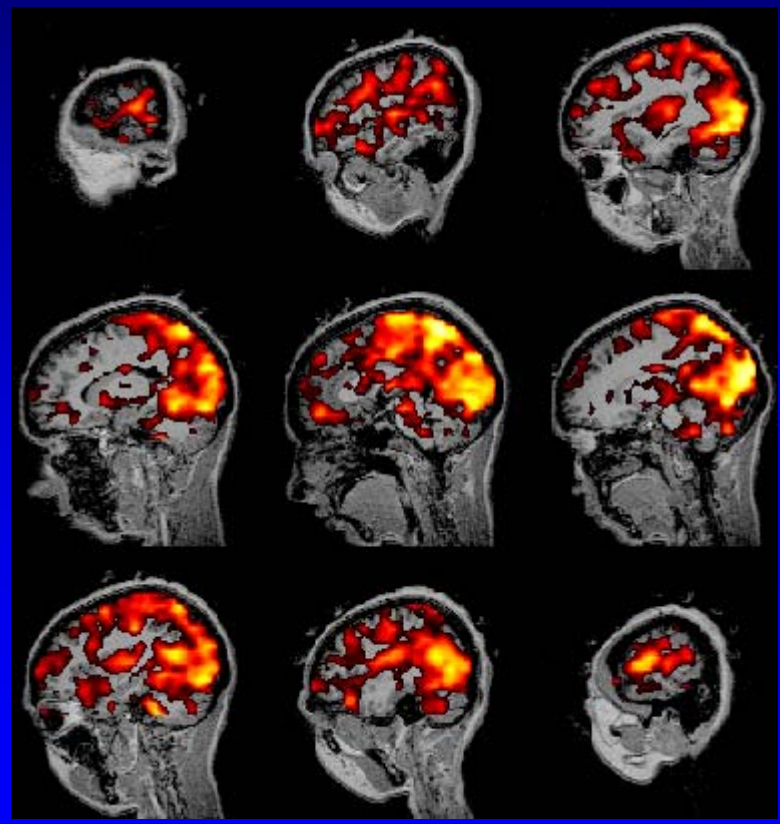
The data driven and the model driven approach give quite similar correlation patterns.

Data driven analysis

Data driven results



Model driven results



The data driven and the model driven approach give quite similar correlation patterns.

Conclusions

- EEG/fMRI is a very interesting tool to study the brain's resting state.
- Model driven approach gives large inter subject variability of amount EEG/fMRI correlation. The HRF of the alpha band *is* mainly reproducible over subjects.

Conclusions

- Alpha power and heart rate are positively correlated.
- Data driven approaches reduce inter subject variability.

The End

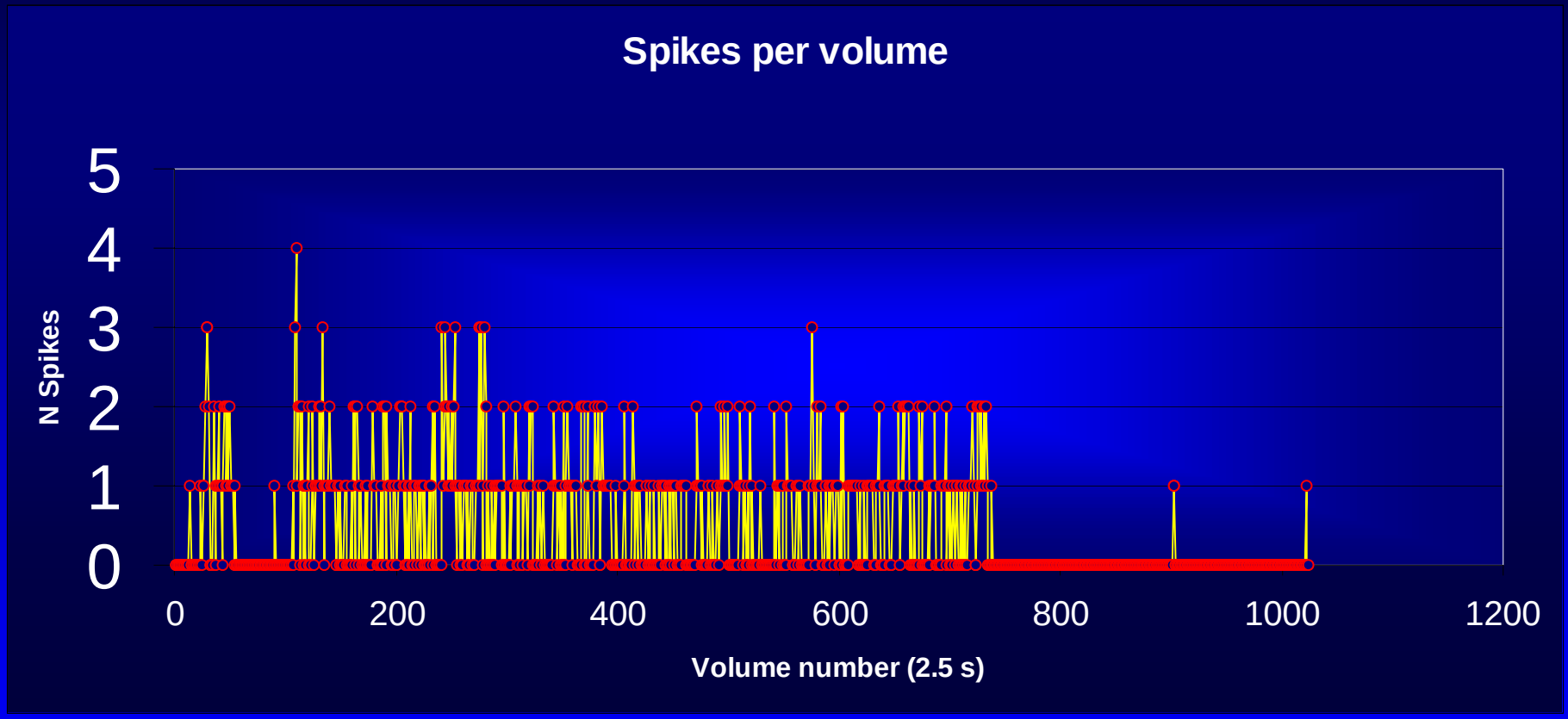
Interictal Spikes

Inter-ictal spike

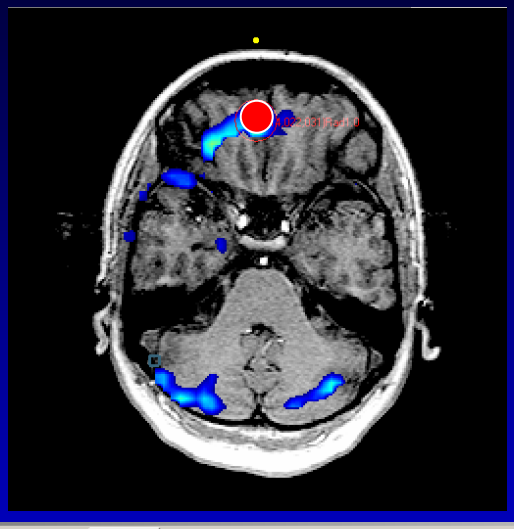
Inter-ictal spikes

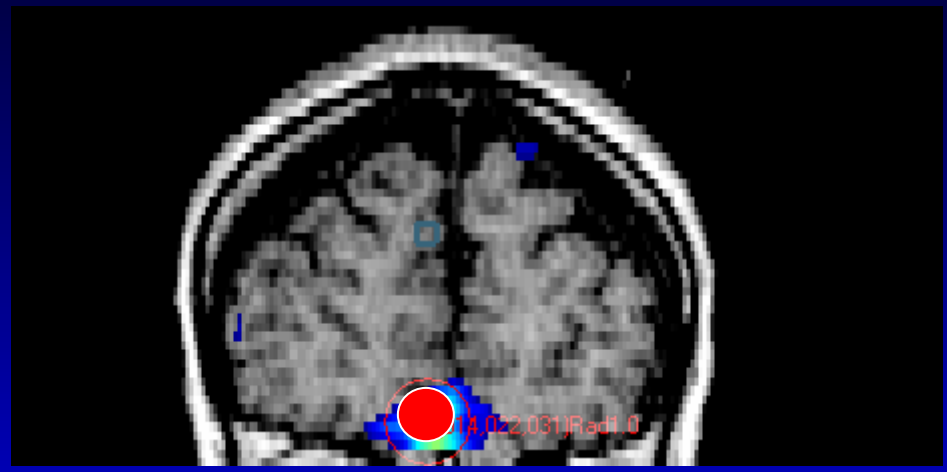
Interictal Spikes

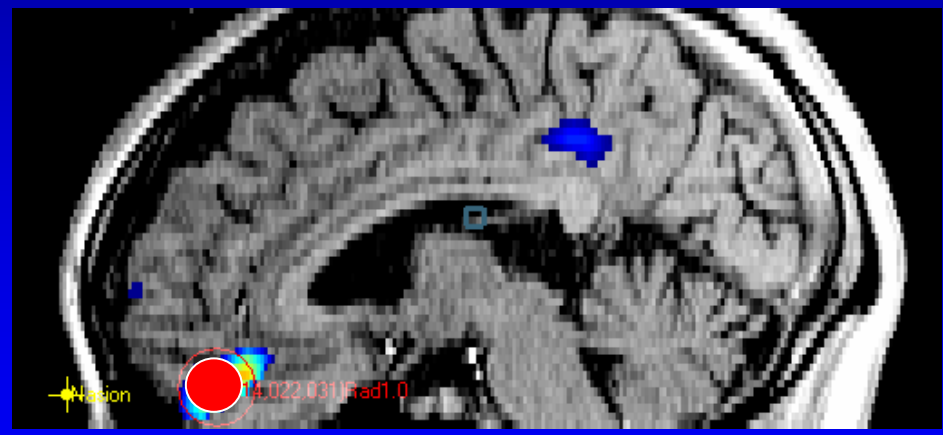
Interictal Spikes

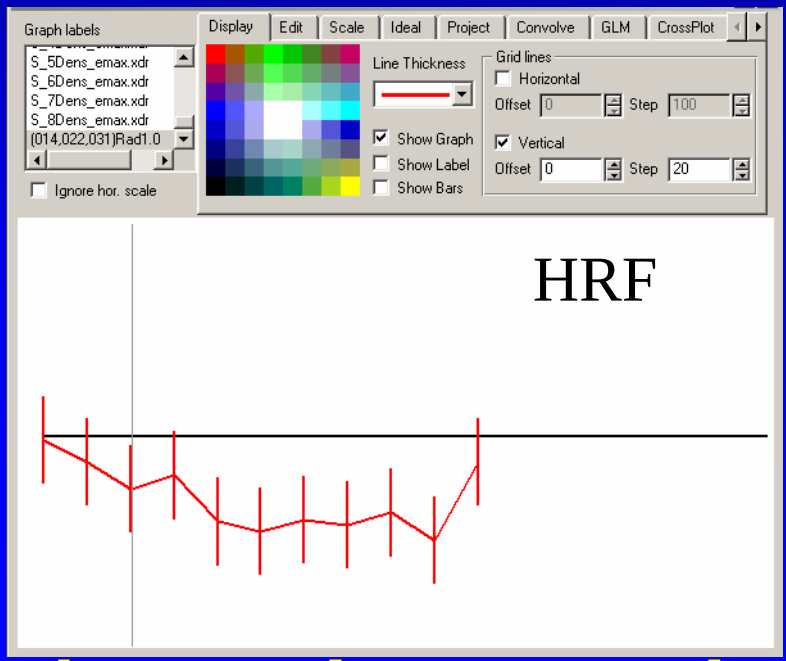


Interictal Spikes



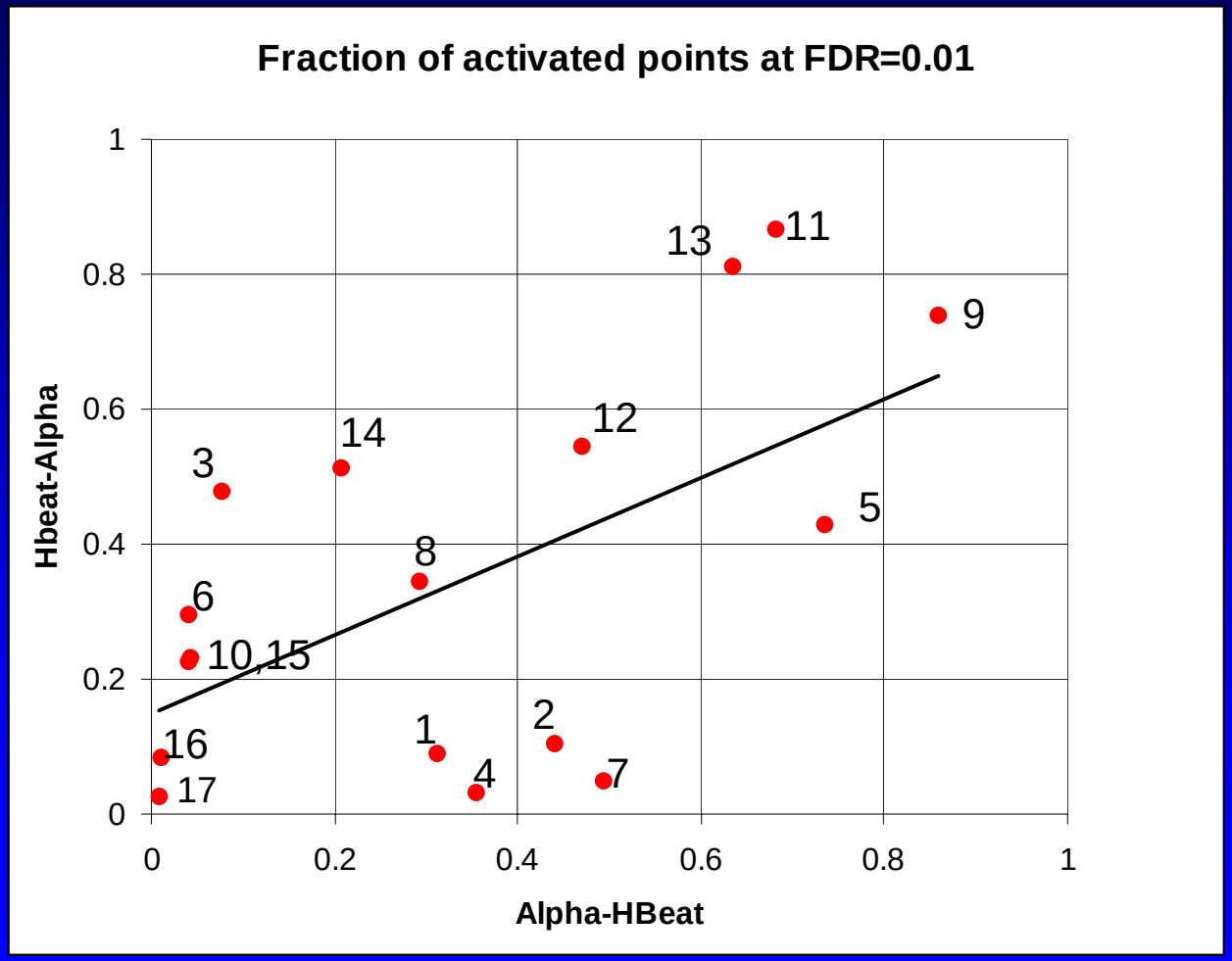






Spikes correlate negatively to BOLD

Relation alpha, heart rate and fMRI

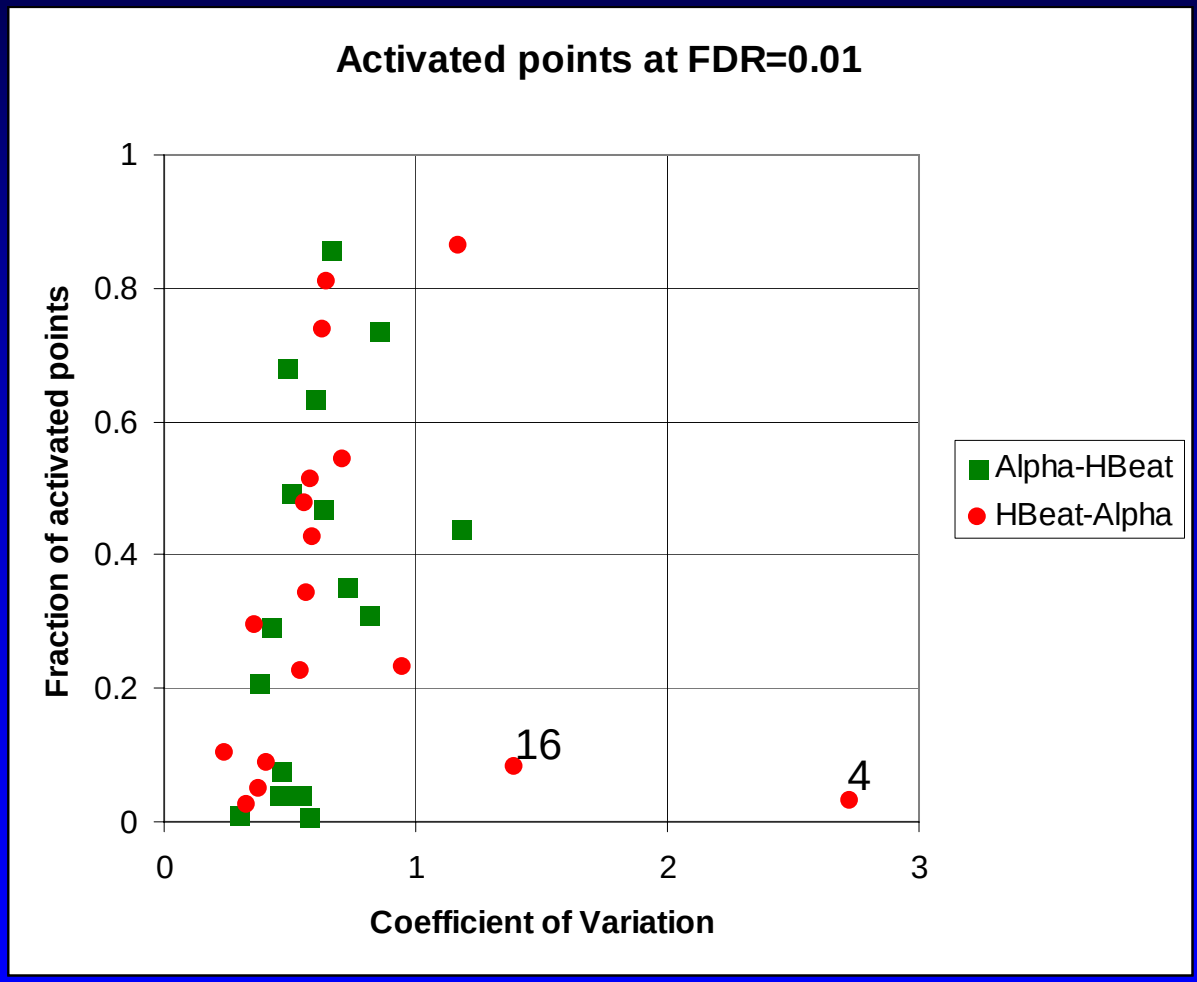


A large alpha-band activation predicts a large heart rate activation.

Relation alpha, heart rate and fMRI

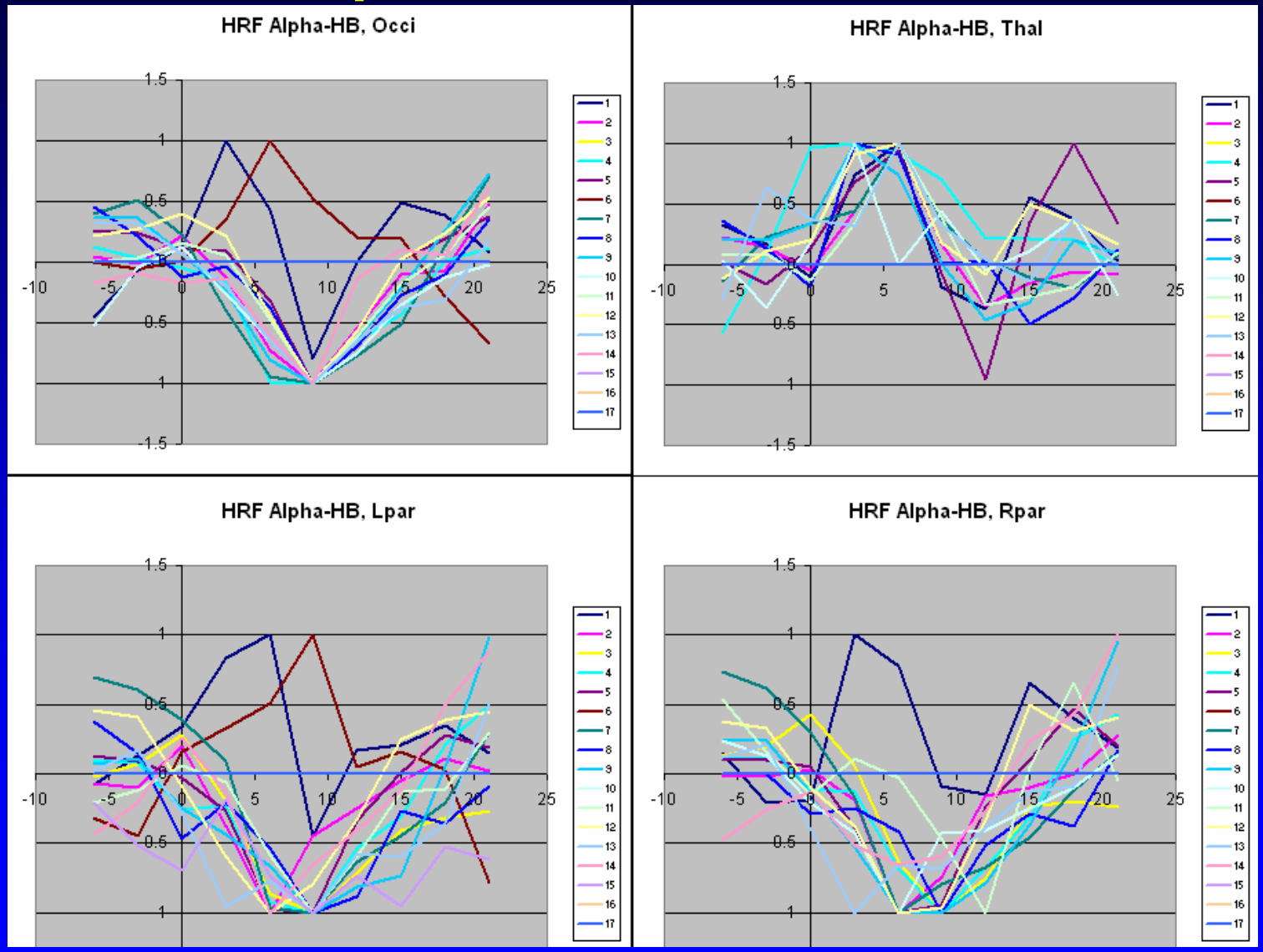
$$\text{Coef.Variation} = \frac{\sqrt{\frac{1}{N}\sum r_n^2 - \left(\frac{1}{N}\sum r_n\right)^2}}{\frac{1}{N}\sum r_n}$$

Relation alpha, heart rate and fMRI



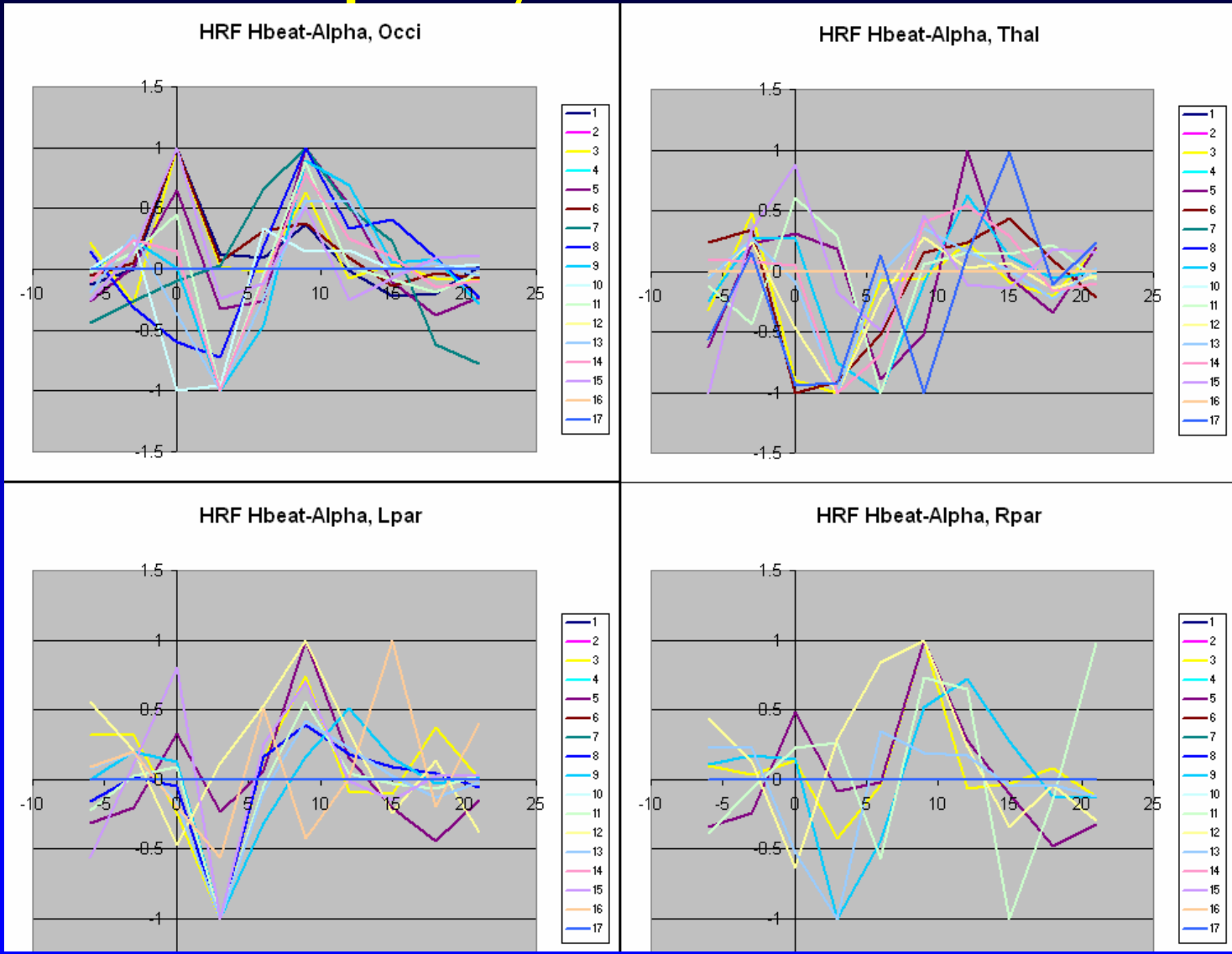
A large coefficient of variation predicts large alpha-band activation and heart rate activation.

Relation alpha, heart rate and fMRI



HRF of alpha band is hardly effected by inclusion of heart rate confounders.

Relation alpha, heart rate and fMRI



"HRF" of heart rate is much faster than BOLD effect.

The hemodynamic response

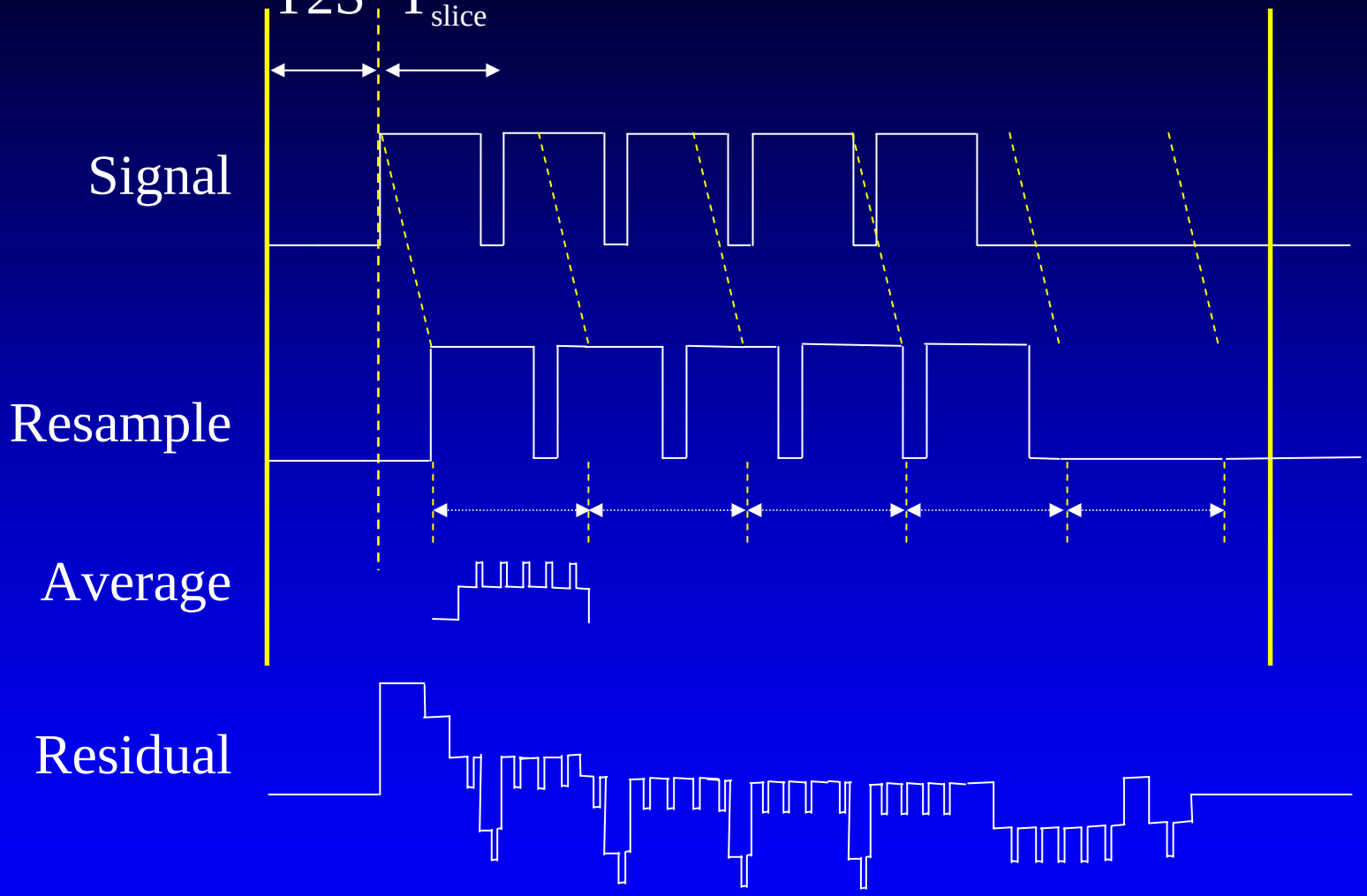
$$\mathrm{BOLD}_n = \sum_{m=0}^{M-1} h_m EEG_{n-m} + \sum_{l=0}^{L-1} \varphi_l DIST_{l,n} + \eta_n$$

$$\mathbf{r} = B\boldsymbol{\theta} + S\varphi + \boldsymbol{\eta}$$

$$\hat{\boldsymbol{\theta}}_{OLS} = \left(B^T P_S B\right)^{inv} B^T P_S \mathbf{r}$$

Projection matrix

Artefacts in the EEG



$Cost(T2S, T_{slice}) = RMS(Residual)$

Dead time and slice time are automatically detected from minimisation of a cost function. Only the number of slices need to be known.

Artefacts in the EEG

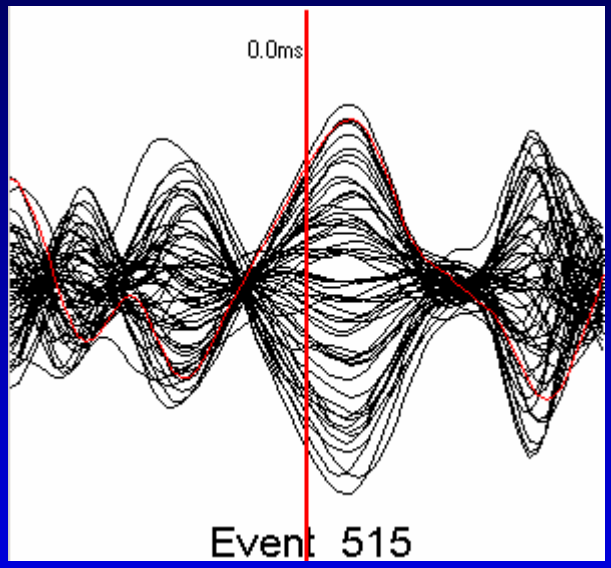
Subject	Dead Time(s)	Slice Time(s)
1	0.00070248	0.12497073
2	0.00071520	0.12497020
3	0.00071448	0.12497023
4	0.00070296	0.12497071
5	0.00070128	0.12497078
6	0.00070344	0.12497069

TR = 3.00000 s (MR)

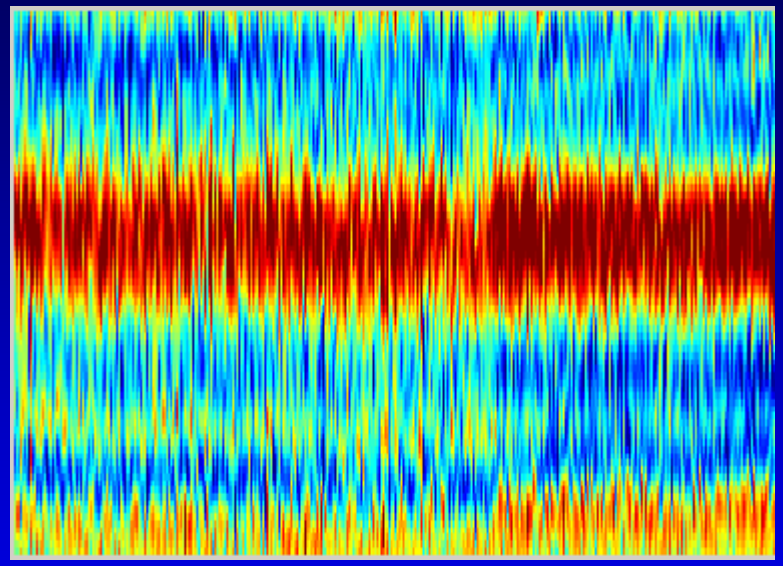
Nslices = 24

There can even a dead time in “regular” MR sequences. This has an effect on the nominal slice time, and on the quality of the corrected EEG data.

Artefacts in the EEG

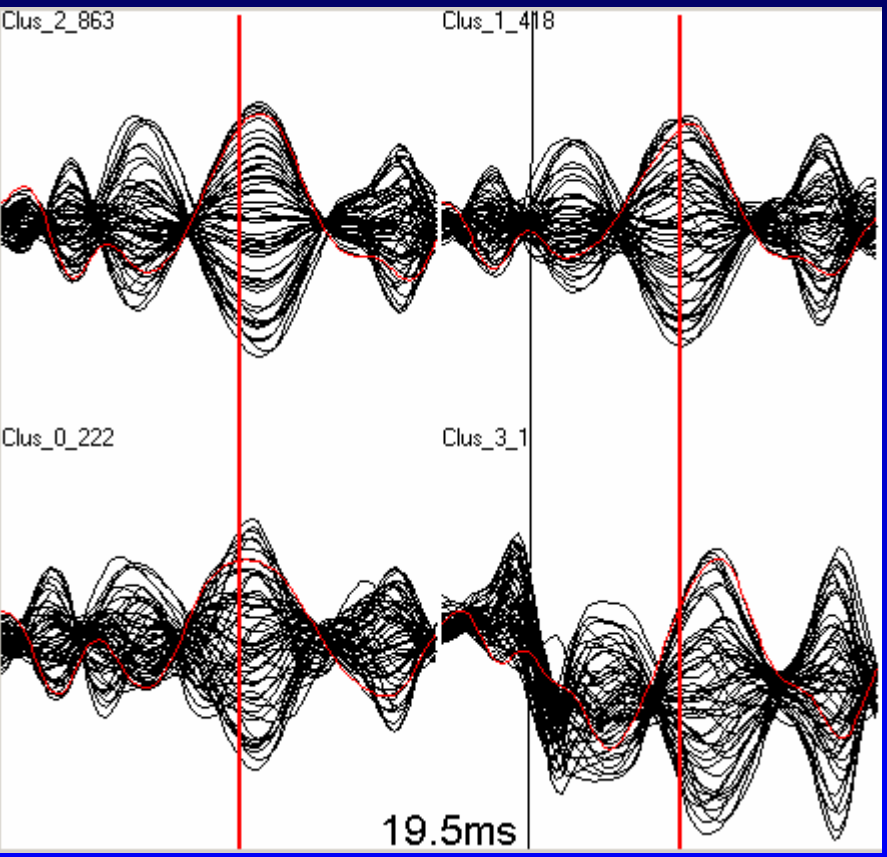


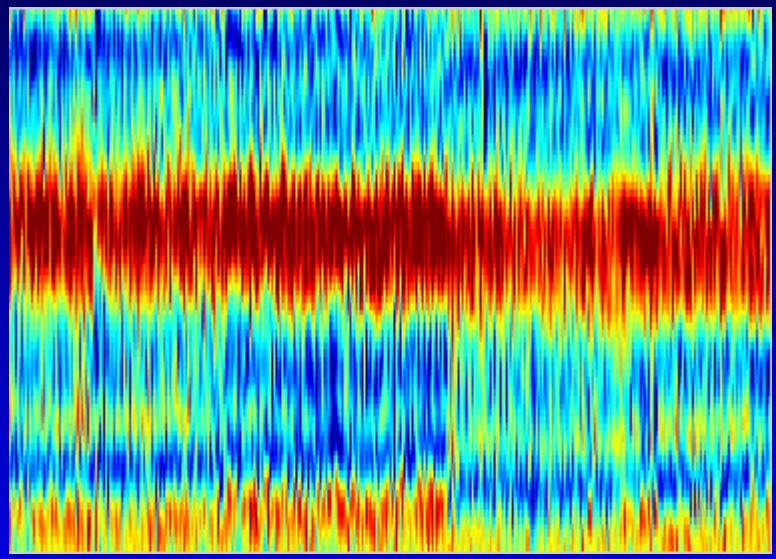
Typical heart beat artefact



Channel AF8, as function of epoch

Artefacts in the EEG

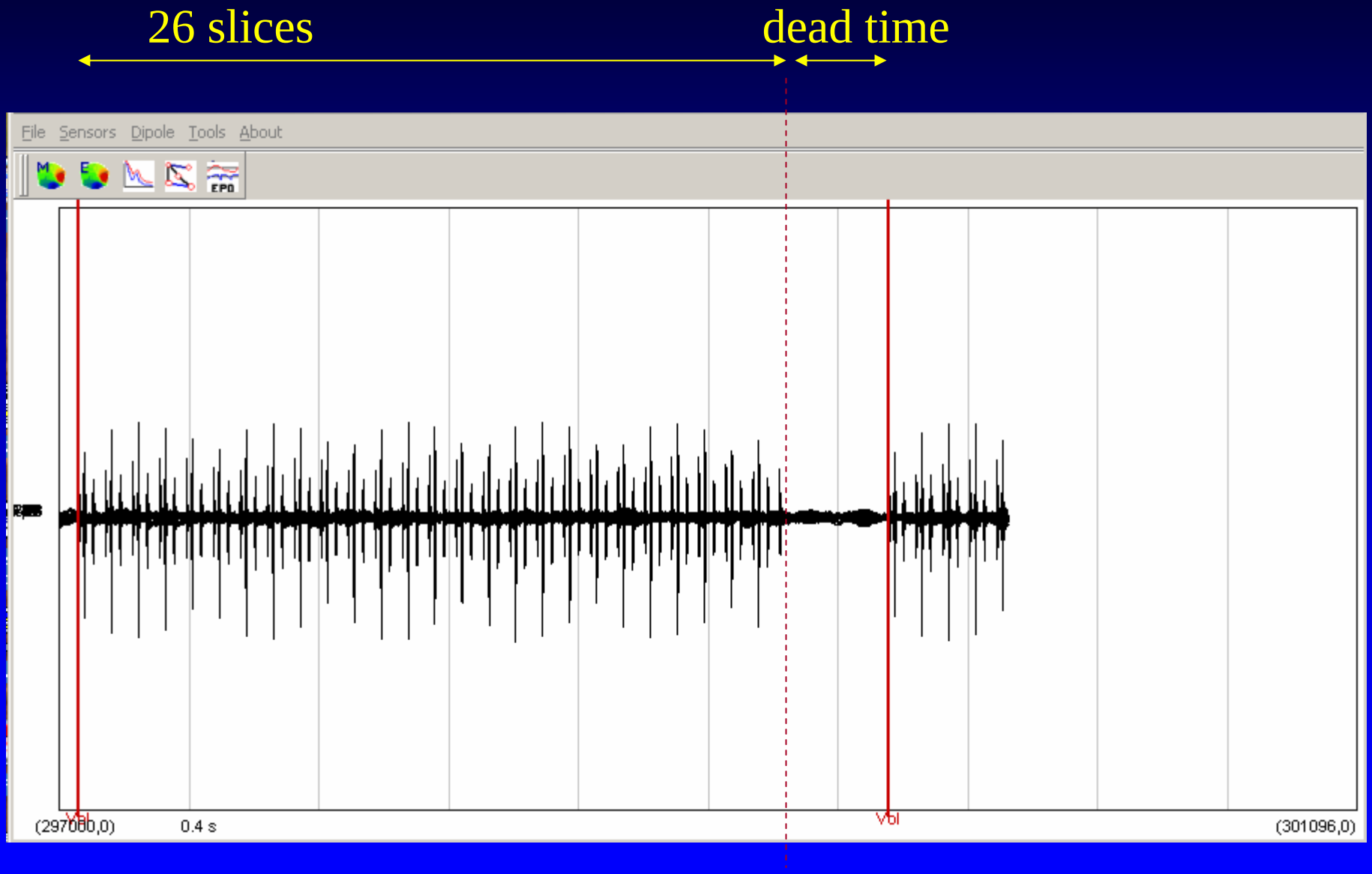




Channel AF8, sorted by cluster

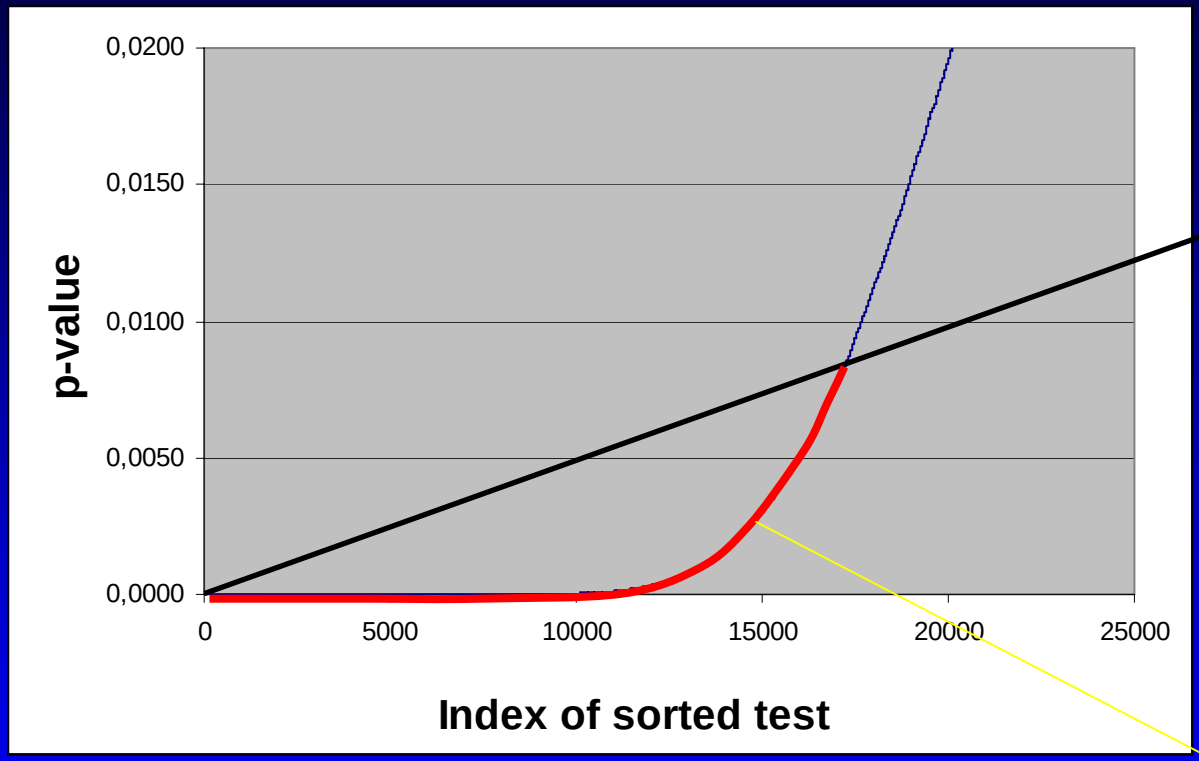
Spatio-temporal cluster analysis of the individual heart beat artefacts shows that the main difference consist of time shifts.

Artefacts in the EEG



Some MR sequences have a dead time between two volumes.

The hemodynamic response

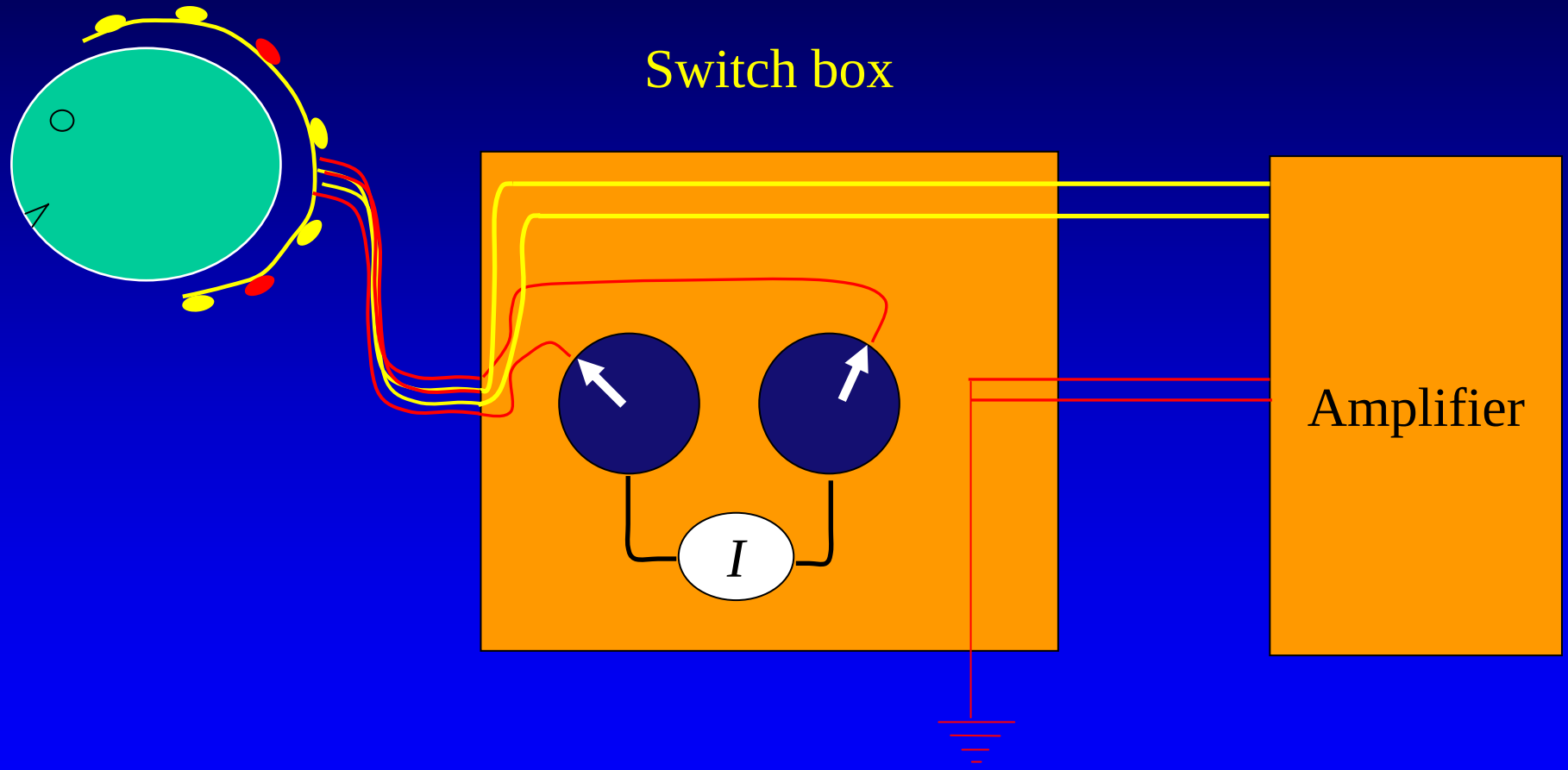


$$p = FDR\frac{i}{N_{voxels}}$$

Tests “significant” at FDR

The False Detection Rate of Benjamini and Hochberg (1995) poses a powerful alternative for the “Bonferroni” correction.

Skull conductivity estimation

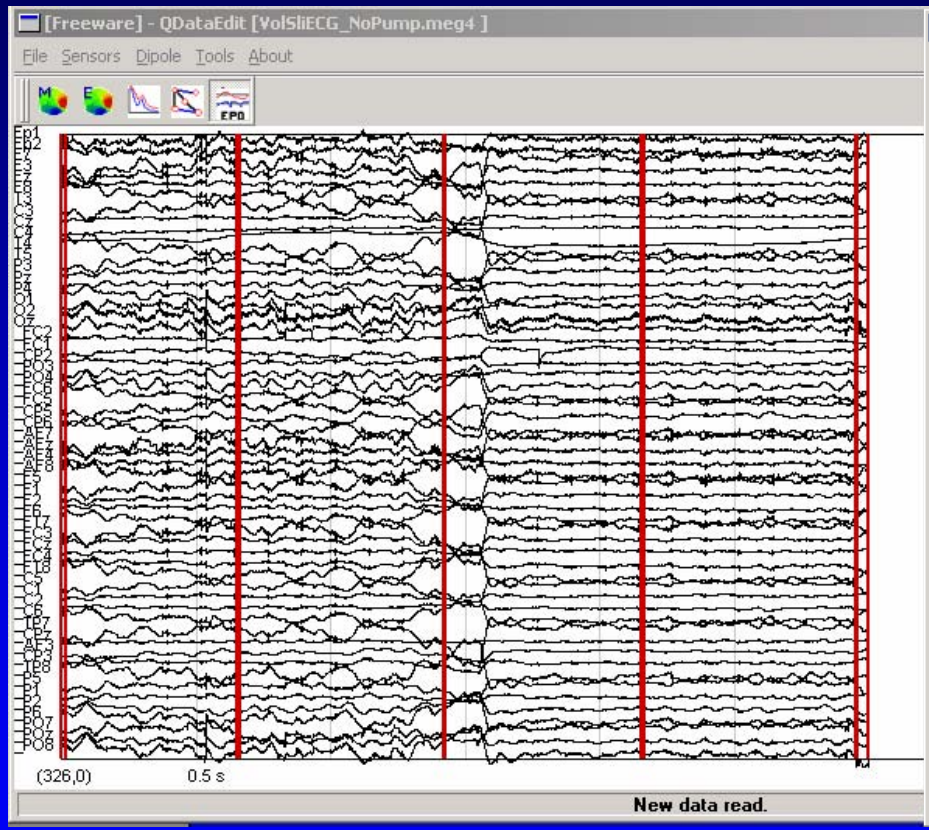


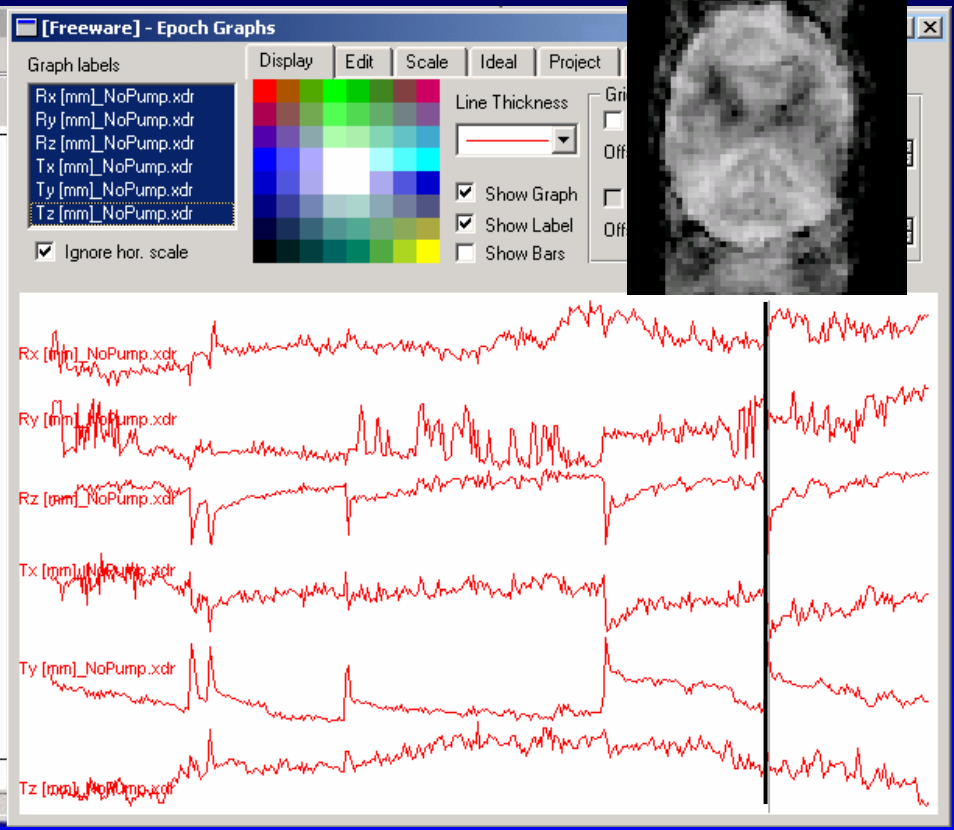
In the future, we plan to develop a “switch box”, with which different pairs of electrodes can be connected to a current source, which operates on different frequencies.

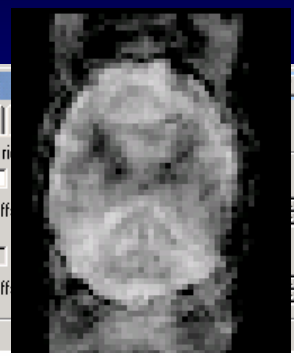
Artefacts in the EEG

EEG during strong motion

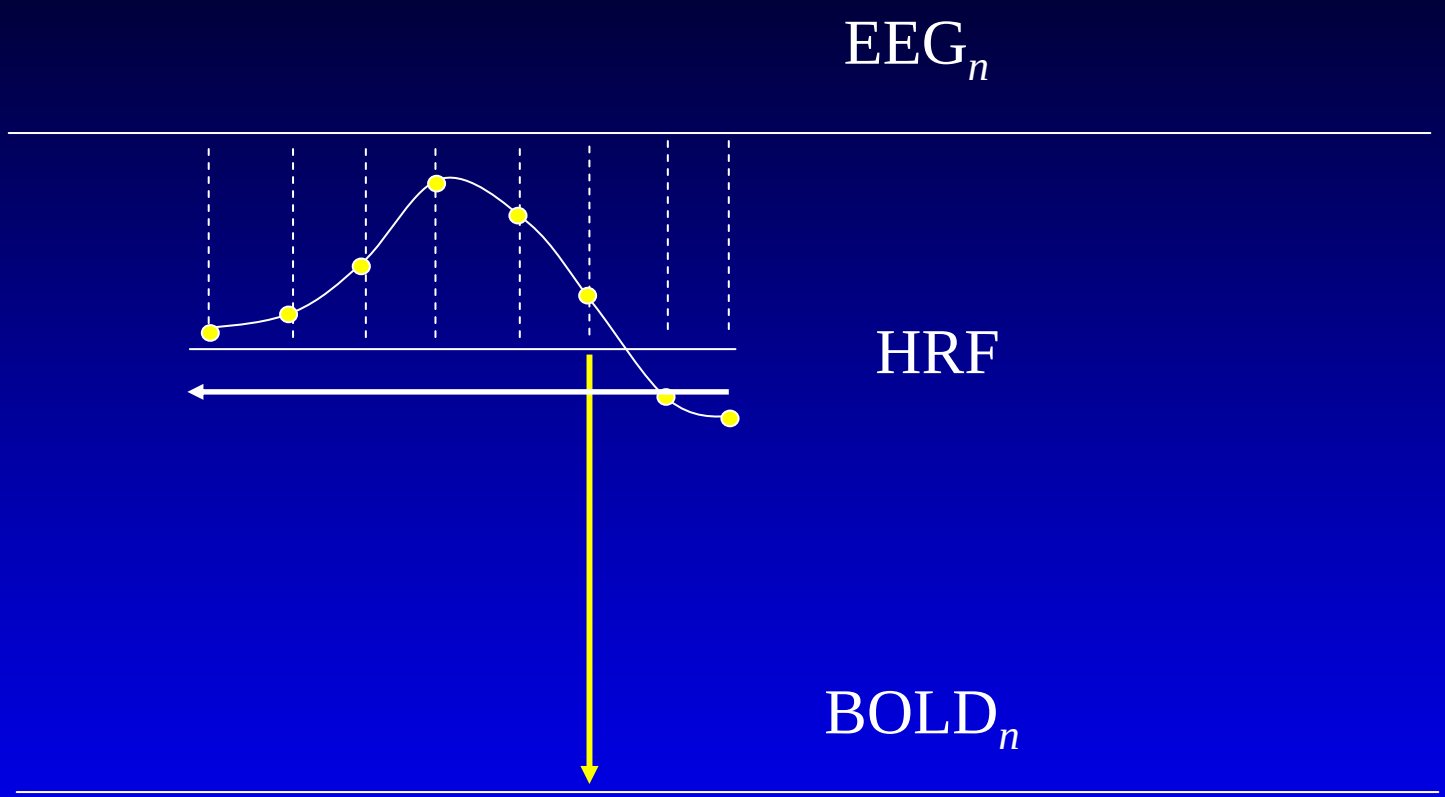
Motion parameters







The corrected EEG can better be interpreted the fMRI motion parameters are considered.



$$\text{BOLD}_n = h_{-2}EEG_{n+2} + h_{-1}EEG_{n+1} + h_0EEG_n + h_1EEG_{n-1} + \ldots + h_5EEG_{n-5}$$

The BOLD signal is considered as a filtered version of the EEG features.