Searching for Nested Oscillations in Frequency and Sensor Space

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Nested Oscillation

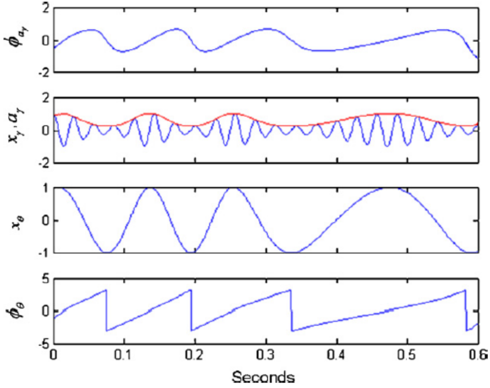


Fig. 1. Instantaneous phase and amplitude. This figure shows the quantities necessary for computing the PAC measures. Firstly, the original signals are bandpass filtered to produce the time series x_θ and x_γ. Hilbert transforms are then applied from which one can estimate the gamma amplitude, a_γ (shown in red) and the theta phase, ϕ_θ. One can then apply a Hilbert transform to the gamma amplitude to obtain the phase of the gamma amplitude, ϕ_{a_γ}. (For interpretation of the references

Phase Amplitude Coupling (PAC).

Modulation Index

Canolty et al (2006) define the modulation index as

$$M = \left| \frac{1}{N} \sum_{n=1}^{N} z[n] \right|$$

where

$$z[n] = a_{\gamma}[n] \exp\left(i \phi_{\theta}[n]\right)$$

The significance of M is then assessed using a surrogate data approach.

Phase Locking Value

Vanhatalo et al. (2004) and Mormann et al. (2005) use the Phase Locking Value (PLV) between the phase of the lower frequency oscillation and the phase of the *amplitude envelope* of the higher frequency oscillation

$$PLV = \left| \frac{1}{N} \sum_{n=1}^{N} \exp\left(i(\phi_\theta[n] - \phi_{a_\gamma}[n]) \right) \right|$$

The significance of *PLV* is then assessed using a surrogate data approach.

Envelope to Signal Correlation

Bruns and Eckhorn (2004) define the Envelope to Signal Correlation as

$$ESC = Corr(x_\theta[n], a_\gamma[n])$$

The significance of *ESC* is assessed using *t* distributions.

General Linear Model

Penny et al. (2008) use a General Linear Model (GLM) approach based on the multiple regression model

$$a_\gamma = X\beta + e$$

where β are regression coefficients, e is additive Gaussian noise and the design matrix X contains three columns:

- $\cos(\phi_\theta[n])$
- $\sin(\phi_\theta[n])$
- A column of 1's

Significance is assessed using F-tests over the first two regression coefficients. More generally, X could be a Fourier series.

ECoG Data

Data from Kai Miller and Jeff Ojemann at Washington State. They collected ECoG data from subjects performing a one-back visual working memory task.

Each item (picture of a house) was presented twice.

On the second presentation of the item subjects press a button.

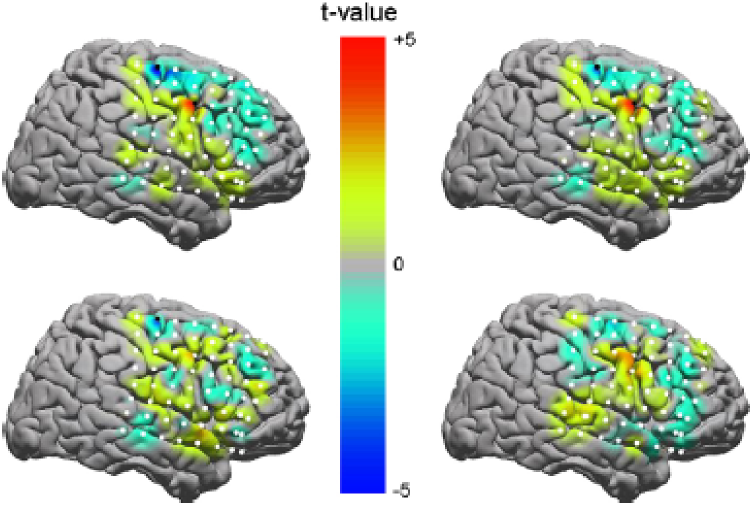
On the second presentation the item therefore does'nt need to be remembered. On the first presentation it does.

We computed PAC measures for each trial between 6Hz theta and high gamma (76 to 200Hz).

The measures were then Gaussianised for each trial, and we tested for between condition (remember vs not) differences using two sample t-tests at each electrode.

ECoG Data

ESC (top left), GLM (top right), PLV (bottom left), Modulation Index (bottom right).



ESC and GLM detect nested oscillations that the other measures don't.

ECoG Data

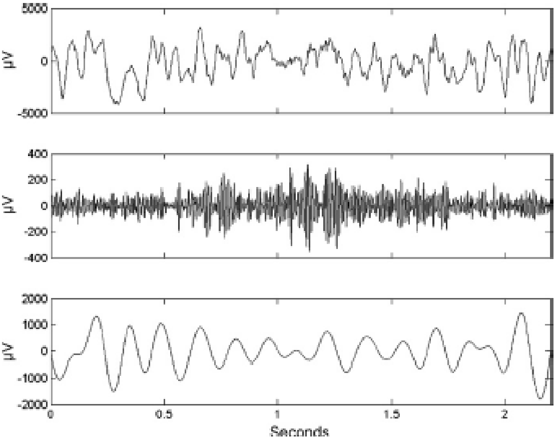


Fig. 4. ECOG time series for target trial. Example target trial at electrode 63 showing the original time series (top), activity in the χ-band (middle) and activity in the theta band (bottom). The PAC measures are $r_{ESC} = 0.02$, $r_{GLM} = 0.06$, PLV = 0.07 and $M = 6.8$.

Current item does not need to be remembered.

ECoG Data

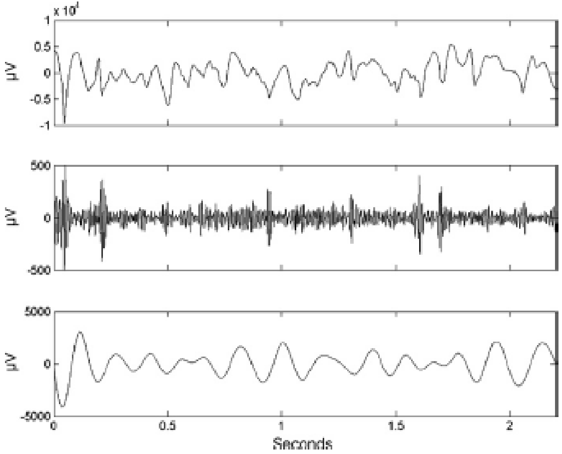
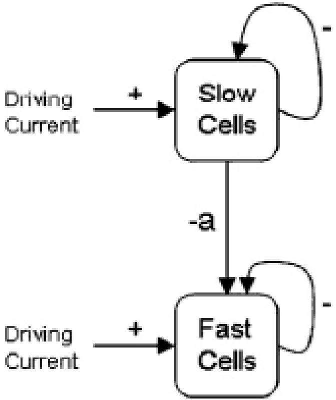


Fig. 3. ECOG time series for non-target trial. Example non-target trial at electrode 63 showing the original time series (top), activity in the χ-band (middle) and activity in the theta band (bottom). The PAC measures are $r_{ESC} = -0.42$, $r_{GLM} = 0.32$, PLV = 0.57 and $M = 12.7$.

Current item needs to be remembered.

Hippocampal Interneuron Network

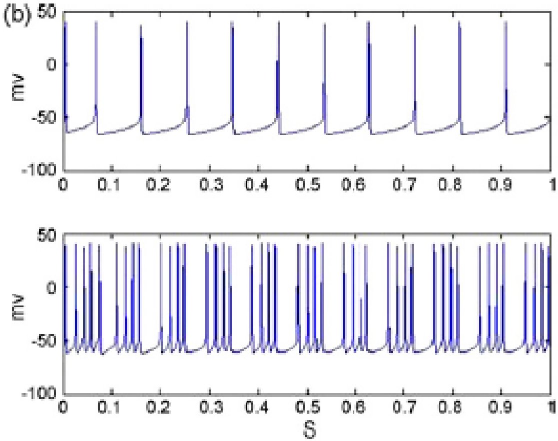
A population of Slow GABA-A cells inhibits a population of Fast GABA-A cells.



Each cell is a single compartment Hodgkin-Huxley model (White et al, 1998).

Hippocampal Interneuron Network

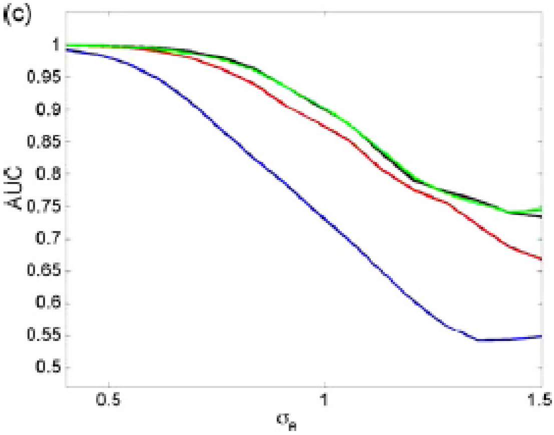
Populations of GABA-B (top,slow) and GABA-A (bottom,fast) cells.



Fast cells had synaptic rise times of 1ms and fall times of 9ms. For the slow cells they are 5ms and 150ms.

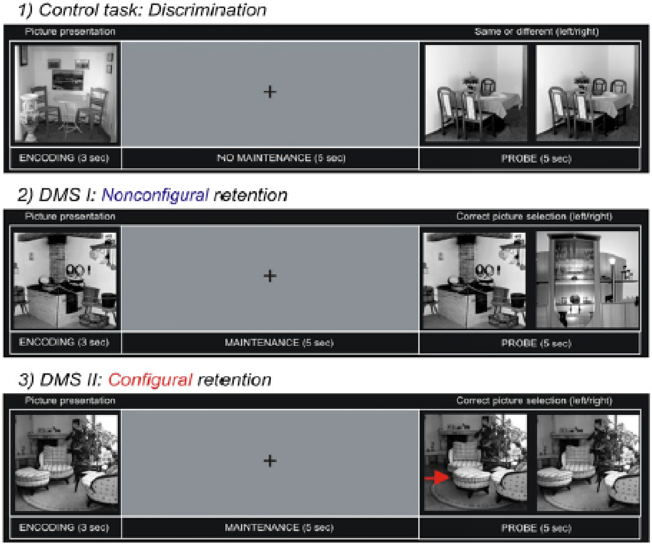
Hippocampal Interneuron Network

Comparison of PAC measures.



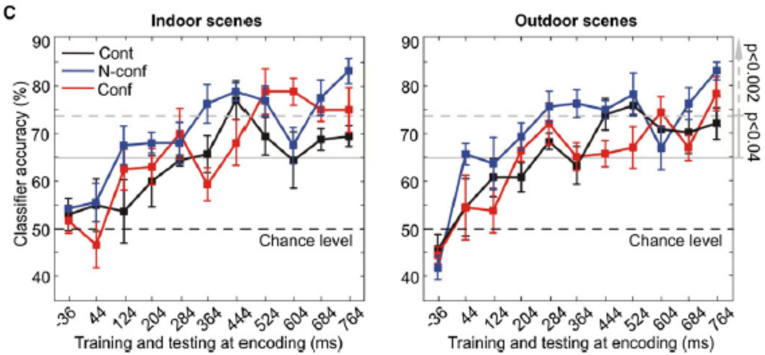
GLM (green), PLV (black), ESC (red), Modulation Index (blue). See Penny et al. (2008) for many further tests.

Experimental Paradigm



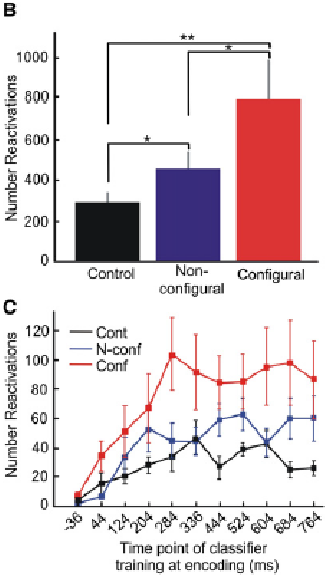
MEG Study of Visual Working Memory (Fuentemilla et al. 2010).

Multivariate Analysis at Encoding



Multivariate classification based on sensor space spectra using features from 13 to 80 Hz.

Multivariate Classification of Maintenance



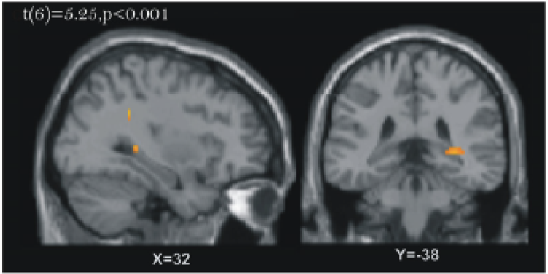
Greater replay during memory conditions.

Replay is Phase-Locked to Theta

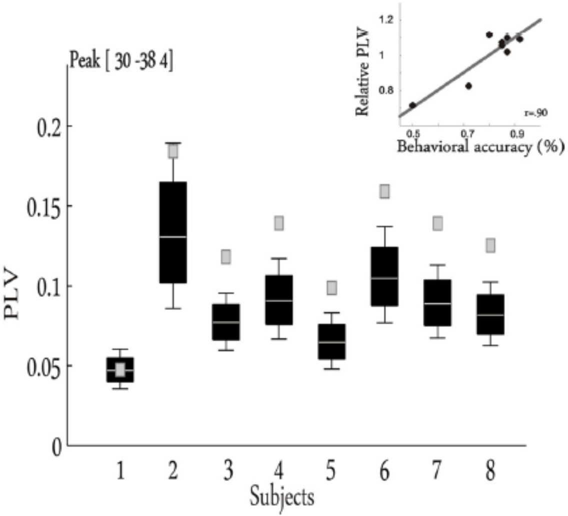
- Theta activity was then projected to source space, and for each source, Poch et al. (2011) computed the phases at which patterns were replayed.
- To see if these phases were non-uniformly distributed, a PLV measure was computed for each source.
- Poch et al. (2011) then tested to see which sources had PLVs that predicted of memory performance.
- This identified a right hippocampal and a right inferior frontal region.

Theta Sources

Right Hippocampus



Theta Sources



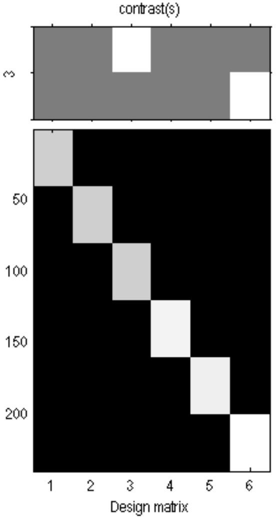
Processing Stream

- Extract phase of theta activity in source region.
- Extract time-frequency maps at each sensor, v, from frequencies $f = 16 : 4 : 128$ Hz during delay period.
- For each trial compute GLM PAC measure. Record fitted regression coefficients s_{fv} and c_{fv}. The sine and cosine terms for each frequency and sensor
- Create a NIFTI format image for each measure.
- There are 3 conditions and 40 trials per condition, with 2 measures per trial. This gives 240 data points per subject
- Set up design matrix in SPM and implement a GLM analysis in 'space-frequency' Litvak et al, 2010)
- Use Random Field Theory to correct for multiple comparisons

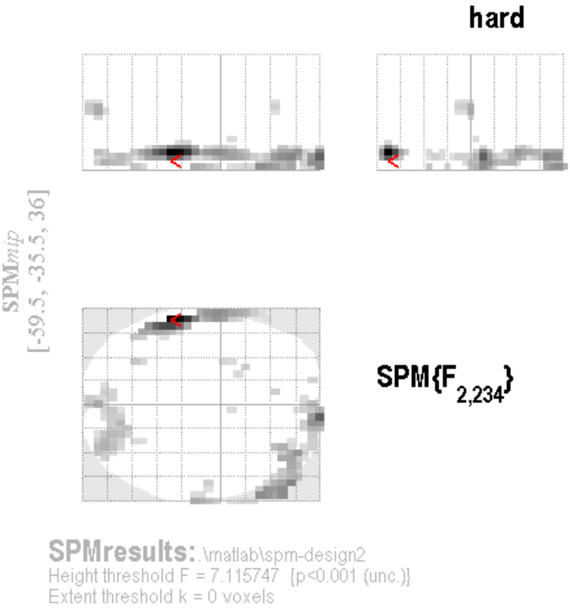
Configural

Images are entered in the following order

- Sine coefficients for Control
- Sine coefficients for Non-Config
- Sine coefficients for Config
- Cos coefficients for Control
- Cos coefficients for Non-Config
- Cos coefficients for Config



Configural


hard
SPMmip
[-59.5, -35.5, 36]
SPM{F2,234}
SPMresults: .\matlab\spm-design2
Height threshold F = 7.115747 {p<0.001 (unc.)}
Extent threshold k = 0 voxels

Configural

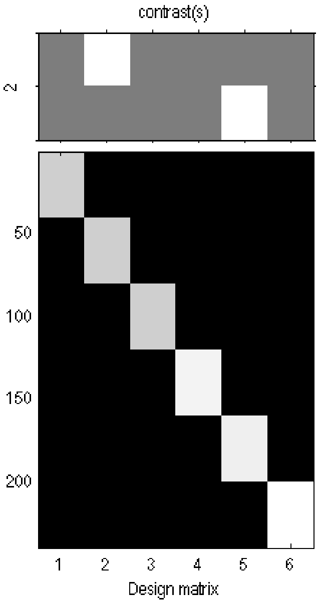
The statistical significance of phase amplitude coupling is corrected for the multiple comparisons over space and frequency using Random Field Theory.

Statistics: ***p-values adjusted for search volume***

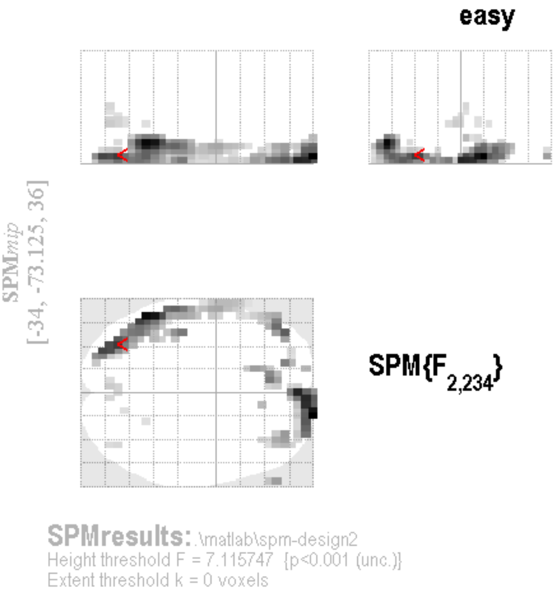
set-level		cluster-level				peak-level					mm mm Hz		
p	c	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	F	$(Z_\equiv)$	p_{uncorr}			
0.009	**12**			**77**		**0.000**	**0.003**	**19.04**	**5.48**	**0.000**	**-60**	**-36**	**44**
						0.201	0.177	11.33	4.11	0.000	-64	-3	44
				115		**0.033**	**0.079**	**13.77**	**4.59**	**0.000**	**9**	**72**	**40**
						0.134	0.177	11.90	4.22	0.000	55	51	40
						0.195	0.177	11.38	4.12	0.000	64	45	40
				12		**0.460**	**0.321**	**10.02**	**3.82**	**0.000**	**0**	**-89**	**80**
				8		**0.541**	**0.365**	**9.71**	**3.75**	**0.000**	**68**	**-19**	**32**
						0.944	0.646	7.96	3.32	0.000	55	-9	32
				52		**0.577**	**0.367**	**9.58**	**3.72**	**0.000**	**30**	**-84**	**36**
						0.706	0.479	9.11	3.61	0.000	13	-73	40
						0.760	0.515	8.91	3.56	0.000	30	-89	44
				2		**0.878**	**0.646**	**8.39**	**3.43**	**0.000**	**-30**	**-62**	**32**
				2		**0.923**	**0.646**	**8.12**	**3.36**	**0.000**	**4**	**61**	**44**
				3		**0.929**	**0.646**	**8.08**	**3.35**	**0.000**	**-26**	**18**	**40**
				3		**0.939**	**0.646**	**8.00**	**3.33**	**0.000**	**-9**	**40**	**84**
				1		**0.976**	**0.775**	**7.61**	**3.23**	**0.001**	**-17**	**67**	**32**
				3		**0.978**	**0.775**	**7.59**	**3.22**	**0.001**	**-30**	**2**	**44**
				1		**0.989**	**0.841**	**7.36**	**3.16**	**0.001**	**4**	**8**	**56**

We can use the standard threshold eg FWE=0.05.

Non-Configural



Non-Configural

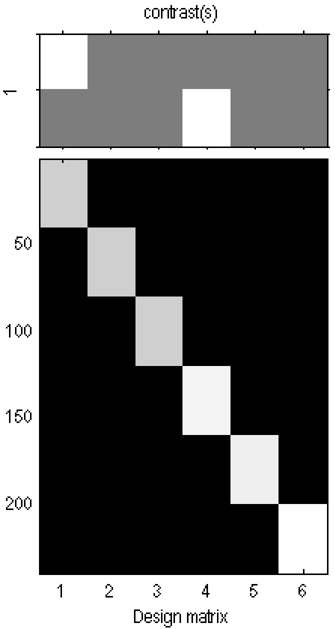


Non-Configural

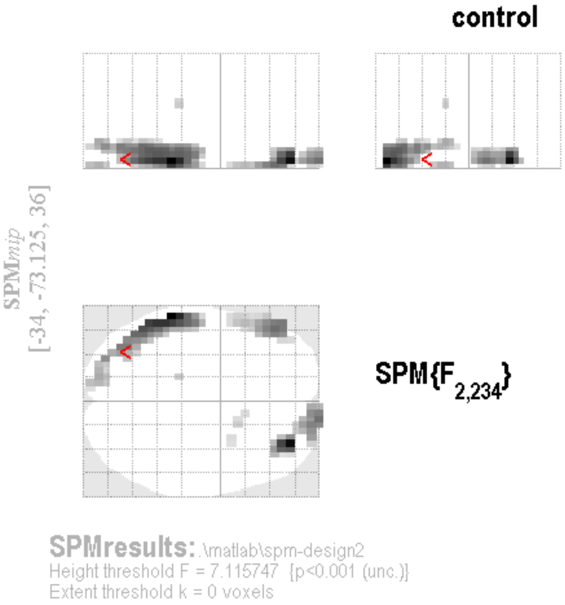
Statistics: ***p-values adjusted for search volume***

set-level		cluster-level				peak-level					mm	mm	Hz
p	c	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	F	$(Z_{\equiv})$	p_{uncorr}			
0.003	**13**			**84**		**0.006**	**0.023**	**15.95**	**4.98**	**0.000**	**17**	**72**	**36**
						0.022	0.037	14.27	4.68	0.000	0	61	32
						0.509	0.314	9.83	3.78	0.000	30	51	36
				215		**0.009**	**0.023**	**15.40**	**4.88**	**0.000**	**-55**	**-52**	**48**
						0.043	0.053	13.44	4.53	0.000	-34	-73	36
						0.057	0.057	13.05	4.45	0.000	-30	-84	36
				14		**0.240**	**0.149**	**11.07**	**4.05**	**0.000**	**-9**	**40**	**32**
						0.547	0.314	9.69	3.74	0.000	-17	29	32
				5		**0.310**	**0.181**	**10.68**	**3.97**	**0.000**	**-21**	**51**	**32**
						0.991	0.952	7.30	3.14	0.001	-30	56	32
				3		**0.566**	**0.314**	**9.62**	**3.73**	**0.000**	**64**	**45**	**36**
				1		**0.813**	**0.528**	**8.69**	**3.51**	**0.000**	**-17**	**67**	**32**
				1		**0.837**	**0.528**	**8.59**	**3.48**	**0.000**	**9**	**34**	**32**
				8		**0.938**	**0.717**	**8.01**	**3.33**	**0.000**	**-4**	**-79**	**64**
				2		**0.985**	**0.926**	**7.44**	**3.18**	**0.001**	**38**	**-73**	**40**
				2		**0.986**	**0.926**	**7.43**	**3.18**	**0.001**	**4**	**-79**	**80**
				1		**0.987**	**0.926**	**7.39**	**3.17**	**0.001**	**-38**	**-73**	**48**
				2		**0.993**	**0.964**	**7.22**	**3.12**	**0.001**	**13**	**-68**	**68**
				1		**0.995**	**0.995**	**7.12**	**3.09**	**0.001**	**21**	**-52**	**64**

Control



Control


control
SPMmip
[-34, -73.125, 36]
SPM{F_2,234}
SPMresults: .\matlab\spm-design2
Height threshold F = 7.115747 {p<0.001 (unc.)}
Extent threshold k = 0 voxels

Control

Statistics: ***p-values adjusted for search volume***

set-level		cluster-level				peak-level					mm mm Hz		
p	c	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	F	$(Z_{\equiv})$	p_{uncorr}			
0.287	7			168		0.002	0.005	17.22	5.19	0.000	-60	-36	36
						0.069	0.058	12.80	4.40	0.000	-51	-52	44
						0.180	0.081	11.49	4.14	0.000	-38	-68	44
				63		0.004	0.005	16.34	5.04	0.000	30	51	36
						0.130	0.068	11.94	4.23	0.000	13	72	36
				30		0.117	0.068	12.09	4.26	0.000	-51	40	32
						0.790	0.381	8.79	3.53	0.000	-55	18	32
				7		0.675	0.305	9.22	3.63	0.000	-21	-89	32
				2		0.922	0.565	8.13	3.36	0.000	-17	-30	84
				3		0.951	0.616	7.90	3.30	0.000	17	13	32
				2		0.986	0.799	7.43	3.18	0.001	26	8	32

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