Supplementary Information

Thursday 4th April, 2024

Keywords

1 Supplementary Figures

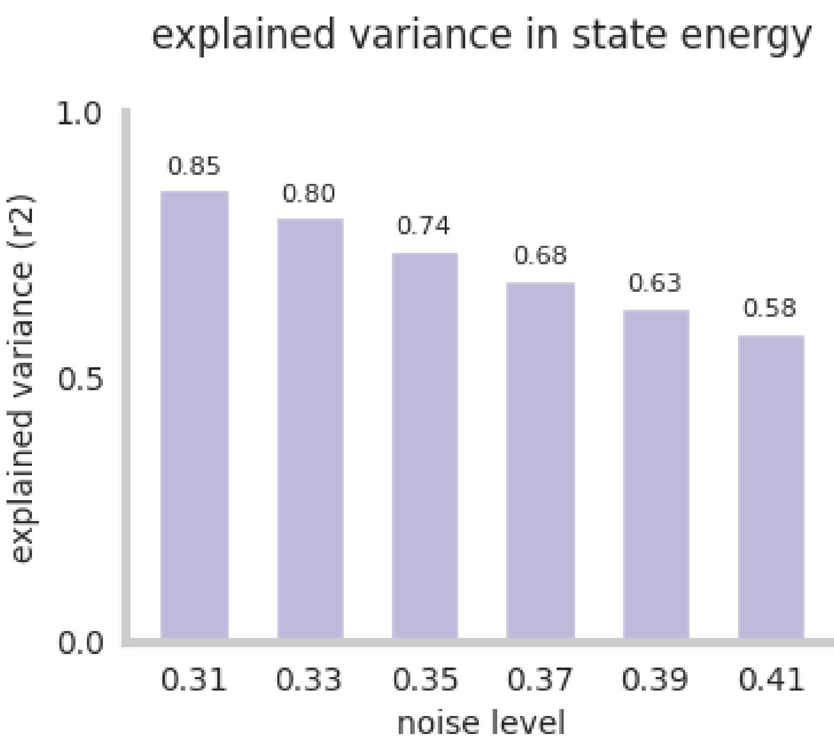

Figure 1: **Explained variance in state energy by first two principal components.** See supplemental_material.ipynb for details.

2 Supplementary Tables

3 Supplementary Methods

Study 4 instructions for upregulation. *"During this scan, we are going to ask you to try to imagine as hard as you can that the thermal stimulations are more painful than they are. Try to focus on how unpleasant the pain is, for instance, how strongly you would like to remove your arm from it. Pay attention to the burning, stinging and shooting sensations. You can use your mind to turn up the dial of the pain,*

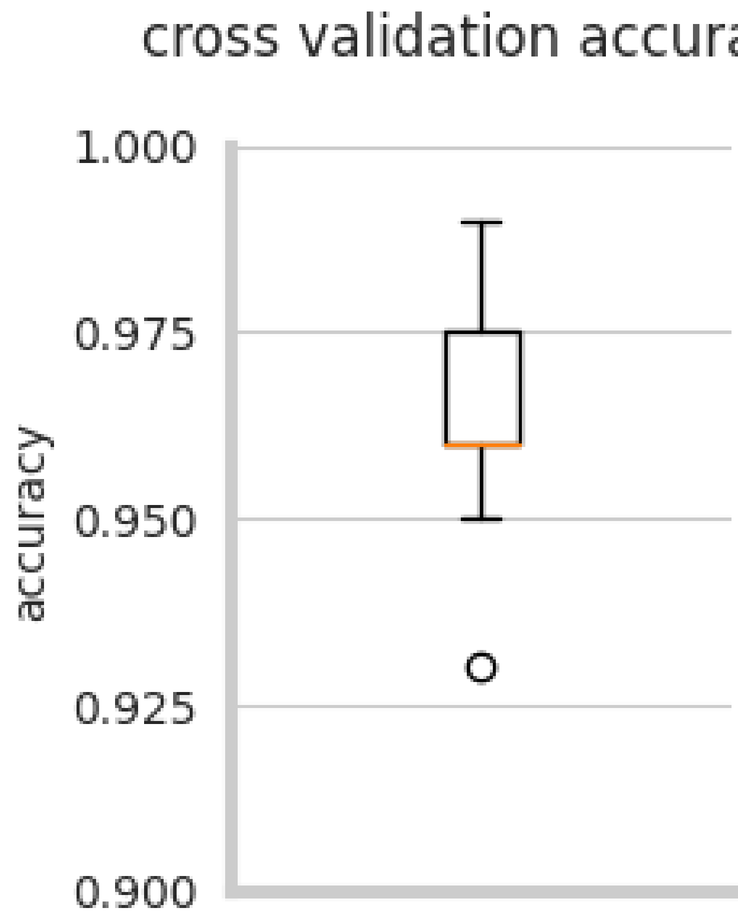

Figure 2: **Cross-validation classification accuracy of the fcHNN, when predicting the attractor state from state activation.** See supplemental_material.ipynb for details.

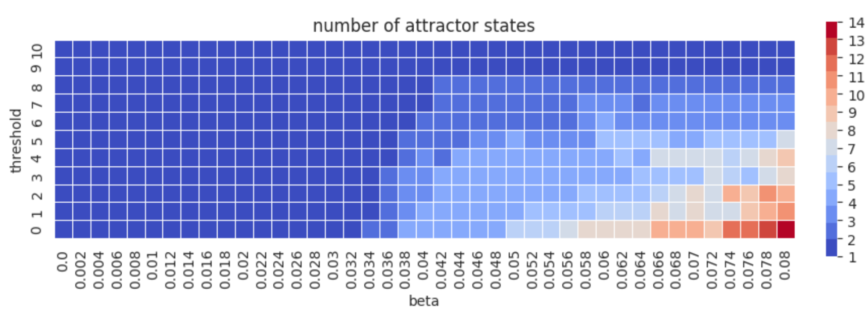

Figure 3: **Parameter sweep of fcHNN parameters threshold and beta.** the number of attractor states is color-coded. See supplemental_material.ipynb for details.

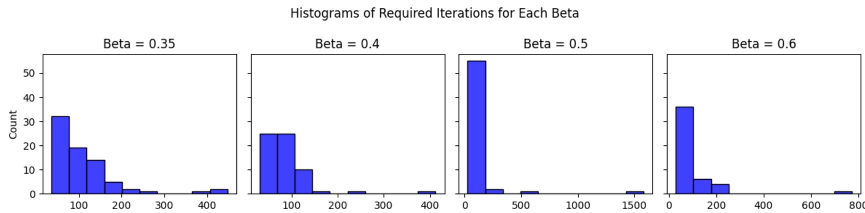

Figure 4: **HNNs initialized with the empirical connectome has better convergence properties than permutation-based null models.** Histograms show the number of iterations until convergence with the real (unpermuted) connectome, for 100 random initializations, with various beta values. HNN models based on the permuted connectivity matrix (with retaining symmetry) did not reach convergence in 10000 iterations in more than 98% of the same random initializations. See convergence-analysis.ipynb for details.

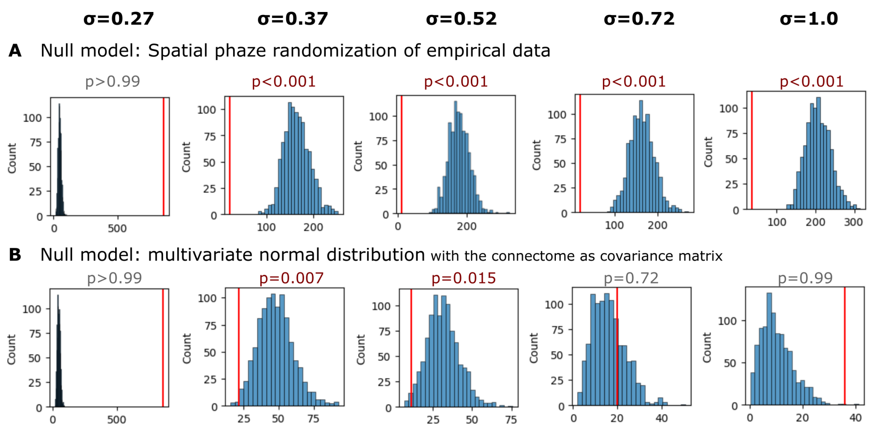

Figure 5: **Statistical inference of the fcHNN state occupancy prediction with different null models. A** Results with a spatial autocorrelation-preserving null model for the empirical activity patterns. See null_models.ipynb for more details. **B** Results where simulated samples are randomly sampled from a multivariate normal distribution, with the functional connectome as the covariance matrix, and compared to the fcHNN performance. See supplemental_material.ipynb for details.

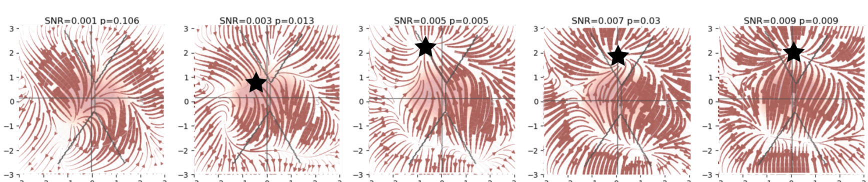

Figure 6: **FcHNN can reconstruct the pain "ghost attractor".** Signal-to-noise values range from 0.003 to 0.009. Asterisk denotes the location of the simulated "ghost attractor". P-values are based on permutation testing, by randomly changing the conditions in a per-participant basis. See main_analyses.ipynb for more details.

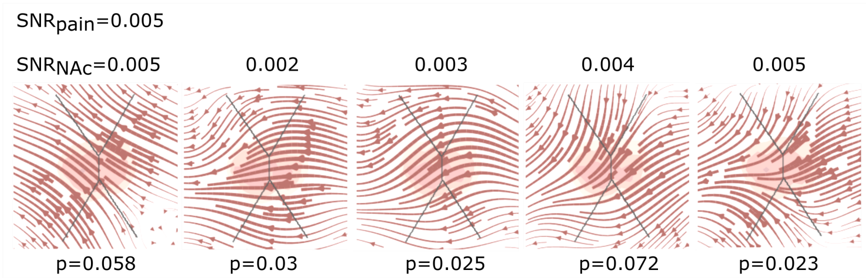

Figure 7: **FcHNN can reconstruct the changes in brain dynamics caused by the voluntary donwregulation of pain (as contrasted to upregulation)** Signal-to-noise values range from 0.001 to 0.005. P-values are based on permutation testing, by randomly changing the conditions in a per-participant basis. See main_analyses.ipynb for more details.

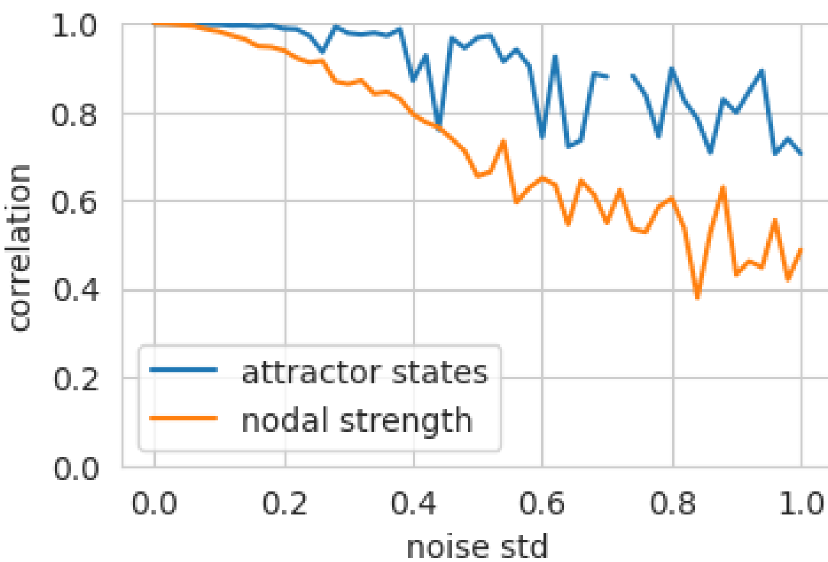

Figure 8: **Robustness of the fcHNN weights to noise.** We set the temperature of the fcHNN, so that two attractor states emerge and iteratively add noise to the connectome. To account for the change in dynamics, we adjust the temperature (beta) of the noisy fcHNN so that exactly two states emerge. We then highlight the decrease in nodal strength of the noisy connectome (the fcHNN weights) as a reference metric vs the correlation of the attractor states that emerge from the noisy connectome. See supplemental_material.ipynb for details.

Table 1: **Neurosynth meta-analyses.** The table includes details about the term used for the automated meta-analyses, as well as the number of studies included in the meta-analysis, the total number of reported activations and the maximal Z-statistic from the meta-analysis.

search term	num. studies	num. activations	max. Z
pain	516	23295	14.8
motor	2565	109491	22.5
auditory	1252	46557	25.3
visual	3110	115726	15.4
face	896	31842	26.8
autobiographical	143	7251	15.7
theory of mind	181	7761	15.1
sentences	356	13461	16.5

label	state	region	effect size	p value
4	execution	POSTERIOR_CINGULATE_CORTEX	0.109	<0.0001
3	execution	INFERIOR_MARGINAL_SULCUS	0.098	<0.0001
2	execution	CINGULATE_SULCUS_posterior	0.092	<0.0001
1	execution	SOMATOMOTOR_NETWORK_mediolateral	0.08	0.00976
0	execution	SOMATOMOTOR_NETWORK_medial	0.074	0.01952
11	internal	HESCHLS GYRUS	-0.126	<0.0001
9	internal	SOMATOMOTOR_NETWORK_mediolateral	-0.099	0.00976
12	internal	SUPERIOR_TEMPORAL_GYRUS_middle	-0.098	<0.0001
10	internal	FRONTAL_EYE_FIELD	-0.095	<0.0001
7	internal	left_SOMATOMOTOR_NETWORK_dorsolateral	-0.094	0.00976
5	internal	PERIGENUAL_ANTERIOR_CINGULATE_CORTEX	-0.087	0.03904
8	internal	SOMATOMOTOR_NETWORK_medial	-0.082	0.01952
13	internal	LATERAL_VISUAL_NETWORK_ventroposterior	0.077	0.02928
6	internal	SUPERIOR_TEMPORAL_GYRUS_anterior	-0.069	0.02928
21	external	left_MIDDLE_FRONTAL_GYRUS_posterocaudal	-0.092	<0.0001
18	external	POSTERIOR_CINGULATE_CORTEX	-0.089	<0.0001
15	external	CEREBELLUM_VIIb_medial	-0.084	<0.0001
28	external	INFERIOR_TEMPORAL_GYRUS	-0.073	<0.0001
20	external	PRECUNEUS_ventral	-0.067	<0.0001
24	external	left_INFERIOR_FRONTAL_SULCUS	-0.062	<0.0001
26	external	DORSOMEDIAL_PREFRONTAL_CORTEX_posterior	-0.06	<0.0001
29	external	SUPERIOR_TEMPORAL_GYRUS_middle	0.058	<0.0001
25	external	right_SUPERIOR_FRONTAL_SULCUS	-0.058	<0.0001
22	external	left_MIDDLE_FRONTAL_GYRUS_posterorostral	-0.058	<0.0001
30	external	MEDIAL_VISUAL_NETWORK_anterodorsal	0.056	<0.0001
16	external	PARIETO_OCCIPITAL_SULCUS_ventral	0.052	<0.0001
17	external	left_MIDDLE_TEMPORAL_GYRUS_posterior	-0.051	<0.0001
23	external	right_MIDDLE_FRONTAL_GYRUS_posterior	-0.051	<0.0001
14	external	left_CEREBELLUM_CRUSII_anterior	-0.048	0.00976
19	external	left_INFERIOR_PARIETAL_LOBULE	-0.047	0.03904
27	external	CAUDATE_NUCLEUS_HEAD_and_NUCLEUS_ACCUMBENS	-0.043	0.00976
32	perception	CEREBELLUM_VIIb_medial	0.104	<0.0001
43	perception	INFERIOR_TEMPORAL_GYRUS	0.091	<0.0001
37	perception	left_MIDDLE_FRONTAL_GYRUS_posterocaudal	0.088	<0.0001
34	perception	POSTERIOR_CINGULATE_CORTEX	0.08	<0.0001
40	perception	left_INFERIOR_FRONTAL_SULCUS	0.066	<0.0001
45	perception	MEDIAL_VISUAL_NETWORK_anterodorsal	-0.065	<0.0001
36	perception	PRECUNEUS_ventral	0.064	<0.0001
38	perception	left_MIDDLE_FRONTAL_GYRUS_posterorostral	0.063	<0.0001
33	perception	left_MIDDLE_TEMPORAL_GYRUS_posterior	0.05	<0.0001
44	perception	MEDIODORSAL_VISUAL_NETWORK_posterior	-0.049	0.02928
31	perception	left_CEREBELLUM_CRUSII_anterior	0.048	0.02928
41	perception	right_SUPERIOR_FRONTAL_SULCUS	0.046	<0.0001
39	perception	right_MIDDLE_FRONTAL_GYRUS_posterior	0.046	0.02928
35	perception	left_INFERIOR_PARIETAL_LOBULE	0.045	<0.0001
42	perception	CAUDATE_NUCLEUS_HEAD_and_NUCLEUS_ACCUMBENS	0.044	<0.0001

Figure 9: **All significant differences of the mean state activation analysis on the ABIDE dataset; label denotes the region in the BASC122 atlas.** See supplemental_material.ipynb for details.

much like turning up the volume dial on a stereo. As you feel the pain rise in intensity, imagine it rising faster and faster and going higher and higher. Picture your skin being held up against a glowing hot metal or fire. Think of how disturbing it is to be burned, and visualize your skin sizzling, melting and bubbling as a result of the intense heat."

Study 4 instructions for downregulation. *"During this scan, we are going to ask you to try to imagine as hard as you can that the thermal stimulations are less painful than they are. Focus on the part of the sensation that is pleasantly warm, like a blanket on a cold day. You can use your mind to turn down the dial of your pain sensation, much like turning down the volume dial on a stereo. As you feel the stimulation rise, let it numb your arm, so any pain you feel simply fades away. Imagine your skin is very cool, from being outside, and think of how good the stimulation feels as it warms you up."*