

Parallel detection of theta and respiration-coupled oscillations throughout the mouse brain

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Supporting Information

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Abbreviations: ACC: anterior cingulate cortex; AMYG: amygdala; Coh: coherence; dHIP: dorsal hippocampus; INS: insular cortex; LEC: lateral entorhinal cortex; LFP: local field potential; MD: mediodorsal thalamus; OBd: deep olfactory bulb; OBS: surface of olfactory bulb; PAC: parietal cortex; PLC: prelimbic cortex; Resp: respiration; RR: respiration-entrained rhythm; SSC: somatosensory cortex; Surrog: surrogate; θ_{ref} : theta reference signal; VC: visual cortex; vHIP: ventral hippocampus; VMC: vibrissal area of motor cortex; VPL: ventral posterior lateral thalamus.

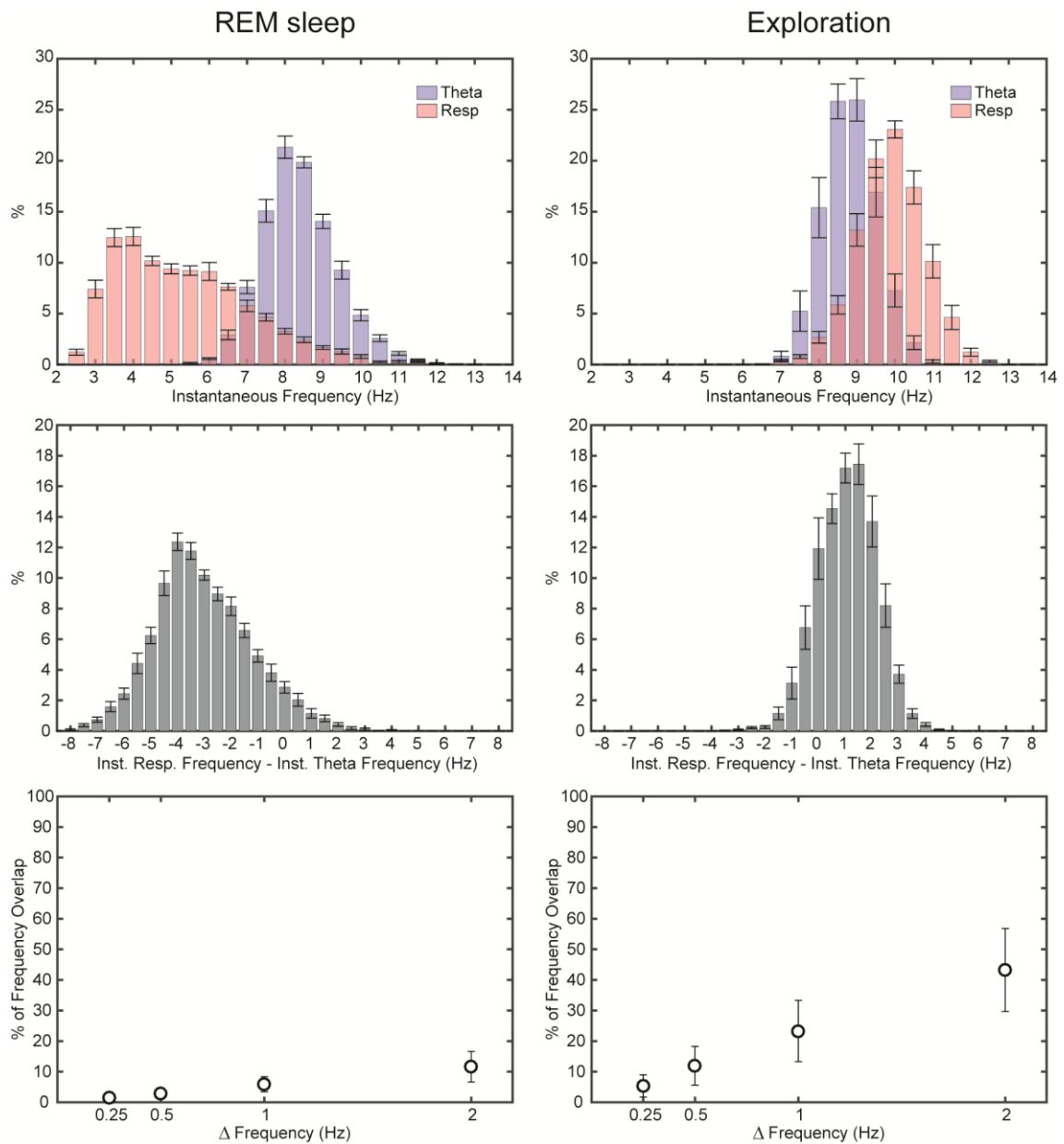


Figure S1. Theta and respiration may overlap in frequency. (Top) Distributions of the instantaneous frequencies of theta (blue) and respiration (red) during REM sleep (left) and exploration (right), computed using non-overlapping windows of 1 second (mean \pm SEM over 10 mice; bin width = 0.5 Hz). (Middle) Distribution of the instantaneous frequency difference between theta and respiration (mean \pm SEM over 10 mice; bin width = 0.5 Hz). Negative values mean respiration slower than theta. (Bottom) Percentage of frequency overlap as a function of the maximum allowed frequency difference between theta and respiration (mean \pm SD over 10 mice).

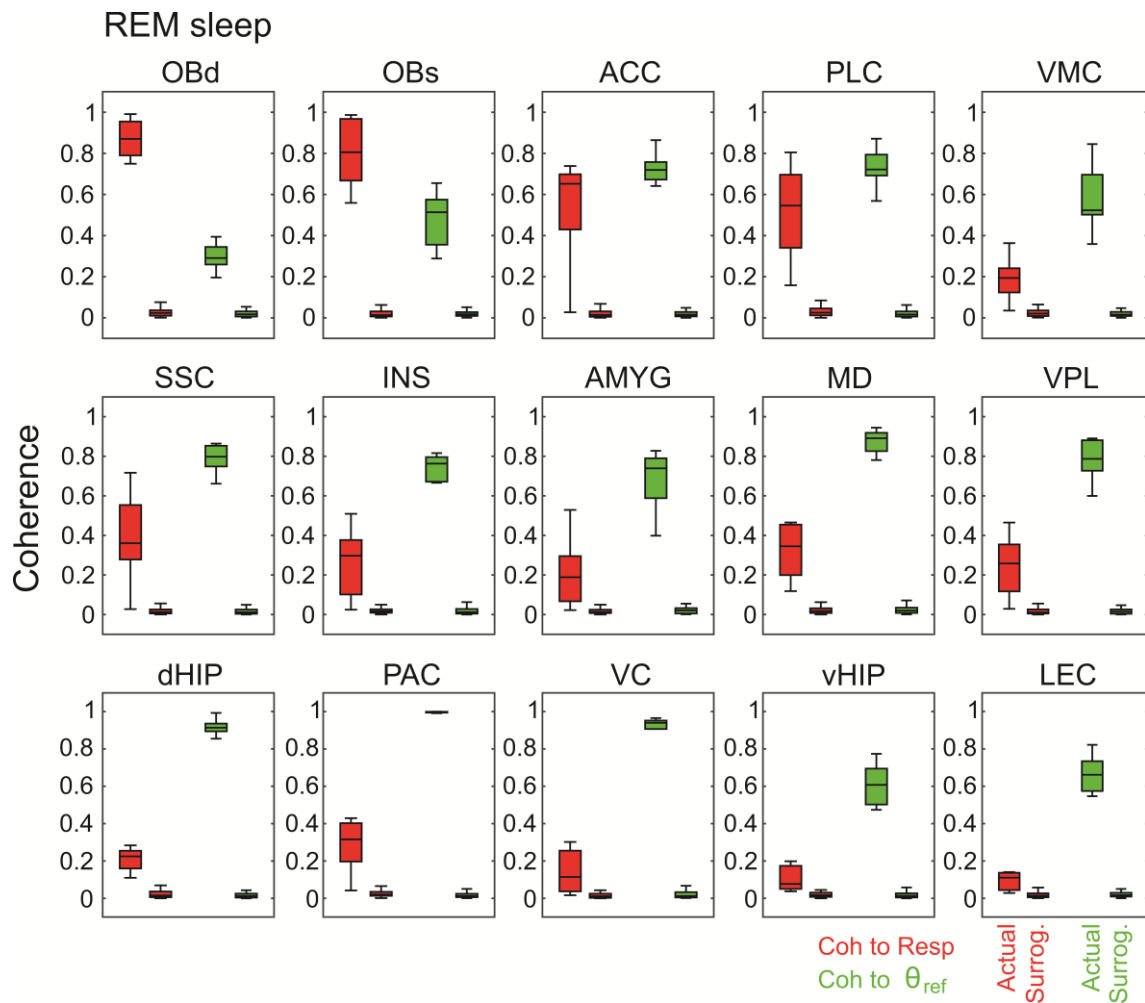


Figure S2. The levels of LFP coherence to either respiration or theta is greater than chance in all recorded regions during REM sleep. Panels show boxplot distributions of the peak coherence values for actual and surrogated data. For each region, surrogated values were obtained by computing phase coherence between the LFP recorded from one animal with the reference signal (respiration or theta) recorded from another animal (see Materials and Methods). This surrogate procedure was performed for all possible pairwise combinations (e.g., for a region with 8 mice recorded, the number of surrogate samples is $8 \times 7 = 56$). The actual and surrogate distributions statistically differ in all recorded regions for both LFP-respiration (red) and LFP-theta coherence (green). See Tables S2 and S3 for statistical analysis.

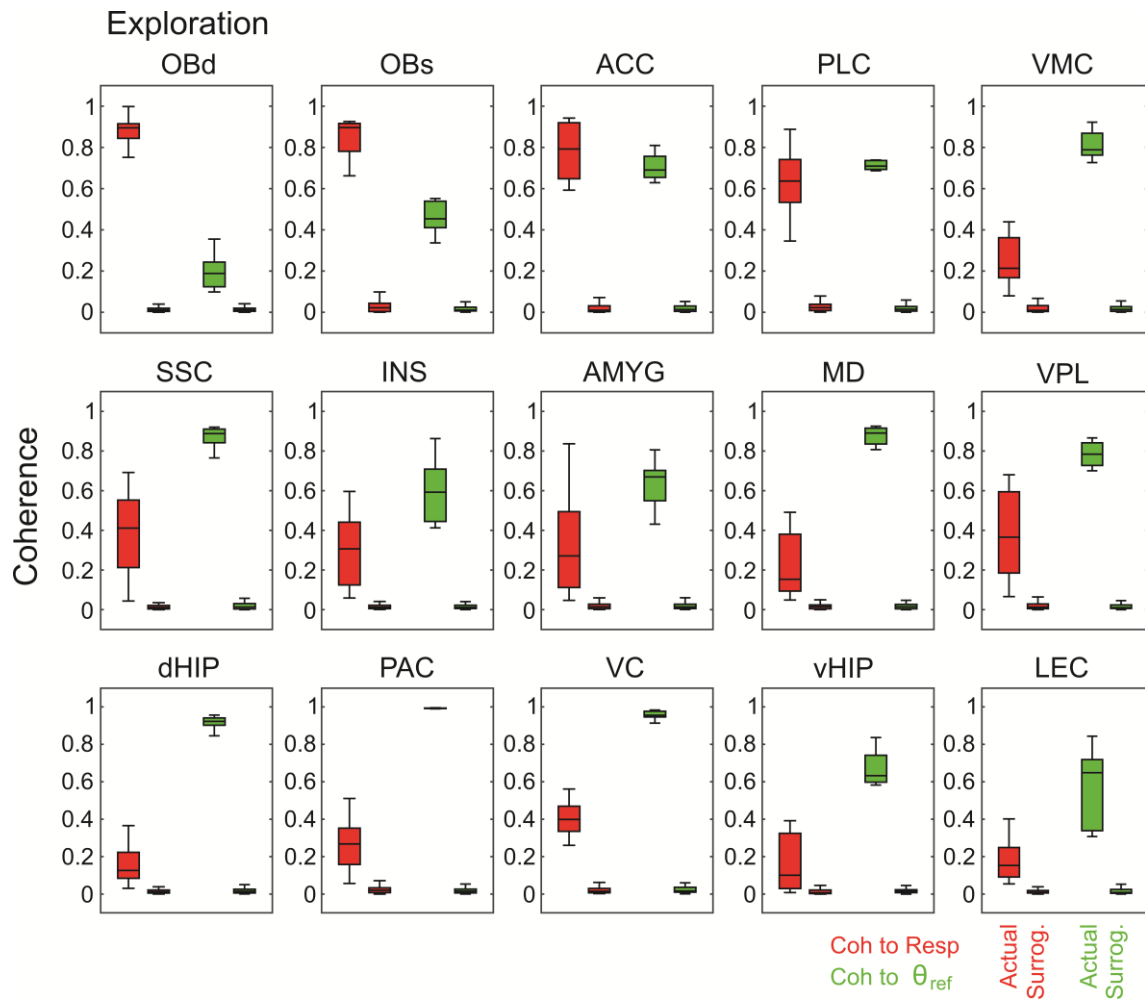


Figure S3. The levels of LFP coherence to either respiration or theta is greater than chance in all recorded regions during exploration. Panels show the same as in Figure S2, but for exploration. See Tables S4 and S5 for statistical analysis.

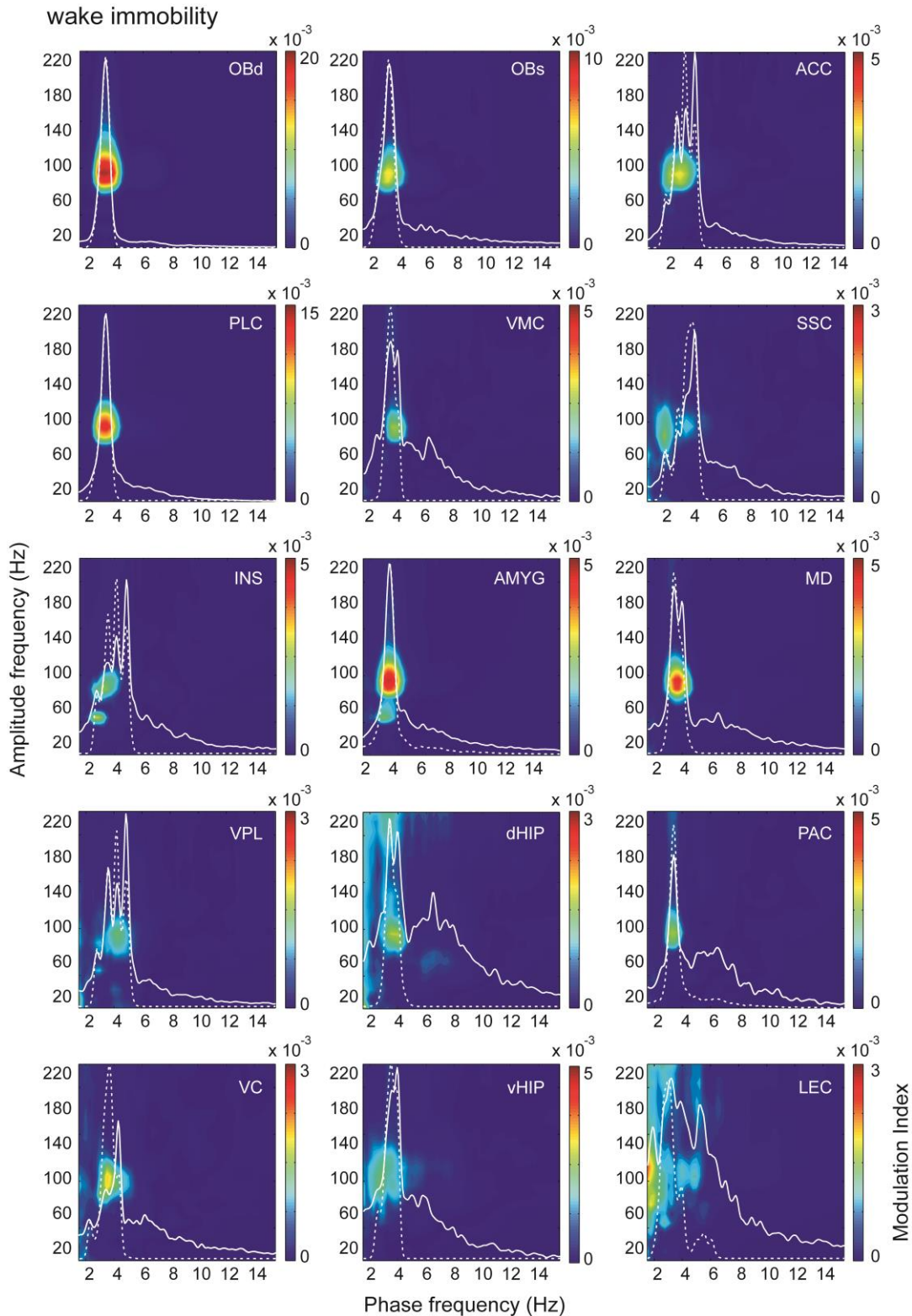


Figure S4. Phase-amplitude comodulograms computed during wake immobility for the 15 recorded regions; warm colors denote cross-frequency coupling (see ref. 10). For each region, the continuous and dashed white lines show the power spectrum of the LFP and respiration signal, respectively (plotted in an arbitrary y-axis scale). The power spectra and comodulograms are group averages. Notice modulation of ~ 70 -120 Hz gamma oscillations by respiration in several brain regions.

Table S1: Analyzed regions per animal and behavioral state

| Animal # | REM sleep | Exploration |
|----------|------------------------------------|---|
| 1 | | VC |
| 2 | dHIP, OBs, VC | VC |
| 3 | VC | VC |
| 4 | VC | VC |
| 5 | VC | dHIP, PAC, PLC, VC |
| 6 | dHIP, VC | |
| 7 | VC | VC |
| 8 | LEC, PAC | LEC, OBs |
| 9 | LEC, OBs | LEC |
| 10 | | LEC |
| 11 | dHIP, LEC | LEC |
| 12 | LEC, OBs | LEC |
| 13 | dHIP, LEC | LEC |
| 14 | dHIP, LEC | LEC |
| 15 | LEC | dHIP, LEC, OBs, PAC, PLC |
| 16 | | VC |
| 17 | LEC, VMC | |
| 18 | MD, PLC, VMC | MD |
| 19 | | vHIP |
| 20 | | vHIP, VMC |
| 21 | PLC, VMC | OBd, VMC |
| 22 | MD, vHIP, VMC | dHIP, MD, OBd, OBs, PAC, PLC, vHIP, VMC |
| 23 | MD, vHIP, VMC, OBs | OBd, vHIP, VMC |
| 24 | MD, dHIP, VMC, OBs | vHIP, VMC |
| 25 | | vHIP, VMC |
| 26 | OBd, OBs, PAC, vHIP, VMC | vHIP, VMC |
| 27 | MD, OBd, vHIP, VMC | MD, OBd, vHIP, VMC |
| 28 | AMYG | |
| 29 | ACC, AMYG, OBd, SSC, VPL | ACC, AMYG, INS, VPL |
| 30 | | AMYG, SSC |
| 31 | ACC, INS, SSC | |
| 32 | | ACC, INS, SSC, VPL |
| 33 | ACC, INS, SSC, PLC, VPL | ACC, INS, SSC, VPL |
| 34 | ACC, PAC, SSC | ACC, AMYG, INS, SSC, VPL |
| 35 | ACC, AMYG, INS, OBd, VPL | ACC, AMYG, INS, OBd, SSC, VPL |
| 36 | ACC, AMYG, INS, SSC, VPL | ACC, AMYG, INS, SSC, VPL |
| 37 | INS, VPL | |
| 38 | AMYG, INS, OBd, SSC, VPL | |
| 39 | ACC, AMYG, INS, SSC, VPL | ACC, AMYG, INS, SSC, VPL |
| 40 | ACC, AMYG, INS, OBd, PAC, SSC, VPL | ACC, AMYG, INS, SSC, VPL |
| 41 | MD | MD, dHIP, OBs, PAC, PLC |
| 42 | MD, OBs | MD, dHIP, OBs, PAC, PLC |
| 43 | PLC | MD, dHIP, OBs, PAC, PLC |
| 44 | dHIP, PLC | MD, dHIP, OBs, PAC, PLC |
| 45 | MD, dHIP, PAC, PLC | MD, dHIP, OBs, PAC, PLC |
| 46 | OBd, PLC | |
| 47 | VC | |
| 48 | PAC | |
| 49 | vHIP | |
| 50 | PAC | |
| 51 | vHIP | |
| 52 | vHIP | |
| 53 | PAC, vHIP | |
| 54 | | OBd |
| 55 | | OBd |
| 56 | PLC | |
| 57 | OBd, OBs | OBd |

Table S2: LFP-Resp coherence during REM sleep

| Region | Mean Coherence | | 99% Confidence Interval of ΔCoh | <i>P</i> |
|-------------|----------------|-----------|---|----------|
| | Actual | Surrogate | | |
| OBd | 0.871 | 0.034 | 0.793-0.882 | <0.0001 |
| OBs | 0.803 | 0.019 | 0.726-0.842 | <0.0001 |
| ACC | 0.541 | 0.021 | 0.432-0.607 | <0.0001 |
| PLC | 0.516 | 0.034 | 0.400-0.564 | <0.0001 |
| VMC | 0.191 | 0.026 | 0.115-0.214 | <0.0001 |
| SSC | 0.391 | 0.018 | 0.297-0.448 | <0.0001 |
| INS | 0.261 | 0.021 | 0.179-0.301 | <0.0001 |
| AMYG | 0.207 | 0.020 | 0.128-0.246 | <0.0001 |
| MD | 0.323 | 0.026 | 0.244-0.349 | <0.0001 |
| VPL | 0.244 | 0.016 | 0.175-0.280 | <0.0001 |
| dHIP | 0.209 | 0.022 | 0.159-0.214 | <0.0001 |
| PAC | 0.288 | 0.028 | 0.208-0.311 | <0.0001 |
| VC | 0.140 | 0.020 | 0.056-0.184 | <0.0001 |
| vHIP | 0.126 | 0.020 | 0.065-0.148 | <0.0001 |
| LEC | 0.116 | 0.017 | 0.058-0.139 | <0.0001 |

Table S3: LFP-Theta coherence during REM sleep

| Region | Mean Coherence | | 99% Confidence Interval of ΔCoh | <i>P</i> |
|-------------|----------------|-----------|---|----------|
| | Actual | Surrogate | | |
| OBd | 0.297 | 0.022 | 0.246-0.305 | <0.0001 |
| OBs | 0.479 | 0.020 | 0.413-0.506 | <0.0001 |
| ACC | 0.726 | 0.022 | 0.671-0.736 | <0.0001 |
| PLC | 0.732 | 0.022 | 0.672-0.747 | <0.0001 |
| VMC | 0.582 | 0.024 | 0.491-0.626 | <0.0001 |
| SSC | 0.791 | 0.019 | 0.741-0.803 | <0.0001 |
| INS | 0.743 | 0.022 | 0.689-0.753 | <0.0001 |
| AMYG | 0.683 | 0.021 | 0.610-0.714 | <0.0001 |
| MD | 0.875 | 0.023 | 0.824-0.879 | <0.0001 |
| VPL | 0.785 | 0.022 | 0.719-0.807 | <0.0001 |
| dHIP | 0.917 | 0.016 | 0.882-0.920 | <0.0001 |
| PAC | 0.996 | 0.017 | 0.966-0.993 | <0.0001 |
| VC | 0.917 | 0.023 | 0.857-0.931 | <0.0001 |
| vHIP | 0.607 | 0.020 | 0.543-0.631 | <0.0001 |
| LEC | 0.624 | 0.021 | 0.528-0.678 | <0.0001 |

Table S4: LFP-Resp coherence during Exploration

| Region | Mean Coherence | | 99% Confidence Interval of ΔCoh | <i>P</i> |
|--------|----------------|-----------|---|----------|
| | Actual | Surrogate | | |
| OBd | 0.882 | 0.017 | 0.835-0.896 | <0.0001 |
| OBs | 0.847 | 0.028 | 0.778-0.860 | <0.0001 |
| ACC | 0.726 | 0.019 | 0.615-0.798 | <0.0001 |
| PLC | 0.632 | 0.029 | 0.541-0.666 | <0.0001 |
| VMC | 0.280 | 0.019 | 0.194-0.330 | <0.0001 |
| SSC | 0.386 | 0.015 | 0.296-0.446 | <0.0001 |
| INS | 0.300 | 0.017 | 0.215-0.350 | <0.0001 |
| AMYG | 0.330 | 0.019 | 0.216-0.404 | <0.0001 |
| MD | 0.224 | 0.017 | 0.145-0.269 | <0.0001 |
| VPL | 0.379 | 0.020 | 0.279-0.440 | <0.0001 |
| dHIP | 0.158 | 0.016 | 0.101-0.183 | <0.0001 |
| PAC | 0.266 | 0.027 | 0.182-0.295 | <0.0001 |
| VC | 0.405 | 0.023 | 0.335-0.430 | <0.0001 |
| vHIP | 0.164 | 0.014 | 0.092-0.207 | <0.0001 |
| LEC | 0.180 | 0.014 | 0.124-0.209 | <0.0001 |

Table S5: LFP-Theta coherence during Exploration

| Region | Mean Coherence | | 99% Confidence Interval of ΔCoh | <i>P</i> |
|--------|----------------|-----------|---|----------|
| | Actual | Surrogate | | |
| OBd | 0.196 | 0.015 | 0.149-0.212 | <0.0001 |
| OBs | 0.462 | 0.018 | 0.412-0.476 | <0.0001 |
| ACC | 0.705 | 0.019 | 0.657-0.715 | <0.0001 |
| PLC | 0.689 | 0.020 | 0.629-0.711 | <0.0001 |
| VMC | 0.811 | 0.018 | 0.764-0.821 | <0.0001 |
| SSC | 0.871 | 0.019 | 0.824-0.878 | <0.0001 |
| INS | 0.596 | 0.017 | 0.522-0.635 | <0.0001 |
| AMYG | 0.635 | 0.020 | 0.568-0.661 | <0.0001 |
| MD | 0.877 | 0.023 | 0.822-0.886 | <0.0001 |
| VPL | 0.756 | 0.018 | 0.693-0.784 | <0.0001 |
| dHIP | 0.917 | 0.018 | 0.879-0.917 | <0.0001 |
| PAC | 0.992 | 0.017 | 0.964-0.987 | <0.0001 |
| VC | 0.956 | 0.024 | 0.909-0.954 | <0.0001 |
| vHIP | 0.643 | 0.018 | 0.574-0.676 | <0.0001 |
| LEC | 0.570 | 0.019 | 0.477-0.626 | <0.0001 |