Supplemental Information

Inducing Gamma Oscillations and Precise Spike Synchrony by Operant Conditioning via Brain-Machine Interface

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Supplemental Figures

**Figure S1** (related to Figure 2)

Task Performance across sessions. (A) Mean power (30-43 Hz band) of the conditioned sites across sessions for the conditioned (green) and pre-conditioning movement (magenta) blocks (Monkey M). Mean power during conditioning increased toward the later sessions, and exhibited improved performance (Pearson $\rho=0.81$, $p<6\times10^{-7}$). Power in the pre-conditioning movement block did not change significantly (Pearson $\rho=-0.28$, but $p>0.15$). However, day-to-day fluctuations present in both were ameliorated by calculating the ratio (Figure 2C, main text). (B) Average reward rate across sessions (cyan) and average power required for reward (black). The power required for reward delivery (power threshold) was manually tuned during the session. Average reward rate was maintained between 3 and 5 per minute, and as the monkeys gained proficiency the power threshold was raised accordingly.
Figure S2 (related to Figure 4)

Averages over all successful conditioning days showing low-\(\gamma\) oscillations in the LFP during conditioning. The traces are shown for one conditioned site. (A) Average LFP traces preceding reward in the pre-conditioning movement (magenta), pseudo-conditioning (yellow) and conditioning (green) blocks. s.e.m. is in light shading (see Experimental Procedures for the averaging procedure). Time 0 is the first peak of the gamma cycle (phase=0) around 500 ms before reward onset. The red horizontal bar indicates range of times of reward delivery. Data averaged over all successful conditioning days for monkey M (B) Average and s.e.m. of power spectra of LFP traces preceding reward for the 3 blocks, averaged over all successful conditioning days for monkey M. (C) same as A, for monkey Q. (D) same as B, for monkey Q.
Figure S3 (related to Figure 7)

EMG recordings and firing rate changes during conditioning. (A) A single trial in the pre-conditioning movement block. The upper left panel shows the LFP from a single conditioned site. The lower left panel shows the cursor distance from the center of the workspace. The rest of the panels show EMG recordings from wrist flexors, wrist extensors, biceps and triceps (traces were normalized by the maximum value after smoothing for each electrode). Time 0 is movement onset. (B) Same as A, but for a single trial in the conditioning block. The Y-axis for the EMG recording panels is the same as in A. Time 0 is target reach. The recordings show no involvement of these arm
muscles during the generation of the low-γ oscillations. (C) Differences of the mean firing rate in the High and Low Power periods for all single units (n=218). Significant differences (p<0.0001, Bonferroni corrected, two-tailed t-test) are shown in black. While many units had significantly different firing rates in the two periods, most of these differences were negative (i.e., the firing rate in the High Power period was lower). However, the mean difference across the population was -0.74 Hz, not significantly different from zero (p>0.17, two-tailed t-test). (D) Same as C, but only for units that were part of a pair that exhibited a significant increase in CCH peak. Most of these units fired less in the High Power period, and the mean difference across the population was -2.11 Hz; not significantly different from zero (p>0.012, two-tailed t-test). Thus the increased synchrony in the High Power period was unlikely to result in increases in the firing rate of the units.
Figure S4 (related to Figure 8)

Spatiotemporal evolvement of low-gamma power across the array and its relationship with single-unit phase locking. (A) The 9 panels show snapshots of the mean low-$\gamma$ power for a single session of monkey Q across the array at different times in the trial, aligned to reward delivery. The conditioned sites are circled in white. Black squares represent either non-recording or damaged electrodes. Similarly to monkey M, the power increased earlier around the conditioned sites, and more gradually for more distant electrodes. The orientation of the increase in power was similar in all sessions for this monkey, and differed from that of monkey M. Note that for monkey Q the increase of the low-gamma power started earlier and evolved more slowly. (B) Array location and orientation in both monkeys. arc, arcuate sulcus. CS, central sulcus. sd, superior dimple. (C) Scatter of the mean 30-43 Hz band power of LFP recorded from electrodes as a function of the mean PLI of the units in the corresponding electrode, in the 500 ms preceding reward (Conditioning block). The correlation coefficient was 0.71. Data were taken only for successful sessions (see Experimental Procedures). Data are from money Q. (D) Same as C, for monkey M.
Supplemental Experimental Procedures

Phase Locking Index (PLI)

We first calculated the low-\(\gamma\) phases (\(\theta\)) at spike times for single units in the High and Low Power periods. The PLI in each period was calculated as (Lachaux et al., 1999):

\[
\frac{1}{N} \left| \sum_{j=1}^{N} \exp(i\theta_j) \right|
\]

(where \(i = \sqrt{-1}\)). To obtain an unbiased measure with regard to the number of spikes (van Wingerden et al., 2010), we fixed \(N\) to be 100 (units with fewer than 100 spikes in either period were disregarded). We randomly drew 10000 samples of 100 spikes, calculated the PLI for each sample, and averaged the results for the final PLI.

Changes in synchronization of LFPs between the High and Low Power periods

For each electrode, the average CC between its LFP and the LFP traces of the 4 conditioned sites was calculated in the High and low Power period using Fisher’s Z transform. CCs were computed separately in the High and Low power periods. To assess the difference between them, we calculated the Fisher transform of the CCs, subtracted the value obtained in the Low Power period from that of the High Power period, and used the inverse Fisher transform to obtain differences in the correlation domain. Non-significant changes (\(p > 0.001\), two-tailed t-test, Bonferroni corrected, the t-test was done over the Fisher Z transform of the CCs) were designated as 0. For the
conditioned sites, the average was computed across the change in correlations of each electrode with the 3 other conditioned sites. To compute the correlation between the topological structure of LFP CC changes and that of the low-\(\gamma\) power we computed the average low-\(\gamma\) power in the High Power period across the array for all successful conditioning days of each of the monkeys. We then calculated the correlation between the low-\(\gamma\) power and LFP CC changes across electrodes.

**Supplemental References**