Supporting Information

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SI Methods

Behavioral Task. All training and recording sessions were conducted with the rats on an elevated T-maze described previously (1). Photobeam units were placed along the outer walls of the maze, allowing the detection of behavioral events, which were stored with time-stamps synchronized with those for the spike and local field potential (LFP) data. Each trial on the T-maze task began with a warning click signaling the beginning of the trial. After the click, a gate was manually swung into place, allowing the animal to run down the central arm of the maze. Approximately half-way down the maze, rats broke a photobeam that in turn triggered either a 1-kHz or 8-kHz tone. The frequency of the tone was associated with reward delivered at the end of either the left or right maze arm, and tone-reward contingencies were counterbalanced across rats. Four rats were trained with a chocolate sprinkles reward, and three of the rats were trained with ~0.3 cc of chocolate milk (Chug brand) as the primary reward. Preliminary analysis of data for these two reward groups indicated no significant differences in learning rates or behavior, so data from all rats were combined for all analyses reported here. Chocolate milk was delivered through a manual pump after animals completed a turn to the correct arm. For reward-delay trials, milk was delivered through automated pumps that were triggered 2 s after the goal-reaching photobeam was broken. After 10 consecutive days of overtraining, these rats were switched to a tactile version of the task (not reported here).

LFP Data Collection and Analysis. Neural signals were amplified (gain: 1,000), filtered (1–475 Hz) and sampled at 1 kHz by Cheetah data acquisition system (Neuralynx). All LFPs were referenced to the recording system ground point, which was also connected to the animal via a skull screw. The spectral content of the LFP signals was analyzed using open-source Chronux algorithms (http://chronux.org), in-house software, and the Matlab Signal Processing Toolkit (MathWorks). Spectrograms were constructed by the multitaper method (2), with three tapers, time bandwidth product of 2, and window width of 0.75 s. Trial-averaged spectrograms that show multiple alignment events were spliced together from separate spectrograms for each alignment event; for each successive pair of events, the splice point was placed at the center of the median interevent-interval. For computing average power around events (Fig. 1C), power in the β-band (15–28 Hz) was averaged for each session (across 40 trials) and then was normalized by converting it to z-scores relative to β-power in all other peri-event windows. All sessions for all rats were then combined separately for correct and incorrect trials. For calculating correlations of β- and γ- (70–90 Hz) power with performance (Fig. 3 G and H), power was first averaged across tetrodes for each session in one of two windows: 3 s before goal reaching or 0 to 1 s after goal-reaching. The z-scores were computed for each session relative to the set of mean power values in the pregoal or postgoal window for each individual rat. The same number of randomly selected correct trials (n = 18) was averaged for each session analyzed. Normalized values for all sessions were then combined across rats to compute linear correlations with performance. High-amplitude β- and γ-oscillations used for spike alignment and synchrony analysis were identified by first band-pass filtering single-trial LFP traces in the β- or γ-range, and then their voltage values were converted to z-scores for each trial separately. Peaks were identified where the normalized trace crossed a threshold of >2.5 SD above the trial mean. Peaks were considered members of individual bursts if

consecutive threshold crossings were separated by at least one oscillation cycle. Only the largest positive going peak of each identified burst was used for analysis. Phase synchrony across LFPs (Fig. 5) was assessed by first identifying the tetrode with the highest-amplitude peak during each identified burst. This tetrode served as the reference for computing phase differences between LFPs on other tetrodes. For convention, this reference phase was set to 90°. Phases on other tetrodes, relative to the peak time for the peak-reference electrode, were calculated using a Hilbert transform on each band-pass filtered trace. These phase values were used to construct the phase difference histograms in Fig. 5.

Spike Data Collection and Analysis. Signals for spike collection were amplified (gain: 2,000–10,000), band-pass filtered (600–6,000 Hz) and sampled at 32 kHz before offline storage. Manual spike sorting for single unit separation was performed using Offline Sorter (Plexon v. 2.8.7, Plexon). After sorting, units were classified as putative medium spiny projection neurons (MSNs), fast-spiking interneurons (FSIs), or tonically active neurons (TANs) by manual examination of interspike intervals (ISIs) and firing rates (3). In general, putative MSNs were easily distinguishable from putative FSIs by their significantly lower baseline firing rates and greater proportion of ISIs >100 ms (Fig. S3). TANs had firing rates intermediate to MSNs and FSIs; these made up a small proportion of our dataset and were not included in the analysis.

Significant modulation of single units was determined using circular statistics on phase histograms. To construct phase histograms (Figs. 4 and 6), instantaneous phases of the band-pass filtered trace for β- and γ-oscillations were determined using a Hilbert transform and spiking was binned by phase (18 degrees per bin) in a window ±150 ms around the peaks of high-amplitude β- and γ-events recorded on the same tetrode as the spikes. The phase distribution for each unit was then tested for uniformity with a Rayleigh test ($P < 0.05$) to identify significant modulation of individual unit spiking by high-amplitude β- or γ-bursts. For determining whether spikes align also to phases of LFPs recorded on spatially separated tetrodes (Fig. 6 C and D), spike-phase histograms were constructed around band-pass filtered LFPs on a randomly chosen tetrode that was different from the one on which the spikes were recorded. Average phase histograms were constructed by computing z-scores for the binned spike counts of each unit relative to the mean and SD of the bin counts for that unit. The mean and SE of the z-scores were computed for each bin across all significantly modulated units. Statistical differences between the strength of average z-score–normalized phase distributions (Fig. 6 C and D) were computed by performing a Kruskal-Wallis test on the absolute values of the average z-score–normalized distributions (local vs. nonlocal for β and γ separately). Spike histograms around burst peaks (Fig. 6 A and B) were constructed by aligning spiking on the peaks of accepted β- and γ-bursts (bin size = 3 ms for β, 2 ms for γ). For the population average, firing rates were converted to z-scores relative to the mean and SD of each unit's distribution. Histograms were then averaged across units and scaled to the absolute value of the minimum of the distribution. To test whether spikes from a particular unit were aligned with peaks of bursts on tetrodes that did not record the unit spiking (Fig. 6 A and B), spikes were aligned to burst peaks from randomly chosen tetrodes. Significant differences between local (Fig. 6 A and B, *Middle*) and nonlocal (Fig. 6 A and B, *Bottom*) histograms were com-

puted by first determining the highest normalized firing rates for each unit around the peak of the β- or γ-burst. The baseline z-score (200–300 ms before burst peak) for each unit was then subtracted from the maximum z-score for that unit. A two-tailed t test was then conducted to compare the mean of all baseline subtracted maximum z-scored firing rates in the local condition with the mean of the maximum z-scored firing rates in the nonlocal condition for β and γ independently. Spike-spike coherence was computed as follows (Fig. S5). First, each spike train was converted to a continuously sampled channel at the same sample rate as the LFPs by placing a 1 at the sample closest to each spike and zeros elsewhere. Then the multitaper coherence between the converted spike trains was calculated over a set of 600-ms wide windows centered on the previously marked burst peaks. This process was performed for each pair of simultaneously recorded β-modulated FSIs over all bursts.

Histology. Brains were fixed by transcardial perfusion with para-formaldehyde and postfixed in 4% paraformaldehyde in 0.1 M $NaKPO_4$ buffer, and 30-μm thick transverse sections were cut on a freezing microtome and were stained with Cresylecht violet to allow reconstruction of the recording sites.

1. Barnes TD, Kubota Y, Hu D, Jin DZ, Graybiel AM (2005) Activity of striatal neurons reflects dynamic encoding and recoding of procedural memories. *Nature* 437: 1158–1161.
2. DeCoteau WE, et al. (2007) Learning-related coordination of striatal and hippocampal theta rhythms during acquisition of a procedural maze task. *Proc Natl Acad Sci USA* 104:5644–5649.
3. Kubota Y, et al. (2009) Stable encoding of task structure coexists with flexible coding of task events in sensorimotor striatum. *J Neurophysiol* 102:2142–2160.

Fig. S1. Tetrode recording locations. Schematic transverse sections illustrating the locations of microlesions made to mark the sites of tetrodes in the ventromedial striatum. Only those for tetrodes with successful recordings are shown. Each color represents tetrode sites for a single rat (*n* = 7 total).

Fig. S2. Dynamics of β- and γ-power across learning. High-γ power (*A*) and β-power (*B*) for 20 consecutively recorded sessions in rat h21 to complement the findings illustrated in Fig. 3. Session averages are computed for 18 randomly selected correct trials for each 40-trial session.

Fig. S3. Subtypes of striatal neurons were distinguished based on firing rate and ISI distribution. Sample waveform (*Left*) and distribution of ISIs (*Right*) are shown for a putative projection neuron (*A*) and a putative FSI (*B*). Note the smaller percentage of long ISIs for the putative FSI relative to those for the putative projection neuron.

Fig. S4. Pairs of simultaneously recorded FSIs are coherent at β-frequency. Average spike-spike coherence for all pairs of β-modulated FSIs that were recorded on different tetrodes simultaneously in single training sessions (*n* = 21 pairs). Coherence was computed for periods of ±300 ms around peaks of high-amplitude β-bursts. Shading represents SEM.

Fig. S5. FSIs are synchronized during high-amplitude β-bursts around each task event analyzed. (*A*) β-Burst probability during 10-ms wide bins centered around successive task events in the maze task trial and session averaged across all rats. Bursts were identified by periods during which the *z*-score–normalized band-pass filtered trace exceeded 2.5 SDs above the mean for the trial. (*B*) Averaged *z*-score–normalized spike histograms aligned to peaks of β-bursts around each task-event, as shown in *A*, for all β-modulated FSIs (*n* = 163) (see Fig. 6 for detail) across all rats and sessions combined. Modulated FSIs fire around the troughs of the β-bursts occurring around each task-event examined.