Supplementary Information for

Action-driven remapping of hippocampal neuronal populations in jumping rats

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Supplementary Information Text

Animal handling and behavioral training

Four adult Long-Evans rats, 2 males and 2 females, were used in this study. Given the few animals in each sex group, we report only combined data. Each animal was handled for 2-3 weeks daily prior to experimental training. After handling, animals were exposed to the linear maze for several days and trained to continuously alternate between the two ends. All stop locations were rewarded with 1/3 piece of Honey Nut Cheerio if animals completed a successful trial without stopping or alternating the incorrect direction. All experiments were approved by the Institutional Animal Care and Use Committee at New York University Medical Center.

Method Details

Surgical procedures

Rats were anesthetized with isoflurane and implanted with silicon probes (NeuroNexus and Cambridge NeuroTech) mounted on custom built microdrives. Each animal was implanted with
two probes in the right hemisphere, one targeting the lateral septum and one targeting dorsal CA1 region. Data on the lateral septum are not reported in this present work but details about of surgery and locations of the probes are available in (34). Briefly, during surgery implants were placed dorsal to target regions, allowing for movement into target regions after recovery from surgery. Craniotomies were sealed with sterile wax. To provide electrical shielding and mechanical protection, copper mesh was shaped around the probes and filled with dental cement. Two stainless steel screws implanted above the cerebellum were used for grounding.

Recording/Data processing
Recordings were conducted using the Intan RHD2000 interface board, sampled at 20 kHz. Amplification and digitization were done on the head stage. Waveform extraction and initial clustering was conducted using SpikeDetekt and Klustakwik. Example parameters for these algorithms can be found in the GitHub repository (https://github.com/DavidTingley/papers). Manual waveform discrimination was then conducted using the Klustaviewa software suite. Waveform amplitude was utilized during this stage to assess unit stability. Any waveforms that changed significantly throughout the duration of the recording were discarded. Waveform isolation quality was quantified using the isolation distance metric (https://github.com/buzsakilab/buzcode) and the waveform amplitude. Position was tracked with the OptiTrack camera system. IR reflective markers were mounted in unique positions on each animals’ head stage and imaged simultaneously by six cameras (Flex 3) placed above the behavioral apparatus. Calibration across cameras allowed for the three-dimensional reconstruction of the animals’ head position, and head orientation, to within 1 mm (avg. displacement error = 0.70 mm ± 1.5 mm) at 120 Hz (34).
Position data was analyzed and segmented using a custom MATLAB software suite. Only ballistic trials, without stopping or deviation from the trained trajectory, were extracted for further analysis. These trials made up ~90%–95% of all trials attempted for any given recording.

Histology
Animals were placed under anesthesia and electrolytic marker lesions were conducted (4 μA for 4 s). Animals were perfused with 4% paraformaldehyde under deep anesthesia. Brains were removed and sliced in 80 μm slices using a vibratome (Leica VT1000S). For implanted animals, a DAPI stain was used to localize probe tracks. The deepest point of lesion, combined with the record of turn depths, was used to estimate the location of each recording (34).

Jump Position
Position during each trial was smoothed using a Kalman filter. The take-off was determined by the peak of the horizontal acceleration and the landing was determined by the peak of the negative horizontal acceleration. Wait time was determined by the time spent at a speed less than 9 cm/s before the jump takeoff.
Spectral analysis
Time-frequency spectrograms were created by convolving the LFP signal with Morlet wavelets of each frequency of interest. The median spectrogram from all jump trials was computed and then log-transformed to account for 1/f slope in the power of the LFP.

The average theta frequency at the time points of interest were computed by computing the median spectrogram from each session, and then finding the frequency with the highest power at each timepoint of interest.

Population average firing rates were computed by averaging the firing rates of each neuron in 20 ms bins across each trial. The average trial firing rate of each neuron was z-scored, and the mean and standard deviation of the z-scored firing rates was computed.

Theta phase reset
Theta phase was extracted by filtering the LFP signal with a 3rd order Butterworth bandpass filter (6-13 Hz), then applying the Hilbert transform to extract just the phase. The phase was then binned into 0.1 rad bins in phase and 15 ms bins in time. Circular deviance, the circular analogue of standard deviation was measured across each time bin.

Population Vector Correlations
The firing rate of each neuron was computed in 2 cm bins and normalized by time occupancy. Neurons with an average firing rate of less than 0.01 Hz were excluded. The firing rates were then z-scored to form the population vectors. The Pearson correlation between each column of the population vectors were computed to form the population vector correlations. (68) Average population vector correlations were computed by averaging the population vector correlation values at distances of 0-150 cm.

Place fields
Place fields were determined on the linear track using a heuristic method. A place field was included if the minimum peak firing rate was 5 Hz, the place field was within 5-150 cm, and the firing rate decreased to 0.1 times the peak firing rate within the place field. Place fields on the jump trials were determined by selecting the spikes that occurred in the same location on the jump track, ±50 cm as on the running track. Place field width was determined by the distance in which 95% of spikes occur. Jump-specific cells were identified by eye. Circular-linear correlations, circular deviance, and the Rayleigh test were performed using the CircStat toolbox for circular statistics by Philipp Berens (91).

Spatial-temporal compression metrics were calculated as in (92). The distance between place field locations was calculated as the difference in peak within-field firing rates. Temporal offset between overlapping fields was determined with a 1 ms bin-sized cross-correlogram, convolved
with a 60 bin-wide Gaussian window. The phase offset was determined with a 0.01\(\pi\) bin-sized cross-correlogram convolved with a 60 bin-wide Gaussian window.
Supplemental Figure 1. Determination of spatial position during jump.
A. Horizontal position and acceleration during a jump trial. The jump time was detected using the maximum acceleration in the horizontal direction, marked by the green circle and line. The landing is denoted by the red line. B. Vertical position and acceleration during a jump trial. The landing time was detected using the maximum positive acceleration prior to a manually-selected time point, marked by the red circle and line. The green line marks the jump take-off time. Time, in seconds, is relative to the jump take-off time.

$\mu_1 = 57 \text{ cm/s}, \sigma_1 = 26, \mu_2 = 119 \text{ cm/s}, \sigma_2 = 28, n = 2360$
C. Velocity pre- and post-jump. The animal runs significantly faster after the jump than before.
D. Average velocity during each condition for one session.
E. Average acceleration during each condition for one session.

Supplemental figure 2. **Population firing rates and place cell locations.**
A. Average z-score firing rates of interneurons in CA1 and CA3. The reference time at 0 s is the jump take-off.
B. Average z-score firing rates of pyramidal cells in CA1 and CA3. The reference time at 0 s is the jump take-off. Note that both interneurons and pyramidal neurons in CA1 fire before CA3 neurons, suggesting that CA1 activity is not inherited from CA3 but are potentially driven by the entorhinal input or subcortical neuromodulatory effects.
C. Place field center-of-mass on pre-jump control trials versus post-jump control trials in CA1. Place field locations are not significantly different (Kruskal-Wallis, p = 0.76). Right: same, but for CA3 place fields (Kruskal-Wallis, p = 0.78).
D. Firing rates of place cells in CA1 from one session across conditions. Rat ran from right to left. Note partial remapping on each trial type.
Supplemental figure 3. **Persistent and novel place fields.**

A-D. Persistent place fields maintain similar characteristics on control and jump trials.

E-F. Novel place fields occur only on jump trials.
Supplemental figure 4. **Attenuated place cells.**

A-G. Attenuated place fields show decreased firing rates and place field widths during jump trials.
Supplemental figure 5. **Amplified place fields.**

A-H. Amplified place fields show increased activity during jump trials.
Supplemental figure 6. Jump-related cells.
A-D. Cells that are active before the animal jumps. 
E-G. Cells that are active during the jump. 
H-J. Cells that are active after the jump.

Supplemental figure 7. Jump-specific cell in both running directions.
A-B. A jump-specific cell that shows activity only after completing the jump, when running in both directions along the track. Only one such bidirectional jump cell was observed, while the majority of jumps cells corresponded to a conjunction of jump and position (specific for the direction of travel).
Supplemental figure 8. **Example unclassified cells.**

A-C. Cells with activity that varies with trial condition. D, E, neuron with symmetric fields.
Supplemental figure 9. **Example interneuron.**

A. B. An example CA1 interneuron with varying firing rates on control versus jump trials during both directions of travel. Most interneurons varied their firing rates with speed.
Supplemental figure 10. **Phase reset detection method.**
The raw LFP from each jump trial, centered on the jump take-off, is filtered to theta frequency (6-13 Hz), and the phase is extracted using the Hilbert transform. The theta phases are then binned and used to detect a phase reset. We define a phase reset as a unimodal deviation from uniformity in circular space, using the Rayleigh test.

Supplementary Movie 1. **Jumping the gap.**
A single trial of leftward direction of walking-jumping-walking sequence. Note the long pause and bobbing head movements prior to take off.