Synchronous Ensembles of Hippocampal CA1 Pyramidal Neurons During Novel Exploration

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Abstract

Synchronous neuronal ensembles play a pivotal role in the consolidation of long-term memory in the hippocampus. However, their organization during the acquisition of spatial memory remains less clear. In this study, we used neuronal population voltage imaging to investigate the synchronization patterns of CA1 pyramidal neuronal ensembles during the exploration of a new environment, a critical phase for spatial memory acquisition. We found synchronous ensembles comprising approximately 40% of CA1 pyramidal neurons, firing simultaneously in brief windows (~25ms) during immobility and locomotion in novel exploration. Notably, these synchronous ensembles were not associated with contralateral ripple oscillations but were instead phase-locked to theta waves recorded in the contralateral CA1 region. Moreover, the subthreshold membrane potentials of neurons exhibited coherent intracellular theta oscillations with a depolarizing peak at the moment of synchrony. Among newly formed place cells, pairs with more robust synchronization during locomotion displayed more distinct place-specific activities. These findings underscore the role of synchronous ensembles in coordinating place cells of different place fields.

Introduction

The establishment of long-term memory involves the initial acquisition and subsequent consolidation of memory traces, processes intricately connected to the modification of synaptic transmission[1,2]. Synchronous ensembles, characterized by the simultaneous firing of multiple neurons over tens of milliseconds (referred to as population synchrony), play a pivotal role in influencing synaptic plasticity[3-5]. The hippocampus, a crucial region for long-term memory formation[6,7], has been a focal point of synchronous ensemble studies. Within the hippocampus, synchronous ensembles are hypothesized to play roles in reactivating and consolidating labile memory traces[8]. However, their organization during memory acquisition remains less understood.

In the hippocampus, synchronous ensembles among CA1 pyramidal cells (CA1PCs) are predominantly observed during sharp-wave ripples, the brain waves associated with memory consolidation[8-13]. During these events, 10-18% of CA1PCs generate spikes, particularly during offline consummatory behavioral states or sleep[14,15]. These synchronous ensembles are biased toward experience-dependent reactivation, consolidating labile memory traces[16,17]. Furthermore, synchronous ensembles firing action potentials in short windows of 10-30 milliseconds enhance information processing[6] and discriminate distinct behavioral contingencies[18]. Although synchronous ensembles of CA1PCs during offline memory consolidation are well-characterized, their organization during online acquisition of spatial memory, such as when animals enter a new environment and new place cells form, remains unclear.

Previous studies have identified correlated activities among place cells during theta oscillation, where 1-3% of place cells' spikes co-activate in a forward order matching animals' trajectory in the theta cycles when animals' locations overlap in the place fields of these cells[19-21]. Because these place cells fire at distinct theta phases in the same cycle, this coordinated firing operates on the timescale of theta periods (~125ms)[22,23]. Population synchrony on shorter timescales (10-30 ms) is

52 speculated to be reduced by the presence of theta oscillations[22].

53

54 The subthreshold membrane voltage (subVm), influenced by synaptic inputs and intrinsic
55 conductances, directly triggers spiking activity[24,25]. Additionally, properties of subVm support the
56 organization of neuronal representation[26]. Although correlated membrane potentials have been
57 proposed to underlie the synchrony of neuronal ensembles[27,28], multicellular recordings of subVms
58 have not yet provided direct experimental evidence. Given the intricate interaction among subVm,
59 spiking, and place cell formation, it is crucial to investigate the temporal relationships of sub- and
60 suprathreshold neuronal activities among CA1PCs during novel exploration.

61

62 In this study, we used voltage imaging to investigate the temporal dynamics of sub- and
63 suprathreshold neuronal activities in CA1PCs during novel exploration. Additionally, we implanted
64 electrodes in the contralateral CA1 region to monitor theta and ripple oscillations. We found
65 synchronous ensembles involving approximately 40% of CA1PCs exhibited transient population
66 synchrony and correlated subthreshold membrane potentials when mice ran and stopped in a new
67 maze. Moreover, these synchronous ensembles occurred outside of contralateral ripples (c-ripples)
68 and were phase-locked to intracellular theta oscillations as well as extracellular theta oscillations
69 recorded from the contralateral CA1 region. Notably, cell pairs with stronger synchronous activities
70 established more distinct place fields that overlapped less. In essence, synchronous ensembles
71 facilitated temporal association among place cells representing diverse features of spatial memory.
72 This plastic network, driven by synchronous ensembles, may contribute to the stabilization of place
73 cells, establishing place fields that effectively tile the environment.

74

75 Results

76 To investigate the temporal relationships between neuronal activities during novel exploration, we
77 simultaneously recorded many neurons as animals explored a new environment for the first time.

78 To achieve this, we employed voltage imaging in conjunction with an air-lifted plastic track that
79 allowed mice to explore an environment while remaining head-fixed under a microscope (Figure
80 1A). To ensure a genuinely novel experience, all pre-training and habituation were performed in a
81 separate room distinct from the one where the imaging experiments were conducted. On the day of
82 imaging, the mice were introduced to the recording room for the first time and initially confined to
83 a specific corner of the track (Figure 1A top view). Subsequently, as the imaging session
84 commenced, the confinement was lifted, granting mice the freedom to explore the track while
85 imaging was conducted.
86
87 In novel exploration, mice moved at a speed of 8.3±0.9 cm/s during locomotion (speed>3 cm/s) and
88 spent 53±7% and 36±6% of their time in locomotion and immobility (speed<1 cm/s), respectively
89 (n=5 mice). Meanwhile, they completed 10±2.5 laps during the 180-s imaging periods (n=5 mice).
90
91 For voltage imaging, we expressed the voltage indicator Voltron2[29] in CA1 pyramidal cells (CA1PCs)
92 that were born on embryonic day (E) 14.5, allowing us to measure both suprathreshold and
93 subthreshold membrane potentials from multiple CA1PCs (14±4 cells imaged per field of view
94 (mean±s.d.) and, in total, 71 cells imaged from 5 fields of view in 5 mice; Figure 1B, Supplementary
95 Figure 1A, 1B). Simultaneously, we monitored the animals' positions and speed within the track
96 while recording the local field potential (LFP) from the contralateral side of the hippocampus (Figure
97 1B, Figure 1-figure supplement 1). Consistent with previous studies, neurons labeled on E14.5
98 located more on the deep side of the pyramidal layer than those labeled on E17.5 ($t_{(601)}$=22.8,
99 p<0.0001, Student's t-test; Supplementary Figure 1C, D)[30-34].
100
101 The mean firing rates of cells ranged from 2.3 to 4.3 Hz (25th-75th percentiles) with a median of 3.2
102 Hz (n=71 cells, Supplementary Figure 2A). Additionally, most CA1PCs exhibited elevated mean firing
103 rates during immobility relative to locomotion, and their firing rates showed a negative correlation

with the animals' speed (Supplementary Figure 2B, 2C), consistent with previous research[35].

Synchronous ensembles among many CA1 pyramidal neurons

Figure 1C shows the fluorescence traces of all neurons in a session as an example. Instances of synchronous activity, where many neurons emitted spikes within a narrow time window, were frequently observed (Figure 1C). To investigate synchronous activity within the neuronal population, we selected a reference cell and counted the number of spikes across all other cells that were aligned with the spikes of the reference cell. This approach yielded a grand average cross-correlogram (CCG) capable of elucidating the timing of spikes from the reference cell relative to the combined spikes of the rest of the population. Notably, the grand average CCG exhibited heightened spike counts around zero lags, unlike flattened counts calculated from randomly selected cells of different sessions (Figure 1D and 1E). The full width at half maximum (FWHM) of the peak in the grand average CCG measured 23±14 ms (mean±s.d., n=71 cells from 5 sessions; Figure 1F), indicating the timescale of the population synchrony. Furthermore, pairwise CCGs of many cell pairs showed significant peaks compared to jittered data (percentage of significant pairs: 63% (median) n=497 pairs, Figure 1-figure supplement 2A and 2B). Among pairs with significant peaks, the absolute values of the peak lags ranged from 0.8 to 4.3 ms (25th-75th percentiles) with a median of 2.1 ms, and the FWHM of the peaks ranged from 20 to 46 ms (25th-75th percentiles) with a median of 30 ms (n=315 pairs, Figure 1-figure supplement 2C and 2D). These results highlight the synchronous spiking between neurons on the millisecond timescale.

To systematically reveal individual synchronous events, we counted the number of spikes from all simultaneously recorded neurons within sliding windows of 25 ms. To compare the summed spikes with controls, we randomly jittered the spike trains to perturb spike timings while maintaining spike rates. We identified moments of population synchrony when spike sums exceeded the average of the jittered spike sums plus four standard deviations (Figure 1C). Using the same criterion for event

130 detection, we observed over a 7.8-fold increase in synchronous events in the original data
131 compared to jittered controls (mean event rate: 0.94±0.17 Hz for the original data, 0.12±0.01 Hz for
132 the jittered data, n=10 segments, p=0.002, W=55, Wilcoxon signed-rank test; Figure 1G). The
133 observed population synchrony was not attributable to spikes in complex bursts, as synchronous
134 event rates did not differ significantly with or without the inclusion of later spikes in bursts
135 (Supplementary Figure 3). Furthermore, we calculated the percentage of neurons participating in
136 these synchronous events to examine the synchronous ensemble sizes. The ensemble sizes ranged
137 from 32% to 53% (25th-75th percentiles) with a median of 42%, which were larger than the
138 synchronous ensemble sizes associated with c-ripples[14] (Figure 1H). These results demonstrate
139 synchronous ensembles of CA1PCs engaging many neurons.
140

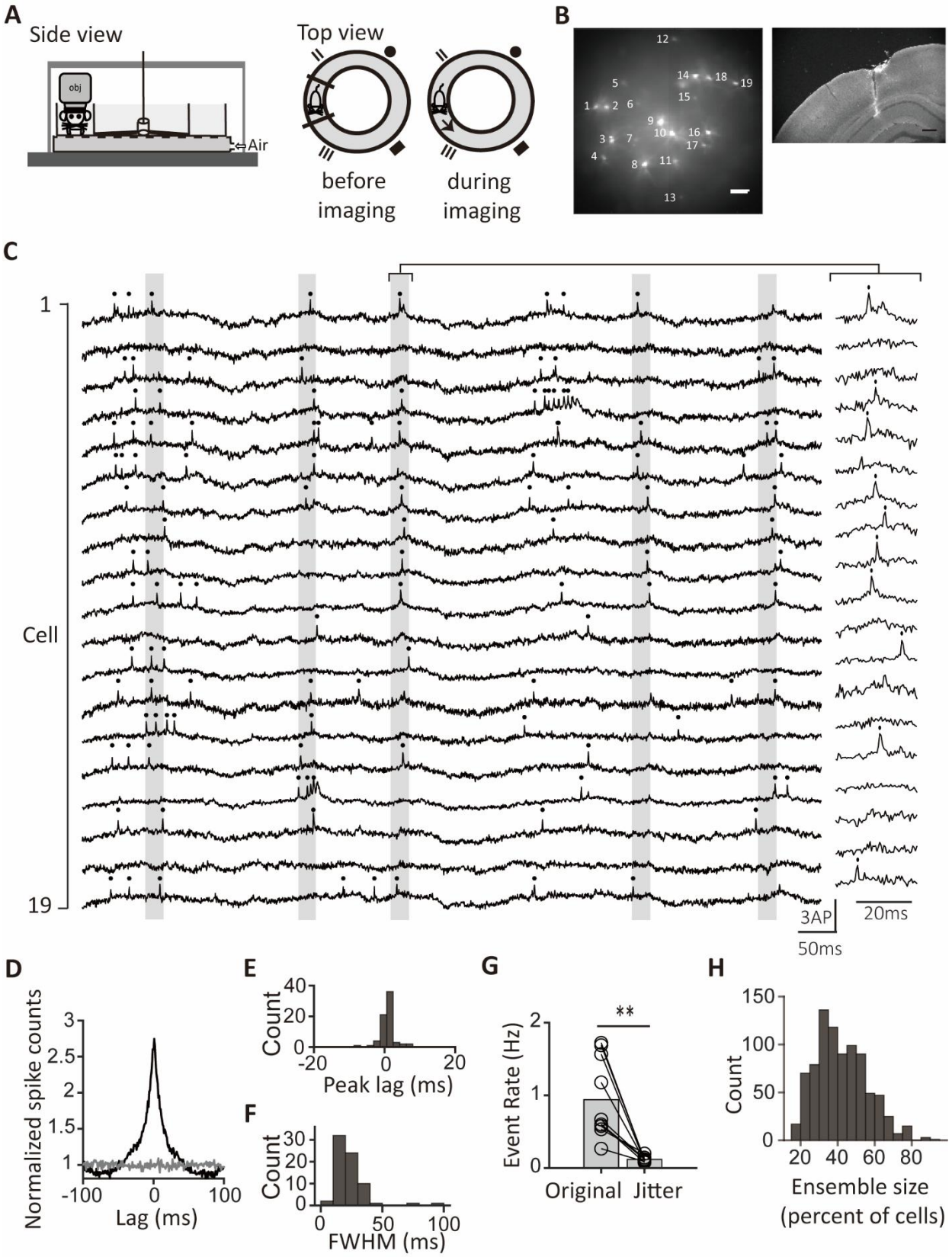


Figure 1. Population synchrony during novel exploration.

(A) Schematic of the behavioral setup for voltage imaging. Mice explored a novel one-way track

while fluorescence images were captured at the CA1 pyramidal layer. Left: side view; right: top view of the setup.

(B) Left: example time-averaged image of CA1 pyramidal cells expressing Voltron2-ST labeled with JF_{552}-HaloTag ligand. Scale bar, 100 μm. Right: a microphotograph of a brain slice with the contralateral LFP electrode track from the same mouse as the left. Scale bar, 300 μm.

(C) Fluorescence traces of cells in an example session with identified synchronous ensembles (labeled with gray vertical bars). Right: an example of magnified fluorescence traces within the bracket, pinpointing the occurrence of the identified synchronous ensemble. Spikes are indicated by dots on the top.

(D) The grand average cross-correlogram (CCG) averaged across all 71 cells. The gray line represents the mean grand average CCG between reference cells and randomly selected cells from different sessions.

(E) Distribution of the grand average CCG peak lags of all cells (n=71).

(F) Distribution of the full width at half maximum (FWHM) of the grand average CCGs (n=71 cells).

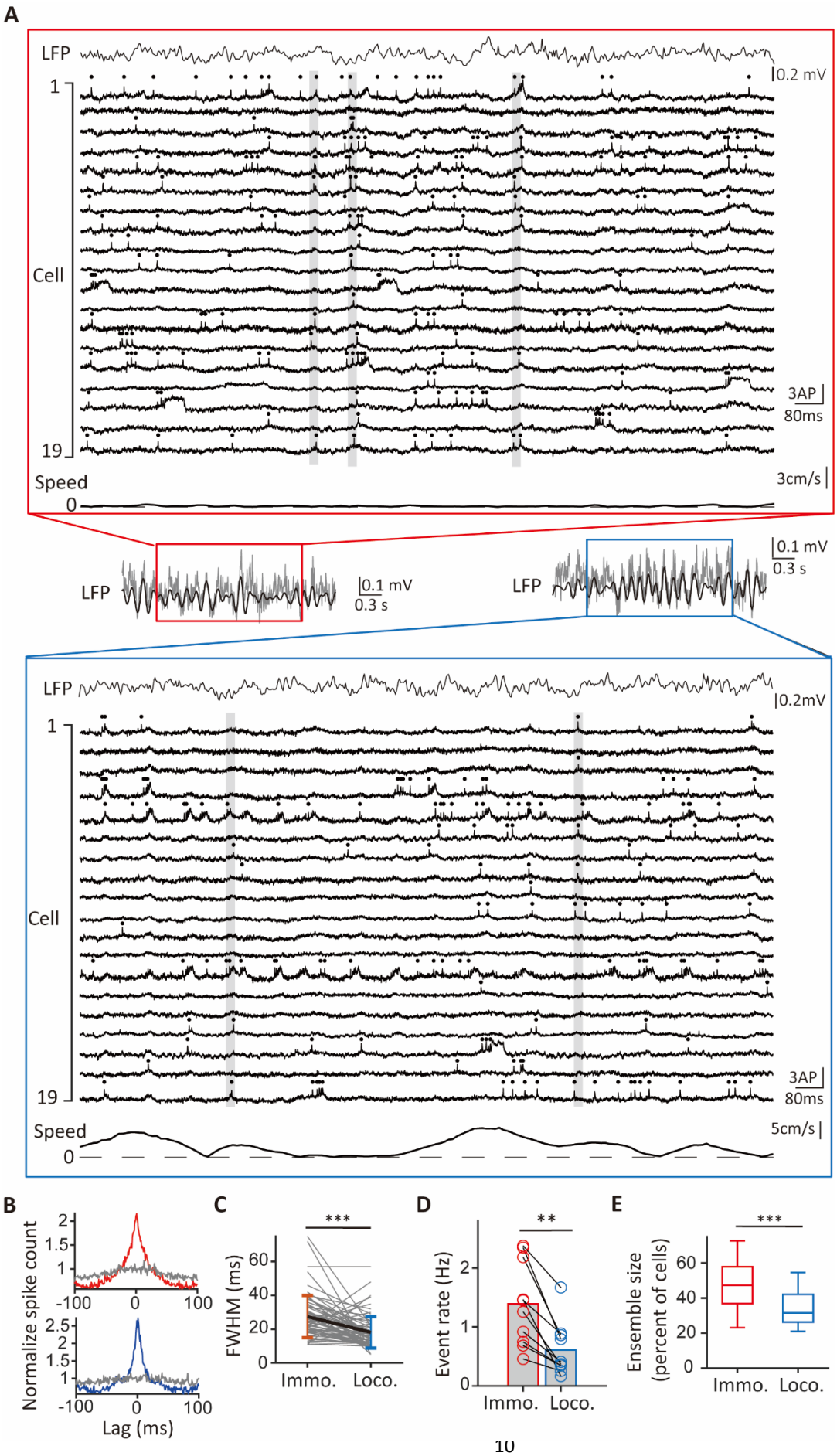
(G) Pairwise comparison of the event rates of population synchrony between original and jittered data. Bar heights indicate group means. **p<0.01

(**H**) Histogram of the ensemble sizes as percentages of cells participating in the synchronous ensembles.

Synchronous ensembles during locomotion and immobility of novel exploration

The hippocampus exhibits state-dependent activities when rodents are engaged in locomotion and immobility[35,36]. In novel exploration, CA1PCs showed synchronous spiking during locomotion and immobility (Figure 2A). To investigate whether these synchronous activities differed between these behavioral states, we compared grant average CCGs and synchronous ensembles under these conditions. During both immobility and locomotion, grant average CCGs showed prominent peaks

compared to jittered data (Figure 2B). Moreover, synchronous ensembles were rich in both immobility and locomotion periods (Figure 2A, 2B and 2D). Nevertheless, the FWHMs of grand average CCGs were broader in the immobility group compared to the locomotion group (Figure 2B and 2C). Synchronous events occurred more frequently during immobility compared to locomotion (Figure 2D). Additionally, ensemble sizes were significantly larger in the immobility group compared to the locomotion group (Figure 2E). Taken together, with differences in sizes and kinetics, there were synchronous ensembles during both immobility and locomotion periods of novel exploration.


A
LFP
0.2 mV
1
Cell
19
3AP
80ms
Speed
0
3cm/s
LFP
0.1 mV
0.3 s
LFP
0.1 mV
0.3 s
LFP
0.2mV
1
Cell
19
3AP
80ms
Speed
0
5cm/s
B
Normalize spike count
Lag (ms)
C
FWHM (ms)
Immo.
Loco.
D
Event rate (Hz)
Immo.
Loco.
E
Ensemble size (percent of cells)
Immo.
Loco.

178 **Figure 2. Comparison of synchronous ensembles between immobility and locomotion.**

179 **(A)** Example traces of cells in a session with identified synchronous ensembles (gray vertical bars)
180 during periods of immobility (red rectangular frame) and locomotion (blue rectangular frame).
181 Spikes are indicated by dots at the top of individual traces. Top: the simultaneously recorded LFP
182 trace. Bottom: simultaneously recorded speed of the animal. Inset: the band-pass filtered LFP trace
183 at the theta frequency range (black line) overlaid on the raw LFP trace (gray line).

184 **(B)** The grand average cross-correlograms (CCGs) during immobility (red) and locomotion (blue)
185 averaged across all cells (n=71). The gray lines represent the mean grand average CCGs calculated
186 from jittered data.

187 **(C)** Pairwise comparison of peak widths (FWHM) in the grand average CCGs between immobility
188 (red) and locomotion (blue). Vertical bars represent means and standard deviations for both groups
189 (FWHM: 27±12 ms for immobility, 18±9 ms for locomotion, mean±s.d., $t_{(70)}$=5.45, p<0.001, paired t-
190 test, n=71 cells). ***p<0.001

191 **(D)** Pairwise comparison of event rates of population synchrony during immobility and locomotion.
192 Bar heights indicate group means (immobility: 1.4±0.7 Hz, locomotion: 0.6±0.5 Hz, mean±s.d., n=10
193 segments, W=55, p=0.002, Wilcoxon signed-rank test). **p<0.01

194 **(E)** Boxplot of ensemble sizes for synchronous ensembles occurring during immobility (red) and
195 locomotion (blue) (median ensemble size: 47% for immobility, n=446 events, 32% for locomotion,
196 n=313 events, $t_{(757)}$=13.54, p<0.001, Student's t-test). ***p<0.001

197

198

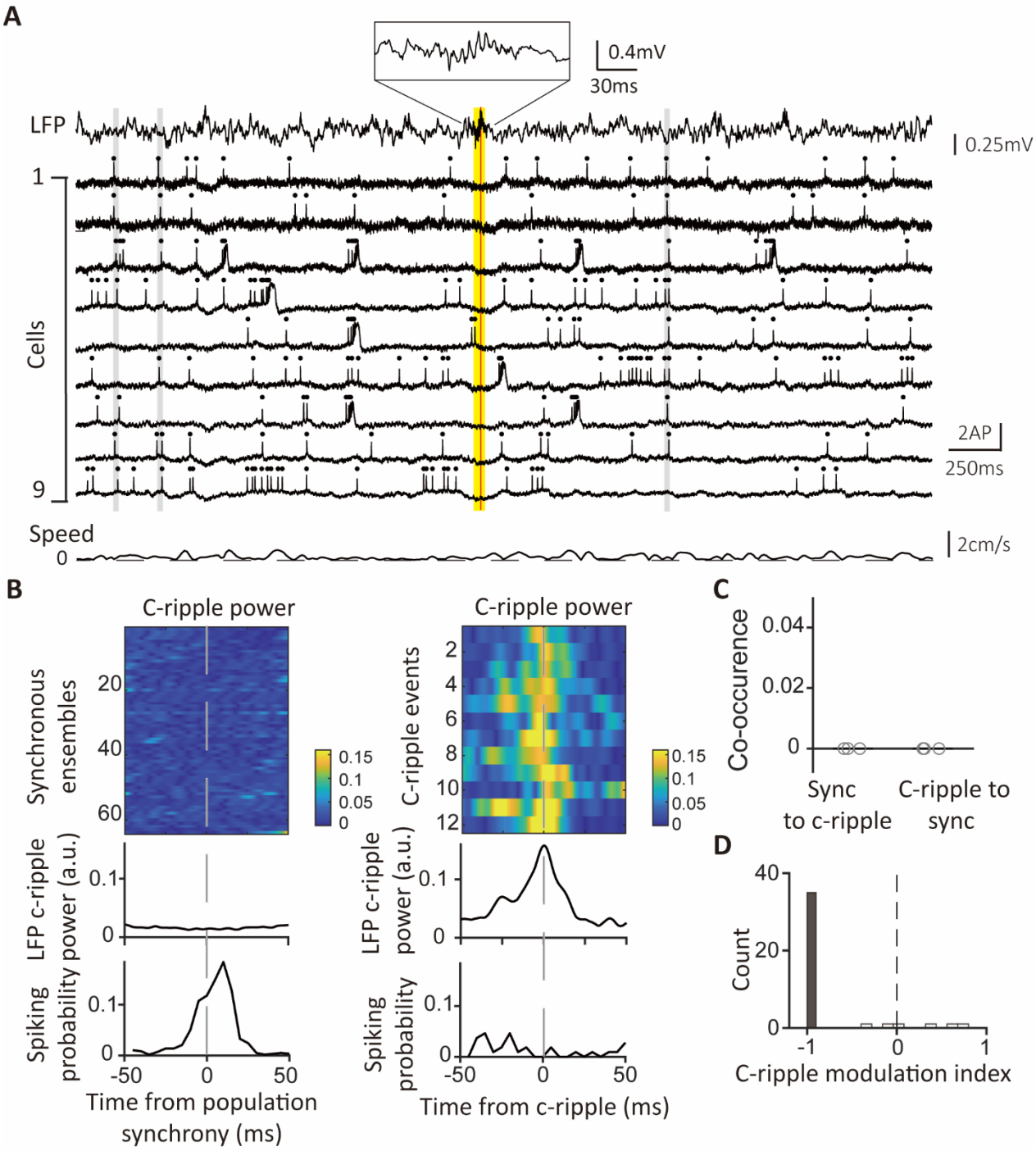
199 ## Synchronous ensembles occur outside c-ripple episodes

200 CA1PCs exhibit synchronous activities when the hippocampal network emits ripple waves[8,14]. To test
201 whether there is a co-occurrence of synchronous ensembles and c-ripples, we first detected c-
202 ripples from LFP recordings. C-ripples were detected in three of the five recording sessions, and all
203 occurred during immobility (mean c-ripple rate: 0.04±0.02 Hz during immobility, 0 Hz during

204 locomotion). In the two recording sessions where we did not detect any c-ripples, we verified the
205 recording quality of the LFP signal by running multiple tests after the recording sessions. C-ripples
206 were identified in the same animals during quality tests, indicating that the absence of c-ripples
207 during novel immobility in the recording session was not due to the deterioration of LFP recordings
208 (Figure 3-figure supplement 1).
209
210 To visualize both c-ripples and synchronous ensembles, we plotted voltage traces of neurons
211 alongside simultaneously recorded c-ripple oscillations. It was typical for synchronous ensembles to
212 occur far away from c-ripple episodes (Figure 3A). To delve into the relationship between neuronal
213 activities and c-ripples, we aligned traces of c-ripple power with population synchrony and c-ripples.
214 In a recording session where 64 synchronous ensembles and 12 c-ripples were detected during
215 immobility, the LFP power at c-ripple frequency (120-240 Hz) exhibited no discernible peaks within
216 any of the synchronous events (Figure 3B, left upper and middle panels). Nevertheless, the same
217 LFP power displayed substantial peaks during every c-ripple event (Figure 3B, right upper and
218 middle panels). A striking contrast between synchronous events and c-ripples was also evident
219 when spiking probabilities during these events were examined. During population synchrony, the
220 mean spiking probability averaged across all cells was high, while the spiking probability was almost
221 zero during c-ripple events (Figure 3B, lower panel). In the three sessions where c-ripples were
222 identified, we calculated the percentages of c-ripple events coinciding with synchronous ensembles
223 and vice versa. Remarkably, there was no co-occurrence of c-ripples and synchronous ensembles
224 (Figure 3C). Furthermore, we quantified c-ripple-modulated spiking by calculating the ratio of the
225 difference in mean firing rates during in-c-ripple and out-c-ripple periods to the sum of the mean
226 firing rates during both periods. Indexes of most cells were negative, and a striking 85% of cells
227 displayed c-ripple modulation indexes of -1, indicating complete suppression of their spiking
228 activities during c-ripples (Figure 3D). Taken together, during novel exploration, synchronous
229 ensembles involved many neurons with millisecond-synchronized spikes and occurred outside the

230 time frames of c-ripples.

231



232

233 **Figure 3. Synchronous ensembles occur outside c-ripple episodes.**

234 **(A)** Example traces with c-ripples and synchronous ensembles. Top: simultaneously recorded LFP

235 displaying an episode of c-ripple oscillation. A red vertical line indicates the timing of the peak c-

236 ripple power in the LFP trace. A yellow vertical bar marks the duration of the c-ripple episode. Inset

237 at the top: a magnified view of the c-ripple oscillation. Middle: fluorescence traces of 9 CA1PCs.
238 Gray vertical bars mark the timings of the synchronous ensembles on all traces. Bottom: animals'
239 speed recorded simultaneously with voltage imaging.
240 **(B)** LFP c-ripple power and spiking probability aligned to synchrony ensembles and c-ripple events.
241 Upper panel: color-coded LFP power at c-ripple frequency (120-240Hz) aligned to the timings of 64
242 synchronous ensembles (left) and 12 c-ripple events (right). Middle panel: Average LFP power of c-
243 ripple frequency aligned to the timings of the synchronous ensembles (left) and the c-ripple events
244 (right). Lower panel: Average spike counts of all cells aligned to the timings of the synchronous
245 ensembles (left) and c-ripple events (right).
246 **(C)** Percentages of co-occurrences between population synchrony and c-ripples. The co-occurrences
247 in the "sync to c-ripples" group represent the percentages of c-ripple episodes co-occurring with
248 synchronous ensembles in the same episodes. The co-occurrences in the "c-ripples to sync" group
249 indicate the percentages of synchronous ensembles co-occurring with c-ripple episodes. Each gray
250 circle represents an individual session.
251 **(D)** Distribution of the c-ripple modulation indexes (*n*=41 cells). Gray bar: modulation indexes with
252 significant p values (*n*=35 cells); white bars: modulation indexes without significance (*n*=6 cells).
253
254 It was puzzling that these CA1PCs exhibited robust spiking activities outside of c-ripples, yet
255 generated few spikes during c-ripples. To further investigate neuronal activities during c-ripples, we
256 established a recording condition that allowed us to capture more c-ripple episodes. Specifically, we
257 immobilized mice in a tube to promote behaviors favoring c-ripple generation. The mice were
258 habituated to head fixation in a tube in a room distinct from the one where imaging experiments
259 were conducted. On the imaging day, the mice were introduced to the recording room and head-
260 fixed under the microscope for the first time.
261
262 CA1PCs were labeled *in utero* on embryonic day (E) 14.5 (*n*=56 cells from 3 sessions in 3 mice) and

263 E17.5 (*n*=55 cells from 3 sessions in 3 mice) and imaged in adult brains. Both neuronal populations
264 exhibited prominent peaks in their grand average CCGs and significantly higher synchronous event
265 rates compared to jittered data (Figure 3-figure supplement 2A, B). Approximately 40% of the
266 recorded neurons participated in synchronous ensembles, indicating robust synchronous activity
267 involving a substantial proportion of the recorded cells (Figure 3-figure supplement 2C).
268
269 In total, 1052 synchronous ensembles and 174 c-ripple episodes were detected across these
270 imaging sessions. Consistent with findings from walking animals, few synchronous ensembles
271 occurred during c-ripples when animals were immobilized in a tube (Figure 3-figure supplement 3A,
272 B). Moreover, no distinguishable c-ripple oscillations were observed in synchronous events, and the
273 average firing rates during c-ripple episodes were near zero (Figure 3-figure supplement 3C, D). At
274 the single-cell level, 90% of neurons showed significant negative spiking modulation during c-
275 ripples, with c-ripple modulation indexes close to -1, indicating strong suppression of spiking (Figure
276 4Ai). This suppression extended to subthreshold membrane potentials, as nearly all cells exhibited
277 decreased fluorescence during c-ripples compared to baseline (Figure 4Bi, Ci). These results
278 demonstrate that spiking activity and subthreshold membrane potentials are robustly suppressed
279 during c-ripples.
280
281 Contextual novelty plays a critical role in shaping hippocampal neuronal activities[37-43]. To assess its
282 influence, we trained mice to become familiar with the imaging procedure and the recording
283 environment over five days and recorded CA1PC activities on the final day. Mean firing rates were
284 significantly reduced in the familiar group compared to the novel group (Familiar group: 1.1 to 5.2
285 Hz (25th-75th percentiles), median=2.3 Hz, *n*=66 cells, 6 sessions, 4 mice; Novel group: 1.7 to 6.0 Hz
286 (25th-75th percentiles), median=4.2 Hz, *n*=111 cells, 6 sessions, 6 mice, *p*=0.0083, Wilcoxon signed-
287 rank test). Additionally, 15% of the neurons in the familiar group exhibited significantly positive
288 spiking modulation by c-ripples, while fewer cells showed negative modulation compared to the

novel group (Figure 4A). During c-ripples, neurons in the novel group predominantly displayed hyperpolarizing membrane voltage responses, whereas a subset of neurons in the familiar group exhibited prominent depolarizing responses (Figure 4B). The mean fluorescence changes in the familiar group shifted toward depolarization compared to the novel group (Figure 4C). Finally, synchronous event frequencies were significantly lower in the familiar context, indicating weaker synchronous activities under familiar conditions (Figure 4D). These results demonstrate that hippocampal neuronal activities, particularly synchronous ensembles, are strongly influenced by contextual novelty.

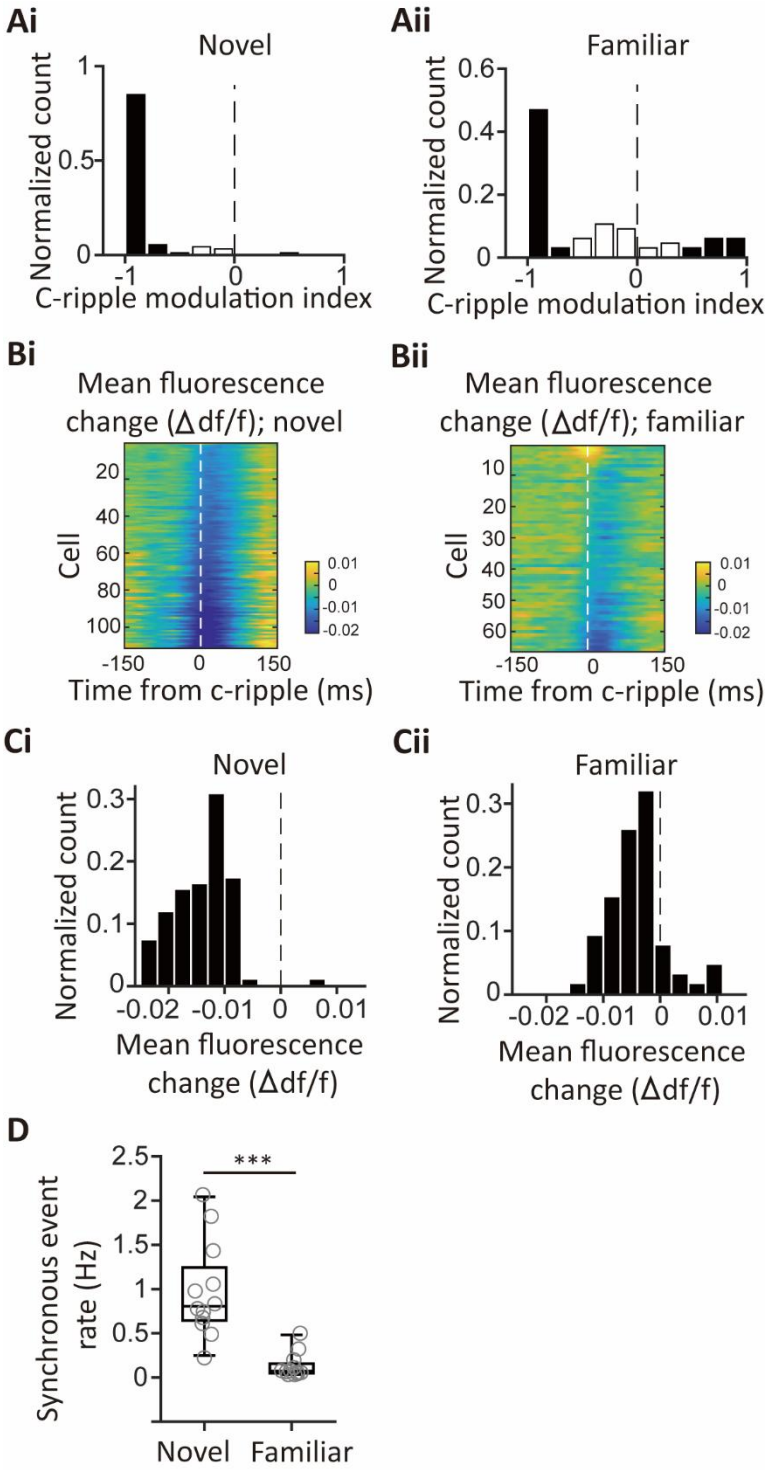


Figure 4. Comparison of c-ripple-associated neuronal activities and synchronous event rates between novel and familiar recording contexts.

(A) Histograms of c-ripple modulation indices for the novel (Ai) and familiar (Aii) recording contexts. Gray bars represent modulation indices with significant *p*-values, while white bars indicate non-significant modulation indices.

(B) Color-coded representations of mean fluorescence changes relative to baseline fluorescence for individual neurons, averaged across c-ripple events, in the novel (Bi) and familiar (Bii) recording contexts.

(C) Histograms of mean fluorescence changes within a ±10-ms window centered on the peak power of c-ripple events. Ci corresponds to the novel context, while Cii corresponds to the familiar context.

(D) Boxplots of synchronous event rates for the novel and familiar recording contexts. Mean event rates were 0.98±0.16 Hz for the novel context and 0.13±0.04 Hz for the familiar context ($t(22)=5.20$, $p<0.001$, Student's *t*-test). ***$p<0.001$

Synchronous ensembles are associated with theta oscillations

To compare the network dynamics associated with synchronous ensembles during immobility and locomotion, we aligned LFP traces triggered to the timings of synchronous ensembles. The average LFP traces of a representative session showed prominent theta oscillations around the timings of both immobility and locomotion population synchrony (Figure 5A). Spectral analysis of the mean synchrony-triggered LFP traces during immobility and locomotion revealed theta frequency components of 4-12 Hz, with a slightly higher peak frequency in locomotion LFP compared to immobility LFP (Figure 5B). Furthermore, we computed LFP theta modulation and identified preferred phases of synchronous ensembles. In line with the previous result, synchronous ensembles displayed a high level of modulation by LFP theta oscillation (modulation strength: 0.61± 0.05 during immobility and 0.74±0.04 during locomotion, n=5 sessions). Although the preferred phases varied from session to session due to differences in recording sites along the proximal-distal axis of the hippocampus, the timings of individual ensembles were consistently locked to the preferred phase of each session (Figure 5C). These results establish a strong link between synchronous ensembles and LFP theta oscillation.

330 Subthreshold membrane voltage (subVm) is one of the critical parameters supporting the
331 generation of action potentials. To investigate the subthreshold signals underlying population
332 synchrony, we aligned subVm traces with the timings of synchronous ensembles and observed that
333 both immobility and locomotion synchrony rode on a subVm waveform oscillating at theta
334 frequency (Figure 5D). To elucidate further the relationship between subVm theta oscillation and
335 spikes involved in population synchrony, we calculated the subVm theta modulation and preferred
336 phases of spikes. Spikes participating in both immobility and locomotion synchrony were strongly
337 coupled to the subVm theta oscillation of neurons, with the mean preferred phase being in the
338 latter half of the rising phase closer to subVm theta peaks (Figure 5E). Conversely, spikes not
339 participating in synchronous ensembles had weaker modulation strength compared to spikes
340 involved in synchrony (Figure 5-figure supplement 1A, B). Furthermore, the membrane voltages
341 triggered by these two categories of spikes showed a significant difference in the hyperpolarization
342 phase of the theta oscillation. Synchronous spikes were situated within cycles of theta oscillations
343 featuring more hyperpolarized troughs than spikes outside synchronous ensembles (Figure 5-figure
344 supplement 1C, D). Thus, compared to spikes not participating in synchronous ensembles,
345 synchronous spikes showed a more robust modulation by theta oscillation of membrane voltage
346 during immobility and locomotion in the context of novel exploration.
347
348 Notably, phase locking of spikes to their subVm theta oscillation and the synchronous spikes among
349 many neurons suggest that subVms of different neurons would be correlated at the theta frequency.
350 To explore the possibility, we divided the 180-second subVm traces into 1-second segments with
351 50% overlap and calculated the cross-correlation and magnitude-squared coherence function for
352 each pair of cell segments. Segments were sorted into the immobility or locomotion group based on
353 the animals' speed during each segment (kept below 1 cm/s for immobility and above 3 cm/s for
354 locomotion for more than 90% of the time). In total, we analyzed 511 cell pairs from 5 sessions.
355 Indeed, the cross-correlation of subVm between cell pairs revealed a high correlation at zero lag and

356 periodic modulation of the correlation at theta frequency (Figure 5F). Furthermore, the subVm
357 theta coherences were increased in both groups (immobility: 0.50, locomotion: 0.40, median, *n*=511
358 pairs) and were negatively correlated with soma distances (immobility: -0.46, locomotion: -0.48,
359 *n*=511 pairs, Figure 5G). Taken together, during novel exploration, CA1PCs generate synchronous
360 activity associated with theta oscillation and exhibit correlated and theta-coherent subVms.
361
362 Correlated intracellular theta and theta-phase locking of the synchronous ensembles raise the
363 question of whether population synchrony among CA1PCs extends beyond synchrony derived from
364 these effects. To address this, we analyzed population synchrony after randomizing the theta cycles
365 during which neurons spiked, while keeping their theta phases unchanged. Supplementary Figure 4
366 illustrates a significant reduction in synchronous event rates following theta cycle randomization.
367 The finding indicates spiking at specific theta cycles plays a major role in driving population
368 synchrony.
369
370 To further investigate synchronous ensembles across different datasets, we analyzed publicly
371 available hippocampal recordings 'hc-11' from the CRCNS repository[43,44], where rats navigated novel
372 mazes for water rewards (see Method). Using our algorithm, we identified a significant number of
373 synchronous ensembles during the first three minutes of novel navigation. On average, the rates of
374 synchronous events were 6.4-fold higher than those detected in jittered controls (mean event rate:
375 2.0 ± 0.3 Hz for the original data vs. 0.32 ± 0.03 Hz for jittered data, n = 8 sessions, p = 0.0078, W =
376 36, Wilcoxon signed-rank test; Supplementary Figure 5A). To assess whether ripple oscillations were
377 associated with these synchronous ensembles, we analyzed ripple event rates and their relationship
378 to population synchrony. During this period, ripple events were infrequent (mean ripple rate: 0.02 ±
379 0.01, n = 8 sessions), and ripple power peaked during ripple episodes but remained low at the
380 timings of population synchrony (Supplementary Figure 5B). Nevertheless, LFP traces aligned to
381 population synchrony revealed prominent theta oscillations (Supplementary Figure 5C).

382 Synchronous ensembles were modulated by LFP theta oscillation (modulation strength: 0.30 ± 0.04,
383 n = 8 sessions, $p < 0.001$), and the timings of individual ensembles were consistently locked to the
384 preferred phase of each session, suggesting a functional coupling of synchronous ensembles to
385 theta oscillations important for information processing (Supplementary Figure 5D).
386

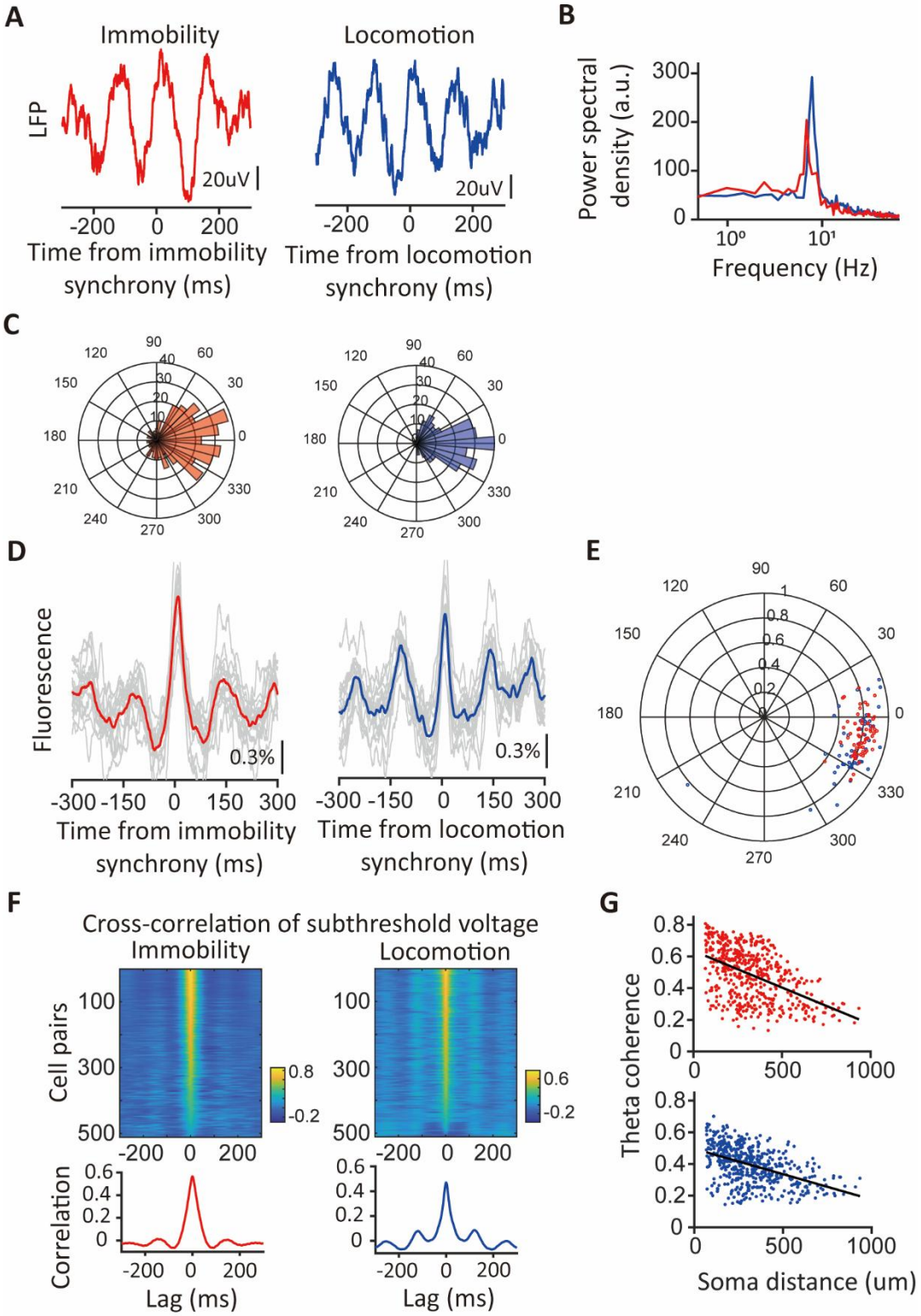


Figure 5. Theta oscillations in the LFP and subthreshold membrane potential were linked to population synchrony.

(A) LFP waveforms triggered by timings of synchronous ensembles. Red: triggered by timings of immobility synchrony; blue: triggered by timings of locomotion synchrony.

(B) Power spectral densities of the triggered LFP waveforms. Red: immobility; blue: locomotion.

(C) Distributions of the differences between LFP theta phases of individual synchronous ensembles and their preferred phases of the session. Note that most ensembles show minor differences within ±30 degrees. Red: immobility; blue: locomotion.

(D) Fluorescence traces triggered by timings of synchronous ensembles. Traces with spikes are excluded. Left panel: traces triggered by timings of immobility synchrony. Right panel: traces triggered by timings of locomotion synchrony. Thin gray lines: mean triggered fluorescence traces averaged across triggers for representative cells. Thick red and blue lines: mean triggered fluorescence traces averaged across cells.

(E) Polar plot illustrating theta modulation of spikes participating in the immobility synchrony (red dots) and of spikes participating in the locomotion synchrony (blue dots). The angle of the dots indicates the preferred phase, and the distance from the center of the circle represents the modulation strength. Each dot represents the averages from a neuron.

(F) Pairwise cross-correlation of the subthreshold membrane voltages (subVm). Top: color-coded cross-correlation of subVm between cell pairs during immobility and locomotion periods. Bottom: averaged cross-correlation over all cell pairs for immobility (red) and locomotion (blue) subVm. Both show a central peak at zero lag flanked by theta oscillation.

(G) Scatter plots of theta coherence against soma distances of immobility subVm (red) and locomotion subVm (blue) between cell pairs.

411 **Synchrony between place cells with distinct place tunings**

412 When animals explore a novel maze, spatially tuned spiking activity can form within a few
413 minutes[45,46]. However, how synchronous ensembles organize their spatially tuned activities during
414 novel exploration remains to be determined. Synchronous ensembles, generating spikes
415 coincidently in short intervals, might display correlated spiking at longer time windows that match
416 behavioral timescales of exploration, potentially leading to shared place responses. On the other
417 hand, CA1PCs are interconnected through inhibitory interneurons[47-49]. Modulation of activities in
418 inhibitory interneurons by some place cells may influence the activities of other place cells,
419 resulting in divergent spatial tunings[45,50,51].

420

421 To compare the spatial tunings of synchronous cell pairs, we first calculated the spatial tuning
422 curves of individual neurons by computing the mean firing rates in every spatial bin. On average,
423 40% of cells displayed selective spatial tunings of their spiking activities and were qualified as place
424 cells[52] (Figure 6A). Among place cell pairs, some showed similar spatial tunings, while others did not
425 (Figure 6B). For instance, in an illustrative session depicted in Figure 6B, the seventh and eighth
426 place cells had highly similar spatial tunings with a correlation coefficient as high as 0.7. In contrast,
427 the fifth and tenth place cells exhibited vastly different spatial tunings with a correlation coefficient
428 as low as -0.5.

429

430 We further explored the relationship between the similarity of spatial tunings and synchronization
431 strength among pairs of place cells. We measured synchronization strength as the peak of the CCG
432 normalized by the averaged jittered spike count within the same bin as the CCG peak. We
433 segregated spikes based on these behavioral states to accommodate differences between
434 locomotion and immobility and calculated the corresponding CCG and synchronization strength.

435

436 During locomotion, we observed a robust negative correlation between synchronization strength

437 and the similarity of spatial tunings among cell pairs. In other words, cell pairs with more precisely
438 co-active spikes during locomotion exhibited more distinct place-tuning profiles (Figure 6C, D). This
439 anti-correlation between synchronization strength and place tunings indicates coordination
440 between place cells' temporal and spatial coding. On the other hand, synchronization strength
441 during immobility showed little correlation with the similarity of spatial tunings among place cell
442 pairs, suggesting that correlated activities at the millisecond timescale do not extend to slow,
443 behavioral-relevant timescales (Figure 6-figure supplement 1). Thus, place cells with distinct place
444 fields are linked by synchronous activity during novel locomotion.
445

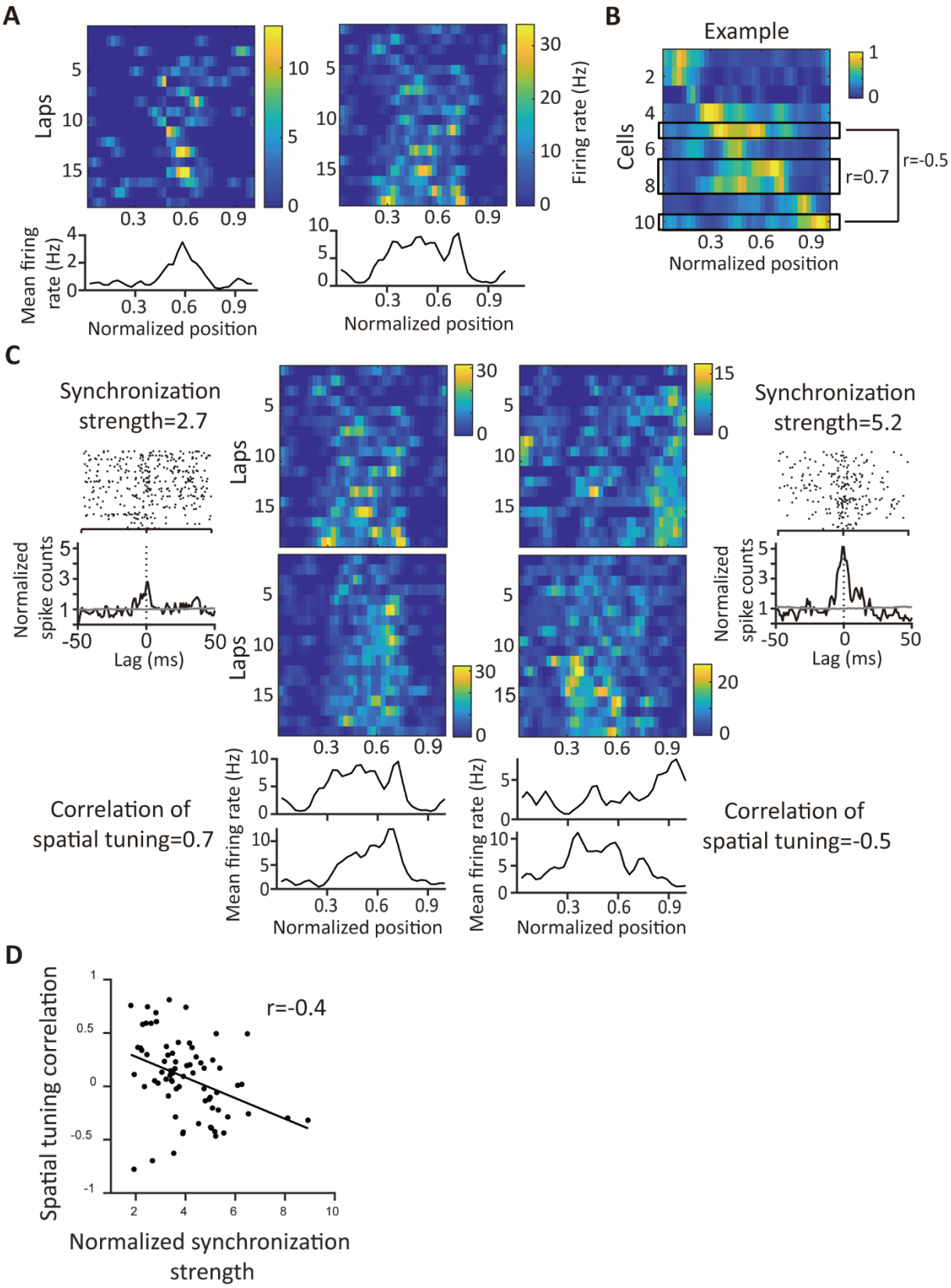


Figure 6. Negative correlation between spatial tuning similarity and synchronization strength during novel exploration.

449 **(A)** Spatially binned rate maps of place cells. High firing rates are indicated in yellow, and low firing
450 rates are noted in blue. Bottom: the mean firing rates along spatial bins averaged across laps.
451 **(B)** Spatial tunings of 10 place cells from an example session. Cells are sorted based on the locations
452 of their peak firing rates.
453 **(C)** Two example pairs of neurons with cross correlograms during locomotion and spatially binned
454 firing rate maps.
455 **(D)** A scatter plot of correlation coefficients of spatial tunings against normalized synchronization
456 strengths for place cell pairs. Each dot represents a pair of place cells. Synchronization strengths are
457 negatively correlated with similarities of spatial tunings (Spearman correlation coefficient=-0.4,
458 $p<0.001$, $n=73$ pairs).
459
460

461 ## Discussion

462 Our findings reveal the presence of synchronous ensembles comprising a substantial number of
463 CA1PCs during both locomotion and immobility in a novel environment. These ensembles
464 concurrently engage neurons representing diverse aspects of the environment and are rarely
465 observed during c-ripple events. Instead, they closely align with LFP and intracellular theta
466 oscillations. Our data demonstrate theta-associated synchronous ensembles during spatial memory
467 acquisition, coordinating numerous CA1 place cells that transmit information about different
468 segments of the environment.
469
470 The correlation between observed population synchrony and theta oscillations is intriguing. Theta
471 oscillations are typically associated with the sequential activation of neurons over time, resulting in
472 reduced neuronal synchrony[22]. However, theta oscillations come in different types, each
473 characterized by distinct pharmacological properties and behavioral correlates[53-55]. For example,
474 type 1 theta, or translational theta, occurs during voluntary movements and is sensitive to N-

methyl-D-aspartate receptor (NMDAR) blockers. On the other hand, type 2 theta, or attentional theta, is slightly slower and is blocked by muscarinic receptor antagonists, emerging during states of arousal or attention, such as when entering a new environment[56-58]. Consistent with these distinctions, the peak of the power spectrum density shows a distinctively slower theta frequency during immobility compared to locomotion (Figure 5B).

During theta oscillations, cholinergic neurons in the medial septum excite downstream CA1PCs, leading to increased firing rates and membrane potentials[59-61]. Given the widespread influence of cholinergic inputs on numerous CA1PCs, theta-coupled cholinergic inputs may drive depolarization and firing across many CA1PCs. Additionally, they could enhance the likelihood of synchronicity. Furthermore, GABAergic neurons in the medial septum, activated during theta oscillations, could activate interneurons in the CA1 region[55,62,63]. These CA1 interneurons, in turn, have the capability to entrain the activities of pyramidal neurons at both sub- and suprathreshold levels, thereby promoting synchronization among pyramidal neurons[64,65]. In summary, cholinergic and GABAergic neuron activation during theta waves may contribute to the excitation of CA1PCs and the consequent increase in their synchronicity.

Theta oscillations have long been implicated in memory acquisition. Specifically, theta power correlates positively with learning performance[66-68]. Perturbing generation of theta waves leads to impairment in memory acquisition[69-73], while electrical stimulation restoring theta rhythms rescues learning performance[74,75]. Furthermore, increased spike-theta coherence correlates with better memory, and stimulations that boost theta phase-locking of spikes enhance memory[76-78]. Despite abundant evidence supporting a link between theta oscillations and memory, the precise network mechanism by which theta oscillations support memory acquisition remains unclear. Theta oscillations are hypothesized to link spatially distributed neurons into functional ensembles to support memory acquisition[13]. The identified synchronous ensembles support the hypothesis,

501 providing a network substrate that links theta rhythms to the initial stage of memory acquisition.
502
503 Recent studies have demonstrated elevated coactivity of hippocampal principal cells during theta-
504 associated dentate spikes, events that are temporally coupled to theta oscillations and distinct from
505 sharp-wave ripples[79-81]. These findings highlight a network state characterized by rich synchronous
506 ensembles associated with theta, but not ripple, oscillations- a pattern consistent with our results.
507 Our analyses of publicly available data further support these observations, revealing theta-
508 associated population synchrony in a different dataset (Supplementary Figure 5). These results
509 suggest that hippocampal neurons achieve synchrony through network mechanisms distinct from
510 ripple-related events, reinforcing the hypothesis that this phenomenon is generalizable across
511 experimental conditions and behavioral contexts.
512
513 Previous studies have reported that a small percentage of CA1PCs generate spikes during ripple
514 episodes[8,14,17]. These measurements are typically conducted in familiar environments. In contrast,
515 when animals are introduced to a novel environment, c-ripple-associated spiking activities are
516 strongly suppressed, and CA1PCs exhibit prominent hyperpolarizing responses in their membrane
517 potentials (Figure 3, 4Ai-Ci, and Figure 3-figure supplement 3). Interestingly, after familiarization
518 training, a larger proportion of CA1PCs display positive c-ripple modulation of spiking activities and
519 depolarizing responses associated with c-ripples (Figure 4Aii-Cii). Consistent with the observation of
520 ripple-associated spiking activity in familiar environments, our study underscores the influence of
521 contextual novelty on hippocampal dynamics. Specifically, brain states associated with novelty may
522 modulate the activity of neurons upstream of CA1PCs, driving their membrane potentials toward
523 hyperpolarization during c-ripples. While the reduced correlation between c-ripples and spikes in
524 novel environments may initially appear counterintuitive, this unique neuronal activity pattern likely
525 reflects adaptive changes in hippocampal circuits related to the animals' behavioral states, such as
526 heightened vigilance in novel environments.

While contralateral LFP recordings can capture large-scale hippocampal theta and ripple oscillations, they do not fully reflect ipsilateral-specific dynamics, such as variations in theta phase alignment or locally generated ripple events[82-84]. Given that ripple oscillations can emerge locally and independently in each hemisphere, interpretations based on contralateral recordings must be made with caution. Further studies incorporating simultaneous ipsilateral field potential recordings will be essential to more precisely understand local-global network interactions. Despite these considerations, our findings provide robust evidence for the existence of synchronous neuronal ensembles and their role in coordinating newly formed place cells. These results advance our understanding of how synchronous neuronal ensembles contribute to spatial memory acquisition and hippocampal network coordination.

Although CA1PCs are known to exhibit weaker recurrent connectivity than that of CA3 pyramidal neurons, CA1PCs did communicate through monosynaptic connections[85]. These connections can be dynamically adjusted by the spike-timing-dependent plasticity mechanism[86-88], and therefore could be affected by the transient population synchrony. In addition, CA1PCs are known to communicate through inhibitory interneurons. Multiple pyramidal neurons converge onto a single interneuron, and individual connections are often weak and unreliable[48,89,90]. This connectivity scheme requires multiple pyramidal neurons spiking synchronously within the time window of synaptic integration to effectively activate postsynaptic neurons[48]. Furthermore, population synchrony among CA1PCs may propagate to downstream areas, synchronizing neurons outside the hippocampus. With their large ensemble sizes, these synchronous ensembles may synergistically convey relevant information or reorganize the connectivity of the neuronal networks.

Prior studies in sensory systems have commonly revealed that neurons with synchronous activities typically share similar sensory responses[91,92]. However, the synchronous ensembles we have

553 identified often encompass neurons with distinct preferences for place fields. Pairwise synchrony
554 demonstrates a negative correlation with place field overlap (Figure 6). These findings indicate that
555 synchrony does not necessarily imply similar tunings between neurons. Furthermore, these
556 synchronous ensembles involve place cells encoding different spatial information. Recognizing the
557 crucial role of neuronal synchrony in binding distributed neurons in the brain[3,5], population
558 synchrony may serve as a mechanism to integrate diverse features of the same environment into a
559 cohesive mental map.
560

561 # Methods

562 **Animal**

563 Time-pregnant wild-type C57BL/6J female mice underwent in utero virus injection of CamkII-cre
564 virus (105558-AAV1, Addgene) into the left side of the lateral ventricles. The resulting offspring
565 were raised in a breeding room under controlled temperature and humidity conditions and a 12-
566 hour light/dark cycle (lights on from 7:00 to 19:00). The mice used in the experiments were
567 between 12 and 18 weeks old at the time of the recordings. All surgical procedures, behavioral
568 training, and recording protocols were approved by the NYCU Institutional Animal Care and Use
569 Committee.

570

571 **In-utero virus injection**

572 Time-pregnant mice on embryonic day 14.5 or 17.5 were anesthetized with isoflurane (induction:4-
573 5%; maintenance:1-3%) before surgery. The animals were placed on a heating pad in a supine
574 position to maintain body temperature. Aseptic procedures were implemented to maintain sterile
575 conditions during the surgery. Uterine horns were exposed one at a time using spoons and fingers.
576 Warm and sterile phosphate-buffered saline (PBS) was used to rinse the uterus to prevent it from
577 drying out. Micropipettes loaded with CamkII-cre virus solution were used to inject 0.2 μL of virus
578 suspension into the left side of the lateral ventricle of each embryo. The injection resulted in Cre
579 expression among neurons born on the day of injection, with earlier injection labeling neurons
580 located on the deeper side of the cell layer. The uterine horn was then gently returned to the
581 abdominal cavity. The exact process was repeated to the other uterine horn. After the surgery,
582 ketorolac (6mg/kg) and cefazolin (1g/kg) were administered for two days to minimize pain and
583 inflammation.

584

585 **Cranial window and cannula implantation**

586 The offspring of the mice that had undergone in-utero injection were subjected to chronic
587 hippocampal window surgery when they were between 2 and 4 months old. The animals were
588 initially anesthetized using isoflurane (induction:4-5%; maintenance:1-3%). Topical anesthesia was
589 applied by administering 0.5% lidocaine to the wound margins. After achieving deep anesthesia, an
590 incision was made in the skin, and a circular section of the skull was removed, centered 2 mm
591 caudal and 1.8 mm left to the bregma. Using 30-gauge needles and forceps, the dura was removed
592 from the exposed area, and cortical tissue within the craniotomy was aspirated. A serial dilution
593 experiment was conducted to determine an optimal titer of the virus carrying Voltron2 genes,
594 minimizing cell toxicity, for use in this and in previous imaging experiments[29]. A fine injection
595 pipette (tip diameter 10-60 um) was used to inject AAV2/1-CAG-flex-Voltron2-ST (2.7×10^{12} GC/ml, a
596 generous gift from Dr. Eric Schreiter and the GENIE team at HHMI Janelia Research Campus) into the
597 exposed regions at a depth of 200 μm (up to six injection sites and 100-200 nL of viral
598 suspension). An optical chamber was constructed by placing a cannula with a cover slip attached at
599 the bottom over the craniotomy and sealing it with dental acrylic or C&B Metabond (Sun Medical).
600 A custom-built titanium frame was then cemented to the animal's head using dental acrylic or C&B
601 Metabond. Mice received ketorolac (6mg/kg) and cefazolin (1g/kg) for two days following surgery to
602 minimize pain and inflammation.
603
604 **Behavioral training**
605 After at least two weeks of recovery from the window surgery, the mice underwent behavioral
606 training to ensure they were calm and attentive in the test environment. For mice subjected to
607 imaging experiments where they explored an air-lifted plastic track, the initial training phase
608 involved acclimating the mice to head fixation and treadmill running, which took place over 3-5 days
609 in a separate room distinct from the recording setup. Following this training, the imaging
610 experiments were conducted. On the day designated for imaging, the mice were introduced to the
611 recording room for the first time just before the imaging session. During the imaging experiments,

612 the mice were securely held in a head-fixed position beneath the microscope and on an air-lifted
613 plastic track that rested on an air table (AirLift, Neurotar; Figure 1A). The track was adorned with
614 various shapes of signs to help the mice navigate the track. Subdued blue lighting was provided to
615 illuminate the track. Before the initiation of imaging, the mice were confined in a corner of the track
616 using gates. Subsequently, the gates were opened upon the start of imaging, allowing the mice to
617 explore the new environment during their initial laps (Figure 1A Top view). The Mobile HomeCage
618 tracking system (Neurotar) was used to track the mice's position and speed. During the acquisition
619 of image frames, TTL pulses were sent by the high-speed camera to the Mobile HomeCage tracking
620 system to facilitate data alignment. Mice subjected to imaging experiments with head fixation in a
621 tube were first trained in a separate room, distinct from the recording setup, for 1-2 days to
622 habituate them to the head fixation procedure. Following this training, the mice were introduced to
623 the recording room for the first time immediately before the imaging session. During imaging, the
624 mice were securely positioned in a head-fixation setup within an acrylic tube and remained
625 stationary. To further familiarize the mice with the recording context, the imaging procedure was
626 repeated for 4 days without injecting the JF-HaloTag ligand. On the fifth day, the JF-HaloTag ligand
627 was injected prior to imaging, and voltage imaging was performed following the same procedure as
628 in the previous sessions.
629
630 **Voltage imaging**
631 JF_{552}-HaloTag ligand[93] (a generous gift from Dr. Luke Lavis) was first dissolved in DMSO (20 μl,
632 Sigma) and then diluted in Pluronic™ F-127 (20 μl, P3000MP, Invitrogen) and PBS to achieve a
633 final concentration of 0.83 mM of JF_{552}-HaloTag ligand. The solution was then injected intravenously
634 through the retro-orbital sinus. Imaging sessions were initiated 3 hours after the injection of the
635 JF_{552}-HaloTag ligand. Fluorescence sensors were excited using a 532-nm laser (Opus 532, Laser
636 Quantum) with an excitation filter (FF02-520-28, Semrock), and the emitted light was separated
637 from the excitation light using a dichroic mirror (540lpxr Chroma) and passed through an emission

filter (FF01-596183 Semrock). A 16X, 0.8 NA objective (Nikon) was used to collect the emission light which was then imaged on a CMOS camera (DaVinci-1K, RedShirt) with a 50-mm camera lens (Nikkor 50mm f1.2, Nikon) as the tube lens. Images were acquired using Turbo-SM64 (Sci-Measure) at 2kHz with a resolution of 190 x 160 pixels, corresponding to a field of view of 1.4 x 1.2 mm. The number of frames in an image session was set at 360,000, corresponding to a duration of 180 seconds per session. Imaging depths ranged between 70 and 170 μm from the window surface, where the CA1 pyramidal neurons were located. Time-lapse images were collected, and image stacks of the same field of view along the z-axis were acquired. The image stacks consisted of 100 plans separated by two μm, covering the depth from the window surface to 200 um from the surface.

LFP recording

The LFP signal from the contralateral CA1 region of the hippocampus was simultaneously recorded during voltage imaging. To implant the LFP electrode, a small craniotomy was performed at the dorsal CA1 coordinate (2mm caudal and 1.8 mm right to the bregma). A tungsten electrode (#100211, 38 μm in diameter, polyimide insulated, California Fine Wire) was inserted into the dorsal CA1 region, and the wire and pins were cemented in place with dental acrylic. In order to target the CA1 pyramidal layer, the depth of the electrode was controlled and tracked by a micromanipulator (Sutter Instrument, MP-285). Pyramidal layer-specific signatures of the LFP signals, such as complex bursts and high-frequency ripple oscillations, were used to guide the targeting. The electrode location was verified by using tungsten electrodes coated with DiI (Invitrogen™, D282), followed by brain slicing after the recordings. The electrical signal was amplified and filtered (1-1kHz) using a DAM80 amplifier (Word Precision Instruments). The amplified signal was acquired by an I/O device (National Instruments USB-6341) and recorded using WaveSurfer (Adam Taylor, HHMI Janelia Research Campus) at 10 kHz during implantation and TurboSM64 (RedShirt) at 8 kHz during imaging.

664

665 **Imaging somata and dendrites *in vivo* using a two-photon microscope**

666 Immediately after voltage imaging, Voltron-labeled neurons were examined *in vivo* under a two-
667 photon microscope to assess the integrity of their membranes and dendrites. Images were acquired
668 using a two-photon scanning microscope equipped with a femtosecond-pulsed laser (Chameleon,
669 Coherent) and a resonant scanner controlled by ScanImage 4.2 software[94] (http://scanimage.org). A
670 16x water-immersion objective (Nikon, 0.8 NA, 3 mm working distance) was used for imaging. Z-
671 stacks of images (512 x 512 pixels, 600 μm x 600 μm) were collected with excitation light at 800
672 nm. The emission light was separated from the excitation light using a primary dichroic mirror
673 (FF735-Di02-25x36, Semrock), followed by a secondary dichroic mirror (565dclp, Chroma) and an
674 emission filter (FF01-609/57-30-D, Semrock). Each image stack consisted of 100 planes, separated
675 by 2 μm, covering depths from the window surface to 200 um below the surface.

676

677 **Histological processing and quantification of soma depth**

678 Mice with Voltron2$_{552}$ labeling were anesthetized with intraperitoneal injections of ketamine (250
679 mg/kg) and xylazine (25 mg/kg) and transcardially perfused with 4% paraformaldehyde in
680 phosphate-buffered saline (PBS; 2 mL/g). The brains were post-fixed in 4% paraformaldehyde
681 overnight and then washed in PBS. Coronal brain sections, 50 μm thick, were prepared using a
682 VT1200 vibratome (Leica). Sections were mounted with Vectashield mounting medium containing
683 DAPI (VectorLabs) to visualize nuclei. The soma depth of Voltron-labeled cells was measured relative
684 to the border between the *stratum pyramidale* (SP) and the *stratum radiatum*. Depth values were
685 normalized to the thickness of the SP, with larger depth ratios indicating somata located deeper
686 along the radial axis.

687

688 **Voltage imaging preprocessing and spike detection**

689 Fluorescence intensities were corrected for brain movement using rigid registration. Regions of

690 interest (ROIs) were manually selected by grouping pixels that cover individual somata. Previous
691 studies have described and validated the procedure for imaging preprocessing and spike
692 detection[29,84,95]. In short, the fluorescence intensities of individual neurons were calculated by
693 averaging the fluorescence intensities of pixels from the same ROIs. Bleaching was corrected by
694 calculating the baseline fluorescence (F_0) at each time point as an average of the fluorescence
695 intensities within $\pm$0.5 seconds around the time point. The dF/F was calculated as the F_0 minus the
696 fluorescence intensity of the same time point divided by F_0. Positive fluorescence transients were
697 detected to identify spikes from the high-passed dF/F traces created by subtracting the dF/F traces
698 from the median-filtered version with a 5-ms window. To simulate the noise of recordings, high-
699 passed dF/F traces were inverted, and the amplitudes of the transients detected from the inverted
700 traces were used to construct a noise distribution of the spike amplitudes. A threshold was set by
701 comparing the amplitudes of the detected transients with the noise distribution of the spike
702 amplitudes to minimize the sum of type I and type II errors. Spikes were first detected when
703 transients were larger than the threshold. Then, spike amplitudes smaller than half of the top 5%
704 spike amplitudes were excluded. The signal-to-noise ratio (SNR) was calculated for each neuron as a
705 ratio of the averaged spike amplitudes over the standard deviation of the high-passed dF/F traces,
706 excluding points 2 ms before and 4 ms after each detected spike to estimate the quality of the
707 recordings. The crosstalk between ROIs was routinely checked by examining the refractory periods
708 of neurons in auto-correlograms. Only neurons meeting the following criteria were included: (1)
709 SNR larger than 5, (2) full width at half maximum of the spike waveform longer than 0.8 ms, (3)
710 mean spike rates higher than 0.1 Hz, (4) distances between soma pairs at least 70 μm. Sessions
711 with at least nine neurons meeting the selection criteria were used for further analysis.
712

713 **Behavioral states of locomotion and immobility**

714 The periods of locomotion were defined as instances when the animals' speed exceeded 3 cm/s,
715 while periods of immobility were determined as instances when the animals' speed fell below 1

716 cm/s.

717

718 **Mean firing rates during locomotion and immobility**

719 To calculate the mean firing rates during locomotion, we counted the number of spikes during
720 locomotion periods and divided this number by the total duration of locomotion. Similarly, for mean
721 firing rates during immobility, we calculated the number of spikes that occurred during immobility
722 periods and divided this number by the total duration of immobility.

723

724 **Correlation between instantaneous firing rate and animal speed**

725 To estimate the instantaneous firing rates of individual neurons over time, we convolved their spike
726 trains with a Gaussian window of 250 ms. Subsequently, we calculated the Pearson correlation
727 coefficient between these instantaneous firing rates and the animal's speed for each neuron.

728

729 **Grand average cross-correlogram (CCG)**

730 Grand average CCGs were generated by constructing histograms of relative spike timings between
731 spikes of a reference cell and spikes of all other neurons in the same session as the target cell
732 population. Histograms were binned using 1-ms time bins. Spike counts were normalized by the
733 number of reference spikes times the number of all other neurons. An equal number of cells from
734 different sessions were randomly selected to form the shuffled target cell population to assess the
735 statistical significance of the CCG peaks. Subsequently, grand average CCGs were computed using
736 shuffled spike trains for comparison. Grand average CCGs were calculated using all spikes in the 180-
737 s recording periods, subsets of spikes during immobility periods (immobility grand average CCGs),
738 and subsets of spikes during locomotion periods (locomotion grand average CCGs).

739

740 **Detection of the population synchrony**

741 To assess population synchrony, we counted the number of spikes from all neurons within a sliding

742 window of 25 ms. To test the significance of the synchrony, we generated surrogate data by jittering
743 spike timings within a ±75-ms window 500 times. The means and standard deviations of each
744 sample point were calculated over the jitter population. Population synchrony was detected as
745 peaks when the spike count in the original data exceeded the mean plus four standard deviations of
746 the spike counts in the jittered data. Synchrony was also evaluated in modified spike trains,
747 including those where later spikes in bursts were removed and those where spike times were
748 shuffled across theta cycles while preserving phases. To estimate synchronous event rates, we
749 divided the entire 180-second recordings into halves and calculated the event rate in each of the 90-
750 s segments. Additionally, ensemble sizes were quantified by counting the percentage of neurons
751 participating in each synchronous event.
752 To detect population synchrony in a publicly available dataset, we analyzed the "hc-11" dataset
753 from CRCNS, which contains hippocampal recordings from rats running on novel mazes for water
754 rewards at designated locations[43,44]. Spikes recorded during the first three minutes of the novel-
755 maze running epochs were used to identify synchronous ensembles and generate jittered control
756 data. Spike counts for both the original and jittered data were calculated using a sliding 25-ms
757 window. The algorithm for testing the significance of synchrony was the same as described above.
758 Synchronous event rates were estimated using the entire 3-minute spike trains for both the original
759 and jittered data.
760
761 **Pairwise cross-correlogram (CCG) of neuronal pairs**
762 To compute the CCG, we first determined the time difference between spikes in the target and
763 reference neurons and then binned these values into 1-ms time bins. CCGs were only computed for
764 pairs with more than 100 counts within the CCG window of ±500 ms to ensure reliable correlation.
765 We defined the peak of the CCG as the local maxima within ±30 ms of lag. To assess the significance
766 of cross-correlations, we generated surrogate data by jittering the spike times of the target neuron

767 within a ±75 ms window. We computed the CCG peak for a thousand iterations and calculated p-
768 values by comparing the percentile of the peak in the null distribution of the jittered peak values.
769 The synchronization strength was estimated as the ratio between the original CCG peak and the
770 mean spike count of the same bin as the original CCG peak averaged across the jittered histograms.
771 For display purposes, the CCGs were smoothed using a 5-point moving average. CCGs were
772 calculated using all spikes in the 180-s recording periods, subsets of spikes during immobility
773 periods (immobility pairwise CCGs), and subsets of spikes during locomotion periods (locomotion
774 pairwise CCGs).
775
776 **LFP c-ripple analysis**
777 To detect c-ripples, we performed band-pass filtering of the LFP signal between 120 and 240 Hz,
778 followed by computing the envelope using the absolute values of the Hilbert transform, which was
779 then low-pass filtered at 20 Hz. The start and end times of c-ripples were identified by setting the
780 upper and lower thresholds at the mean plus 7 and 3.5 times the standard deviation of the
781 envelope, respectively. For a c-ripple event to be included, three conditions had to be met: (1)
782 values within the event were higher than the lower threshold, (2) at least one value exceeded the
783 upper threshold, and (3) the minimum duration of the event was 30 ms. The start and end times of
784 a c-ripple event were defined as the positive and negative crossings of the lower threshold,
785 respectively. We defined in-c-ripple periods as the time between the start and end of detected c-
786 ripple events, while out-c-ripple periods were periods outside the in-c-ripple periods. The envelope
787 peak values of the detected c-ripple events were used as the time of c-ripple occurrence. These
788 timings were utilized as trigger timings to calculate averages triggered by c-ripples. Two co-
789 occurrences were quantified: the percentages of c-ripple oscillations that occurred with
790 synchronous ensembles and the percentages of synchronous ensembles that occurred with c-ripple
791 oscillations. The same ripple detection algorithm was applied to the hc-11 dataset. To account for
792 artifacts in the recordings, raw traces and power spectra of the detected events were plotted and

inspected for false positives.

C-ripple modulation index

We utilized the c-ripple modulation index to assess changes in firing rates during c-ripples compared to periods outside c-ripples. This index was computed as the ratio of the difference in mean firing rates during in- and out-c-ripple periods to the sum of the mean firing rates during both periods. Specifically, we first calculated the mean firing rate during in-c-ripple periods and the mean firing rate during out-c-ripple periods. Next, we subtracted the mean firing rate during out-c-ripple periods from the mean firing rate during in-c-ripple periods and divided the result by the sum of the mean firing rates during both periods. The resulting c-ripple modulation index indicates the magnitude and direction of the firing rate modulation during c-ripples compared to periods outside c-ripples. To assess the significance of the modulation index, we shuffled the spike timings and repeated the calculation a thousand times to generate a distribution of modulation indices from the shuffled data. The original modulation index was then compared to this distribution, and its significance was determined if it exceeded the 95% confidence level of the shuffled indices.

LFP traces triggered by population synchrony and analysis

The midpoints of the synchronous event intervals were utilized as triggers to align LFP traces from both our recordings and the hc-11 dataset. These traces were aligned within a $\pm$1-second window around the trigger time points. To calculate the spectral density functions of the aligned LFP traces, we performed a 16,384-point fast Fourier transform of the 2-second LFP traces. The power spectra were then estimated as the squared absolute values of the Fourier coefficients. C-ripple power was calculated as the sum of the power distributed between 120 and 240 Hz. To calculate theta modulation strength and preferred angles of the synchronous ensembles, LFP was first filtered within the theta frequency range. Then, the phase $\varphi(t)$ and the instantaneous amplitude $A(t)$ of

818 the filtered LFP were computed using the Hilbert transform. A vector $V_k = A(t_k)e^{i\varphi(t_k)}$ was
819 assigned to each synchronous ensemble that occurred at time t_k. The modulation strength and the
820 preferred phase angle were determined as the absolute value and the phase angle of the summed
821 vector over all ensembles, respectively. Modulation strengths were normalized by the total length
822 of all vectors.
823
824 **Subthreshold membrane voltage (subVm)**
825 To compute the subVm of individual neurons, we began by determining the difference between the
826 raw dF/F signal and the high-pass version of dF/F. Next, we calculated the spike threshold for each
827 cell by identifying the voltage value corresponding to the peak of the first derivative of the spike
828 waveforms. Any fluorescence values in the slow dF/F time courses that surpassed the spike
829 thresholds were linearly interpolated.
830
831 **SubVm traces triggered by population synchrony**
832 The midpoint of the time intervals, during which synchronous ensembles were detected, served as
833 the reference points for aligning fluorescence traces within a $\pm$300 ms window around those
834 reference points. To eliminate any interference from membrane potential fluctuations associated
835 with spikes, we excluded aligned traces in cases where any spike occurred within the time intervals
836 of the aligned traces.
837
838 **SubVm theta modulation and phase preference of spikes occurred inside and outside the**
839 **population synchrony events**
840 The subVm was initially filtered within the theta frequency range. Subsequently, the phase $\varphi(t)$
841 and the instantaneous amplitude $A(t)$ of the filtered subVm were computed using the Hilbert
842 transform. Spikes were categorized into four groups: those occurring during or outside immobility
843 synchronous events and those occurring during or outside locomotion synchronous events. Within

each category, a vector $V_k = A(t_k)e^{i\varphi(t_k)}$ was assigned to each spike that occurred at time t_k. The modulation strength and preferred phase angle were determined as the absolute value and phase angle, respectively, of the summed vector over all spikes within a category. To facilitate comparison between neurons, modulation strengths were normalized by the total length of all vectors. The significance of the modulation strength was tested by shuffling the spike timings and recalculating the modulation strength a thousand times to generate a distribution based on the shuffled spike timings. The original modulation strength was then compared to the distribution, with significance determined if it exceeded the 95% confidence interval of the shuffled values. Significant modulation strengths were plotted and compared across groups.

Spike-triggered fluorescence traces

We extracted segments of fluorescence traces using a $\pm$300 ms time window centered on the spike timings. To examine variations in fluorescence waveforms triggered by spikes within and outside synchronous events, we categorized the fluorescence traces based on whether the spikes occurred within or outside these events. Subsequently, we performed pairwise comparisons of the fluorescence values from the same neuron, concentrating on spikes occurring during corresponding behavioral states. Neurons with four or fewer triggering events in any of these categories were omitted from the analysis.

Cross-correlation and coherence analysis to the subVm traces

To calculate cross-correlation and theta coherence of subVm between pairs of neurons during locomotion and immobility, we initially divided the 180-second subVm traces into 1-second segments with a 50% overlap. These segments were then categorized into the locomotion group if the animal's speed remained above three cm/s for more than 90% of the time within that segment. Similarly, segments were sorted into the immobility group if the animal's speed remained below one cm/s for more than 90% of the time within that segment. Subsequently, we computed the

870 cross-correlation and magnitude-squared coherence function of frequency for pairs of co-occurred
871 segments belonging to a specific cell pair. Mean cross-correlations of individual cell pairs were
872 averaged across segments that occurred in the same behavioral states (i.e., locomotion or
873 immobility states). To estimate theta coherence, we averaged the values of the coherence function
874 within the theta frequency range (4-12 Hz). Theta coherences from the same cell pair during the
875 same behavioral state were pooled together, and the average was used as an estimate for the theta
876 coherence of that cell pair during a particular behavioral state. Finally, Spearman correlation
877 coefficients were calculated between the mean theta coherences of cell pairs and their soma
878 distances.
879
880 **Spatial analysis**
881 We partitioned a 90-cm-long track into 36 spatial bins to analyze spatial tuning properties. For each
882 cell, the spatial tuning curve was computed by determining the mean firing rate, defined as the
883 number of spikes within the bin when the animal's speed exceeded three cm/s, divided by the total
884 dwell times using the same speed threshold. The peak firing rates were identified as the maximal
885 rate on the spatial tuning curve. Spatial selectivity was calculated as one minus the circular variance
886 of the spatial tuning curve. Neurons were classified as place cells when their spatial selectivity
887 exceeded 0.25, and peak firing rates exceeded 1 Hz. To assess the similarity of spatial tuning
888 between pairs of neurons, Spearman correlation coefficients were calculated for the spatial tuning
889 curves. To explore the relationship between levels of synchronization and spatial tuning similarity
890 among pairs of place cells, Spearman correlation coefficients were computed between
891 synchronization strengths of cell pairs and correlation coefficients of their spatial tuning curves.
892
893 **Data analysis and statistics**
894 Data analysis was performed using MATLAB (Mathworks, R2019b), and results were presented as
895 standard error of the mean unless otherwise specified. Boxplots were used to depict the median,

first quartile, and third quartile, with the middle line, the upper edge, and the lower edge of the box, respectively. The whiskers of the boxplots represented the 5th and 95th percentiles of the distribution.

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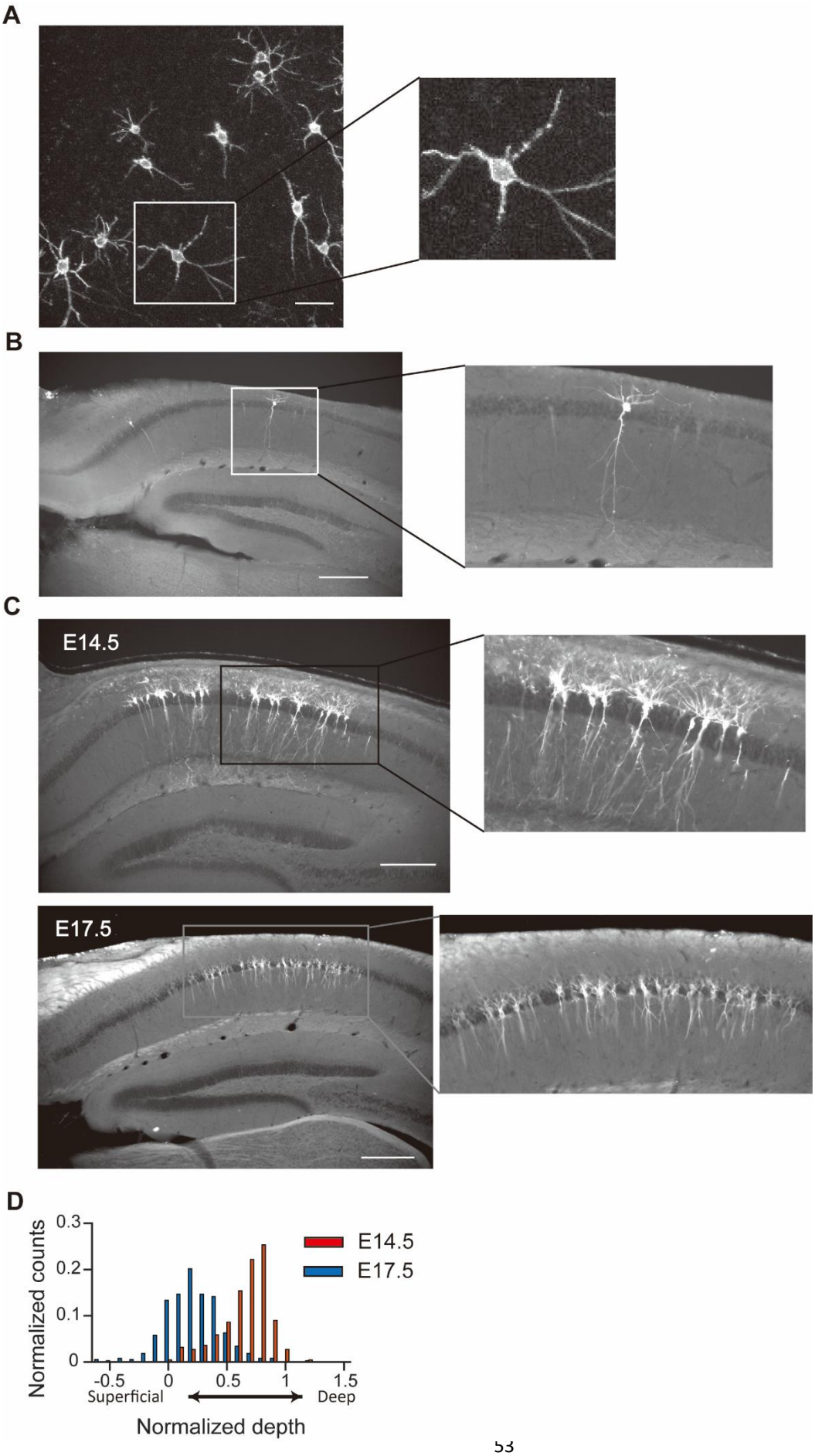
Acknowledgments

We express our sincere gratitude to Dr. Luke Lavis for sharing the JF_{552}-HaloTag ligand. Special thanks to Mr. Yu-Ting Lin and Ms. Hui-Ching Chen for technical assistance. We are grateful to Drs. Shih-Chieh Lin, Kuo-Hua Huang, Shi-Bing Yang, and Fu-Chin Liu for their insightful comments on the manuscript.

Funding statements

National Science and Technology Council, Taiwan (B.-J.L. and T.-W.C.)
Howard Hughes Medical Institute, USA (E.R.S.)


A
B
C
E14.5
E17.5
D
Normalized counts
0.3
0.2
0.1
0
-0.5
0
0.5
1
1.5
Superficial
Deep
Normalized depth
E14.5
E17.5

1161

1162 **Supplementary Figure 1. Morphology of Voltron-expressing neurons and their positions along the**

1163 **deep-superficial axis.**

1164 **(A)** Two-photon z-stack maximum intensity projection images of Voltron-expressing neurons

1165 obtained after imaging experiments. These neurons exhibit well-preserved membrane and dendritic

1166 morphology. Scale bars: 50 μ m.

1167 **(B)** Post-hoc histological images of a sparsely labeled neuron previously subjected to voltage

1168 imaging. Scale bars: 300 μ m.

1169 **(C)** Micrographs of labeled neurons from *in-utero* electroporation at embryonic day 14.5 (E14.5;

1170 upper panel) and E17.5 (lower panel). Scale bars: 300 μ m.

1171 **(D)** Histograms of normalized depths for E14.5 neurons (red) and E17.5 neurons (blue). A higher

1172 normalized depth indicates that the soma is located deeper within the pyramidal layer. Normalized

1173 depths for E14.5 neurons are significantly higher than those for E17.5 neurons ($t_{(601)}$=22.8,

1174 p<0.0001, Student's t-test).

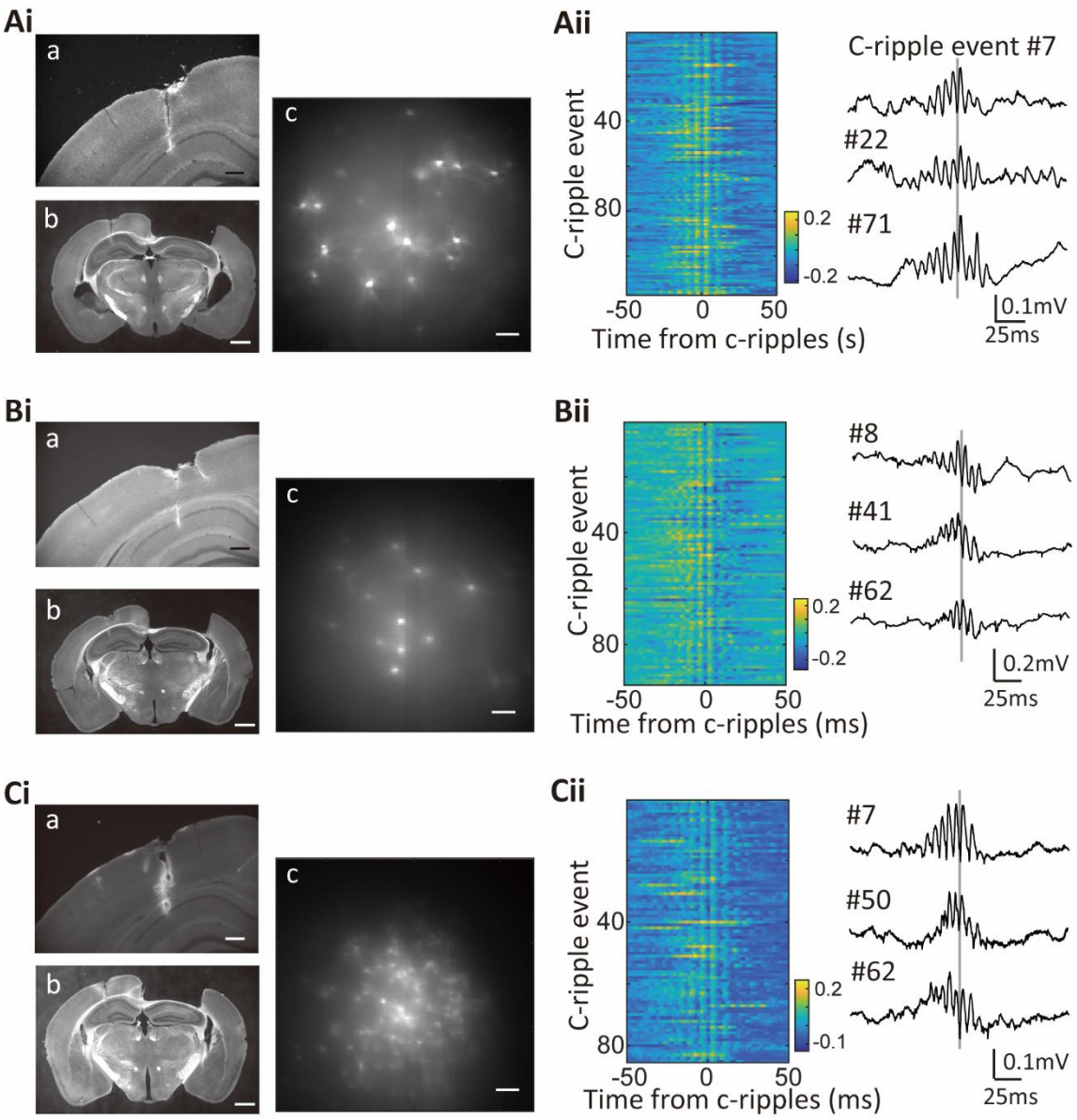
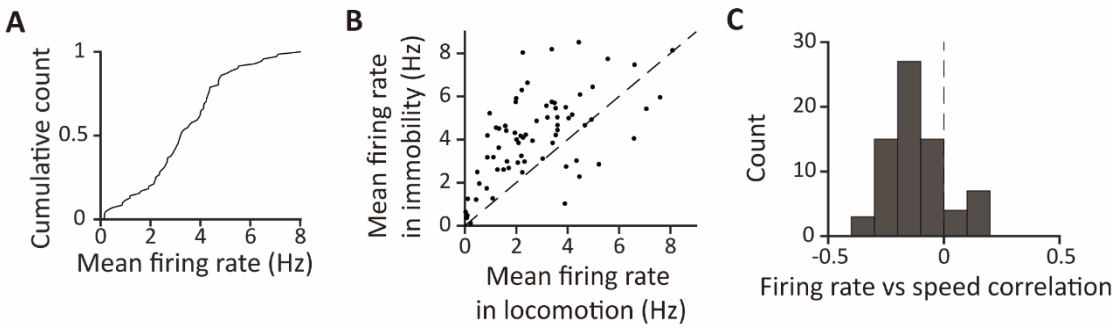


Figure 1-figure supplement 1. Paired photographs of the LFP electrode track and the voltage image from the same animal.

(Ai) Fluorescence images of a brain slice containing the electrode track (a: high magnification; b: low magnification) and the averaged voltage image of CA1 pyramidal cells taken in vivo from the same animal (c). Scale bar: 300 μm (a), 1 mm (b), and 100 μm (c).

(Aii) Voltage traces of the LFP recording aligned to the time of maximum c-ripple power. Left: color-coded voltage traces of all c-ripple events. Right: representative c-ripple traces.

(B, C) Same as in (A), but from different animals.



Supplementary Figure 2. Mean firing rate distribution and correlation with animals' speed.

(A) Cumulative distribution of mean firing rates averaged throughout the entire 180-second recording period.

(B) Mean firing rates during locomotion plotted against mean firing rates during immobility for individual cells. Each dot represents a cell. Mean firing rates are higher during immobility than during locomotion (4.2±0.2 Hz for immobility, 2.8±0.2 Hz for locomotion, $t_{(70)}$=6.63, p<0.0001, Student's t-test).

(C) Histogram of correlation coefficients between instantaneous firing rates and the animals' speed for each neuron.

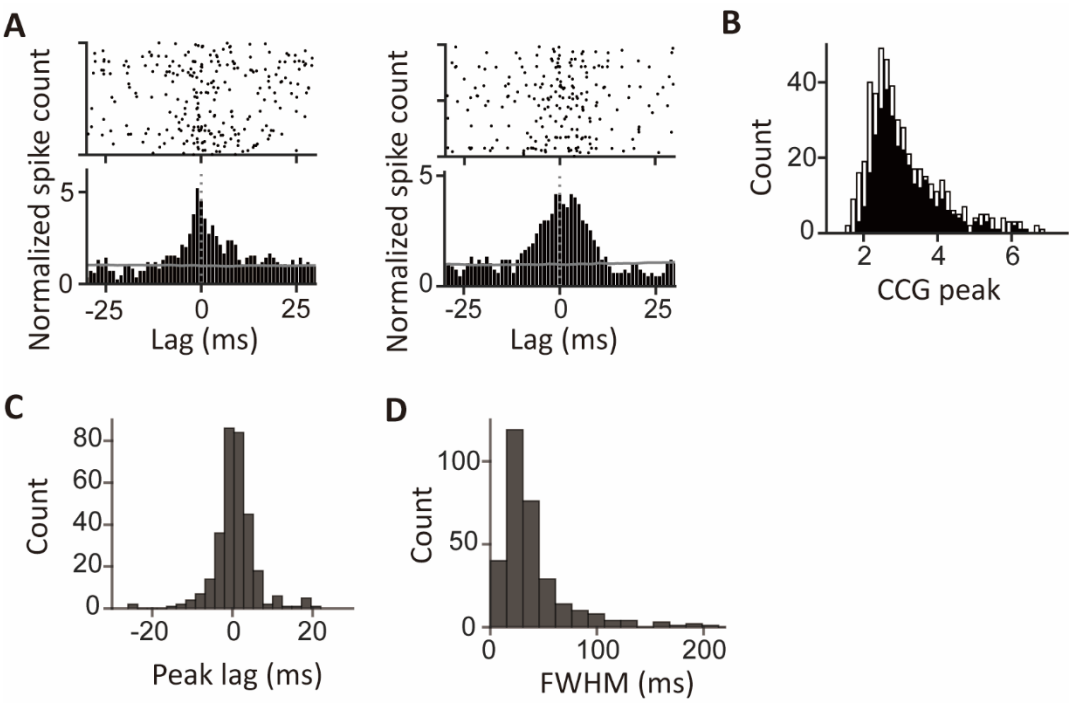


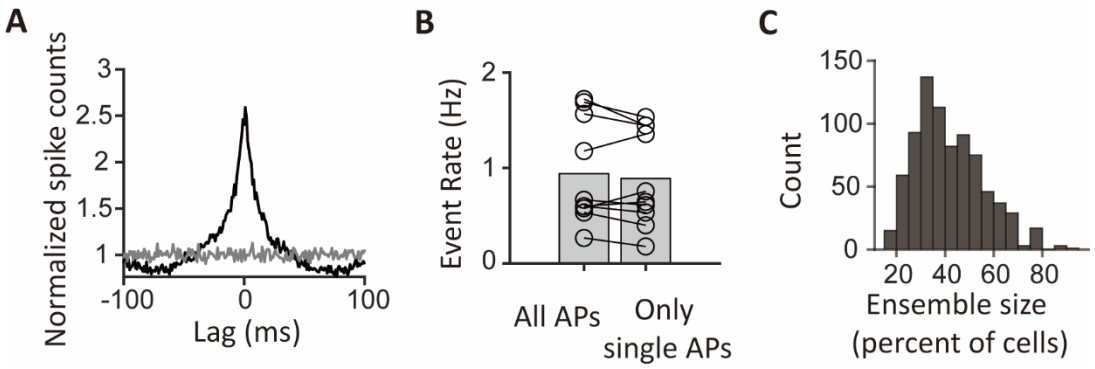
Figure 1-figure supplement 2. Pairwise cross-correlogram (CCG) between CA1 pyramidal cells.

(A) CCGs of two representative cell pairs exhibiting significant peaks compared to the jittered spike trains of the target cells (gray lines).

(B) Distribution of the CCG peaks (*n*=497 pairs). Black: CCG peaks with significance ($p<0.05$). White: CCG peaks without significance ($p>=0.05$).

(C) Histogram of peak lags of significant CCG peaks (*n*=315 pairs).

(D) Histogram of FWHMs of significant CCG peaks (*n*=315 pairs).



Supplementary Figure 3. Population synchrony remains after removing the later spikes in bursts.

(A) Grand-average cross-correlogram (CCG) calculated using spike trains with the later spikes in bursts removed. The gray line represents the mean grand-average CCG between reference cells and randomly selected cells from different sessions.

(B) Pairwise comparison of population synchrony event rates between spike trains containing all spikes and those with the later spikes in bursts removed. Bar heights represent group means (*n*=10 segments, *p*=0.36, Wilcoxon signed-rank test).

(C) Histogram of ensemble sizes showing the percentage of cells participating in synchronous ensembles.

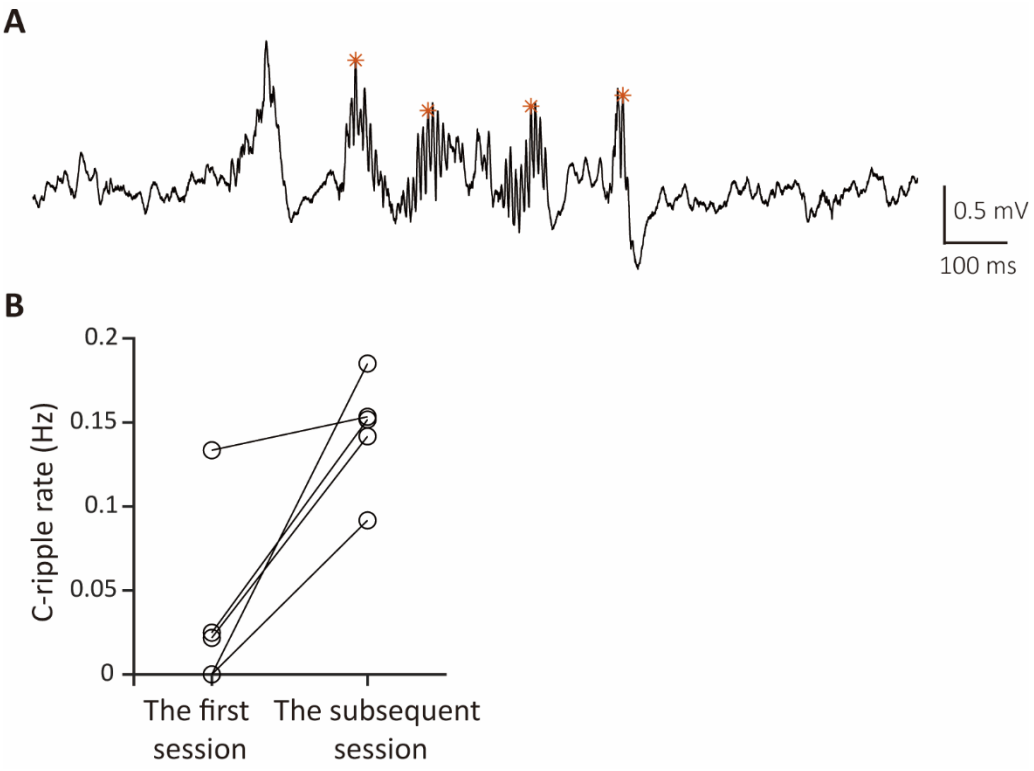


Figure 3-figure supplement 1. LFP c-ripples recorded in the first and subsequent sessions in a novel maze.

(A) An example LFP trace with c-ripples recorded in a subsequent session following the first session of novel exploration, where no c-ripple was detected.

(B) C-ripple rates in the first and subsequent sessions recorded in the same animals (n=5 mice) during novel exploration.

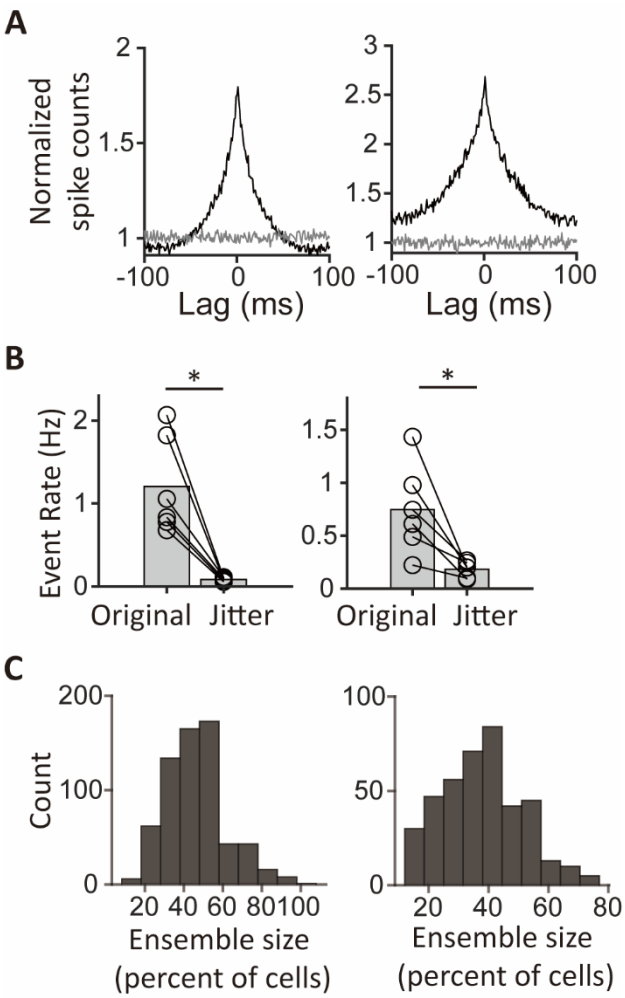


Figure 3-figure supplement 2. Population synchrony during novel immobility.

(A) Grand average cross-correlograms (CCGs) for neurons labeled on E14.5 (left) and on E17.5 (right). The gray line represents the mean grand-average CCG between reference cells and randomly selected cells from different sessions.

(B) Pairwise comparison of synchronous event rates between the original and jittered data. Event rates were significantly higher in the original data compared to jittered controls for E14.5 neurons (left; mean event rate: 1.21 ± 0.24 Hz for the original data, 0.08 ± 0.009 Hz for jittered data, n=6 segments, W=21, p=0.03, Wilcoxon signed-rank test) and E17.5 neurons (right; mean event rate: 0.75 ± 0.17 Hz for the original data, 0.18 ± 0.03 Hz for jittered data, n=6 segments, W=21, p=0.03, Wilcoxon signed-rank test). Bar heights represent group means. *p<0.05

(C) Histograms of ensemble sizes showing the percentage of cells participating in synchronous ensembles for E14.5 neurons (left) and E17.5 neurons (right).

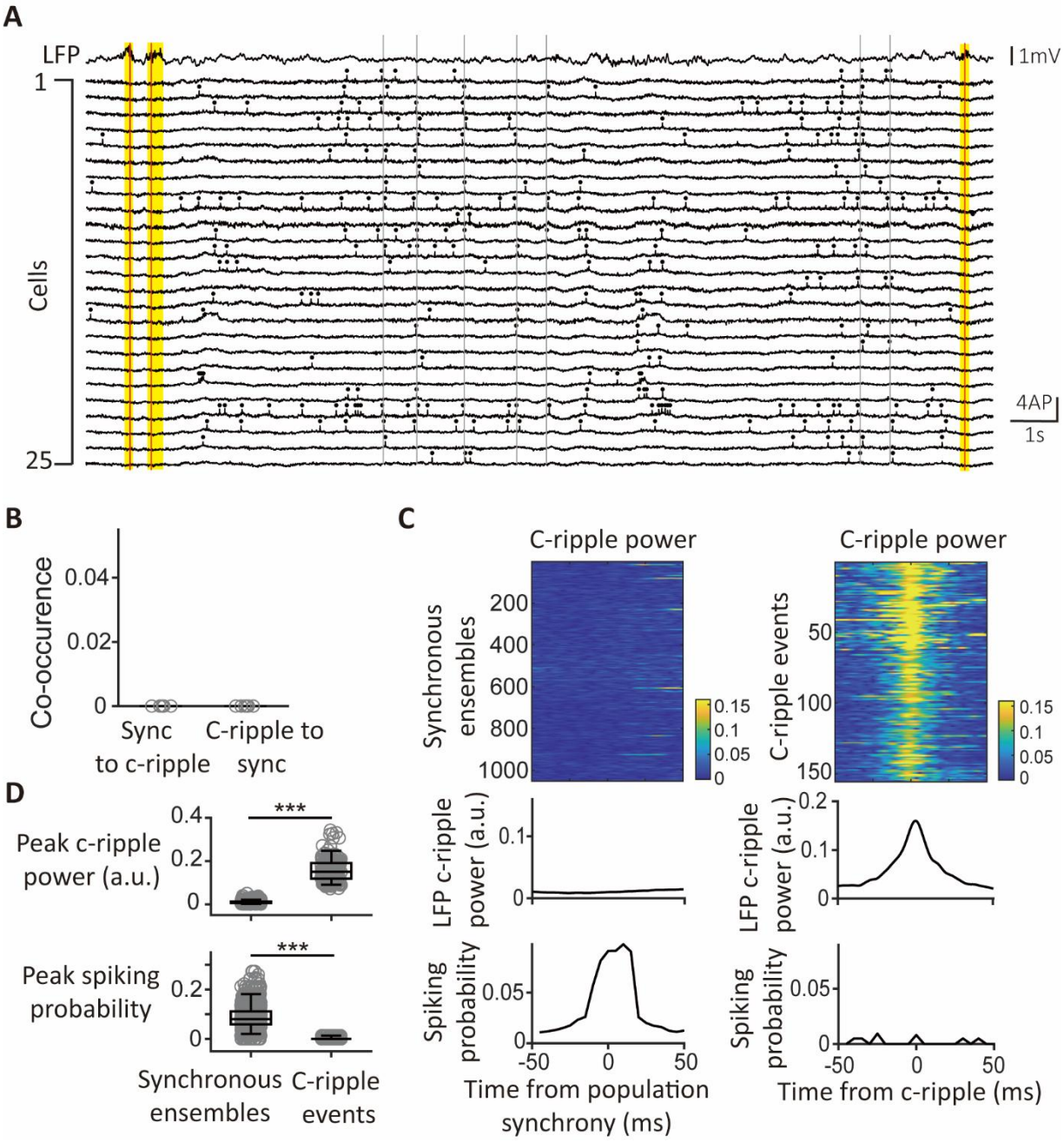


Figure 3-figure supplement 3. Population synchrony outside c-ripple episodes during novel immobility.

(A) Example traces illustrating the distinct timings of c-ripple episodes and synchronous ensembles. Top: Simultaneously recorded LFP trace showing episodes of c-ripple oscillations. Red vertical lines indicate the timings of peak c-ripple power in the LFP trace, while yellow vertical bars mark the duration of c-ripple episodes. Bottom: Fluorescence traces from 25 CA1PCs. Gray vertical lines indicate the timings of synchronous ensembles.

(B) Percentages of co-occurrence between synchronous ensembles and c-ripple events. The “sync to c-ripples” group represents the percentage of c-ripple events that co-occur with synchronous ensembles, while the “c-ripples to sync” group shows the percentage of synchronous ensembles that co-occur with c-ripple events. Each gray circle represents an individual session.

(C) LFP c-ripple power and spiking probability aligned to synchronous ensembles and c-ripple events. **Upper panel**: Color-coded LFP power at c-ripple frequency (120-240Hz), aligned to the timings of 1052 synchronous ensembles (left) and 174 c-ripple events (right). **Middle panel**: Average LFP power at c-ripple frequencies aligned to the timings of synchronous ensembles (left) and c-ripple events (right). **Lower panel**: Average spiking probability of all recorded cells aligned to the timings of synchronous ensembles (left) and c-ripple events (right).

(D) Boxplots and comparisons of peak c-ripple power (upper panel) and peak spiking probability (lower panel) at the timings (t=0) of population synchrony (left) and c-ripple events (right). For peak c-ripple power: $p<0.001$, $t_{(1224)}=86.6$, Student’s *t*-test; for peak spiking probability: $p<0.001$, $t_{(1224)}=24.3$, Student’s *t*-test. Gray circles indicate peak values for individual triggered traces.

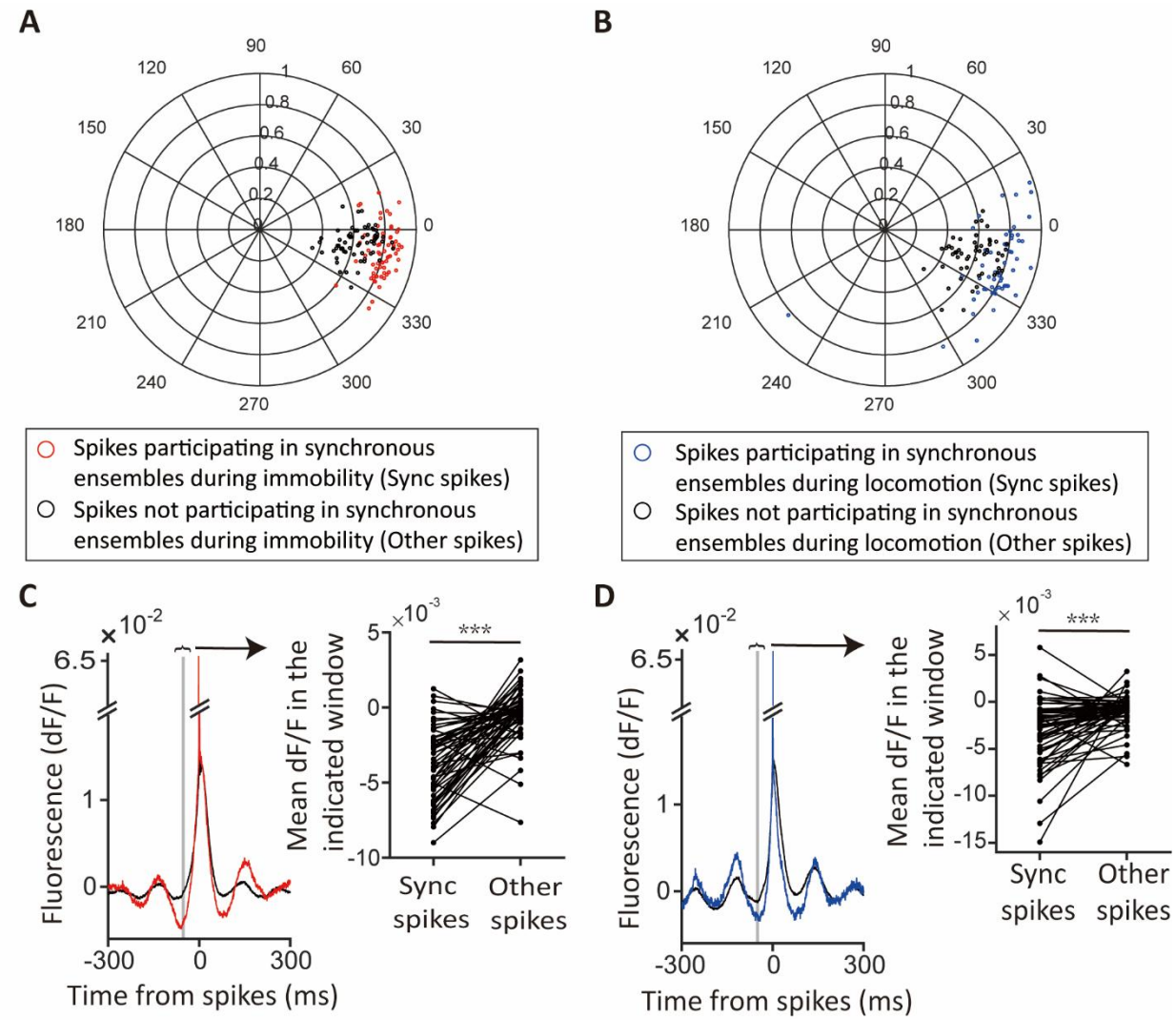


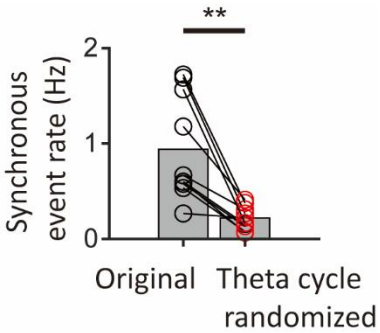
Figure 5-figure supplement 1. SubVm theta modulation of spikes during immobility and locomotion periods of novel exploration.

(A) Polar plot comparing subVm theta modulation between spikes participating in synchronous ensembles (sync spikes) and spikes not participating in synchronous ensembles (other spikes) during immobility. Each dot represents the averaged modulation of a cell. Cells with modulation strengths that are not significant are excluded in the plot and in the comparison. The modulation strengths of spikes participating in synchrony are significantly higher than those of spikes not participating in synchrony (modulation strength for spikes participating in synchronous ensembles: 0.81±0.07, for spikes not participating in synchronous ensembles: 0.64±0.11, mean±s.d., $t_{(64)}$=12.6, p<0.001, paired t-test).

(B) Same as in (A), but during locomotion (modulation strength for spikes participating in synchronous ensembles: 0.80±0.09, for spikes not participating in synchronous ensembles: 0.60± 0.12, mean±s.d., $t_{(53)}$=12.3, p<0.001, paired t-test).

(C) Average fluorescence triggered by cells' spikes participating in synchronous ensembles (red, sync spikes) and not participating in synchronous ensembles during immobility (black, other spikes; n=59 cells). Inset: Pairwise comparison of average fluorescence 50±5 ms before time of spikes (t=0) between the two triggered groups (n=59 cells, p<0.001, paired t-test). ***p<0.001.

(D) Same as in (C), but during locomotion. Inset: Pairwise comparison of average fluorescence (n=59 cells, p<0.001, paired t-test).



Supplementary Figure 4. Significant reduction of population synchrony by randomizing spikes across theta cycles while preserving phases

Pairwise comparison of population synchrony event rates between the original spike trains and randomized spike trains, in which spike timings were shuffled across theta cycles while preserving phases (*n*=10 segments, *p*=0.002, Wilcoxon signed-rank test). Bar heights represent group means.

** $p<0.01$

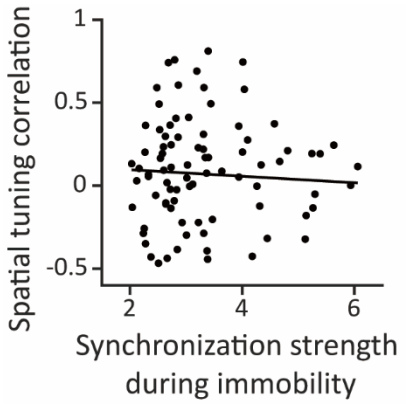
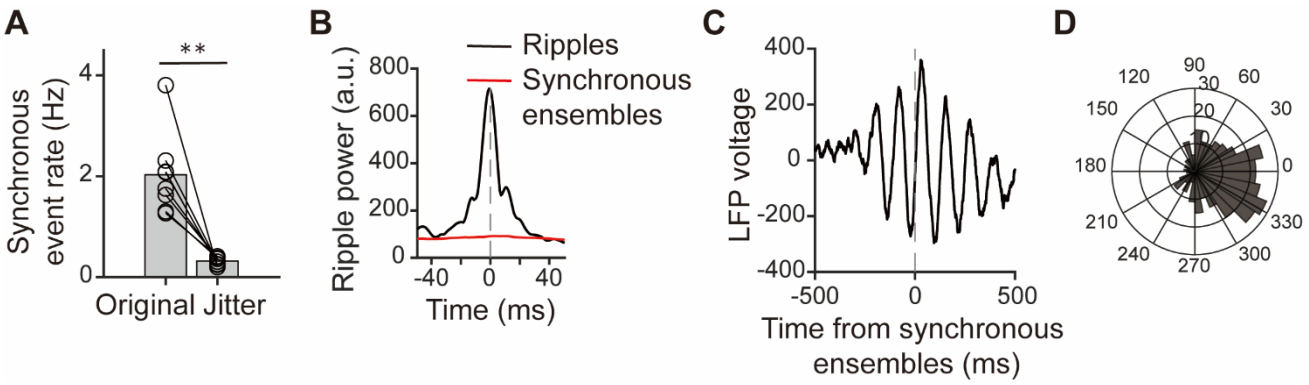


Figure 5-figure supplement 1. Synchronization strengths during immobility show little correlation with the similarity of spatial tunings between place cells. Synchronization strengths during immobility plotted against correlation coefficients of spatial tunings for pairs of place cells. Synchronization strengths show little correlation with similarities of spatial tunings (Spearman correlation coefficient=-0.003, p=0.98, n=88 cell pairs).



Supplementary Figure 5. Analyses of synchronous ensembles in the publicly available data

(A) Pairwise comparison of synchronous event rates between the original and jittered data. Event rates were significantly higher in the original data compared to jittered controls (n=8 sessions, p=0.008, Wilcoxon signed-rank test). Bar heights represent group means. **p<0.01.

(B) Dynamics of ripple power aligned to timings of ripples (black) and timings of synchronous ensembles (red).

(C) Average LFP trace aligned to timings of synchronous ensembles of a session.

(D) Polar histogram of the differences between theta phases of individual synchronous ensembles and the preferred phase of the session.