Waveform shape of hippocampal theta oscillations reflects interneuron spike timing

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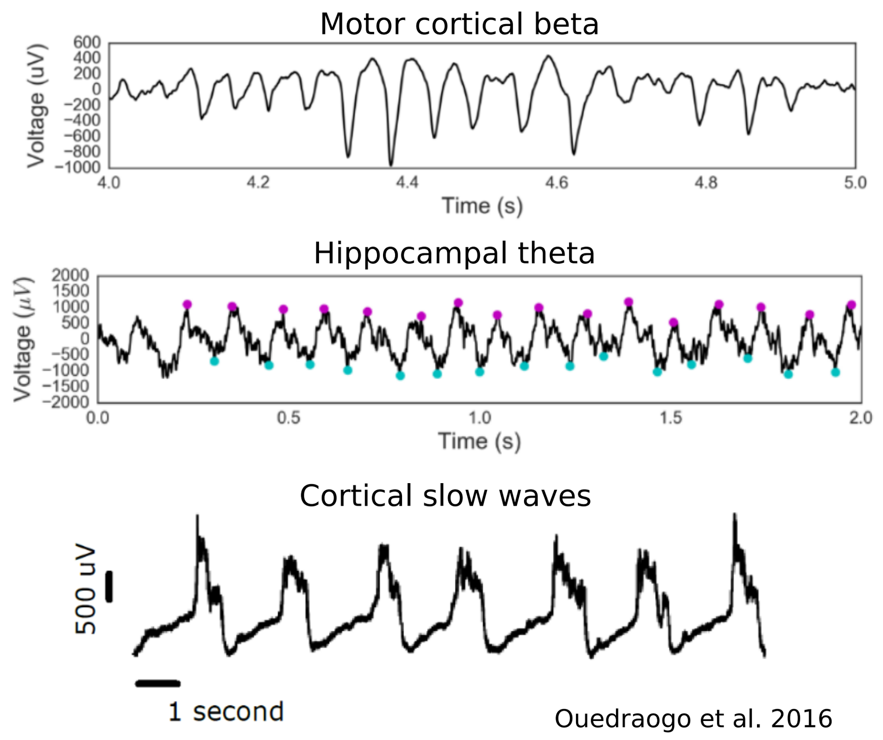
Background

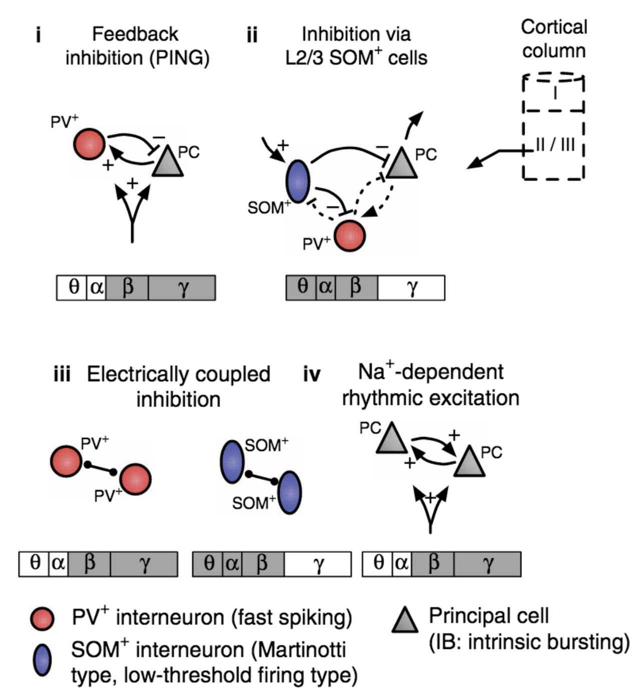
* Oscillations in neural recordings have been widely implicated in mechanisms for neural communication, behavior, and pathologies.
* Classic oscillatory analysis focuses on the frequencies and amplitudes of these rhythms but are not sensitive to their shapes. Recent algorithms can extract repeated oscillatory waveforms (Jas et al. 2017, Arxiv)
* Field potentials are a complex spatiotemporal summation of current sources, and their temporal dynamics may reflect properties of these sources.
* The hippocampal theta rhythm has been related to spatial navigation and associative memory. It has a characteristic sawtooth shape, but its variations may reflect changes in neural computation.

Neural oscillation waveform shape

Oscillations are generated by a variety of mechanisms that may yield field potentials with distinct temporal profiles.



Ouedraogo et al. 2016

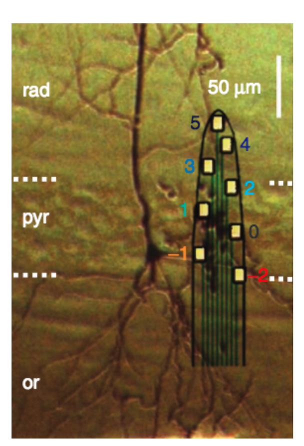


Womelsdorf et al. 2014

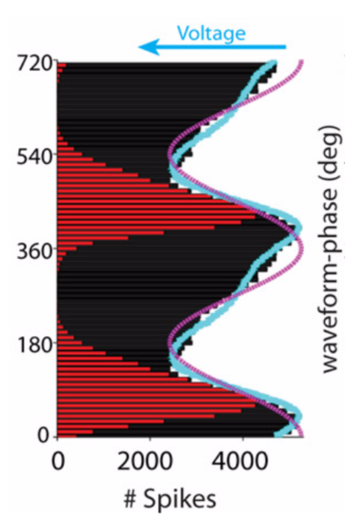
Theta waves

The sawtooth shape of hippocampal theta oscillations has been related to CA1 pyramidal cell spike timing and memory performance.

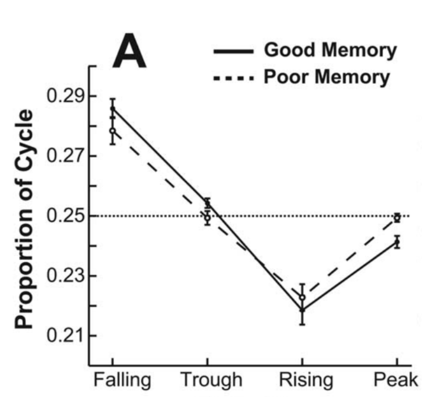
Field potentials and extracellular spiking were recorded in and around the hippocampus of 9 rats. Example electrode (Right). Data from CRCNS (hc3, Buzsaki group).



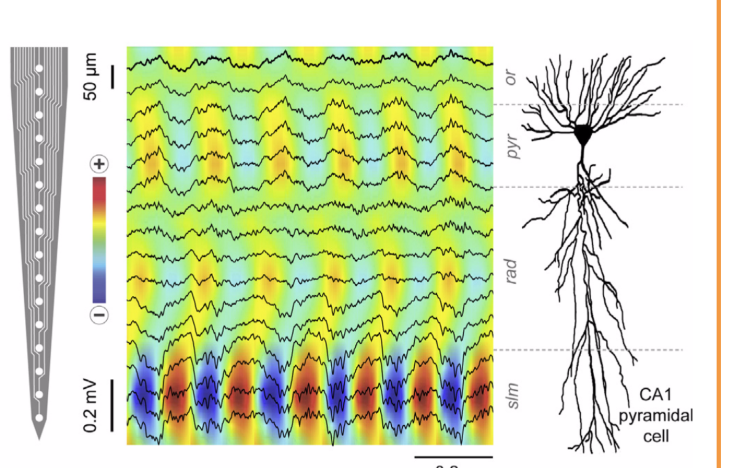
Mizuseki et al. 2011



Belluscio et al. 2012



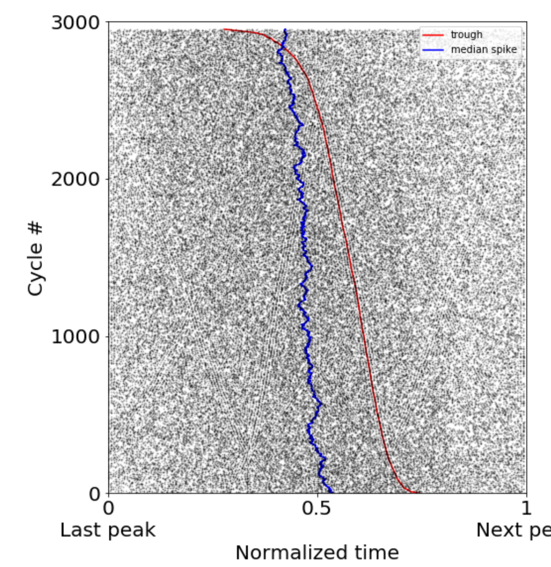
Tripimer et al. 2014



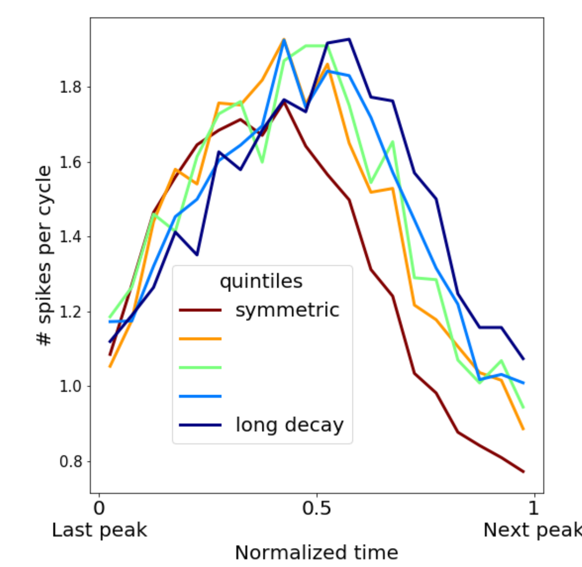
Pignatelli et al. 2012

Theta asymmetry and CA1 interneuron spike timing

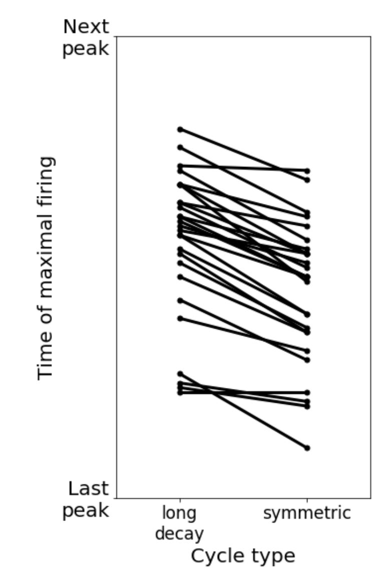
The symmetry of the theta oscillation varies from cycle to cycle. We hypothesize that this variance reflects variance in the spike timing of the CA1 interneuron population. In these figures, we show that CA1 interneuron spiking occurs later in cycles that are more asymmetric (long decay and short rise). This is consistent with constant spike-field coupling across cycles of different shapes.



Raster of CA1 interneuron spiking. Cycles sorted by symmetry. Data shown for 1 example recording. Notice that the spikes tend to occur later in the cycle (blue line) when the trough of the peak-to-peak cycle occurs later (red line).



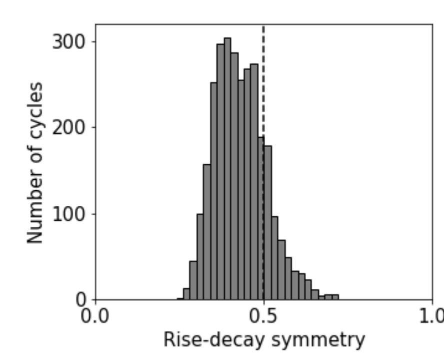
Number of CA1 interneuron spikes binned by time normalized to cycle duration. Each time bin is 5% of a cycle. Each line represents the mean across 20% of all cycles, sorted by their rise-decay symmetry. Data shown for 1 example recording. Notice that spiking occurs later in the peak-to-peak cycles with longer decay periods.



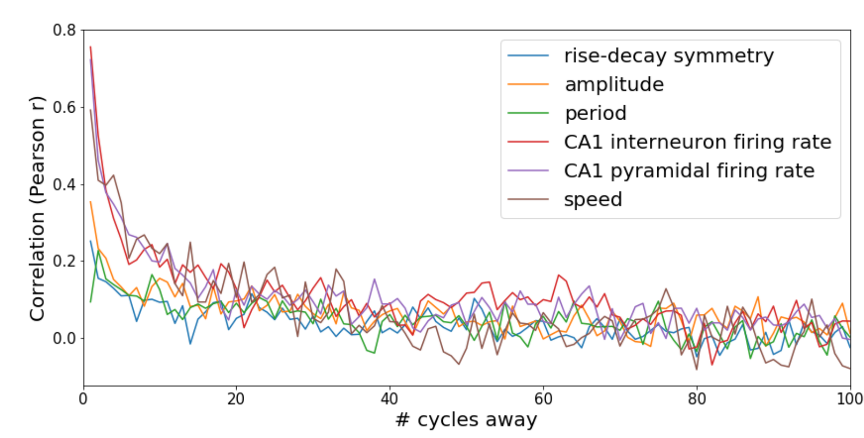
Across all recordings, the peak time of CA1 interneuron firing is later for cycles with the longest decay periods compared to the cycles with roughly equivalent rise and decay periods ($p < 10^{-5}$).

Methods

Oscillations are analyzed on a cycle-by-cycle basis. Features are computed for individual cycles and compared to population spiking patterns.



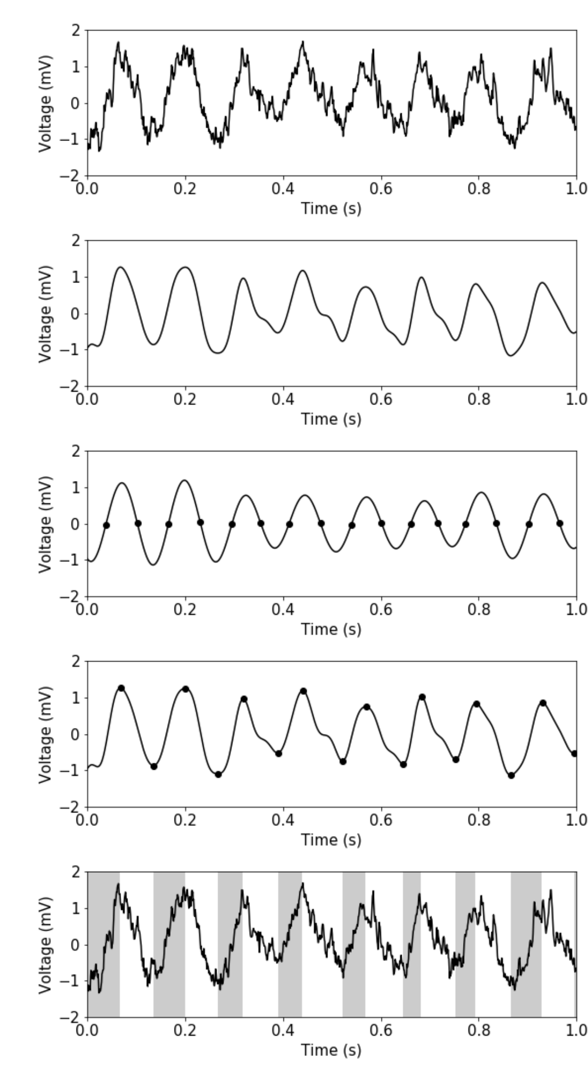
Histogram of rise-decay symmetry of all cycles in 1 recording.



Autocorrelations of cycle-by-cycle features and running speed.

	oscillator_amplitude	period	sample_trough	time_rise	time_decay	time_peak	time_trough	time_rdsym	volt_rise	volt_decay
0	36.695154	27	457962	16	11	11	14	0.592593	189.336803	124.687013
1	36.281067	17	457989	6	11	15	5	0.352941	120.007189	53.727644
2	24.654254	19	458005	9	10	8	10	0.473684	78.153610	37.674850
3	45.612182	26	458032	8	18	18	8	0.307692	143.353545	158.246214
4	73.370292	19	458049	10	9	9	11	0.526316	200.048851	184.019981

Dataframe of features for each cycle in a recording.

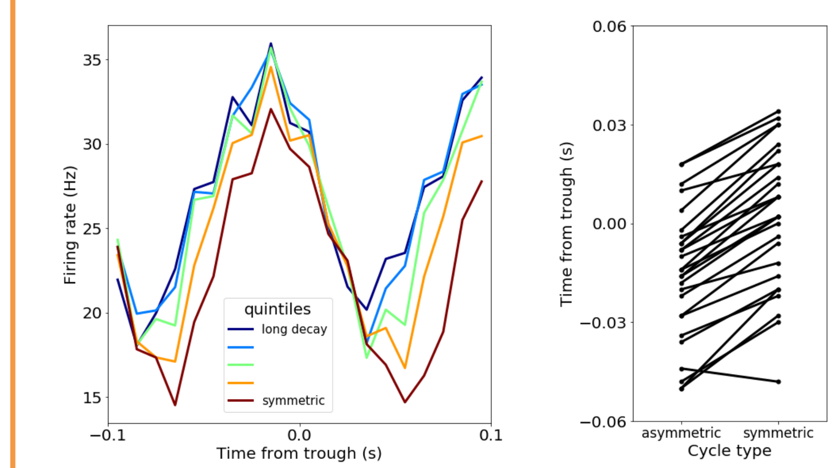


Outline of signal processing to split up an oscillation into individual cycles and quantify their rise-decay symmetries. Code available at:

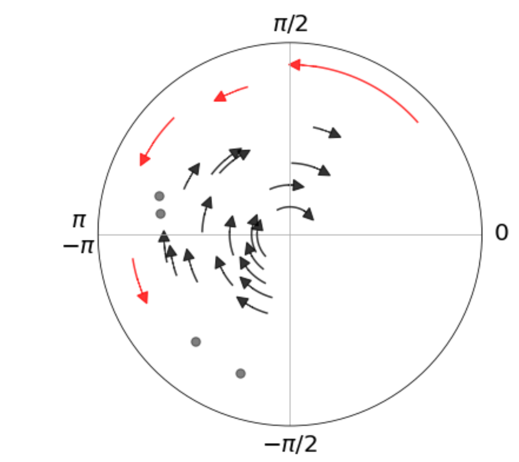
voytekresearch/neurodsp

Asymmetry and spike timing (contd.)

We analyzed the relationship between CA1 interneuron firing and rise-decay symmetry with different reference times.

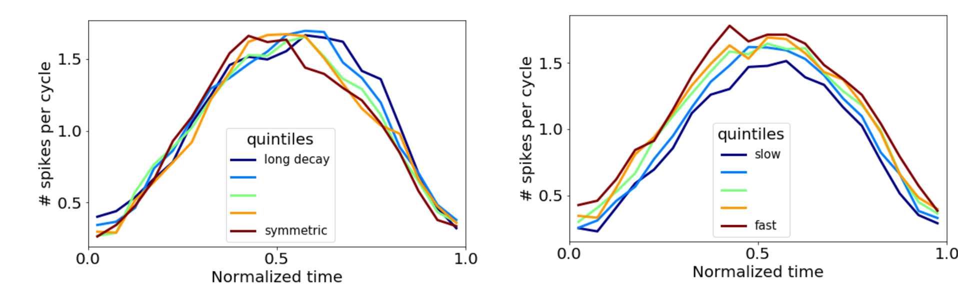


CA1 interneurons fire more before the trough for cycles with longer decay periods. Shown for 1 example recording (left) and for all recordings (right, $p < 10^{-5}$).



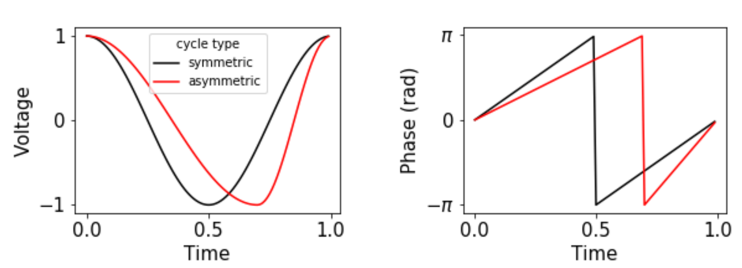
The preferred spiking phase of the CA1 interneurons occurs earlier for asymmetric cycles (arrowhead) compared to symmetric cycles (arrow start). Each arrow is 1 recording. (p = .003).

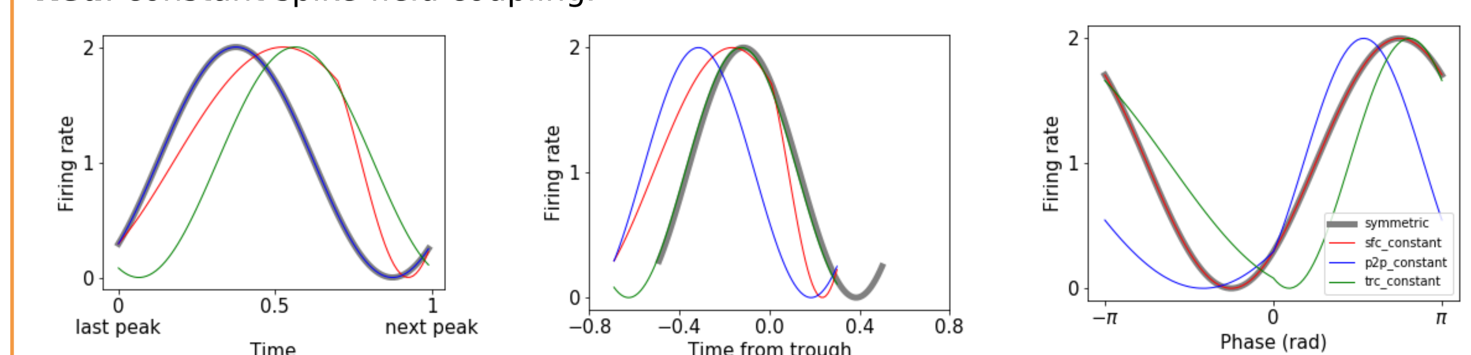
While (1) CA1 interneurons fire later in cycles with longer decay periods (left), and (2) theta cycles have longer decay periods during running (GLM, speed ~ amp + freq + rdsym, $p < 10^{-12}$), it does not follow that CA1 interneurons fire later in cycles during running (right).



Potential models for spike-field coupling

Consider a symmetric (left, black) and asymmetric (left, red) cycle. Firing is coupled to the end of the decay period for the symmetric cycle (below, gray). Also shown are 3 scenarios of coupling changes with shape. **Blue**: constant peak-to-peak firing. **Green**: constant trough-centered firing. **Red**: constant spike-field coupling.





Conclusions

* Rise-decay symmetry of theta oscillations covaries with CA1 interneuron spike timing.
* The relationship between symmetry and CA1 firing does not fully align with any of the 3 simple rules of spike field coupling.
* Oscillation shape may contain information about firing patterns.

Future Work

* How does the hippocampal theta waveform reflect spike timing of other populations (e.g. CA1 pyramidal cells) and subpopulations of interneurons?
* Do the spatial patterns of waveform shape contain further information on spiking patterns? (Agarwal et al. 2014)

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