FAST EMERGENT OSCILLATIONS IN A MUTUALLY INHIBITORY NETWORK

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ABSTRACT

We study a network of mutually all-to-all inhibiting Hodgkin-Huxley model neurons each of which is driven by an independent Poisson train (rate, λ) of subthreshold excitatory alpha function inputs. The inhibitory synaptic conductance (with decay time constant of τ_{syn}) from each presynaptic neuron incorporates a synaptic time delay, δ. In the absence of inhibitory coupling, cells fire irregularly and asynchronously with a "spontaneous" rate of 52 Hz (when λ=300 Hz) due to temporal summation of subthreshold synaptic inputs. When coupled, the network shows an emergent synchrony with a population firing rate (213 Hz) that is substantially enhanced (by a factor of 4) compared to the spontaneous rate of isolated cells. The cells show strong cross correlations and they skip cycles of the population rhythm but still fire faster (74 Hz) than when isolated. The resultant interspike interval histogram of each cell has multiple peaks at multiples of the network oscillation period. The network's frequency and individual cell frequency decrease as δ or τ_{syn} increase. If τ_{syn} is above a critical value (1.6 ms), the individual cell's firing rate falls below its spontaneous rate, while the network population rate still exceeds the spontaneous rate.

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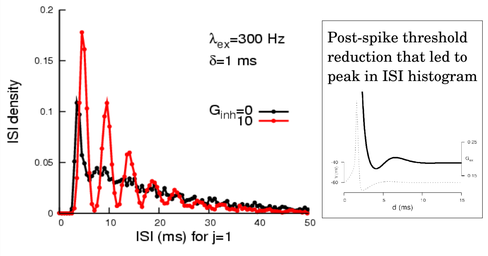
MODEL

- Each cell is a single compartment HH neuron [1] at T=22 C. Shows no postinhibitory rebound (PIR).
- Number of neurons in simulations is 100.
- Neurons are coupled all-to-all with mutual inhibition: synaptic delay δ, synaptic time constant τ_s and strength G_{inh} [2]
- Each neuron receives independent external excitatory synaptic input with Poisson rate λ (=300 Hz). Conductance is delivered with alpha-function pulses each with time constant τ_{ex}= 1 ms and strength G_{ex}=0.1 mS/cm^2; 53% of the spike threshold.

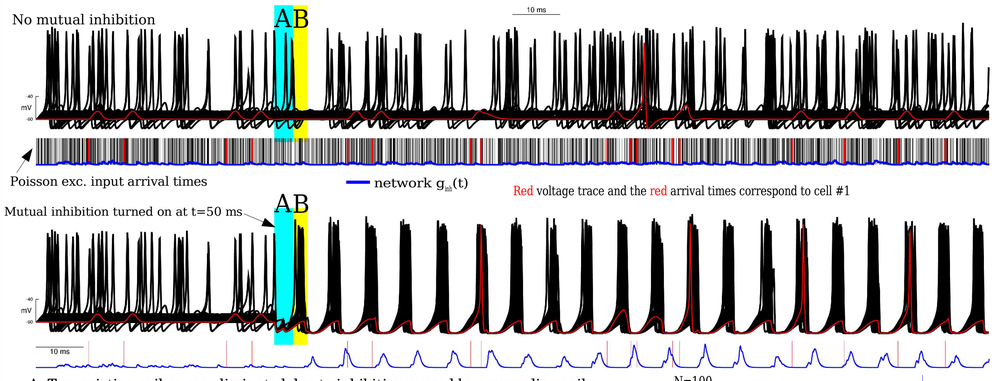
ISI HISTOGRAM OF EACH CELL



In the absence of mutual coupling, the ISI histogram shows a peak corresponding to the post-spike reduction in threshold followed by a tail corresponding to the Poisson waiting time gamma distribution.

Under mutual coupling, the histogram shows oscillations corresponding to the network frequency, followed by a decay corresponding to the gamma distribution. Here the oscillation period is about 5 ms.

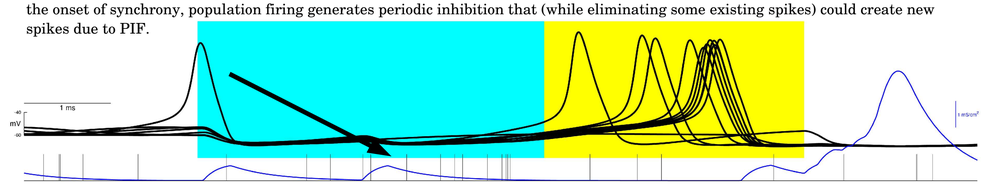
EMERGENCE OF SYNCHRONY



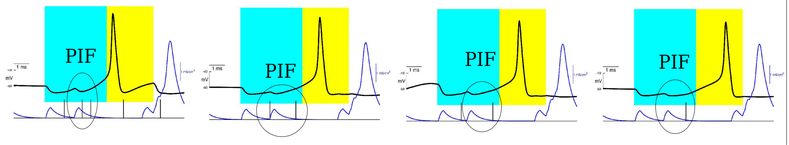
A: Two existing spikes are eliminated due to inhibition caused by a preceding spike.
B. 11 new spikes are induced and form the first of the synchronized activity.

ONSET OF SYNCHRONY CAUSED BY BRIEF INHIBITION PRECEDING BRIEF EXCITATION

The inhibition (with a synaptic delay, 2ms) caused by the spike at the onset of region A eliminated some existing spikes in region A, but created several spikes in region B due to inhibition-excitation sequences [via postinhibitory facilitation, PIF, mechanism (see later)]. After the onset of synchrony, population firing generates periodic inhibition that (while eliminating some existing spikes) could create new spikes due to PIF.



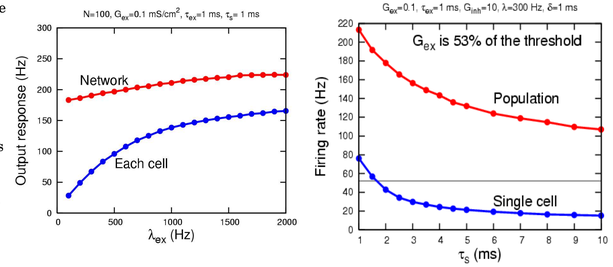
In this example, all the eleven spikes in the synchronous firing resulted due to inhibition-excitation sequences by PIF mechanism. Four of the spikes, and their corresponding input arrivals and g_{inh}(t) are shown:



FAST POPULATION FIRING RATE: EFFECT OF INPUT RATE AND INH TIME CONST

The population period is determined by several factors including the latency, external input frequency, level of G_{ex}, and G_{inh}.

The population frequency is nearly independent of the input frequency, but each cell's frequency reflects the input rate. The synchrony across population can become tighter with increased input rate due to higher probability of i-e pairs favorable for PIF.

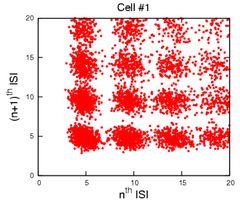


Both population and single cell firing rates decay with τ_s.

At very fast τ_s, the individual cell's firing rate is above its background level.

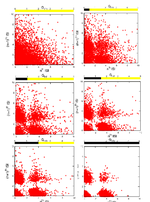
The population firing rate is about 2.5 times faster than the individual cell's firing rate at τ_s=1 ms, and at τ_s=10 ms, it is about 6 times faster.

SAMPLING POPULATION PERIOD



Each cell skips cycles of the population period randomly. A plot of its present and next ISIs reveals that each cell can skip several population periods at once.

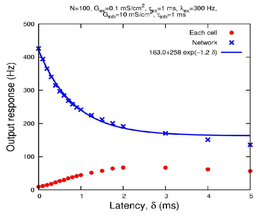
EFFECT OF INH STRENGTH



Spike times of all cells are projected onto the same time axis, and are treated as a single cumulative spike train. Clustering is formed with increased G_{inh} in the plot of nth ISI vs. (n+1)th ISI.

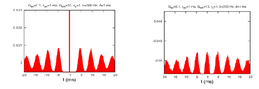
The cluster size around "0" is due to finite jitter in the synchrony, and the separation between clusters is due to the variability in the population period.

EFFECT OF SYNAPTIC DELAY



With increased synaptic delay, the favorable i-e pairs are delayed, and hence the population frequency decreases.

STAC AND PAIRWISE CROSS CORRELATIONS

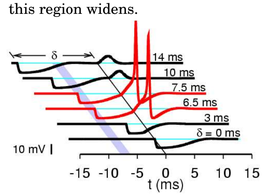


Both the auto correlations (shown here for one of the cells, left) and pairwise cross correlations (shown here for cell #1 with all other cells, right) show oscillations reflecting the synchrony among the cells.

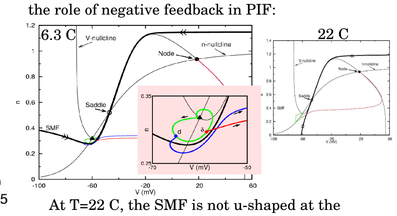
POSTINHIBITORY FACILITATION (PIF): HOW INH-EXC SEQUENCE HELPS INDUCE A SPIKE?

If a subthreshold excitation is preceded by a subthreshold (for PIR) inhibition, a spike can be induced in a resting membrane due to transient reduction in spike threshold following the brief inhibition. We term this as postinhibitory facilitation (PIF) [3,4,5]

At T=22 C, the shaded temporal window exhibits PIF. At low T, this region widens.



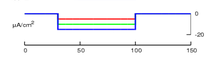
A reduced 2 dimensional model explaining the role of negative feedback in PIF:



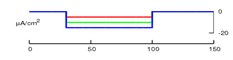
At T=22 C, the SMF is not u-shaped at the bottom, but PIF can still be realized.

BUT EACH CELL DOES NOT SHOW PIR.

The HH membrane shows classic PIR for a step of hyperpolarizing current at low temperatures, say T=6.3 C.



But at high temperatures, say at T=22 C (for the results of the present work), PIR effect is absent due to fast dynamics.



CONCLUSIONS

- Spontaneously driven cells can synchronize and fire faster and create even faster population rhythms when coupled with mutual and brief inhibition. The underlying mechanism is postinhibitory facilitation (PIF).
- Population frequency is nearly independent of external input rate, but each cell's frequency reflects the external driving.
- Each cell could fire faster than its background level for very brief time constants of inhibition.

REFERENCES

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