Interaction between synaptic dynamics and synaptic configuration determines the phase of the response to rhythmic inputs

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Introduction

The postsynaptic response of a neuron to time-varying inputs is determined by the interaction of presynaptic spike times with the short-term dynamics of each synapse. For a neuron driven by stochastic synapses and operating in a fluctuation-driven regime, synaptic depression results in a quite different postsynaptic response to a large population input depending on how correlated in time the spikes across individual synapses are [1,2]. Here we show that not only the rate but the phase of the postsynaptic response to a rhythmic population input varies as a function of synaptic dynamics and synaptic configuration, which contributes to input correlations.

Synaptic Configuration Model

In computer simulations, a single-compartment spiking model neuron is fed excitatory inputs via a synaptic pathway containing 512 vesicle release sites. The pathway is configured in different ways by assigning release sites equally between varying numbers of active zones (AZ). Each active zone is driven by an axon from a different presynaptic neuron which produces its own independent spike train.
Different synaptic configurations are shown in Figure 1.

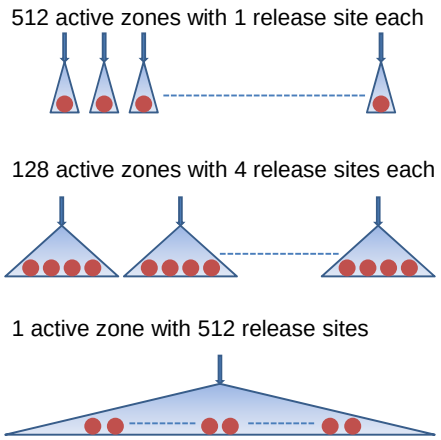

Figure 1. Different synaptic configurations for the same number of vesicle release sites. Arrows indicate axons arriving at presynaptic boutons from different neurons.

Synaptic Dynamics

- Available vesicles release stochastically (p) on arrival of a presynaptic action potential (AP)
- Empty release sites refill at a rate (r) that may increase in a stimulation-frequency-dependent manner (R).
- Refilling rate may be slow compared to the arrival rate of spikes, resulting in synaptic depression (D).
- Probability of vesicle release may increase with each spike, decaying to baseline at a slow rate, resulting in facilitation (F).

Input Stimulus

- Input signal is a 30Hz carrier frequency modulated sinusoidally between 50Hz and 10Hz at different modulation frequencies.
- Signal is carried by up to 512 independent inhomogeneous Poisson-distributed spike trains.

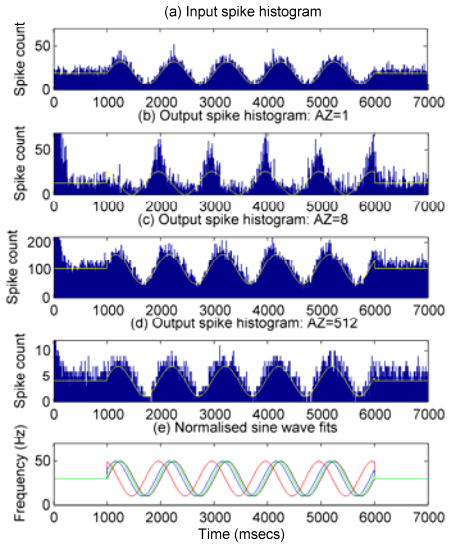

Figure 2. Histograms of postsynaptic spiking in response to 1Hz-modulated population inputs for different synaptic configurations with depressing synapses. Spike times from all cells in all runs with a particular synaptic configuration are binned in 5 msec time bins. Yellow lines are optimally fitted sine waves. Panel (e) shows overlay of fitted sine waves with normalised amplitudes (Black: input; Red: AZ=1; Blue: AZ=8; Green: AZ=512).

Results

- For all configurations, synaptic depression (D) results in the output response leading the input oscillations.
- The lead increases as the inputs become more correlated (fewer active zones).
- This effect is amplified by facilitation (F) for correlated synapses (AZ=1 or 2), but reduced for less correlated pathways.
- Lead decreases with modulation frequency for correlated synapses, but is maximal at 1Hz for uncorrelated pathways.
- Frequency-dependent release site refilling (R) turns a depressing synapse into a near-static synapse and produces a virtually in-phase output response.
- Addition of facilitation to this "static" synapse results in a phase lag, which is largest for correlated synapses.

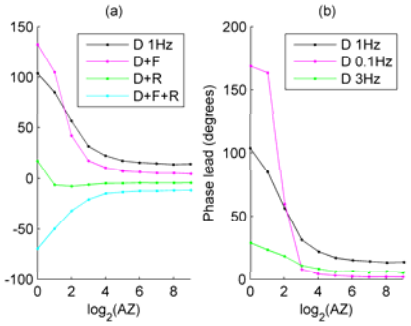

Figure 3. Phase of response to rhythmic population inputs for different synaptic configurations and modulation frequencies. (a) Modulation at 1Hz for different combinations of synaptic dynamics. D: depression; D+F: depression + facilitation; D+F+R: depression + facilitation + frequency-dependent recovery. (b) Various modulation frequencies with a depressing synapse.

Conclusion

Synaptic short term plasticity (STP) can significantly affect the phase of the output response to rhythmically varying input, when the dominant time constants of STP are of the same order as the frequency of input variation. The phase of the response is also a strong function of the synaptic configuration.

References

1. BP Graham, C Stricker: **Short term plasticity provides temporal filtering at chemical synapses**. *ICANN 2008, LNCS*, **5164**:268-276,: Springer, 2008.
2. J de la Rocha, N Parga: **Short-term synaptic depression causes a non-monotonic response to correlated stimuli**. *J Neurosci* 2005, **25**:8416-8431.

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