A simple model of theta-gamma coupling

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Rhythmic oscillations are associated with a variety of brain functions, including attention [5], memory formation and consolidation [3], sensory-motor coordination [9] and several other cognitive tasks [10]. Notably, recent experiments show the presence of two or more interacting rhythms, which have been measured during the performance of different cognitive tasks in different species [1, 7, 8]. We consider a minimal formulation of a fast spiking network (e.g. firing in the gamma frequency band, 30 - 100 Hz) modulated by a slow and periodic input (e.g. operating in the delta-to-theta frequency range, 1-8 Hz). One single Excitatory Gamma (EG) neuron, modeled as a θ-neuron [2] receives an excitatory input coming from a sinusoidal oscillator whose natural frequency lies in the theta band. The canonical θ-neuron model is described by a phase variable lying on a one-dimensional circle. The EG neuron participates in a Pyramidal Interneuron Network Gamma (PING) rhythm, although in our case the inhibitory gamma neuron is instantaneously enslaved to the excitatory cell, meaning that every excitatory spike would immediately prompt a simultaneous inhibitory spike [6]. We first look at two parameters of our system, namely the drive to the excitatory cells (I_E) and the amplitude of the theta rhythms (λ). We investigate the coupling between the phase of slow rhythm (theta) and the amplitude of fast rhythm (gamma). In our model [4] we find that the gamma circuit is subjected to two distinct regimes (*excitable* and *oscillator*) which respond in rather different ways to theta input. In the excitable case the theta oscillator is capable of entraining the phase of the gamma circuit, while in the oscillator case the two phases is remain almost independent. We observe that increasing I_E moves the gamma circuit into the oscillator regime crossing a SNIC bifurcation, thus weakening the theta-gamma coupling, while decreasing λ has the opposite effect. We provide analytical and numerical solutions to compute the time-to-first spike at the beginning of a theta period and the total number of gamma spikes within a full theta cycle. We further extend the aforementioned work by looking at phase relationships between the two rhythms when the input comes in as a rectified sinusoidal or as a pulse-like excitatory kick. We also look at the effect of introducing a more realistic inhibitory feedback to the EG neuron, and show some promising simulations of a network of EG receiving sinusoidal input.

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