Bilingual Spiking Neural Networks

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Abstract

The Critical Brain Hypothesis proposes that the brain acts as a self-tuning dynamical system near criticality; this is supported by an increasing amount of experimental results. The majority of existing numerical models share the dichotomous assumption that neurons are excitatory or inhibitory, also known as Dale's principle - however this is not the case in reality. The author will explore the functional implications of "bilingual" neurons violating this principle, and a minimal model resulting in rich dynamics transitioning between asynchronous, avalanche and oscillatory regimes.

Background

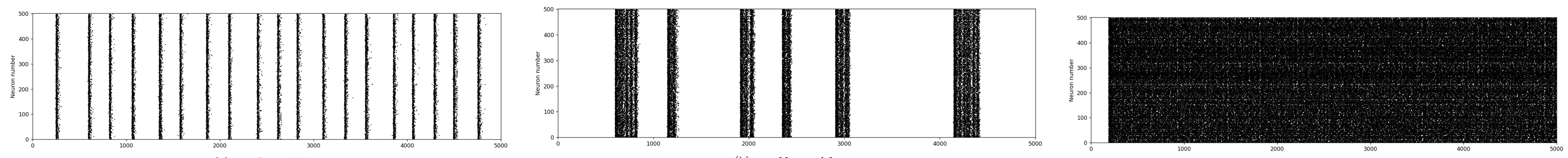
The brain exhibits a diverse array of collective behaviour. In Asynchronous regimes, neurons fire with weak correlation; associated with quiescent, or subcritical brain states.
Neurons also oscillate in Synchronous regimes; while this occurs to different degrees and frequencies, this can be observed in its strongest, supercritical form in epileptic seizures.
At criticality, we have experimentally observed Neuronal Avalanches; bursts of activity with power law distributions in size and time. It is posited that information processing is maximised in this state [1].

SNNs and Dale's Principle

Much literature is devoted to modelling phase changes between these regimes, notably through the use of Excitatory-Inhibitory ratio [2], network architecture transitions [3], and Spike Time Dependent Plasticity mechanisms [4].
Most models rely on the non-reciprocal interaction between excitatory and inhibitory neurons to regulate balance. However, studies have found evidence of so-called "Bilingual" neurons that co-release GABA and Glutamate [5] [6]. We hence study a single population of neurons that both excite and inhibit their neighbours.

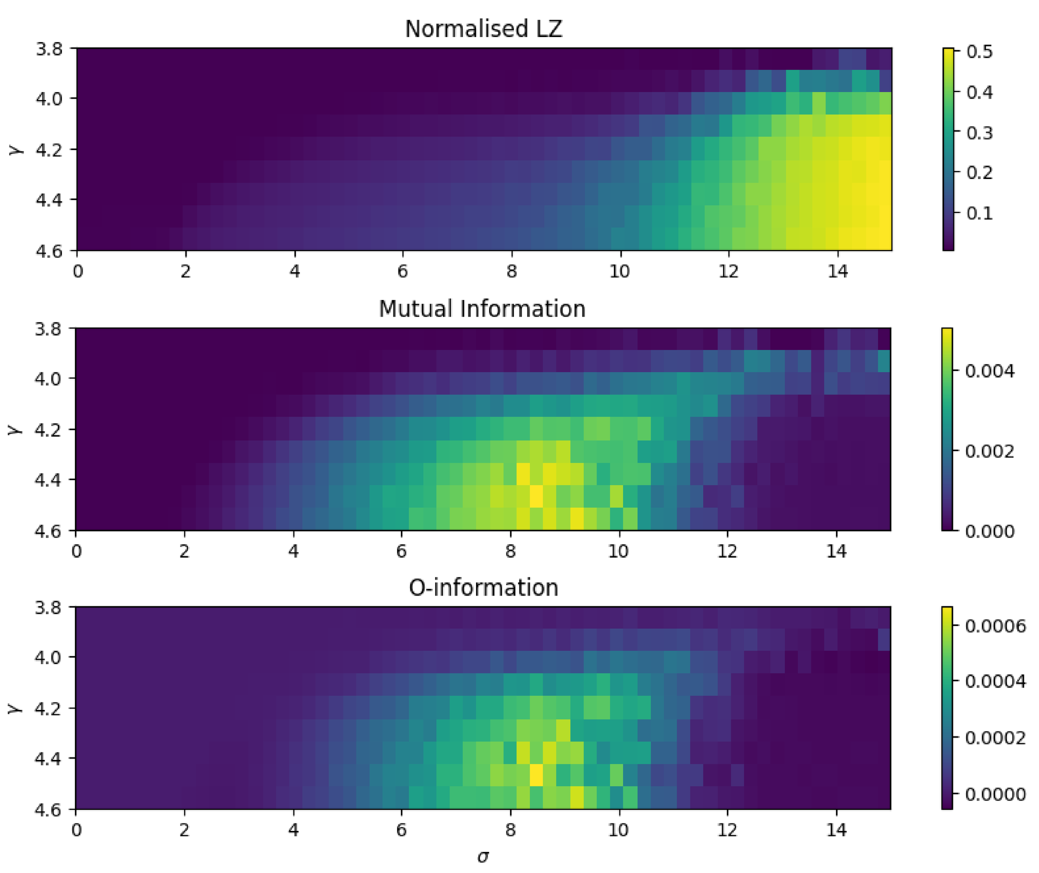
Results

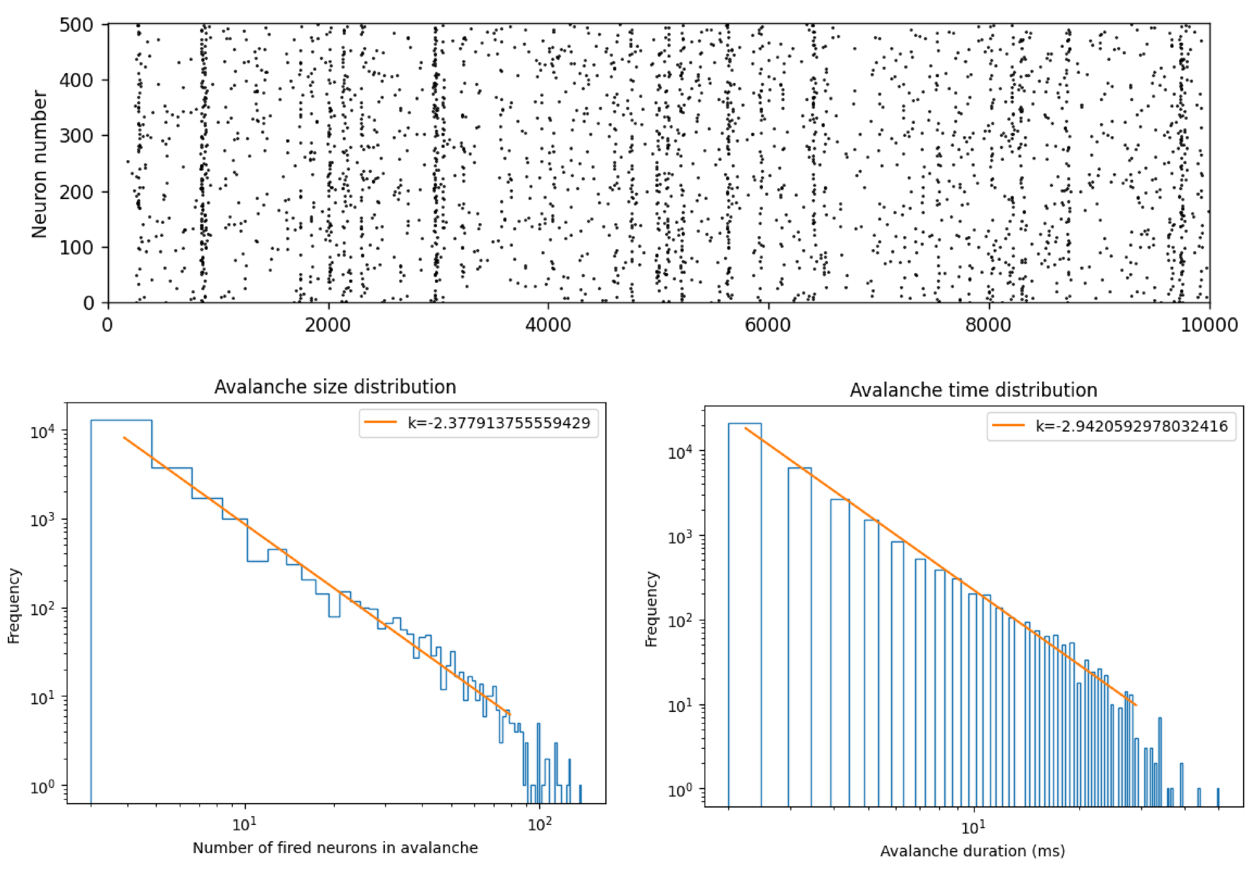
Using (σ, γ) as control parameters, the complete network model yields synchronous, asynchronous and bursting activity. We note that each cascade involves every neuron, and hence is not an avalanche.



(a) $\sigma = 6, \gamma = 4.4$ (b) $\sigma = 11, \gamma = 4.1$ (c) $\sigma = 15, \gamma = 4.5$

We visualise the (σ, γ) phase space using information-theoretic measures: Entropy Rate, Mutual Information and O-Information to quantify first, second and third order interactions respectively.
We also find that a power law degree distribution induces avalanche dynamics; cascades follow power laws in size and time.





Network Model

We model a network of Izhikevich neurons, with a symmetric uniform distribution of weights of magnitude σ, and driving uniform noise of magnitude γ:

$$\begin{aligned} v_i' &= 0.04{v_i}^2 + 5v_i + 140 - u_i + I_i \\ u_i' &= a(bv_i - u_i) \\ v_i \geq 30 &\Rightarrow v_i \leftarrow c, u_i \leftarrow u_i + d \\ i = 1, \ldots 500, &\; a = 0.02, b = 0.2, c = -65, d = 8 \end{aligned} \tag{1}$$

$$\begin{aligned} I_i &= \sum_{j=1}^{n} w_{ij} F_j + R_i \\ F_i &= \begin{cases} 1, & \text{if Neuron i fired last timestep} \\ 0, & \text{otherwise} \end{cases} \\ R_i &\sim U(0, \gamma) \\ w_{ij} &\sim U(-\sigma, \sigma) \end{aligned} \tag{2}$$

In the simplest case, we consider a fully connected network architecture. We then consider a truncated power law degree distribution [4]:

$$P(k_{out}) \propto k_{out}^2, k_{out} \in [4, 101] \tag{3}$$

Discussion

In a uniform all-to-all network, we observe that synchrony arises in a "Goldilocks zone" of inter-neuronal interaction and external noise - too little of either yields quiescent dynamics, while too much of either disrupts the coupling between neurons, giving rise to asynchronous dynamics. Within this synchronous region, varying σ varies the mean duration of active and inactive periods. It is of note that sufficiently high levels of noise may drive supercritical oscillations. The simplicity of this model facilitates mean-field theoretic analysis, which is a focus for future work.
In addition, it is known that STDP mechanisms self-organise networks to a scale-free distribution [7]; it is hence possible that a bilingual plasticity mechanism can tune such a network to a critical avalanche state as above.
The ability of each neuron to both excite and inhibit provides an intrinsic stable self-regulatory mechanism, whilst also satisfying the balance condition in a biologically efficient manner. The principle of Bilingual neurons is easily implementable in other SNN models, warranting further study.

References

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