Supplementary material

Neural and synaptic dynamics

We use the mathematical formulation of the integrate-and-fire neurons and synaptic currents described in Brunel & Wang (2001). Here we provide a brief summary of this framework.

The dynamics of the sub-threshold membrane potential \( V \) of a neuron are given by the equation:

\[
C_m \frac{dV(t)}{dt} = -g_m(V(t) - V_L) - I_{syn}(t),
\]

Both excitatory and inhibitory neurons have a resting potential \( V_L = -70 \text{mV} \), a firing threshold \( V_{thr} = -50 \text{mV} \) and a reset potential \( V_{reset} = -55 \text{mV} \). The membrane parameters are different for both types of neurons: Excitatory (Inhibitory) neurons are modeled with a membrane capacitance \( C_m = 0.5nF(0.2nF) \), a leak conductance \( g_m = 25nS(20nS) \), a membrane time constant \( \tau_m = 20ms(10ms) \), and a refractory period \( t_{ref} = 2ms(1ms) \). Values are extracted from McCormick et al. (1985).

When the threshold membrane potential \( V_{thr} \) is reached, the neuron is set to the reset potential \( V_{reset} \) at which it is kept for a refractory period \( t_{ref} \) and the action potential is propagated to the other neurons.

Each network module is fully connected with \( N_E = 400 \) excitatory neurons and \( N_I = 100 \) inhibitory neurons, which is consistent with the observed proportions of the pyramidal neurons and interneurons in the cerebral cortex (Braitenberg & Schütz 1991, Abeles 1991). The synaptic current impinging on each neuron is given by the sum of recurrent excitatory currents (\( I_{AMPA,rec} \) and \( I_{NMDA,rec} \)), the external excitatory current (\( I_{AMPA,ext} \)) the inhibitory current (\( I_{GABA} \)):

\[
I_{syn}(t) = I_{AMPA,ext}(t) + I_{AMPA,rec}(t) + I_{NMDA,rec}(t) + I_{GABA}(t).
\]

The recurrent excitation mediated by the AMPA and NMDA receptors, inhibition by GABA receptors. In addition, the neurons are exposed to external Poisson input spike trains mediated by AMPA receptors at a rate of 2.4kHz. These can be viewed as originating from \( N_{ext} = 800 \) external neurons at average rate of 3Hz per neuron, consistently with the spontaneous activity observed in the cerebral cortex (Wilson et al. 1994, Rolls & Treves 1998). The currents are defined by:

\[
I_{AMPA,ext}(t) = g_{AMPA,ext}(V(t) - V_E) \sum_{j=1}^{N_{ext}} s_{ji}^{AMPA,ext}(t)
\]

\[
I_{AMPA,rec}(t) = g_{AMPA,rec}(V(t) - V_E) \sum_{j=1}^{N_E} w_{ji}^{AMPA,AMPA,rec} s_{ji}^{AMPA,rec}(t)
\]

\[
I_{NMDA,rec}(t) = \frac{g_{NMDA}(V(t) - V_E)}{1 + [Mg^{++}] \exp(-0.062V(t))/3.57} \sum_{j=1}^{N_E} w_{ji}^{NMDA,NMDA} s_{ji}^{NMDA}(t)
\]

\[
I_{GABA}(t) = g_{GABA}(V(t) - V_I) \sum_{j=1}^{N_I} w_{ji}^{GABA,GABA} s_{ji}^{GABA}(t)
\]
where $V_E = 0$ mV, $V_I = -70$ mV, $w_j$ are the synaptic weights, $s_j$’s the fractions of open channels for the different receptors and $g$’s the synaptic conductances for the different channels. The NMDA synaptic current depends on the membrane potential and the extracellular concentration of Magnesium ($[\text{Mg}^{+}+] = 1$ mM, Jahr & Stevens (1990)). The values for the synaptic conductances for excitatory neurons are $g_{\text{AMPA,ext}} = 2.08$ nS, $g_{\text{AMPA,rec}} = 0.104$ nS, $g_{\text{NMDA}} = 0.327$ nS and for inhibitory neurons $g_{\text{AMPA,ext}} = 1.62$ nS, $g_{\text{AMPA,rec}} = 0.081$ nS, $g_{\text{NMDA}} = 0.258$ nS and $g_{\text{GABA}} = 0.973$ nS. These values are obtained from the ones used by Brunel & Wang (2001) by correcting for the different number of neurons. The conductances were calculated so that in an unstructured network the excitatory neurons have a spontaneous spiking rate of 3 Hz and the inhibitory neurons a spontaneous rate of 9 Hz. The fractions of open channels are described by:

$$\frac{ds_{j,\text{AMPA,ext}}(t)}{dt} = -\frac{s_{j,\text{AMPA,ext}}(t)}{\tau_{\text{AMPA}}} + \sum_k \delta(t - t^k_j)$$

(7)

$$\frac{ds_{j,\text{AMPA,rec}}(t)}{dt} = -\frac{s_{j,\text{AMPA,rec}}(t)}{\tau_{\text{AMPA}}} + \sum_k \delta(t - t^k_j)$$

(8)

$$\frac{ds_{j,\text{NMDA}}(t)}{dt} = -\frac{s_{j,\text{NMDA}}(t)}{\tau_{\text{NMDA,decay}}} + \alpha x_j(t)(1 - s_{j,\text{NMDA}}(t))$$

(9)

$$\frac{dx_j(t)}{dt} = -\frac{x_j(t)}{\tau_{\text{NMDA,rise}}} + \sum_k \delta(t - t^k_j)$$

(10)

$$\frac{ds_{j,\text{GABA}}(t)}{dt} = -\frac{s_{j,\text{GABA}}(t)}{\tau_{\text{GABA}}} + \sum_k \delta(t - t^k_j),$$

(11)

where $\tau_{\text{NMDA,decay}} = 100$ ms is the decay time for NMDA synapses, $\tau_{\text{AMPA}} = 2$ ms for AMPA synapses (Hestrin et al. 1990, Spruston et al. 1995) and $\tau_{\text{GABA}} = 10$ ms for GABA synapses (Salin & Prince 1996, Xiang et al. 1998); $\tau_{\text{NMDA,rise}} = 2$ ms is the rise time for NMDA synapses (the rise times for AMPA and GABA are neglected because they are typically very short) and $\alpha = 0.5$ ms$^{-1}$. The sums over $k$ represent a sum over spikes formulated as $\delta$-Peaks $\delta(t)$ emitted by presynaptic neuron $j$ at time $t^k_j$.

The equations were integrated numerically using a second order Runge-Kutta method with step size 0.02 ms. The Mersenne Twister algorithm was used as random number generator for the external Poisson spike trains and different trails for equal parameter configurations were run with different random seeds (as only difference).

**Connection Matrices**

**Fraction of pool sizes $f_i$**

Values are relative to all neurons, not only excitatory the portion.

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>NS</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.12</td>
<td>0.12</td>
<td>0.56</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Connection matrix for AMPA and NMDA – [from, to]

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>NS</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>$w_+$</td>
<td>$w_-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>A2</td>
<td>$w_-$</td>
<td>$w_+$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NS</td>
<td>$w_-$</td>
<td>$w_-$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>IH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Connection matrix for GABA – [from, to]

<table>
<thead>
<tr>
<th></th>
<th>A1</th>
<th>A2</th>
<th>NS</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IH</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Inter-module connections (only AMPA)

A1 $\leftrightarrow$ V1: $w_{mc}$
A2 $\leftrightarrow$ V2: $w_{mc}$

References


