SI Appendix

Neuronal models

E cell: We use the pyramidal cell model of Ermentrout and Kopell (1998), which is a reduction of a model due to Traub & Miles (1991):

$$
\begin{aligned}
C\frac{dV}{dt} &= g_{Na}m_\infty(V)^3h(V_{Na}-V)+g_Kn^4(V_K-V)+g_L(V_L-V)+I\ , &(1)\\
\frac{dn}{dt} &= \frac{n_\infty(V)-n}{\tau_n(V)}\ , &(2)\\
h &= \max(1-1.25n,0)\ , &(3)
\end{aligned}
$$

with

$$
\begin{aligned}
x_\infty(V) &= \frac{\alpha_x(V)}{\alpha_x(V)+\beta_x(V)} \quad \text{for } x=m \text{ or } n, &(4)\\
\tau_x(V) &= \frac{1}{\alpha_x(V)+\beta_x(V)} \quad \text{for } x=n, &(5)\\
\alpha_m(V) &= \frac{0.32(V+54)}{1-\exp(-(V+54)/4)}\ ,\\
\beta_m(V) &= \frac{0.28(V+27)}{\exp((V+27)/5)-1)}\ ,\\
\alpha_n(V) &= \frac{0.032(V+52)}{1-\exp(-(V+52)/5))}\ ,\\
\beta_n(V) &= 0.5\exp(-(V+57)/40)\ .
\end{aligned}
$$

In Equations (1)–(2), the letters C, V, t and τ, g, and I denote capacitance density, voltage, time, conductance density, and current density, respectively. The units that we use for these quantities are μF/cm^2, mV, ms, mS/cm^2, and μA/cm^2. For brevity, units will usually be omitted from here on. The parameter values of the model are $C=1$, $g_{Na}=100$, $g_K=80$, $g_L=0.1$, $V_{Na}=50$, $V_K=-100$, and $V_L=-67$.

I cells: For fast-spiking PV-positive interneurons, we use the Wang & Buzsaki (1996) model:

$$
\begin{aligned}
C\frac{dV}{dt} &= g_{Na}m_\infty(V)^3h(V_{Na}-V)+g_Kn^4(V_K-V)+g_L(V_L-V)+I\ , &(6)\\
\frac{dn}{dt} &= \frac{n_\infty(V)-n}{\tau_n(V)}\ , &(7)\\
\frac{dh}{dt} &= \frac{h_\infty(V)-h}{\tau_h(V)}\ , &(8)
\end{aligned}
$$

with

$$x_\infty(V) = \frac{\alpha_x(V)}{\alpha_x(V)+\beta_x(V)} \quad \text{for } x = m, h \text{ or } n, \tag{9}$$

$$\tau_x(V) = \frac{0.2}{\alpha_x(V)+\beta_x(V)} \quad \text{for } x = h \text{ or } n, \tag{10}$$

The rate functions α_x and β_x, $x = m, h$, and n, are defined as follows:

$$\begin{aligned}
\alpha_m(V) &= \frac{0.1(V+35)}{1-\exp(-(V+35)/10))}\ , \\
\beta_m(V) &= 4\exp(-(V+60)/18)\ , \\
\alpha_h(V) &= 0.07\exp(-(V+58)/20)\ , \\
\beta_h(V) &= \frac{1}{\exp(-0.1(V+28))+1}\ , \\
\alpha_n(V) &= \frac{0.01(V+34)}{1-\exp(-0.1(V+34))}\ , \\
\beta_n(V) &= 0.125\exp(-(V+44)/80)\ .
\end{aligned}$$

The parameter values, using the same units as for the E cell, are $C = 1$, $g_{Na} = 35$, $g_K = 9$, $g_L = 0.1$, $V_{Na} = 55$, $V_K = -90$, and $V_L = -65$.

T cells: For the theta interneurons, we use the model described in Tort *et al.* (2007), which is a reduction of the multi-compartmental O-LM cell model described in Saraga *et al.* (2003):

$$C\frac{dV}{dt} = g_{Na}m^3h(V_{Na}-V) + g_Kn^4(V_K-V) + g_Aab(V_A-V)$$

$$+g_hr(V_h-V) + g_L(V_L-V) + I\ , \tag{11}$$

with

$$\frac{dx}{dt} = \frac{x_\infty(V)-x}{\tau_x(V)} \quad \text{for } x = m, h, n, a, b, r\ . \tag{12}$$

For $x = m, n, h$, the functions $x_\infty(V)$ and $\tau_x(V)$ are the same as in (4) and (5), and the rate functions α_x and β_x, are defined as follows:

$$
\begin{aligned}
\alpha_m(V) &= \frac{-0.1(V+38)}{\exp(-(V+38)/10)-1} \ , \\
\beta_m(V) &= 4\exp(-(V+65)/18) \ , \\
\alpha_h(V) &= 0.07\exp(-(V+63)/20) \ , \\
\beta_h(V) &= \frac{1}{1+\exp(-(V+33)/10)} \ , \\
\alpha_n(V) &= \frac{0.018(V-25)}{1-\exp(-(V-25)/25)} \ , \\
\beta_n(V) &= \frac{0.0036(V-35)}{\exp((V-35)/12)-1} \ .
\end{aligned}
$$

For $x = a, b, r$, we provide the functions $x_\infty(V)$ and $\tau_x(V)$ below:

$$
\begin{aligned}
a_\infty(V) &= \frac{1}{1+\exp(-(V+14)/16.6)} \ , \\
\tau_a(V) &= 5 \ , \\
b_\infty(V) &= \frac{1}{1+\exp((V+71)/7.3)} \ , \\
\tau_b(V) &= \frac{1}{\frac{0.000009}{\exp((V-26)/18.5)}+\frac{0.014}{0.2+\exp(-(V+70))/11)}} \ , \\
r_\infty(V) &= \frac{1}{1+\exp((V+84)/10.2)} \ , \\
\tau_r(V) &= \frac{1}{\exp(-14.59-0.086V)+\exp(-1.87+0.0701V)} \ .
\end{aligned}
$$

The parameter values are $C = 1.3$, $g_L = 0.05$, $g_{Na} = 30$, $g_K = 23$, $g_A = 16$, $g_h = 8$, $V_{Na} = 90$, $V_K = -100$, $V_A = -90$, $V_h = -32$, $V_L = -70$.

Synaptic model: Each synaptic input was modeled as a current of the form $I_{syn,XY} = G_{XY}/N_X s(V - V_{syn})$, where X and Y denote the type of the pre and post-synaptic cell, respectively (ie, $X, Y =$ E, I or T), G_{XY} is the maximal synaptic conductance, N_X is the number of X cells, V is the membrane potential of the post-synaptic cell, and V_{syn} is the reversal potential. The variable s is a normalized double-exponential function characterized by rise (τ_{rise}) and decay (τ_{decay}) time constants. The synapses were implemented using the *Exp2Syn()* built-in function of NEURON. The IPSPs originating from the T cells synapses were slower than IPSPs originating from the I cells synapses; we used $\tau_{rise} =$ 2 ms, and $\tau_{decay} = 22$ ms for T synapses, $\tau_{rise} = 0.07$ ms and $\tau_{decay} = 9.1$ ms for I synapses, and $\tau_{rise} = 0.05$ ms and $\tau_{decay} = 5.3$ ms for E synapses. The reversal potential was set to 0 mV for E synapses and to -80 mV for T

and I synapses. We used $G_{II} = 0.01$, $G_{TI} = 0.15$, $G_{IT} = 0.2$, $G_{IE} = 0.05$, $G_{TE} = 0.15$, $G_{EI} = 0.05$, $G_{ET} = 0.07$, $I_E = U(1.9, 2.1)$, $I_I = 0.3$, $I_T = 0$. The model KO network is obtained by setting G_{TI} and G_{II} equal to zero.

Model Local Field Potential: The model local field potential (LFP) consisted of the membrane potential of a "passive" E cell programmed inside the network. This cell receives the same synaptic inputs as the "active" E cell. However, this cell does not send any synaptic output onto other cells and, moreover, it also does not spike given that its external drive current is set to zero. The model LFP was analyzed in MATLAB (The MathWorks, Inc. Natwick, MA). Power spectrum density was obtained using the Welch's averaged periodogram using a 6 s window length with 50% overlap (*pwelch()* function from the Signal Processing toolbox). Gamma (40-80 Hz) and theta (5-9 Hz) filtered signals were obtained by using a linear finite impulse response (FIR) filter (*eegfilt()* function from the EEGLAB toolbox; Delorme and Makeig, 2004). The amplitude and phase of the filtered signals were obtained from the the Hilbert transform. The instantaneous gamma frequency was calculated from the inter peak intervals of the gamma filtered signal. The theta-phase was binned into 18 intervals (i.e., bin size = 20^o), and the mean gamma frequency and amplitude were computed for each theta-phase bin.

Numeric and Random Aspects: All simulations were carried out using the NEURON simulation program version 5.9 (Hines and Carnevale, 1997) with a time step of 25 μs. As initial conditions, the membrane potential of each cell was uniformly distributed between -85 and -60 mV and the channel-gating variables were set to their corresponding steady-state values. Each cell was further randomized using an IClamp of random uniform magnitude and random uniform duration between 0 and $t_{syn}/2$, where t_{syn}=500 ms is the time when synapses were turned on. For each of the 50 trials, the total simulation time was of 12 s, and the last 10 s were used for the analysis. In each trial, the E cell drive was chosen from a uniform distribution between 1.9 and 2.1 μA/cm^2; therefore, the exact gamma peak frequency varied from trial to trial.

References

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