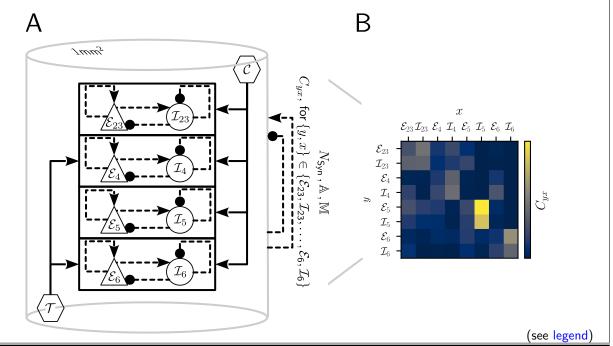# Detailed description of the
cortical microcircuit model (Potjans et al., 2014)

Contents

1 Model description

Summary	
Populations	8 cortical populations in 4 layers (L2/3, L4, L5, L6), driven by a thalamic population ($\mathcal{T}$) and cortico-cortical inputs ($\mathcal{C}$)
Connectivity	random, independent, population specific
Neuron model	cortex: leaky integrate-and-fire (LIF); thalamus, cortico-cortical inputs: Poisson point process
Synapse model	exponential postsynaptic currents with static, normally distributed weights and delays
Predictions	population specific spiking activity

(see legend)

Populations		
Name	**Elements**	**Size**
$x \in \{\mathcal{E}_{23}, \mathcal{E}_4, \mathcal{E}_5, \mathcal{E}_6, \mathcal{I}_{23}, \mathcal{I}_4, \mathcal{I}_5, \mathcal{I}_6\}$	LIF	N_x
$\mathcal{P} = \bigcup_{x \in \{\mathcal{E}_{23}, \mathcal{E}_4, \mathcal{E}_5, \mathcal{E}_6, \mathcal{I}_{23}, \mathcal{I}_4, \mathcal{I}_5, \mathcal{I}_6\}}$	LIF	$N = \sum_x N_x$
$\mathcal{T}$	realizations of Poisson point process	$N_{\mathcal{T}}$
$\mathcal{C} = \bigcup_x \mathcal{C}_x$	realizations of Poisson point process	$N = \sum_x N_x$

Table 1: Description of the network model (continued on next page).

Connectivity		
Source	**Target**	**Pattern**
$x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$	$y \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$	• random, fixed total number K_{yx} of connections[1] • synaptic weights J_{ij} $(\forall i \in y, j \in x)$ • spike-transmission delays d_{ij} $(\forall i \in y, j \in x)$
$\mathcal{T}$	$y \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$	• random, fixed total number $K_{y\mathcal{T}}$ of connections[1] • synaptic weights J_{ij} $(\forall i \in y, j \in \mathcal{T})$ • spike-transmission delays d_{ij} $(\forall i \in y, j \in \mathcal{T})$
$\mathcal{C}_y$	$y \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$	• one-to-one[2] • synaptic weights J_{ij} $(\forall i \in y, j \in \mathcal{C}_y)$ • spike-transmission delays d_{ij} $(\forall i \in y, j \in \mathcal{C}_y)$

Connectivity patterns:

[1] *random, fixed total number* (N_{Syn}): This rule establishes a total number of

$$K_{yx} = \frac{\ln\left(1 - C_{yx}\right)}{\ln\left(1 - (N_x N_y)^{-1}\right)},$$

connections between a source population x of size N_x and a target population y of size N_y. C_{yx} denotes the connection probability. Sources and targets are randomly and independently drawn from x and y with replacement. Multiple connections between two neurons and self-connections are permitted ($\mathbb{M}$, $\mathbb{A}$).

[2] *one-to-one* (δ): Each neuron in the source population is connected to one corresponding neuron in the target population (bijection).

(see "Network sketch" above and Senk et al., 2022)

Table 1: Description of the network model (continued).

Neurons	
Cortical neurons	
Type	leaky integrate-and-fire (LIF)
Description	dynamics of membrane potential $V_i(t)$ and spiking activity $s_i(t)$ of neuron $i \in x$ for $x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$: - emission of kth $(k = 1, 2, \ldots)$ spike of neuron i at time t_i^k if $$V_i(t_i^k) \geq \theta$$ with spike threshold θ - reset and refractoriness: $$\forall k, \ \forall t \in [t_k^i, t_k^i + \tau_{\mathsf{ref}}] : \quad V_i(t) = V_{\mathsf{reset}}$$ with refractory period τ_{ref} and reset potential V_{reset} - spike train $s_i(t) = \sum_k \delta(t - t_i^k)$ - subthreshold dynamics of membrane potential $V_i(t)$: $$\forall k, \ \forall t \notin [t_i^k, t_i^k + \tau_{\mathsf{ref}}) :$$ $$\tau_{\mathsf{m}} \frac{\mathrm{d}V_i(t)}{\mathrm{d}t} = \left[E_{\mathsf{L}} - V_i(t)\right] + R_{\mathsf{m}} I_i(t) \qquad (1)$$ with membrane time constant τ_{m}, membrane resistance R_{m}, resting potential E_{L}, and total synaptic input current $I_i(t)$
Thalamic neurons	
Type	Poisson point process
Description	spike trains $s_i(t)$ $(i \in \mathcal{T})$ modeled as independent realizations of Poisson point process with piece-wise constant rate $$\nu_{\mathcal{T}}(t) = \nu_{\mathcal{T}} \cdot (\Theta(t - t_{\mathsf{start}}) - \Theta(t - t_{\mathsf{stop}}))$$
Cortico-cortical inputs	
Type	Poisson point process
Description	independent realizations $s_i(t)$ $(i \in \mathcal{C}_x$ for $x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\})$ of a Poisson point process with constant rate $$\nu_{\mathcal{C}_x} = K_{\mathcal{C}_x} \cdot \nu_{\mathcal{C}},$$ where $K_{\mathcal{C}_x}$ is the cortico-cortica in-degree and $\nu_{\mathcal{C}}$ a constant rate

Table 2: Description of the network model (continued).

Synapses	
Type	exponential postsynaptic currents with static weights and delays
Description	- total synaptic input current $I_i(t)$ to neuron i ($\forall i \in y \in \{\mathcal{E}_{23}, \dots, \mathcal{I}_6\}$) is governed by: $$\left(\frac{\mathrm{d}}{\mathrm{d}t} + \frac{1}{\tau_\mathsf{s}}\right) I_i(t) = f_i(t) \qquad (2)$$ with superposition from all neurons $j \in x$, $\forall x \in \{\mathcal{E}_{23}, \dots, \mathcal{I}_6, \mathcal{T}, \mathcal{C}\}$ $$f_i(t) = \sum_x \sum_j f_{ij}(t) = \sum_x \sum_j \hat{I}_{ij} s_j(t - d_{ij})$$ of weighted spike trains with static synaptic weigths $\hat{I}_{ij}$, synaptic time constant τ_s, and spike transmission delays d_{ij} - solution of (2) for $f_{ij}(t) = \hat{I}_{ij} s_j(t)$ and $I_{ij}(t=0) = 0$: $$\mathsf{PSC}_{ij}(t) = \hat{I}_{ij} \exp(-t/\tau_\mathsf{s})\Theta(t)$$ with Heaviside function $\Theta(\cdot)$ $\curvearrowright$ (exponential decaying) posynaptic current triggered by a single presynaptic spike - solution of (1) for $I_i(t) = \mathsf{PSC}_{ij}(t)$, $V_i(t=0) = 0$, and $E_\mathsf{L} = 0$: $$\mathsf{PSP}_{ij}(t) = \hat{I}_{ij} R_\mathsf{m} \frac{\tau_\mathsf{s}}{\tau_\mathsf{s} - \tau_\mathsf{m}} \left(e^{-t/\tau_\mathsf{s}} - e^{-t/\tau_\mathsf{m}}\right)\Theta(t)$$ - PSC amplitude (synaptic weight): $$\hat{I}_{ij} = \frac{J_{ij}}{J_\mathsf{unit}(\tau_\mathsf{m}, \tau_\mathsf{s}, R_\mathsf{m})}$$ parameterized by PSP amplitude $J_{ij} = \max_t\left(\mathsf{PSP}_{ij}(t)\right)$ with unit PSP amplitude (PSP amplitude for $\hat{I}_{ij} = 1$): $$J_\mathsf{unit}(\tau_\mathsf{m}, \tau_\mathsf{s}, R_\mathsf{m}) = R_\mathsf{m} \frac{\tau_\mathsf{s}}{\tau_\mathsf{s} - \tau_\mathsf{m}} \left(\left[\frac{\tau_\mathsf{m}}{\tau_\mathsf{s}}\right]^{-\tau_\mathsf{m}/(\tau_\mathsf{m} - \tau_\mathsf{s})} - \left[\frac{\tau_\mathsf{m}}{\tau_\mathsf{s}}\right]^{-\tau_\mathsf{s}/(\tau_\mathsf{m} - \tau_\mathsf{s})}\right)$$ and time to PSP maximum: $$t_\mathsf{max} = \frac{\tau_\mathsf{s}\tau_\mathsf{m}}{\tau_\mathsf{m} - \tau_\mathsf{s}} \ln\left(\frac{\tau_\mathsf{m}}{\tau_\mathsf{s}}\right)$$

Table 3: Description of the network model (continued).

Synapses (continued)	
Description	• synaptic weights $$\hat{I}_{ij} = \begin{cases} \max(0, z_{yx}), & j \in x \in \{\mathcal{E}_{23}, \mathcal{E}_4, \mathcal{E}_5, \mathcal{E}_6, \mathcal{T}\} \\ \min(0, z_{yx}), & j \in x \in \{\mathcal{I}_{23}, \mathcal{I}_4, \mathcal{I}_5, \mathcal{I}_6\} \\ \bar{I}_{yx}, & j \in x = \mathcal{C} \end{cases}$$ with $$z_{yx} \sim \mathcal{N}\left\{\bar{I}_{yx}, \sigma^2_{\mathsf{s},yx}\right\}$$ drawn from a normal distribution with mean $\bar{I}_{y,x}$, variance $\sigma^2_{\mathsf{s},yx}$ note: clipping of synaptic weights leads to a deviation of the total number of synapses with non-zero weights from K_{yx} (see "Connectivity") • distributed synaptic delays $$d_{ij} = \begin{cases} \max(d_{\mathsf{min}}, z_x), & j \in x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6, \mathcal{T}\} \\ \bar{d}_x, & j \in x = \mathcal{C} \end{cases}$$ with $$z_x \sim \mathcal{N}\left\{\bar{d}_x, \sigma^2_{\mathsf{d},x}\right\}$$ drawn from a normal distribution with mean $\bar{d}_x$, variance $\sigma^2_{\mathsf{d},x}$, and minimal delay $d_{\mathsf{min}} > 0$

Initial conditions	
Type	random initial membrane potentials and homogeneous initial synaptic currents
Description	• membrane potentials $$V_i(t=0) \sim \mathcal{N}(\bar{V}_{0,x}, \sigma^2_{\mathsf{v},x})$$ randomly and independently drawn from a normal distribution with mean $\bar{V}_{0,x}$ and variance $\sigma^2_{\mathsf{v},x}$ ($\forall i \in x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$) • synaptic currents: $I_i(t=0) = 0\,\mathsf{pA}$ ($\forall i \in y \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$)

Table 4: Description of the network model (continued).

2 Model parameters

Network and connectivity

Population sizes

x	$\mathcal{E}_{23}$	$\mathcal{I}_{23}$	$\mathcal{E}_4$	$\mathcal{I}_4$	$\mathcal{E}_5$	$\mathcal{I}_5$	$\mathcal{E}_6$	$\mathcal{I}_6$	$\mathcal{T}$
N_x	$20{,}683$	$5{,}834$	$21{,}915$	$5{,}479$	$4{,}850$	$1{,}065$	$14{,}395$	$2{,}948$	902

Connection probabilities C_{yx}

x \ y	$\mathcal{E}_{23}$	$\mathcal{I}_{23}$	$\mathcal{E}_4$	$\mathcal{I}_4$	$\mathcal{E}_5$	$\mathcal{I}_5$	$\mathcal{E}_6$	$\mathcal{I}_6$	$\mathcal{T}$
$\mathcal{E}_{23}$	0.1009	0.1689	0.0437	0.0818	0.0323	0.0	0.0076	0.0	0.0
$\mathcal{I}_{23}$	0.1346	0.1371	0.0316	0.0515	0.0755	0.0	0.0042	0.0	0.0
$\mathcal{E}_4$	0.0077	0.0059	0.0497	0.1350	0.0067	0.0003	0.0453	0.0	0.0983
$\mathcal{I}_4$	0.0691	0.0029	0.0794	0.1597	0.0033	0.0	0.1057	0.0	0.0619
$\mathcal{E}_5$	0.1004	0.0622	0.0505	0.0057	0.0831	0.3726	0.0204	0.0	0.0
$\mathcal{I}_5$	0.0548	0.0269	0.0257	0.0022	0.0600	0.3158	0.0086	0.0	0.0
$\mathcal{E}_6$	0.0156	0.0066	0.0211	0.0166	0.0572	0.0197	0.0396	0.2252	0.0512
$\mathcal{I}_6$	0.0364	0.0010	0.0034	0.0005	0.0277	0.0080	0.0658	0.1443	0.0196

Neuron		
Name	**Value**	**Description**
θ	$-50\,\text{mV}$	spike threshold
E_L	$-65\,\text{mV}$	resting potential
τ_m	$10\,\text{ms}$	membrane time constant
C_m	$250\,\text{pF}$	membrane capacitance
R_m	$\tau_\text{m}/C_\text{m} = 40\,\text{M}\Omega$	membrane resistance
V_reset	$-65\,\text{mV}$	reset potential
τ_ref	$2\,\text{ms}$	absolute refractory period
τ_s	$0.5\,\text{ms}$	postsynaptic current time constant
$\nu_\mathcal{T}$	$120\,\text{s}^{-1}$	rate of thalamic neurons
t_start	$700\,\text{ms}$	start time of thalamic input
$\Delta t_\mathcal{T}$	$10\,\text{ms}$	duration of thalamic input
t_stop	$t_\text{start}+\Delta t_\mathcal{T} = 710\,\text{ms}$	stop time of thalamic input
$\nu_\mathcal{C}$	$8\,\text{s}^{-1}$	rate of cortico-cortical inputs

Population specific cortico-cortica in-degree $K_{\mathcal{C}_x}$

$\mathcal{C}_x$	$\mathcal{C}_{\mathcal{E}_{23}}$	$\mathcal{C}_{\mathcal{I}_{23}}$	$\mathcal{C}_{\mathcal{E}_4}$	$\mathcal{C}_{\mathcal{I}_4}$	$\mathcal{C}_{\mathcal{E}_5}$	$\mathcal{C}_{\mathcal{I}_5}$	$\mathcal{C}_{\mathcal{E}_6}$	$\mathcal{C}_{\mathcal{I}_6}$	$\mathcal{C}_\mathcal{T}$
$K_{\mathcal{C}_x}$	1600	1500	2100	1900	2000	1900	2900	2100	—

Table 5: Model parameters (continued on next page).

Synapse		
Name	**Value**	**Description**
J	$0.15\,\text{mV}$	(mean) weight (PSP amplitude) of excitatory synapses
$\bar{I}_{yx}$	$J/J_{\text{unit}} \approx 87.81\,\text{pA}$ $-4J/J_{\text{unit}}$ $2J/J_{\text{unit}}$	synaptic weights: $x \in \{\mathcal{E}_{23}, \mathcal{E}_4, \mathcal{E}_5, \mathcal{E}_6, \mathcal{T}, \mathcal{C}\}$ $x \in \{\mathcal{I}_{23}, \mathcal{I}_4, \mathcal{I}_5, \mathcal{I}_6\}$, except for: $(x,y) = (\mathcal{E}_{23}, \mathcal{E}_4)$
$\sigma_{\mathsf{s},yx}$	$0.1 \cdot \bar{I}_{yx}$	standard deviation of weight distribution
$\bar{d}_x$	$1.5\,\text{ms}$ $0.75\,\text{ms}$	mean spike transmission delays: $x \in \{\mathcal{E}_{23}, \mathcal{E}_4, \mathcal{E}_5, \mathcal{E}_6, \mathcal{T}, \mathcal{C}\}$ $x \in \{\mathcal{I}_{23}, \mathcal{I}_4, \mathcal{I}_5, \mathcal{I}_6\}$
$\sigma_{\mathsf{d},x}$	$0.5 \cdot \bar{d}_x$	standard deviation of spike transmission delays
d_{min}	$0.1\,\text{ms}$	minimal spike transmission delay
Initial conditions		
Population specific mean and standard deviation of initial membrane-potential distributions		

population x	$\mathcal{E}_{23}$	$\mathcal{I}_{23}$	$\mathcal{E}_4$	$\mathcal{I}_4$	$\mathcal{E}_5$	$\mathcal{I}_5$	$\mathcal{E}_6$	$\mathcal{I}_6$
$\bar{V}_{0,x}$ (mV)	-68.28	-63.16	-63.33	-63.45	-63.11	-61.66	-66.72	-61.45
$\sigma_{\mathsf{v},x}$ (mV)	5.36	4.57	4.74	4.94	4.94	4.55	5.46	4.48

Table 6: Model parameters (continued).

A Single-neuron dynamics in normal form (subthreshold)

- linear, inhomogeneous dynamics of synaptic input currents and (subthreshold) membrane potential for neuron $i \in y \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6\}$ (cf. eqs. (1) and (2)):

$$\dot{I}_i + \frac{1}{\tau_{\mathsf{s}}} I_i = f_i(t)$$
$$\dot{V}_i + \frac{1}{\tau_{\mathsf{m}}} \left[V_i - E_{\mathsf{L}} \right] - \frac{R_{\mathsf{m}}}{\tau_{\mathsf{m}}} I_i = 0 \tag{3}$$

with

$$f_i(t) = \sum_x \sum_{j \in x} \hat{I}_{ij} s_j(t - d_{ij}) \qquad (x \in \{\mathcal{E}_{23}, \ldots, \mathcal{I}_6, \mathcal{T}, \mathcal{C}\}) \tag{4}$$

- rescale membrane potential $v_i(t) = V_i(t) - E_{\mathsf{L}}$ and total current $x_i(t) = \frac{R_{\mathsf{m}}}{\tau_{\mathsf{m}}} I_i(t)$:

$$\dot{x}_i + \frac{1}{\tau_{\mathsf{s}}} x_i = \frac{R_{\mathsf{m}}}{\tau_{\mathsf{m}}} f_i(t)$$
$$\dot{v}_i + \frac{1}{\tau_{\mathsf{m}}} v_i - x_i = 0 \tag{5}$$

- normal form of neuron-i dynamics (5):

$$\frac{\mathsf{d}}{\mathsf{d}t} \boldsymbol{y}_i = \boldsymbol{A} \boldsymbol{y}_i + \boldsymbol{f}_i(t) \tag{6}$$

  with $D = 2$ dimensional state vector

$$\boldsymbol{y}_i(t) = \Big(x_i(t), \, v_i(t) \Big)^{\mathsf{T}}, \tag{7}$$

  with constant $(D \times D)$ matrix

$$\boldsymbol{A} = \begin{bmatrix} -1/\tau_{\mathsf{s}} & 0 \\ 1 & -1/\tau_{\mathsf{m}} \end{bmatrix}, \tag{8}$$

  and inhomogeneity vector

$$\boldsymbol{f}_i(t) = \left(\frac{R_{\mathsf{m}}}{\tau_{\mathsf{m}}} f_i(t), \, 0 \right)^{\mathsf{T}} \tag{9}$$

  (see Sec. 3.2.2 in Rotter & Diesmann, 1999)

- see App. B for an efficient, exact integration scheme of (6)

- back-transform to physical quantities:

$$V_i(t) = v_i(t) + E_{\mathsf{L}}$$
$$I_i(t) = \frac{\tau_{\mathsf{m}}}{R_{\mathsf{m}}} x_i(t) \tag{10}$$

B Exact integration of single-neuron dynamics (subthreshold)

- exact integration of (6) for spikes arriving at the target neuron i on a time grid $\mathcal{T}_\Delta = \{t_k = k\Delta | k \in \mathbb{N}, \Delta \in \mathbb{R}^+\}$, i.e., for spike trains $s_j(t) = \sum_l \delta(t - t_j^l)$ with $t_j^l \in \mathcal{T}_\Delta$ (Rotter & Diesmann, 1999):

$$\boldsymbol{y}_i(t_{k+1}) = \boldsymbol{P}\boldsymbol{y}_i(t_k) + \boldsymbol{f}_i(t_{k+1}) \tag{11}$$

with $(D \times D)$ propagator matrix (matrix exponential)

$$\boldsymbol{P} = e^{\boldsymbol{A}\Delta} \tag{12}$$

with components

$$\boldsymbol{P} = \begin{bmatrix} e^{-\Delta/\tau_\mathrm{s}} & 0 \\ \frac{e^{-\Delta/\tau_\mathrm{m}} - e^{-\Delta/\tau_\mathrm{s}}}{1/\tau_\mathrm{s} - 1/\tau_\mathrm{m}} & e^{-\Delta/\tau_\mathrm{m}} \end{bmatrix} \tag{13}$$

(see Sec. 3.2.2 in Rotter & Diesmann, 1999)

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