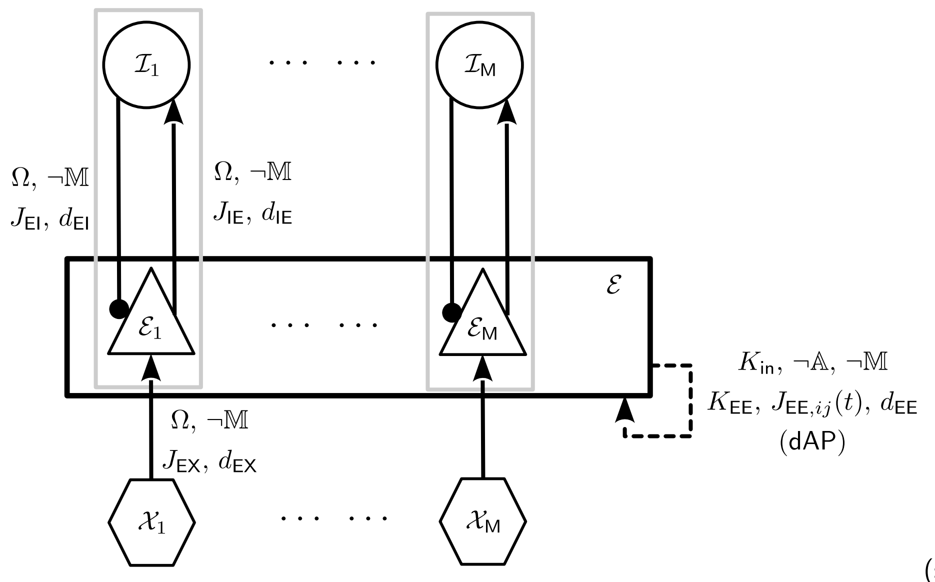
Model description:

Spiking Temporal Memory (STM) model

1 Network model

Summary	
Populations	excitatory ($\mathcal{E}$), inhibitory ($\mathcal{I}$) and external ($\mathcal{X}$)
Connectivity	• sparse random connectivity between excitatory neurons (plastic) • local recurrent connectivity between excitatory and inhibitory neurons (static)
Neuron model	• excitatory neurons: leaky integrate-and-fire (LIF) with nonlinear input integration (dendritic action potentials) • inhibitory neurons: leaky integrate-and-fire (LIF)
Synapse model	exponential or alpha-shaped postsynaptic currents (PSCs)
Plasticity	spike-timing dependent structural plasticity and weight decay in excitatory to excitatory connections
Input	external spike sources, connected to excitatory neurons



(see legend)

Table 1: Summary of the network model. Parameter values are given in Table Tab. 9.

Populations		
$\mathcal{E} = \cup_{i=k}^{M} \mathcal{M}_k$	excitatory (E) neurons	N_{E}
$\mathcal{I}$	inhibitory (I) neurons	N_{I}
$\mathcal{M}_k$	excitatory neurons in subpopulation k, $\mathcal{M}_k \cap \mathcal{M}_l = \emptyset$ $(\forall k \neq l \in [1, M])$	n_{E}

Table 2: Description of the populations. Parameter values are given in Tab. 9

Connectivity		
Source population	**Target population**	**Pattern**
$\mathcal{E}$	$\mathcal{E}$	random; fixed in-degrees $K_i = K_{\mathsf{EE}}$, delays $d_{ij} = d_{\mathsf{EE}}$, and synaptic time constants $\tau_{ij} = \tau_{\mathsf{EE}}$, plastic synaptic weights J_{ij} ($\forall i \in \mathcal{E}$, $\forall j \in \mathcal{E}$; "EE connections")
$\mathcal{E}$	$\mathcal{I}$	all-to-all; fixed delays $d_{ij} = d_{\mathsf{IE}}$, synaptic time constants $\tau_{ij} = \tau_{\mathsf{IE}}$, and weights $J_{ij} = J_{\mathsf{IE}}$ ($\forall i \in \mathcal{I}$, $\forall j \in \mathcal{E}$; "IE connections")
$\mathcal{I}$	$\mathcal{E}$	all-to-all; fixed delays $d_{ij} = d_{\mathsf{EI}}$, synaptic time constants $\tau_{ij} = \tau_{\mathsf{EI}}$, and weights $J_{ij} = J_{\mathsf{EI}}$ ($\forall i \in \mathcal{E}$, $\forall j \in \mathcal{I}$; "EI connections")
$\mathcal{I}$	$\mathcal{I}$	none ("II connections")
all	all	no self-connections ("autapses"), no multiple connections ("multapses")

Table 3: Description of the connectivity. Parameter values are given in Table Tab. 9.

Neuron	
Type	leaky integrate-and-fire (LIF) dynamics
Description	dynamics of membrane potential $V_i(t)$ and spiking activity $s_i(t)$ of neuron i: • emission of the kth spike of neuron i at time t_i^k if $$V_i(t_i^k) \geq \theta_i \quad (1)$$ with somatic spike threshold θ_i • spike train: $s_i(t) = \sum_k \delta(t - t_i^k)$ • reset and refractoriness: $$V_i(t) = V_{\mathsf{r}} \quad \forall k,\ \forall t \in \left(t_i^k,\, t_i^k + \tau_{\mathsf{ref},i}\right]$$ with refractory time $\tau_{\mathsf{ref},i}$ and reset potential V_{r} • subthreshold dynamics: $$\tau_{\mathsf{m},i}\dot{V}_i(t) = -V_i(t) + R_{\mathsf{m},i} I_i(t) \quad (2)$$ with membrane resistance $R_{\mathsf{m},i} = \frac{\tau_{\mathsf{m},i}}{C_{\mathsf{m},i}}$, membrane time constant $\tau_{\mathsf{m},i}$, and total synaptic input current $I_i(t)$ (see Tab. 5) • excitatory neurons: $\tau_{\mathsf{m},i} = \tau_{\mathsf{m,E}}$, $C_{\mathsf{m},i} = C_{\mathsf{m}}$, $\theta_i = \theta_{\mathsf{E}}$, $\tau_{\mathsf{ref},i} = \tau_{\mathsf{ref,E}}$ $(\forall i \in \mathcal{E})$ • inhibitory neurons: $\tau_{\mathsf{m},i} = \tau_{\mathsf{m},I}$, $C_{\mathsf{m},i} = C_{\mathsf{m}}$, $\theta_i = \theta_{\mathsf{I}}$, $\tau_{\mathsf{ref},i} = \tau_{\mathsf{ref,I}}$ $(\forall i \in \mathcal{I})$

Table 4: Description of the neuron model. Parameter values are given in Tab. 9.

Synapse	
Type	continuous, exponential, or alpha-shaped postsynaptic currents (PSCs)
Description	• total synaptic input current $\begin{aligned} \text{excitatory neurons:}\quad & I_i(t) = I_{\mathsf{ED},i}(t) + I_{\mathsf{EX},i}(t) + I_{\mathsf{EI},i}(t),\ \forall i \in \mathcal{E} \\ \text{inhibitory neurons:}\quad & I_i(t) = I_{\mathsf{IE},i}(t),\ \forall i \in \mathcal{I} \end{aligned} \qquad (3)$ with dendritic, inhibitory, excitatory, and external input currents $I_{\mathsf{ED},i}(t)$, $I_{\mathsf{EI},i}(t)$, $I_{\mathsf{IE},i}(t)$, $I_{\mathsf{EX},i}(t)$ evolving according to $I_{\mathsf{ED},i}(t) = \sum_{j \in \mathcal{E}} (\alpha_{ij} * s_j)(t - d_{ij}) \qquad (4)$ with $\alpha_{ij}(t) = J_{ij} \frac{e}{\tau_{\mathsf{ED}}} t e^{-t/\tau_{\mathsf{ED}}} \Theta(t)$ and $\Theta(t) = \begin{cases} 1 & t \geq 0 \\ 0 & \text{else} \end{cases}$ $\tau_{\mathsf{EI}} \dot{I}_{\mathsf{EI},i} = -I_{\mathsf{EI},i}(t) + \sum_{j \in \mathcal{I}} J_{ij} s_j(t - d_{ij}) \qquad (5)$ $\tau_{\mathsf{IE}} \dot{I}_{\mathsf{IE},i} = -I_{\mathsf{IE},i}(t) + \sum_{j \in \mathcal{E}} J_{ij} s_j(t - d_{ij}) \qquad (6)$ $I_{\mathsf{EX},i}(t) = I_{\mathsf{S},i}(t) + I_{\mathsf{B},i}(t) \qquad (7)$ where $I_{\mathsf{S},i}(t)$ is the stimulus input (see Tab. 7:Input). • suprathreshold dynamics of dendritic currents (dAP generation): – emission of kth dAP of neuron i at time $t^k_{\mathsf{dAP},i}$ if $I_{\mathsf{ED},i}(t^k_{\mathsf{dAP},i}) \geq \theta_{\mathsf{dAP}}$ – dAP current plateau: $I_{\mathsf{ED},i}(t) = I_{\mathsf{dAP}} \quad \forall k,\ \forall t \in \left(t^k_{\mathsf{dAP},i}, t^k_{\mathsf{dAP},i} + \tau_{\mathsf{dAP}}\right) \qquad (8)$ with dAP current plateau amplitude I_{dAP}, dAP current duration τ_{dAP}, and dAP activation threshold θ_{dAP} – reset: $I_{\mathsf{ED},i}(t^k_{\mathsf{dAP},i} + \tau_{\mathsf{dAP}}) = 0$ $(\forall k)$ – reset and refractoriness in response to emission of lth somatic spike of neuron i at time t^l_i: $I_{\mathsf{ED},i}(t) = 0 \quad \forall l,\ \forall t \in \left(t^l_i,\ t^l_i + \tau_{\mathsf{ref},i}\right) \qquad (9)$

Table 5: Description of the synapse model. Parameter values are given in Tab. 9.

<table>
<tr><th colspan="2">Plasticity</th></tr>
<tr><td>Type</td><td>spike-timing dependent structural plasticity and permanence decay</td></tr>
<tr><td>EE synapses</td><td>

- dynamics of synaptic permanence $P_{ij}(t)$ (maturity) in EE connections during learning:

$$\forall P_{\text{min}} < P_{ij} < P_{\text{max}}:$$

$$\begin{aligned}\frac{dP_{ij}}{dt} &= P_{\text{max}}\,\lambda_+ \sum_{\{t_i^*\}'} \delta(t - [t_i^* + d_{\text{EE}}]) I_+(x_j(t), t_i^*, \Delta t_{\text{min}}, \Delta t_{\text{max}}) \\ &\quad - P_{\text{max}}\,\lambda_- \sum_{\{t_j^*\}'} \delta(t - [t_j^* + d_{\text{EE}}]) I_-(x_i(t), t_j^*, \Delta t_{\text{max}}) \\ &\quad + (P_{\text{min}} - P)\frac{1}{\tau_{\text{P}}} \\ \forall \{t \mid P_{ij}(t) < P_{\text{min}}\}&: \quad P_{ij}(t) = P_{\text{min}} \\ \forall \{t \mid P_{ij}(t) > P_{\text{max}}\}&: \quad P_{ij}(t) = P_{\text{max}}\end{aligned} \tag{10}$$

  with

  - list of presynaptic spike times $\{t_j^*\}$,
  - list of postsynaptic spike times $\{t_i^*\}' = \{t_i^* \mid \forall t_j^* : t_i^* - t_j^* + d_{\text{EE}} \geq \Delta t_{\text{min}}\}$
  - increment functions

$$\begin{aligned} I_+(x_j(t), t_i^*, \Delta t_{\text{min}}, \Delta t_{\text{max}}) &= R_+(t_i^* - t_j^+ + d_{\text{EE}}) \\ \text{with} \quad R_+(\tau) &= \begin{cases} x_j(t) & \Delta t_{\text{min}} < \tau < \Delta t_{\text{max}} \\ (x_j(t) - 1) & \tau < \Delta t_{\text{min}} \\ 0 & \text{else,} \end{cases} \\ I_-(x_i(t), t_j^*, \Delta t_{\text{max}}) &= R_-(t_j^* - t_i^- + d_{\text{EE}}) \\ \text{with} \quad R_-(\tau) &= \begin{cases} x_i(t) & \tau < \Delta t_{\text{max}} \\ 0 & \text{else,} \end{cases} \end{aligned} \tag{11}$$

  - maximum permanence P_{max}, minimum permanence P_{max}, potentiation and depression rates λ_+, λ_-, decay time constant τ_{P}, delay d_{EE}, minimum Δt_{min} and maximum Δt_{max} time lags between pairs of pre- and postsynaptic spikes at which synapses are potentiated or depressed, nearest presynaptic spike time t_j^+ preceding t_i^*, nearest postsynaptic spike time t_i^- preceding t_j^*,
  - spike trace of presynaptic neuron j, evolving according to

$$\frac{dx_j}{dt} = -\tau_+^{-1} x_j(t) + \sum_{t_j^*} \delta(t - t_j^*)$$

    with presynaptic spike times t_j^* and potentiation time constant τ_+,
  - spike trace of postynaptic neuron i, evolving according to

$$\frac{dx_i}{dt} = -\tau_-^{-1} x_i(t) + \sum_{t_i^*} \delta(t - t_i^*)$$

    with postynaptic spike times t_i^* and depression time constant τ_-.

- dynamics of synaptic weights $J_{\text{EE},ij}$ according to

$$J_{\text{EE},ij} = \begin{cases} J_{\max} & P_{ij} > P_\theta \\ 0 & \text{else,} \end{cases}$$

  with maximum synaptic weight J_{max} and synapse maturity threshold P_θ.

</td></tr>
<tr><td>all other synapses</td><td>non-plastic</td></tr>
</table>

Table 6: Description of the plasticity model. Parameter values are given in Tab. 9.

Input

- repetitive stimulation of the network using the same set $\mathcal{S} = \{s_1, \ldots, s_S\}$ of sequences $s_i = \{\zeta_{i,1}, \zeta_{i,2}, \ldots, \zeta_{i,C_i}\}$ of ordered discrete items $\zeta_{i,j}$ with number of sequences S and length C_i of ith sequence
- presentation of sequence element $\zeta_{i,j}$ at time $t_{i,j}$ modeled by a single spike $x_k(t) = \delta(t - t_{i,j})$ generated by the corresponding external source x_k
- generated current as a response to the presentation of the sequence elements:

$$\tau_{\mathsf{S}} \dot{I}_{\mathsf{S},i} = -I_{\mathsf{S},i}(t) + \sum_{j \in \mathcal{X}} J_{i,j} x_j(t - d_{ij}) \tag{12}$$

- inter-stimulus interval $\Delta T = t_{i,j+1} - t_{i,j}$ between subsequent sequence elements $\zeta_{i,j}$ and $\zeta_{i,j+1}$ within a sequence s_i
- inter-sequence time interval $\Delta T_{\mathsf{seq}} = t_{i+1,1} - t_{i,C_i}$ between subsequent sequences s_i and s_{i+1}
- example sequence sets:
  - sequence set I: $\mathcal{S}$={{A,F,B,D}, {A,F,C,E}}
  - sequence set II: $\mathcal{S}$={{A,F,B,D}, {A,F,C,E}, {A,F,G,H}, {A,F,I,J}, {A,F,K,L}}
- sequence i of length C_i is generated by uniformly and independently drawing C_i elements from a vocabulary of A unique token with equal probability

Output

- somatic spike times $\{t_i^k | \forall i \in \mathcal{E}, k = 1, 2, \ldots\}$
- dendritic currents $I_{\mathsf{ED},i}(t)$ ($\forall i \in \mathcal{E}$)

Table 7: Description of the input and the output. Parameter values are given in Tab. 9.

Initial conditions and network realizations

- membrane potentials: $V_i(0) = V_\mathsf{r}$ ($\forall i \in \mathcal{E} \cup \mathcal{I}$)
- dendritic currents: $I_{\mathsf{ED},i}(0) = 0$ ($\forall i \in \mathcal{E}$)
- external currents: $I_\mathsf{EX}(0) = 0$ ($\forall i \in \mathcal{E}$)
- inhibitory currents: $I_{\mathsf{EI},i}(0) = 0$ ($\forall i \in \mathcal{E}$)
- excitatory currents: $I_{\mathsf{IE},i}(0) = 0$ ($\forall i \in \mathcal{I}$)
- synaptic permanences: $P_{ij}(0) \sim \mathcal{U}(P_{0,\mathsf{min}}, P_{0,\mathsf{max}})$ (uniform distribution; $\forall i, j \in \mathcal{E}$)
- synaptic weights: $J_{ij}(0) = 0$ ($\forall i, j \in \mathcal{E}$)
- spike traces: $x_i(0) = 0$ ($\forall i \in \mathcal{E}$)
- connectivity and initial weights are randomly and independently drawn for each network realization

Simulation details

- network simulations performed in NEST (Gewaltig & Diesmann, 2007) version 3.6 (Villamar et al., 2023).
- definition of excitatory neuron model and plastic synapse model using NESTML (Plotnikov et al., 2016; Linssen et al., 2025) version 8.0.0 (Linssen et al., 2024).
- synchronous update using exact integration of system dynamics on discrete-time grid with step size Δt Rotter & Diesmann (1999)

Table 8: Description of the initial conditions and simulation details. Parameter values are given in Tab. 9.

1.1 Model and simulation parameters

Name	Value	Description
	Network	
N_{E}	6240	number of excitatory neurons
N_{I}	26	number of inhibitory neurons
M	26	number of subpopulations
n_{E},n_{I}	240,1	number of excitatory and inhibitory neurons per subpopulation
ρ	20	(target) number of active neurons per subpopulation after learning = minimal number of coincident excitatory inputs required to trigger a spike in postsynaptic inhibitory neurons
N_{X}	26	number of external spike sources
	(Potential) Connectivity	
K_{EE}	936	number of excitatory inputs per excitatory neuron (EE in-degree)
p	$K_{\mathsf{EE}}/N_{\mathsf{E}} = 0.15$	connection probability
K_{EI}	1	number of inhibitory inputs per excitatory neuron (EI in-degree)
K_{IE}	n_{E}	number of excitatory inputs per inhibitory neuron (IE in-degree)
K_{II}	0	number of inhibitory inputs per inhibitory neuron (II in-degree)
	Excitatory neurons	
$\tau_{\mathsf{m,E}}$	$10\,\mathrm{ms}$	membrane time constant
$\tau_{\mathsf{ref,E}}$	$10\,\mathrm{ms}$	absolute refractory period
C_{m}	$250\,\mathrm{pF}$	membrane capacity
V_{r}	$0.0\,\mathrm{mV}$	reset potential
θ_{E}	$20\,\mathrm{mV}$	somatic spike threshold
I_{dAP}	$200\,\mathrm{pA}$	dAP current plateau amplitude
τ_{dAP}	$60\,\mathrm{ms}$	dAP duration
θ_{dAP}	$59\,\mathrm{pA}$	dAP threshold
	Inhibitory neurons	
$\tau_{\mathsf{m,I}}$	$5\,\mathrm{ms}$	membrane time constant
$\tau_{\mathsf{ref,I}}$	$2\,\mathrm{ms}$	absolute refractory period
C_{m}	$250\,\mathrm{pF}$	membrane capacity
V_{r}	$0.0\,\mathrm{mV}$	reset potential
θ_{I}	$15\,\mathrm{mV}$	spike threshold

Table 9: Model and simulation parameters (continued on next page).

Name	Value	Description
Synapse		
J_{IE}	~ 581.19 pA	weight of IE connections (EPSC amplitude)
J_{EI}	~ -12915.49 pA	weight of EI connections (IPSC amplitude)
J_{EX}	~ 4112.20 pA	weight of EX connections (EPSC amplitude)
τ_{EE}	5 ms	synaptic time constant of EE connections
τ_{EI}	1 ms	synaptic time constant of EI connections
τ_{EX}	2 ms	synaptic time constant of EX connection
τ_{IE}	0.5 ms	synaptic time constant of IE connections
d_{EE}	2 ms	delay of EE connections (dendritic)
d_{IE}	0.1 ms	delay of IE connections
d_{EI}	0.1 ms	delay of EI connections
d_{EX}	0.1 ms	delay of EX connections
Plasticity		
λ_+	0.6	potentiation rate
λ_-	$\{0.1, 0.8\}$	depression rate
P_{ij}	$[P_{\mathsf{min}}, P_0]$	synaptic permanence
P_θ	20	synapse maturity threshold
P_{max}	20	permanence upper bound
P_{min}	1	permanence lower bound
$P_{0,\max}$	8	permanence initialization upper bound
$P_{0,\min}$	0	permanence initialization upper bound
J_{max}	12.98 pA	maximum weight
τ_+	20 ms	plasticity time constant (potentiation)
τ_-	20 ms	plasticity time constant (depression)
τ_{P}	80 s	permanence leak time constant
Δt_{min}	4 ms	minimum time lag between pairs of pre- and postsynaptic spikes at which synapses are potentiated given the spike trace of the presynaptic neuron of the current time step
Δt_{max}	50 ms	maximum time lag between pairs of pre- and postsynaptic spikes at which synapses are potentiated
Input		
S	1	number of sequences per sequence set
C_i	$[10, 150]$	number of characters per sequence
A	26	alphabet length
ΔT	50 ms	inter-stimulus interval (during training)
ΔT_{seq}	$\mathcal{U}(100, 105)$ ms (uniform distribution)	inter-sequence interval
Simulation		
Δt	0.1 ms	time resolution

Table 9: Model and simulation parameters.

References

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