Memory and recall of information in neural networks with dynamic synapses

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In classical neural network models, information is assumed to travel through links between neurons, or synapses. The complex configuration of these links allows the system to exhibit a rich phenomenology. For example, the system can retrieve $P$ previously stored patterns of neural activity, mimicking the associative memory processes which occur in several brain areas, as the hippocampus\(^1\). The activity patterns are stored in the network via a learning rule, which modifies the strength of the synapses in a proper way. This modification is slow compared with the dynamics for generation of electrical signals or action potentials (APs) in the individual neurons, thus synapses are considered to have "static" values in these models. However, in the last years much attention has been paid to fast synaptic dynamics and its role in the processing and coding of information in the brain\(^2,5,6\). In particular, synapses often present fast activity-dependent dynamics, as for example short-term depression (STD) and short-term facilitation (STF), which notably modifies the behaviour of the system when compared with the case of static synapses. While STD implies a temporal reduction of the synaptic function (STF), which notably modifies the behaviour of the system when compared with the case of static synapses. While STD implies a temporal reduction of the synaptic function (STF), which notably modifies the behaviour of the system when compared with the case of static synapses.

In this work, we study the influence of the competition of STD and STF in the capacity of the network to store and retrieve information. We consider a network of $N$ fully connected binary neurons which follow a probabilistic dynamics $\text{Prob}[s_i(t+1)=+1]=\frac{1}{2}(1+\tanh[2\beta(h_i(t)-\theta_i)])$ where $s_i$ represents the state of the neuron $i$, $\beta$ takes into account the thermal noise in the network, $h_i$ is the local field or the total synaptic current to the neuron $i$, and $\theta_i$ is the neuron firing threshold. To include the dynamic synapses, we consider the following phenomenological model:\(^5\)

\begin{align*}
  x_i(t+1) &= x_i(t) + \frac{1-x_i(t)}{\tau_{rec}} - u_i(t)x_i(t)s_i(t) \\
  u_i(t+1) &= u_i(t) + \frac{U_{SE} - u_i(t)}{\tau_{fac}} + U_{SE}(1 - u_i(t))s_i(t)
\end{align*}

where $x_i$ is the synaptic resources molar fraction in the presynaptic neuron $i$, $u_i$ is related to calcium concentration near the synapse. $U_{SE}$ is the minimal release probability of synaptic resources after an AP, and $\tau_{rec}$, $\tau_{fac}$ represent time constant for STD and STF processes, respectively. Then, the synaptic current is given by $h_i = \sum_j \omega_{ij}x_jU_{SE}s_j$, where $\omega_{ij}$ represents the static synaptic weights.

Figura 1. Storage capacity of a neural network with dynamic synapses with STD and STF mechanisms. STD decreases the storage capacity with $\tau_{rec}$, whereas STF can enhance it for intermediate values of $U_{SE}$. The figure also shows how an standard mean-field theory (lines) agrees qualitatively with simulations (data points).

Figure 1 shows the effect of include STD and STF in the storage capacity of the network. This is measured by the maximum number of patterns (relative to the network size, i.e., $\alpha_c = P/N$) which is able to memorize and retrieve efficiently. Our study reflects that STD makes $\alpha_c$ to decrease for large $\tau_{rec}$, while STF allows to restore this number to eventually its maximum value ($\alpha \simeq 0.138$) for relatively small $U_{SE}$. This results would lead us to think in the positive role of synaptic facilitation in optimal and fast memory retrieval whereas synaptic depression could be more oriented to other tasks concerning, for instance, the dynamical processing of data.

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