

# Non-Reward Neural Mechanisms in the Orbitofrontal Cortex Supplementary Material

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May 3, 2016

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# 1 Supplementary Material

## 1.1 Implementation of neural and synaptic dynamics

We use the mathematical formulation of the integrate-and-fire neurons and synaptic currents described by Brunel and Wang (2001). Here we provide a brief summary of this framework (Rolls 2008, Rolls and Deco 2010, Rolls 2016).

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

$$C_m \frac{dV(t)}{dt} = -g_m(V(t) - V_L) - I_{syn}(t), \quad (1)$$

Both excitatory and inhibitory neurons have a resting potential  $V_L = -70mV$ , a firing threshold  $V_{thr} = -50mV$  and a reset potential  $V_{reset} = -55mV$ . 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, Connors, Lighthall and Prince (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  $\tau_{ref}$  and the action potential is propagated to the other neurons.

The network is fully connected with  $N_E = 800$  excitatory neurons and  $N_I = 200$  inhibitory neurons, which is consistent with the observed proportions of the pyramidal neurons and interneurons in the cerebral cortex (Braitenberg and 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 ( $I_{GABA}$ ):

$$I_{syn}(t) = I_{AMPA,ext}(t) + I_{AMPA,rec}(t) + I_{NMDA,rec}(t) + I_{GABA}(t). \quad (2)$$

The recurrent excitation is 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 2.4 kHz. These can be viewed as originating from  $N_{ext} = 800$  external neurons at an average rate of 3 Hz per neuron, consistent with the spontaneous activity observed in the cerebral cortex (Wilson, O'Scalaidhe and Goldman-Rakic 1994, Rolls and Treves 1998). The currents are defined by:

$$I_{AMPA,ext}(t) = g_{AMPA,ext}(V(t) - V_E) \sum_{j=1}^{N_{ext}} s_j^{AMPA,ext}(t) \quad (3)$$

$$I_{AMPA,rec}(t) = g_{AMPA,rec}(V(t) - V_E) \sum_{j=1}^{N_E} w_{ji}^{AMPA} s_j^{AMPA,rec}(t) \quad (4)$$

$$I_{NMDA,rec}(t) = \frac{g_{NMDA}(V(t) - V_E)}{1 + [Mg^{++}]exp(-0.062V(t))/3.57} \times \sum_{j=1}^{N_E} w_{ji}^{NMDA} s_j^{NMDA}(t) \quad (5)$$

$$I_{GABA}(t) = g_{GABA}(V(t) - V_I) \sum_{j=1}^{N_I} w_{ji}^{GABA} s_j^{GABA}(t) \quad (6)$$

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 ( $[Mg^{++}] = 1$  mM (Jahr and Stevens 1990)). The values for the synaptic conductances for excitatory neurons are  $g_{AMPA,ext} = 2.08$  nS,  $g_{AMPA,rec} = 0.104$  nS,  $g_{NMDA} = 0.327$  nS and  $g_{GABA} = 1,25$  nS ; and for inhibitory neurons  $g_{AMPA,ext} = 1.62$  nS,  $g_{AMPA,rec} = 0.081$  nS,  $g_{NMDA} = 0.258$  nS and  $g_{GABA} = 0.973$  nS. These values are obtained from the ones used by Brunel and Wang (2001) by correcting for the different numbers 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:

$$\frac{ds_j^{AMPA,ext}(t)}{dt} = -\frac{s_j^{AMPA,ext}(t)}{\tau_{AMPA}} + \sum_k \delta(t - t_j^k) \quad (7)$$

$$\frac{ds_j^{AMPA,rec}(t)}{dt} = -\frac{s_j^{AMPA,rec}(t)}{\tau_{AMPA}} + \sum_k \delta(t - t_j^k) \quad (8)$$

$$\frac{ds_j^{NMDA}(t)}{dt} = -\frac{s_j^{NMDA}(t)}{\tau_{NMDA,decay}} + \alpha x_j(t)(1 - s_j^{NMDA}(t)) \quad (9)$$

$$\frac{dx_j(t)}{dt} = -\frac{x_j(t)}{\tau_{NMDA,rise}} + \sum_k \delta(t - t_j^k) \quad (10)$$

$$\frac{ds_j^{GABA}(t)}{dt} = -\frac{s_j^{GABA}(t)}{\tau_{GABA}} + \sum_k \delta(t - t_j^k), \quad (11)$$

where  $\tau_{NMDA,decay} = 100$  ms is the decay time for NMDA synapses,  $\tau_{AMPA} = 2$  ms for AMPA synapses (Hestrin, Sah and Nicoll 1990, Spruston, Jonas and Sakmann 1995) and  $\tau_{GABA} = 10$  ms for GABA synapses (Salin and Prince 1996, Xiang, Huguenard and Prince 1998);  $\tau_{NMDA,rise} = 2$  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<sup>-1</sup>. The sums over  $k$  represent a sum over spikes formulated as  $\delta$ -Peaks  $\delta(t)$  emitted by presynaptic neuron  $j$  at time  $t_j^k$ .

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 trials for equal parameter configurations were run with different random seeds (as the only difference).

## 1.2 Connection Matrices

In the following Tables, S1 is the Reward population, S2 is the Non-Reward population, NS is the non-specific excitatory population, and IH is the inhibitory population.

### 1.2.1 Fraction of pool sizes $f_i$

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

S1	S2	NS	IH
0.08	0.08	0.64	0.2

### 1.2.2 Connection matrix for AMPA and NMDA – [from, to]

	S1	S2	NS	IH
S1	$w_+$	$w_-$	1	1
S2	$w_-$	$w_+ + 0.12$	1	1
NS	$w_-$	$w_-$	1	1
IH	0	0	0	0

where  $w_- = \frac{0.8 - f_{S1} w_+}{0.8 - f_{S1}}$ .

### 1.2.3 Connection matrix for GABA – [from, to]

	S1	S2	NS	IH
S1	0	0	0	0
S2	0	0	0	0
NS	0	0	0	0
IH	1	1	1	1

## 1.3 Short term synaptic depression

A synaptic depression mechanism was used following Dayan and Abbott (2001), page 185. In particular, the probability of transmitter release  $P_{\text{rel}}$  was decreased after each presynaptic spike by a factor  $P_{\text{rel}} = P_{\text{rel}} \cdot f_D$  with  $f_D = 0.988$ . Between presynaptic action potentials the release probability  $P_{\text{rel}}$  is updated by

$$\tau_P \frac{dP_{\text{rel}}}{dt} = P_0 - P_{\text{rel}} \quad (12)$$

with  $P_0 = 1$  and  $\tau_P = 1000$  ms.

## 1.4 The model parameters used in the simulations of memory

The fixed parameters of the model are shown in Table 1, and not only provide information about the values of the parameters used in the simulations, but also enable them to be compared to experimentally measured values.

Table 1: Parameters used in the integrate-and-fire simulations

$N_E$	800
$N_I$	200
$r$	0.1
$w_+$	2.1
$w_I$	1.02
$N_{\text{ext}}$	800
$\nu_{\text{ext}}$	2.4 kHz
$C_m$ (excitatory)	0.5 nF
$C_m$ (inhibitory)	0.2 nF
$g_m$ (excitatory)	25 nS
$g_m$ (inhibitory)	20 nS
$V_L$	-70 mV
$V_{\text{thr}}$	-50 mV
$V_{\text{reset}}$	-55 mV
$V_E$	0 mV
$V_I$	-70 mV
$g_{\text{AMPA,ext}}$ (excitatory)	2.08 nS
$g_{\text{AMPA,rec}}$ (excitatory)	0.104 nS
$g_{\text{NMDA}}$ (excitatory)	0.327 nS
$g_{\text{GABA}}$ (excitatory)	1.25 nS
$g_{\text{AMPA,ext}}$ (inhibitory)	1.62 nS
$g_{\text{AMPA,rec}}$ (inhibitory)	0.081 nS
$g_{\text{NMDA}}$ (inhibitory)	0.258 nS
$g_{\text{GABA}}$ (inhibitory)	0.973 nS
$\tau_{\text{NMDA,decay}}$	100 ms
$\tau_{\text{NMDA,rise}}$	2 ms
$\tau_{\text{AMPA}}$	2 ms
$\tau_{\text{GABA}}$	10 ms

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