Reward-specific satiety and reward-specific motivation: neural bases and significance

Supplementary Material

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1 Integrate-and-fire simulations of the mechanisms of sensory-specific satiety

The architecture implemented with integrate-and-fire neurons is described in the main text of the paper, and is illustrated in Fig. 2 of the paper (Rolls et al.; 2025). In this Supplementary Material, the implementation of the integrate-and-fire simulation (Rolls; 2023) is described.

We use the mathematical formulation of the integrate-and-fire neurons and synaptic currents described by Brunel and Wang (Brunel and Wang; 2001), and used and further developed in subsequent investigations used and developed considerably (Wang; 2002; Deco and Rolls; 2006; Loh et al.; 2007; Rolls and Deco; 2016, 2015a,b; Deco et al.; 2013; Swash; 1989; Rolls et al.; 2012, 2010b,a; Rolls and Deco; 2010; Deco et al.; 2009; Rolls; 2023). Here we provide a brief summary of this framework.

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

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

Both excitatory and inhibitory neurons have a resting potential $V_L = -70$ mV, a firing threshold $V_{thr} = -50$ mV and a reset potential $V_{reset} = -55$ mV. The membrane parameters are different for both types of neurons: Excitatory (Inhibitory) neurons are modeled with a membrane capacitance $C_m = 0.5$ nF (0.2 nF), a leak conductance $g_m = 25$ nS (20 nS), a membrane time constant $\tau_m = 20$ ms (10 ms), and a refractory period $t_{ref} = 2$ ms (1 ms). Values are extracted from McCormick et al (McCormick et al.; 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 τ_{ref} and the action potential is propagated to the other neurons.

Each network has $N_E = 100$ excitatory neurons and $N_I = 25$ inhibitory neurons which are connected to each other, 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($I_{AMPA,ext}$), and the inhibitory current (I_{GABA}):

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

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 2.0 kHz. These can be viewed as originating from $N_{ext} = 800$ external neurons at an average rate of 2.5 Hz per neuron, consistent with the spontaneous activity observed in the cerebral cortex (Wilson et al.; 1994; Rolls and Treves; 1998). The currents are defined by:

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

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

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

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

where $V_E = 0$ mV, $V_I = -70$ mV, w_{ji} 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 for 100 synapses per neuron. These values are obtained from the ones used by Brunel and Wang (Brunel and Wang; 2001). The synaptic weights were set so that the excitatory and inhibitory neurons had a low spontaneous firing rate of several spikes/s. The fractions of open channels are described by:

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

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

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

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

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

where $\tau_{NMDA,decay} = 100$ ms is the decay time for NMDA synapses, $\tau_{AMPA} = 6$ ms for AMPA synapses to allow for propagation effects (Hestrin et al.; 1990; Spruston et al.; 1995) and $\tau_{GABA} = 10$ ms for GABA synapses (Salin and Prince; 1996; Xiang et al.; 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^{-1}. The sums over k represent a sum over spikes formulated as δ-Peaks $\delta(t)$ emitted by presynaptic neuron j at time t_j^k.

The equations were integrated numerically using a forward Euler method with step size 0.1 ms.

1.1 The model parameters used in the integrate-and-fire simulations

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. The conductance values are similar to those in previous research on attractor networks (Brunel and Wang; 2001; Rolls et al.; 2010a; Rolls and Deco; 2015b), and the synaptic weights are scaled to produce similar currents from different sources such as excitatory to inhibitory, inhibitory to excitatory, and excitatory to excitatory, as in this previous research. The conductances shown in the Table are for a network with a total number of neurons = 1000, with 800 excitatory neurons and 200 inhibitory neurons. As the total number of neurons in this simulation was 125, the conductances were scaled up by 8, to provide for the appropriate total current into each neuron.

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

N_{E}	100 in each module
N_{I}	25 in each module
w_{EtoI}	1.0 default, except where stated
w_{ItoE}	1.0
w_{ItoI}	1.0
N_{ext}	800
ν_{ext}	2.0 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_{thr}	–50 mV
V_{reset}	–55 mV
V_{E}	0 mV
V_{I}	–70 mV
$g_{\mathrm{AMPA,ext}}$ (excitatory)	2.08 nS
$g_{\mathrm{AMPA,rec}}$ (excitatory)	0.104 nS
g_{NMDA} (excitatory)	0.327 nS
g_{GABA} (excitatory)	1.25 nS
$g_{\mathrm{AMPA,ext}}$ (inhibitory)	1.62 nS
$g_{\mathrm{AMPA,rec}}$ (inhibitory)	0.081 nS
g_{NMDA} (inhibitory)	0.258 nS
g_{GABA} (inhibitory)	0.973 nS
$\tau_{\mathrm{NMDA,decay}}$	100 ms
$\tau_{\mathrm{NMDA,rise}}$	2 ms
τ_{AMPA}	6 ms
τ_{GABA}	10 ms
α	0.5 ms^{-1} for NMDA dynamics
τ_{D}	2000 s presynaptic depression time constant
X	0.0001 presynaptic depression amount per spike, see text of paper

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