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Dopamine induced bistability enhances signal processing in spiny neurons

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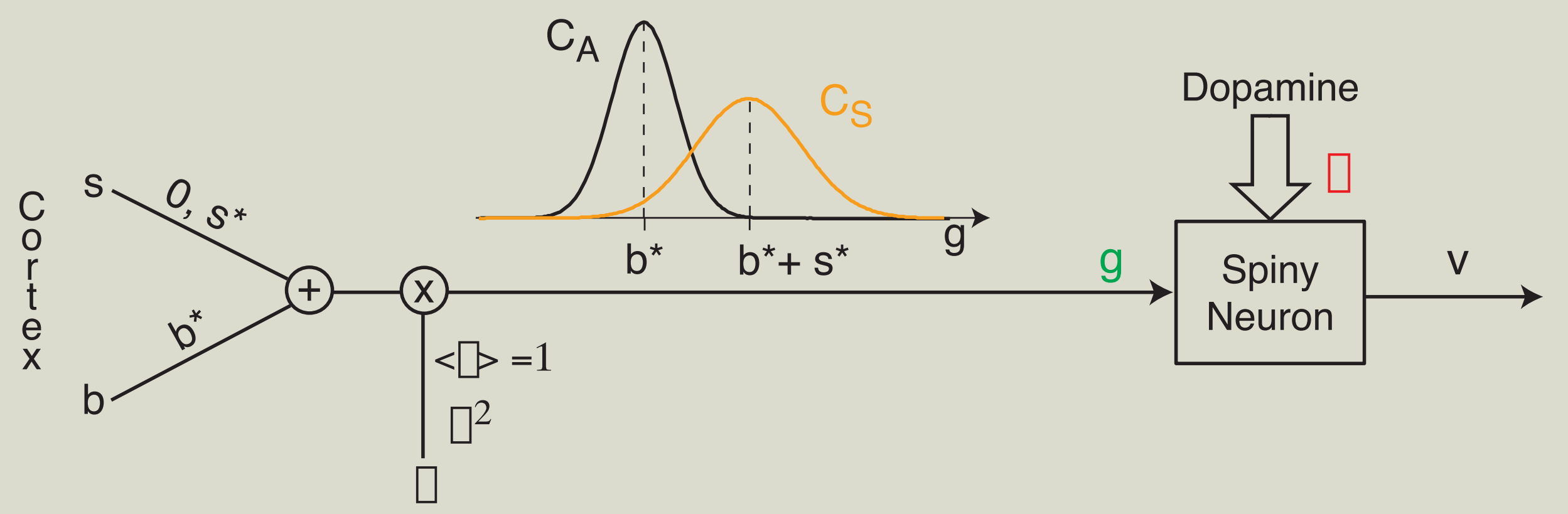
Can dopamine modulation via D1 receptors enhance signal processing in a single spiny neuron ?

- Servan-Schreiber et al [1] showed that the error of a Bayesian classifier can not be reduced by a monotonic mapping, and used this finding to suggest that the effects of a neuromodulator such as dopamine (DA) on the activation function of a neuron will not improve the signal detection abilities of an isolated neuron
- Our recent biophysically grounded model [2] of spiny neurons displays a nonmonotonic mapping (bistable activation function) in high dopamine conditions, which does improve the ability of single neurons to detect temporally correlated inputs

Spiny neuron model

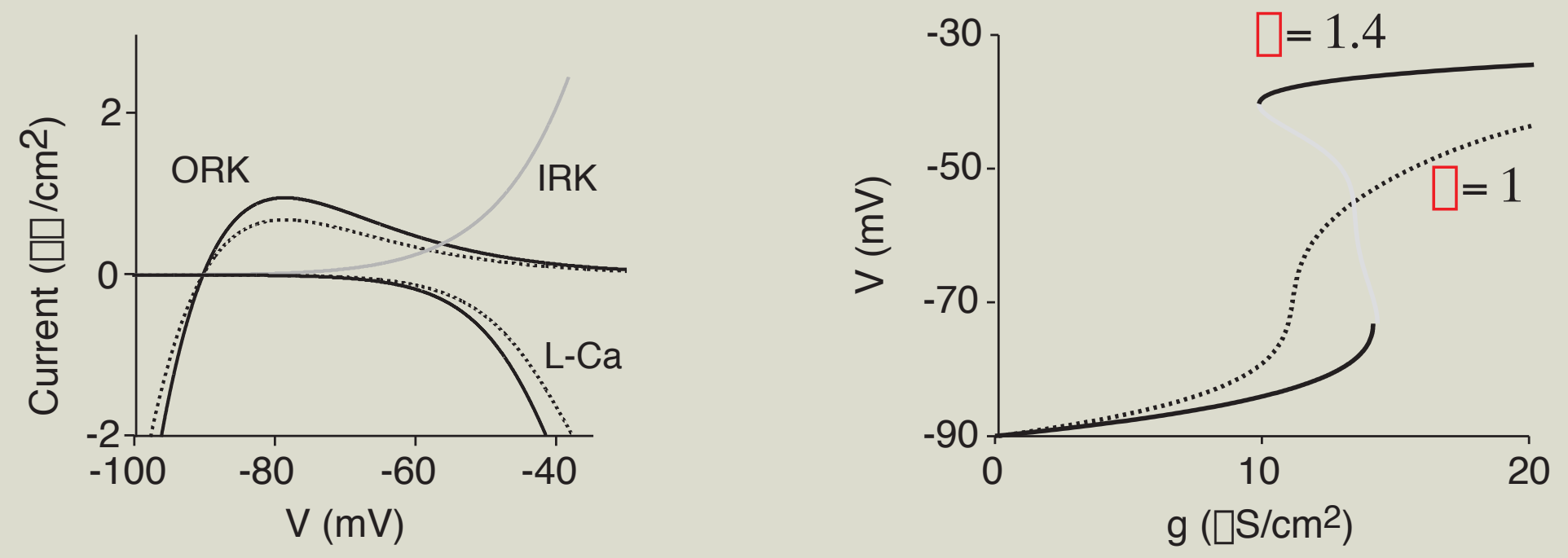
A) Cortical inputs in presence (s = s*) and absence (s = 0) of signal



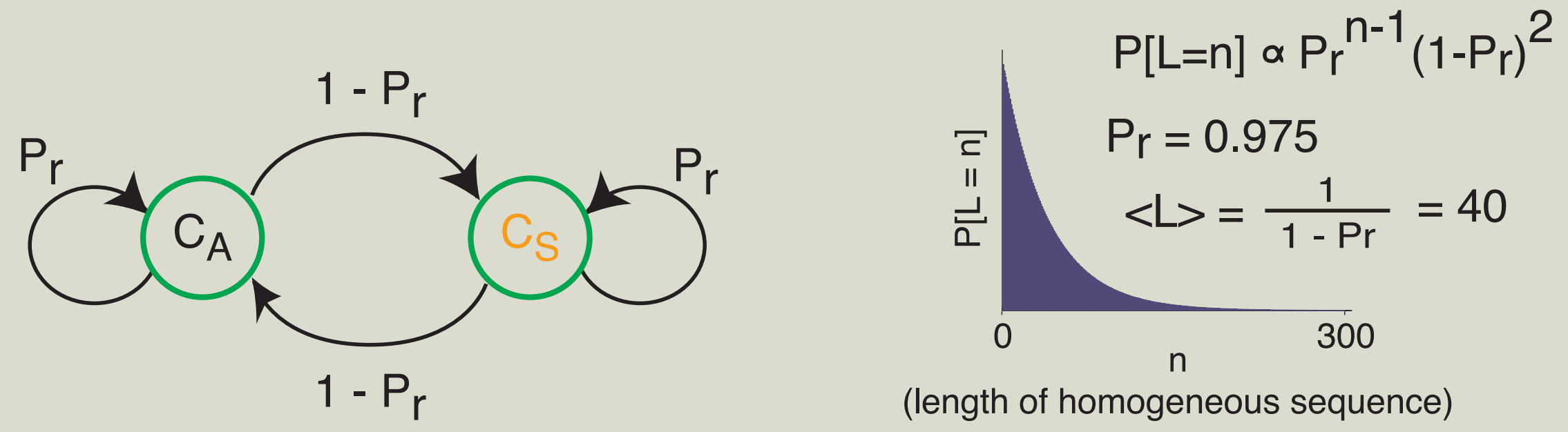
B) The activation funcion of a biophysically based model becomes bistable in high DA (□) via D1 mediated increase of IRK and L-Ca

$$-C\frac{dV}{dt} = \gamma\,(I_{IRK} + I_{LCa}) + I_{ORK} + I_l + I_c$$

$$I_c = g(V - E_{syn})$$



C) Repeat probability Pr controls correlations in the input

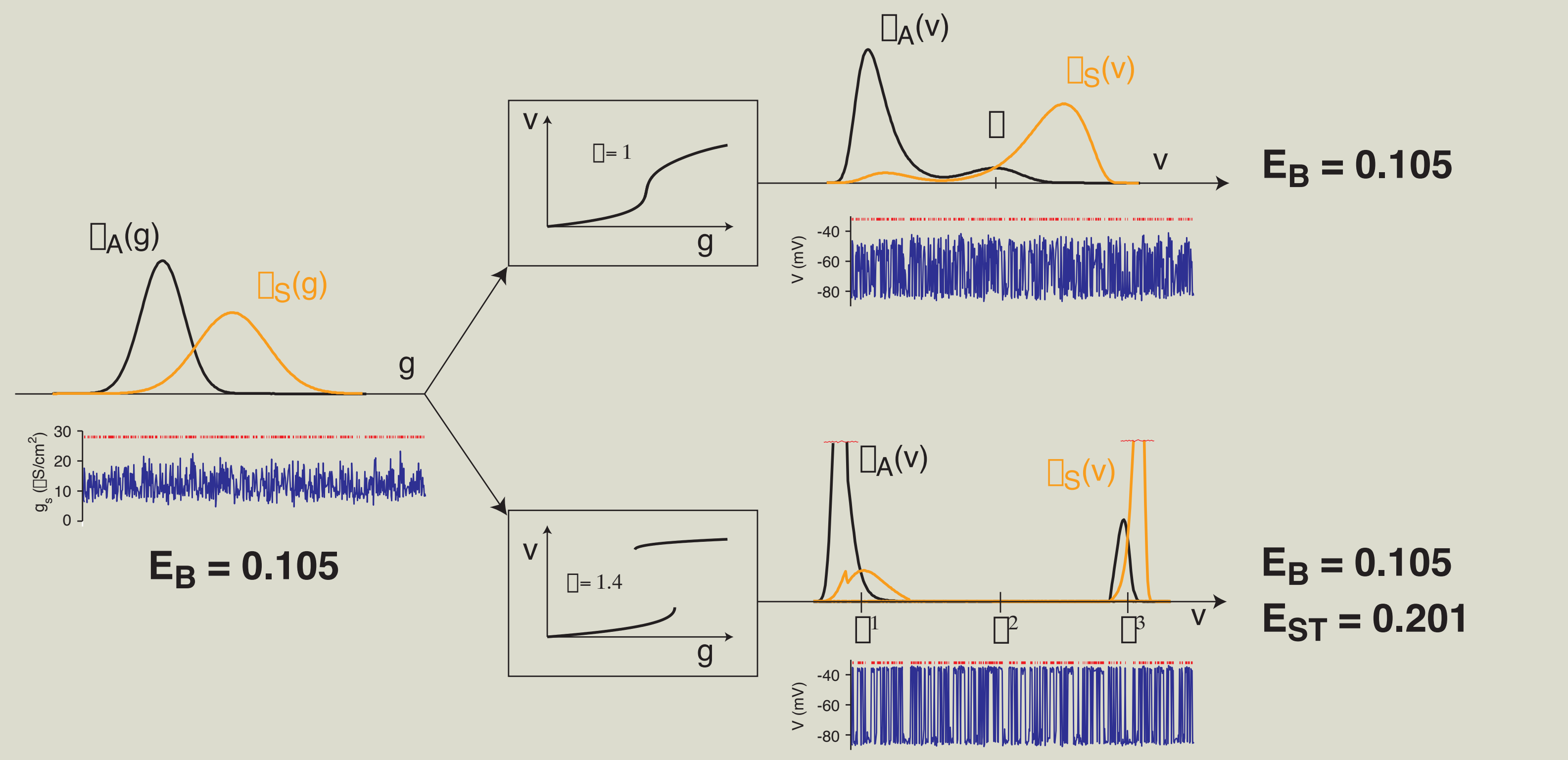


A) A medium spiny neuron recieves both excitatory input from cortex and modulatory input from dopamine releasing neurons. In our model, the cortical input is the sum of a background input b which takes the value b* and a signal input s which takes the values 0 or s*. A gaussian noise factor □ causes an overlap between the pdfs of g in the presence (C_S) and absence (C_A) of signal. The values of b*, s* and $□^2$ are chosen so as to be consistent with intracellular recordings of spiny neuron Vm. **B)** A single compartment model of spiny neurons includes terms for the magnitude and voltage dependence of K^+, Ca^{2+}, and synaptic (I_C) currents. The activation of D1 receptors in high dopamine conditions, modeled by the factor □, causes an increase in IRK and L-Ca. In low DA (□= 1; dotted line), the activation function is monotonically increasing. In high DA (□= 1.4; solid line), the activation function is bistable at intermediate values of g. **C)** The repeat probability Pr is the probability that two consecutive inputs are of the same class (C_A or C_S). Pr =0.5 corresponds to independent draws. We assume that natural stimuli will persist for a mean time of 400 ms and that the neuronal sampling period is 10 ms; we therefore set Pr = 0.975 so as to produces homogeneous sequences of mean lengh <L> = 40.

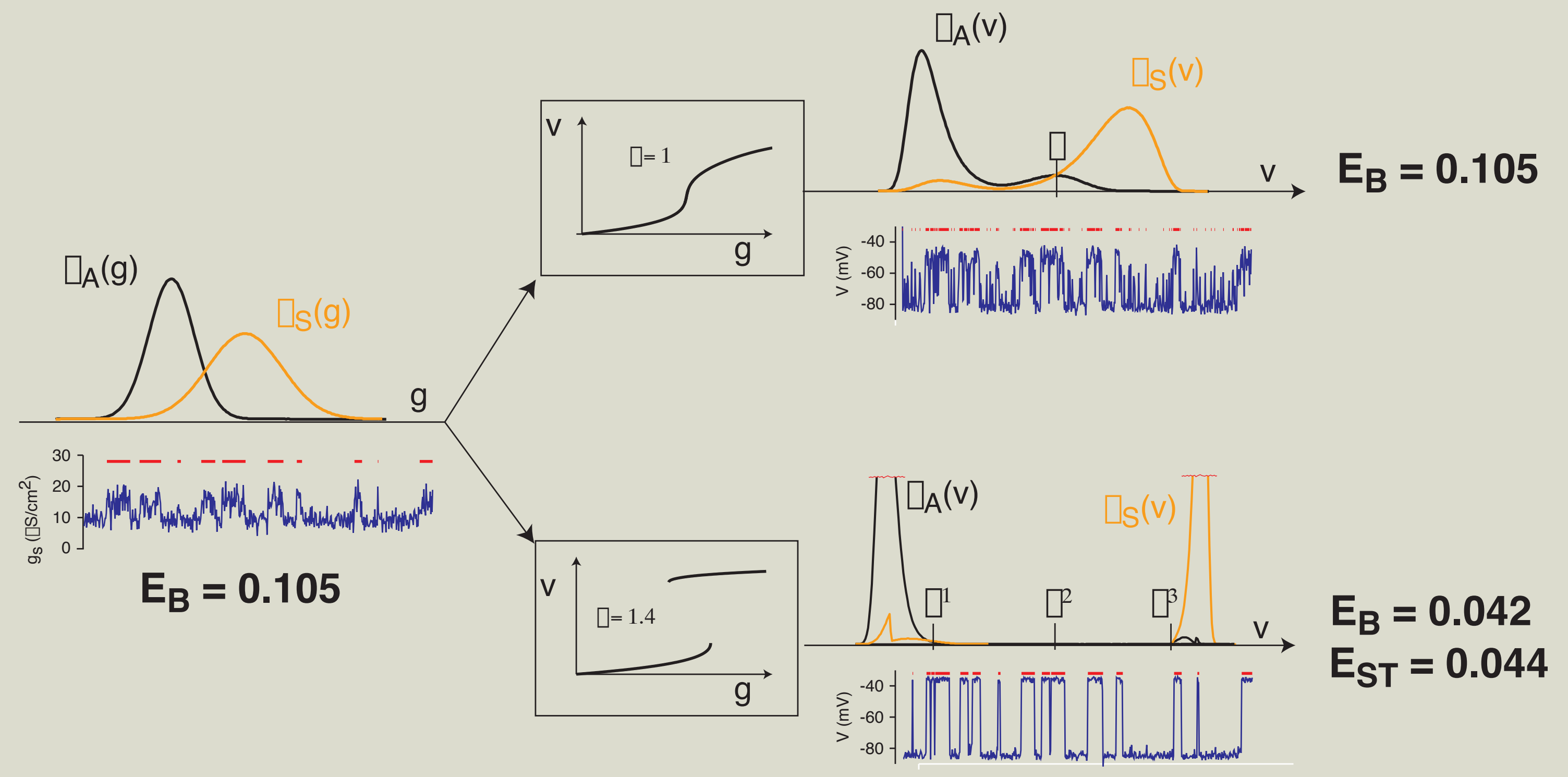
Numerical simulation

A) Error is the same or greater in high DA for uncorrelated inputs (Pr = 0.5)

E_B: Bayesian Error
E_{ST}: Single Threshold



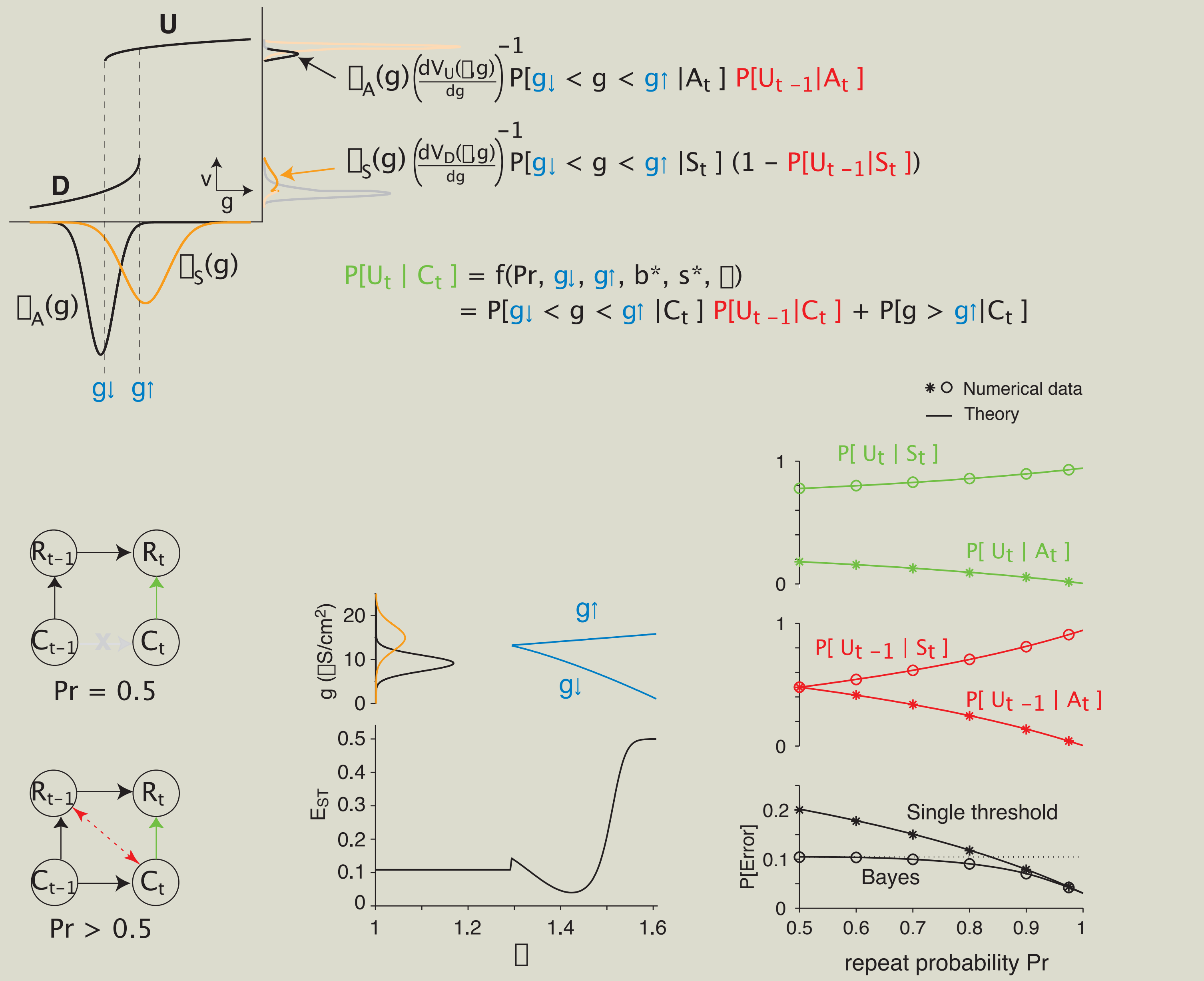
B) Error is reduced in high DA for correlated inputs (Pr = 0.975)



Activation functions in low (□= 1.0) and high (□= 1.4) DA map g into V. The pdfs of g and V are shown for the two classes, signal absent (CA) and signal present (CS). The red lines above the sample time traces of g indicate the class from which g is drawn; the red line indicates that the signal is present (CS) and that g is drawn from $□_S(g)$. The red lines above the corresponding traces of V identify the single-threshold classification of V as belonging to CS. **A)** The Bayesian error E_B for uncorrelated inputs (Pr = 0.5) is 0.105. E_B is not altered by the mapping of g into V through the □=1 curve, in agreement with the theoretical prediction by Servan-Schreiber et al 1990 [1]. E_B is also not affected by the mapping through the bistable curve for □= 1.4. However, computation of the Bayesian error in this case requires 3 decision boundaries; a more natural sheme for a neuron is to use a single boundary, such as the firing threshold. The single-threshold error E_{ST} is nearly double the classification error for g. Bistability degrades the ability of a single-threshold decision maker to detect the signal. **B)** Temporal correlations characteristic of natural stimuli are incorporated in the model through values of Pr > 0.5. For Pr = 0.975, the Bayesian error for g and for the corresponsing mapping into V through the □= 1 curve are the same as for the uncorrelated case. However, both the Bayesian and the single-threshold error are signifigantly reduced by the mapping through the □= 1.4 curve.

Theory

A) Conditional probabilities that control the classification error in the bistable region depend on Pr and □



$$□_A(g)\left(\frac{dV_U(□,g)}{dg}\right)^{-1} P[g_{\downarrow} < g < g_{\uparrow}\,|A_t\,]\; P[U_{t-1}|A_t\,]$$

$$□_S(g)\left(\frac{dV_D(□,g)}{dg}\right)^{-1} P[g_{\downarrow} < g < g_{\uparrow}\,|S_t\,]\;(1 - P[U_{t-1}|S_t\,])$$

$$\begin{aligned} P[U_t \mid C_t\,] &= f(Pr, g_{\downarrow}, g_{\uparrow}, b^*, s^*, □) \\ &= P[g_{\downarrow} < g < g_{\uparrow}\,|C_t\,]\; P[U_{t-1}|C_t\,] + P[g > g_{\uparrow}|C_t\,] \end{aligned}$$

Errors are generated by the mapping of $g \in C_S$ to D and $g \in C_A$ to U. Within the bistable region, the fractional mapping of g into V through the U branch is controlled by the conditional probabilities $P[U_{t-1}|C_t]$, where the class index C refers to either S or A. These conditional probabilities depend on Pr, the transition thresholds $g_{\downarrow}$ and $g_{\uparrow}$, and the statistics of the input. The dependence of $P[U_{t-1}|C_t]$ on Pr is shown by the red curves. No distinction between classes is seen for Pr = 0.5; in this case, bistability does not provide an additional mechanism for signal detection. As Pr increases, $P[U_{t-1}|S_t]$ increases while $P[U_{t-1}|A_t]$ decreases, which reduces the corresponding pdfs along the V axis and thus decreases the classification error. The quantity $P[U_{t-1}|C_t]$, which plays a fundamental role in this theoretical formulation, might seem acausal. For Pr = 0.5, there is no correlation between C_{t-1} and C_t; therefore there is no correlation between the branch parameter R_{t-1} (which can take the values U or D) and C_t. For Pr > 0.5, the correlation between C_{t-1} and C_t induces a correlation between R_{t-1} and C_t. For values of g within the bistable region, R_t is equal to R_{t-1}, independently of C_t. An increased correlation between R_{t-1} and C_t leads to error reduction. This mechanism for improved classification relies on the existence of a bistable region. The resulting classification error thus depends on the width of this region, which can be controlled through changes in □. Minimal error is achieved for an optimal value of □; this phenomenon is reminiscent of stochastic resonance.

Bistability induced by the activation of D1 receptors in high dopamine conditions can improve the ability of single spiny neurons neurons to detect a temporally correlated input signal

[1] Servan-Schreiber D, Printz H, Cohen JD (1990). Science 249:892-895.
[2] Gruber AJ, Solla SA, Suemeier DJ, Houk JC (In Submission) Journal of Neurophysiology.

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