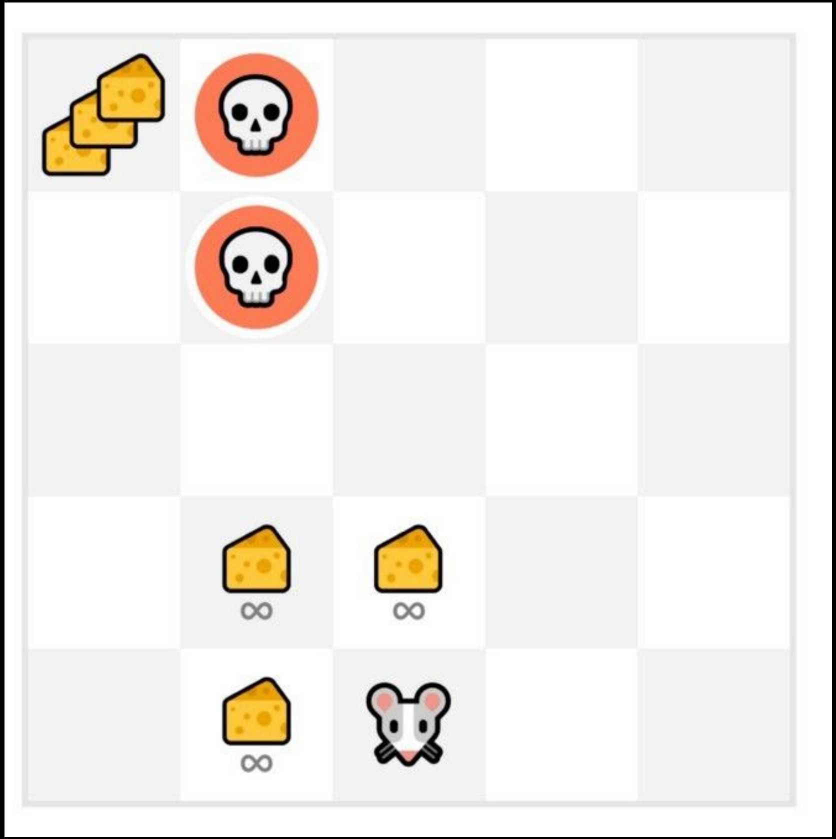
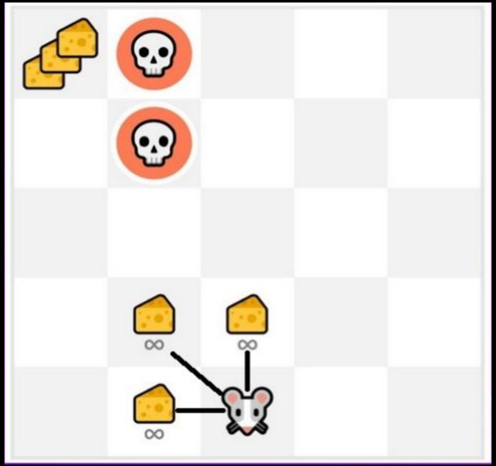
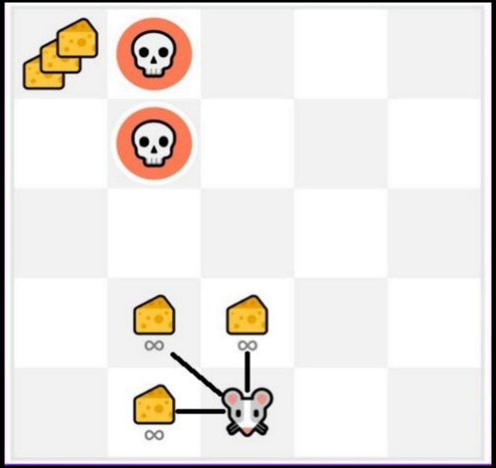
An exploration-exploitation model based on norepinephrine and dopamine activity

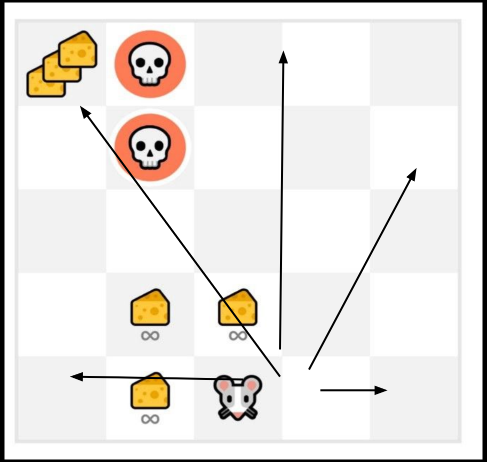
Yervand Azatian

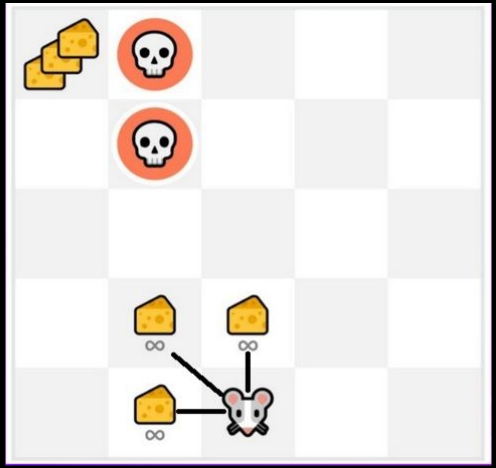
NEU 502A: Systems and Cognitive Neuroscience

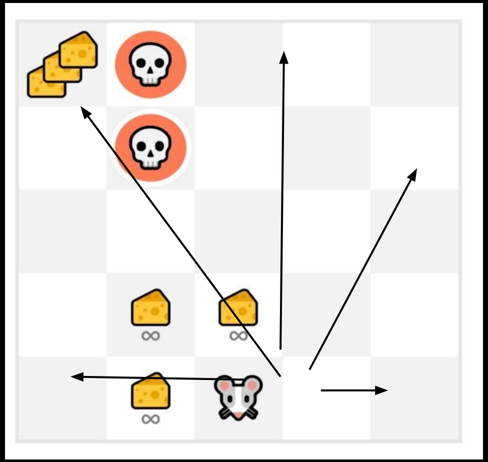


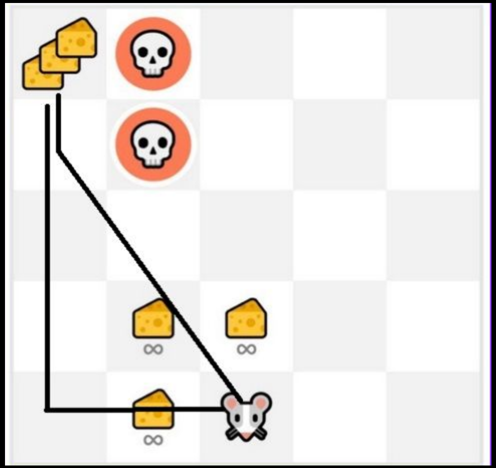


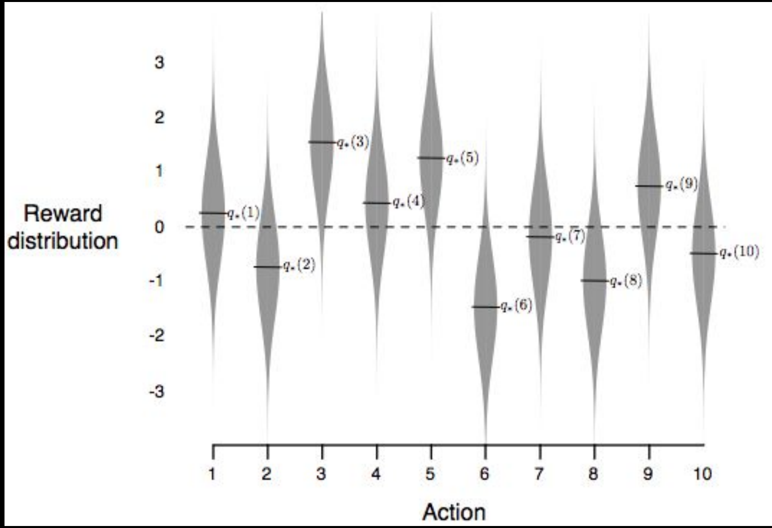






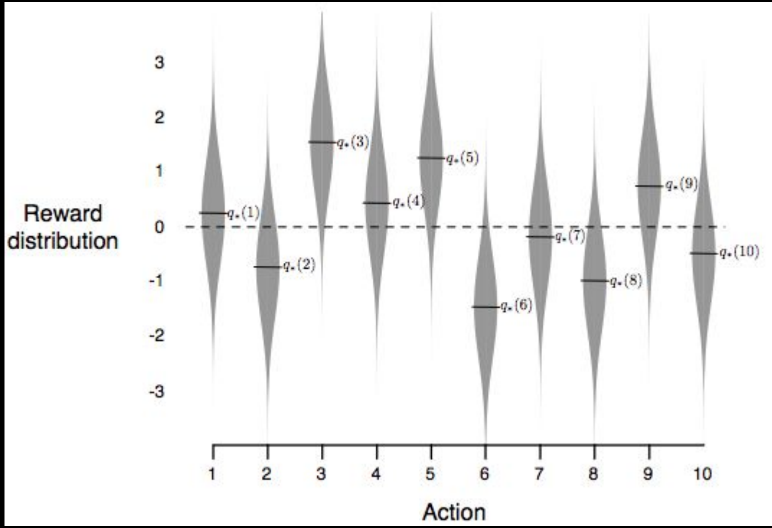






3
2
1
0
-1
-2
-3
Reward distribution
$q_*(1)$
$q_*(2)$
$q_*(3)$
$q_*(4)$
$q_*(5)$
$q_*(6)$
$q_*(7)$
$q_*(8)$
$q_*(9)$
$q_*(10)$
1
2
3
4
5
6
7
8
9
10
Action

$$A_t \leftarrow \begin{cases} \underset{a}{\operatorname{argmax}}\ Q_t(a) & \textbf{with probability } 1-\epsilon \\ a \sim Uniform(\{a_1 \dots a_k\}) & \textbf{with probability } \epsilon \end{cases}$$



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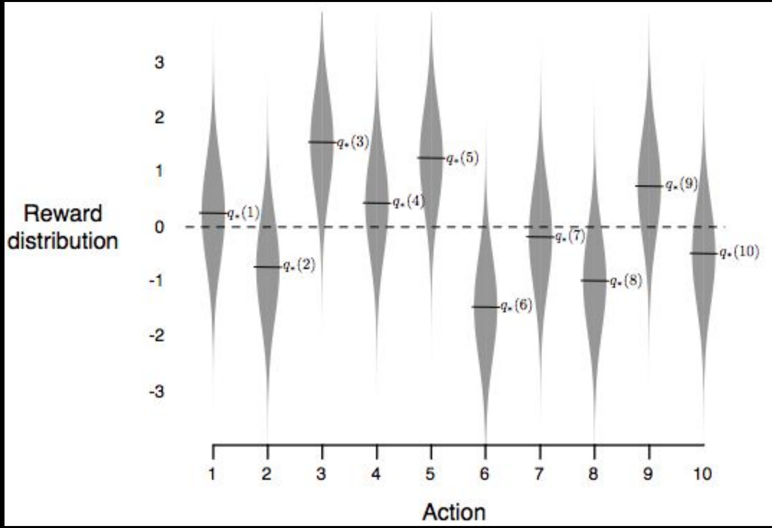
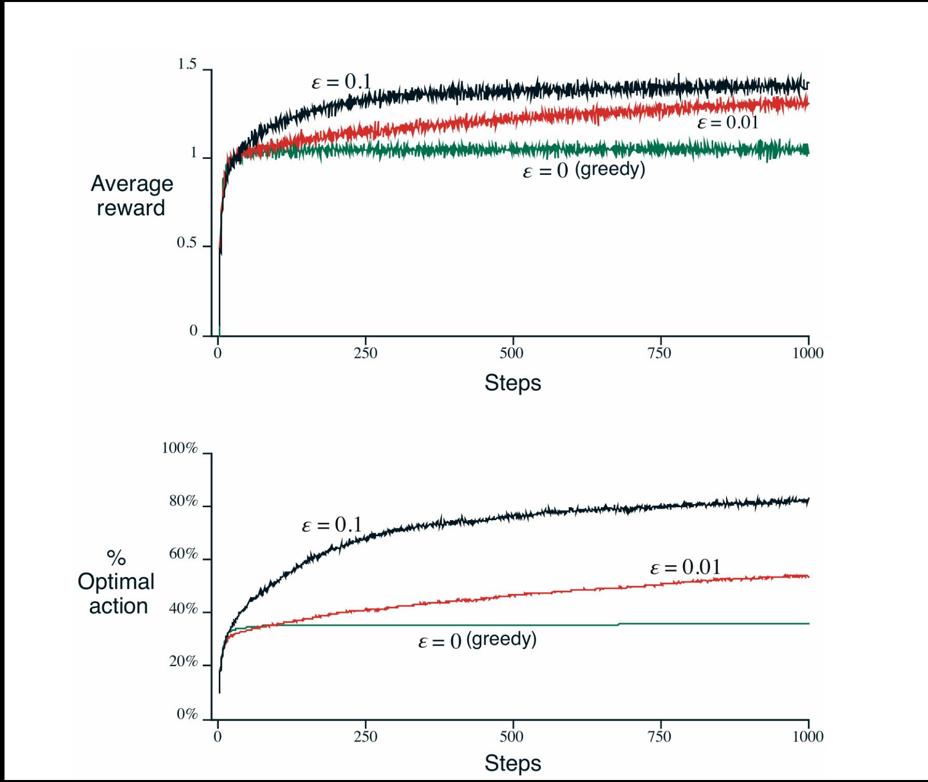
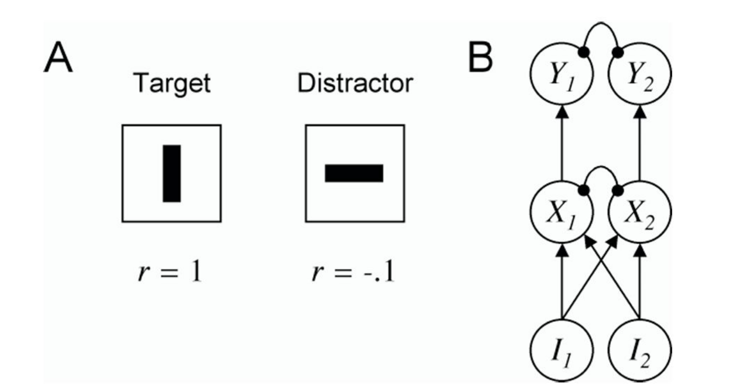
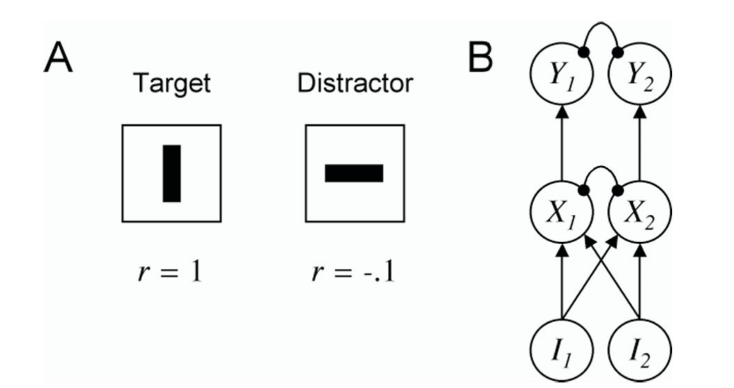




Modeling Integration and Response During Go-No-Go Task



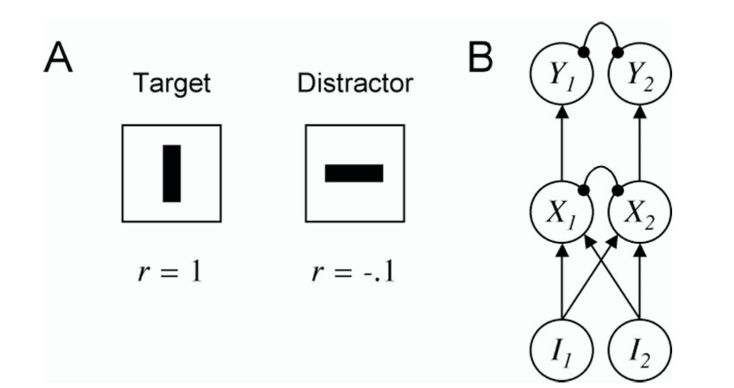
Modeling Integration and Response During Go-No-Go Task



Noisy Leaky Accumulator

$$\dot{X}_i = -X_i + w_{X_i I_i} I_i + w_{X_i I_j} I_j - w_{X_i X_j} f(X_j) + \xi_i \qquad (1)$$

Modeling Integration and Response During Go-No-Go Task



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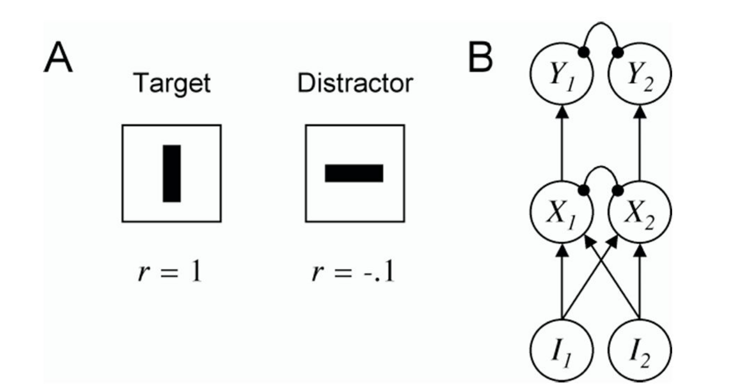
Accumulated Evidence

Drift Terms

Stochastic Noise

Modeling Integration and Response During Go-No-Go Task



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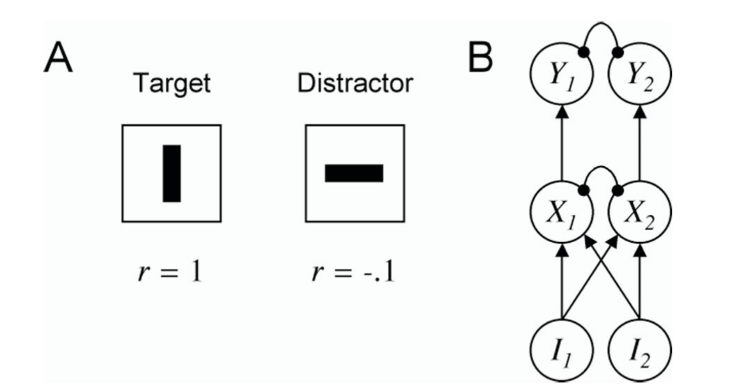
Accumulated Evidence

Drift Terms

Stochastic Noise

$$\dot{Y}_i = -Y_i + w_{Y_i X_i} f(X_i) - w_{Y_i Y_j} f(Y_j) + \xi_i. \quad (2)$$

Modeling Integration and Response During Go-No-Go Task



Noisy Leaky Accumulator

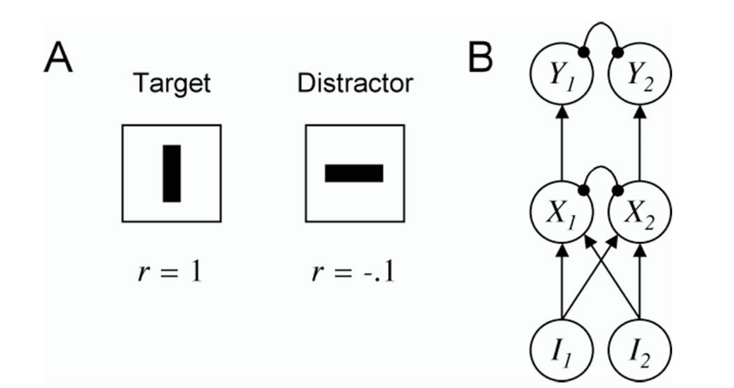
$$\dot{X}_i = -X_i + w_{X_i I_i} I_i + w_{X_i I_j} I_j - w_{X_i X_j} f(X_j) + \xi_i \quad (1)$$

Accumulated Evidence — Drift Terms — Stochastic Noise

$$\dot{Y}_i = -Y_i + w_{Y_i X_i} f(X_i) - w_{Y_i Y_j} f(Y_j) + \xi_i. \quad (2)$$

$$f(X) = \left(1 + e^{-g_t (X-b)}\right)^{-1} \quad (3)$$

Modeling Integration and Response During Go-No-Go Task



Noisy Leaky Accumulator

$$\dot{X}_i = -X_i + w_{X_iI_i} I_i + w_{X_iI_j} I_j - w_{X_iX_j} f(X_j) + \xi_i \qquad (1)$$

Accumulated Evidence

Drift Terms

Stochastic Noise

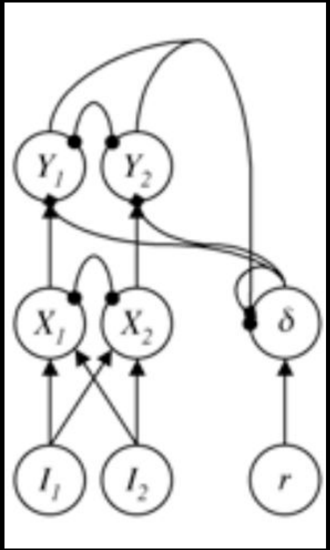
$$\dot{Y}_i = -Y_i + w_{Y_iX_i} f(X_i) - w_{Y_iY_j} f(Y_j) + \xi_i. \qquad (2)$$

$$f(Y_1) > \theta \quad f(Y_2) > \theta$$

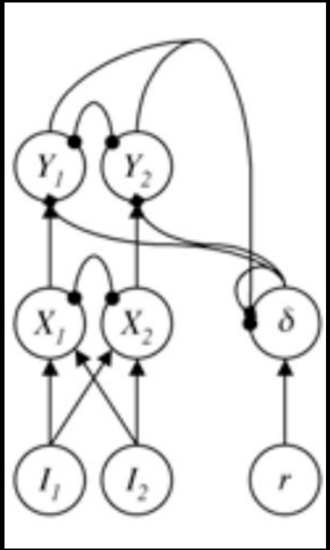
Motor Response

$$f(X) = \left(1 + e^{-g_t (X-b)}\right)^{-1} \qquad (3)$$

Augmenting Model with Dopamine Mediated Learning

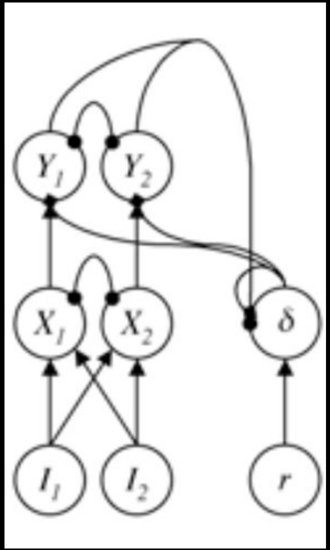


Augmenting Model with Dopamine Mediated Learning



$$\delta(t) = r(t) - w_{\delta Y_1} Z(Y_1(t)) - w_{\delta Y_2} Z(Y_2(t)) \quad (4)$$

Augmenting Model with Dopamine Mediated Learning



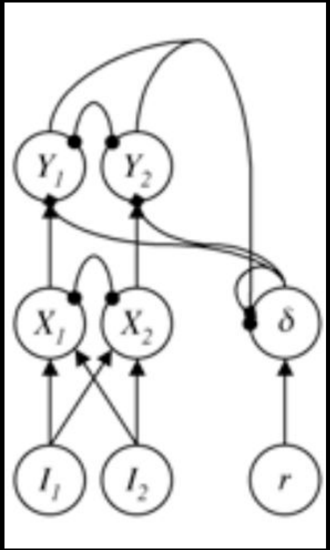
$$\delta(t) = r(t) - w_{\delta Y_1} Z(Y_1(t)) - w_{\delta Y_2} Z(Y_2(t)) \quad (4)$$

Reward received

Expected reward

Reward Prediction Error (RPE)

Augmenting Model with Dopamine Mediated Learning



$$\delta(t) = r(t) - w_{\delta Y_1} Z(Y_1(t)) - w_{\delta Y_2} Z(Y_2(t)) \quad (4)$$

Reward received

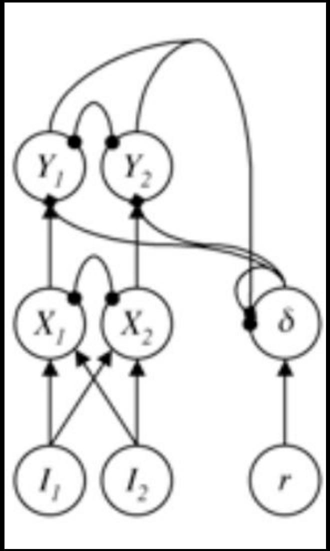
Expected reward

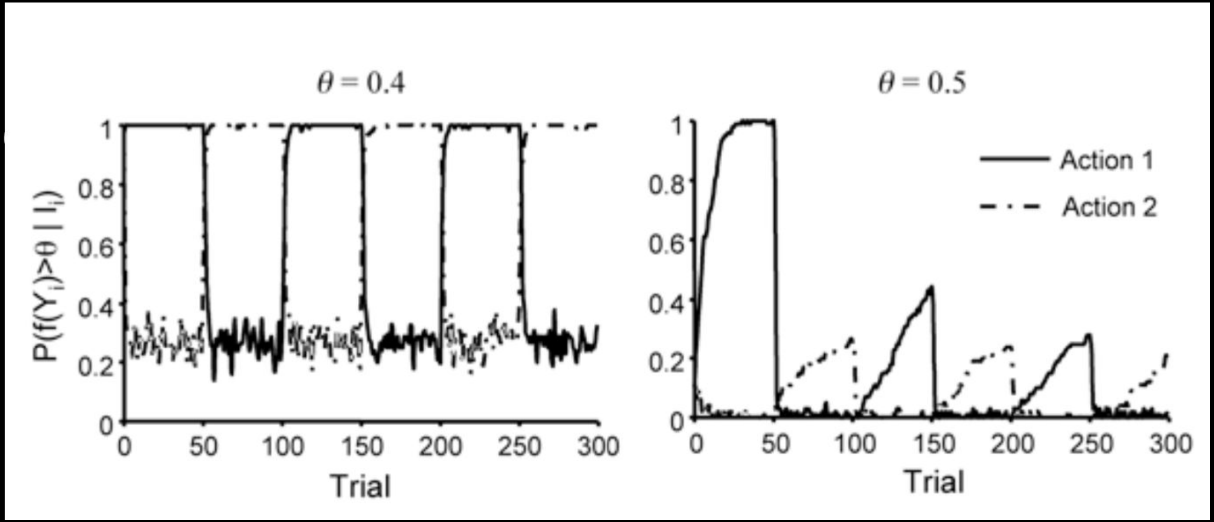
Reward Prediction Error (RPE)

$$w_{\delta Y_i}(t+1) = w_{\delta Y_i}(t) + \lambda \delta(t) Z(Y_i) \quad (5)$$

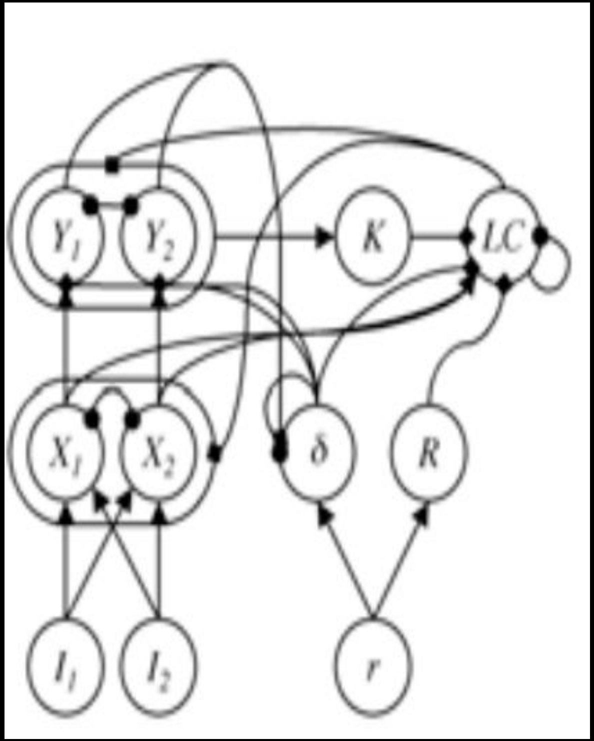
Update weights based on RPE

Performance of Model with Dopamine Mediated Learning

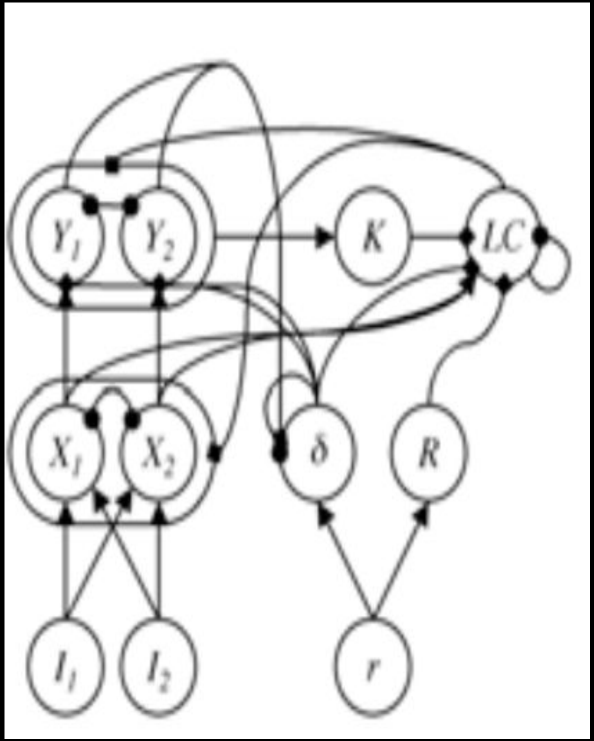




Augmenting Model with Norepinephrine Mediated Annealing



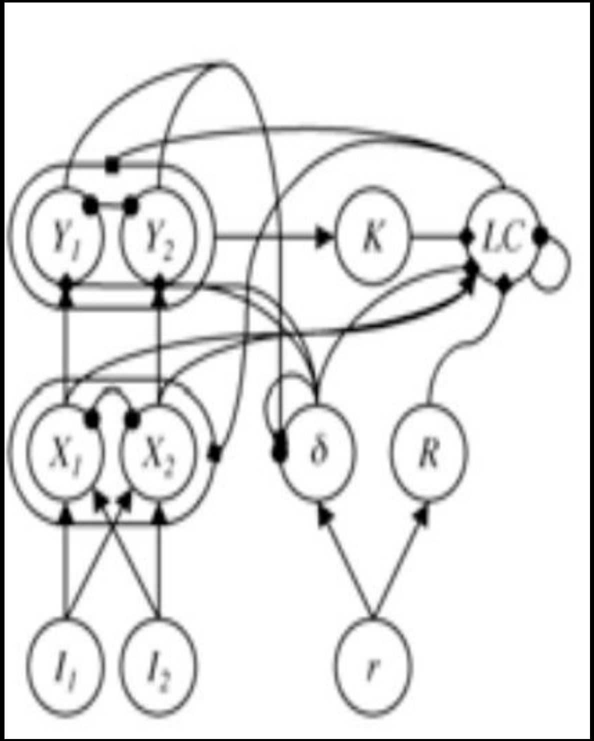
Augmenting Model with Norepinephrine Mediated Annealing



State of the LC is given by the FitzHugh-Nagumo set of differential equations:

$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2) \quad (6)$$

Augmenting Model with Norepinephrine Mediated Annealing



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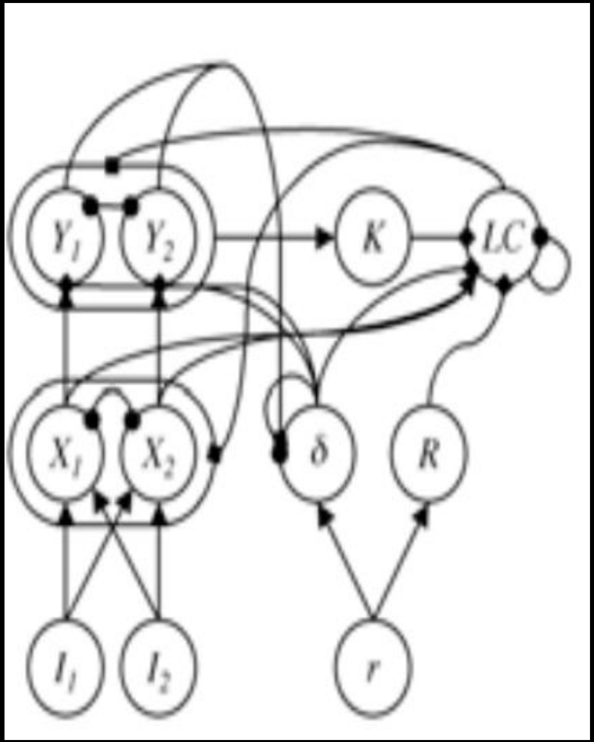
(6)

$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2)$$

Cubic Nonlinearity

Dampening

Augmenting Model with Norepinephrine Mediated Annealing



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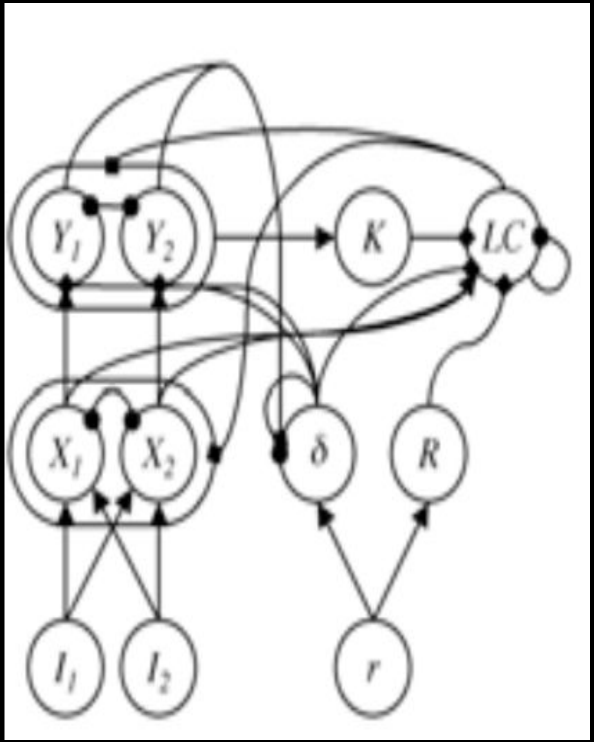
Cubic Nonlinearity

Dampening

$$\tau_u \dot{u} = h(v) - u \qquad (7)$$

Augmenting Model with Norepinephrine Mediated Annealing



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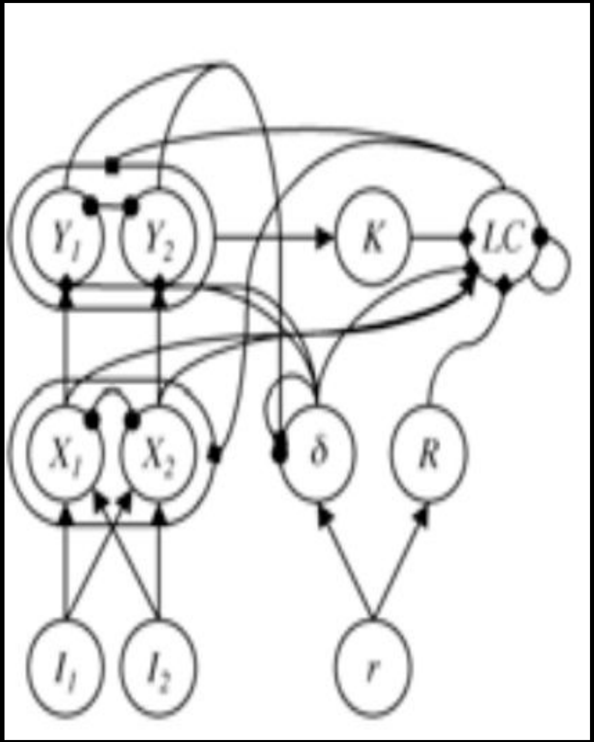
Cubic Nonlinearity — Dampening

$$\tau_u \dot{u} = h(v) - u \quad (7)$$

$$h(v) = Cv + (1-C)d \quad (8)$$

When C =1: phasic mode
When C is small: tonic mode

Augmenting Model with Norepinephrine Mediated Annealing



State of the LC is given by the FitzHugh-Nagumo set of differential equations:

$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2) \tag{6}$$

Cubic Nonlinearity

Dampening

$$\tau_u \dot{u} = h(v) - u \tag{7}$$

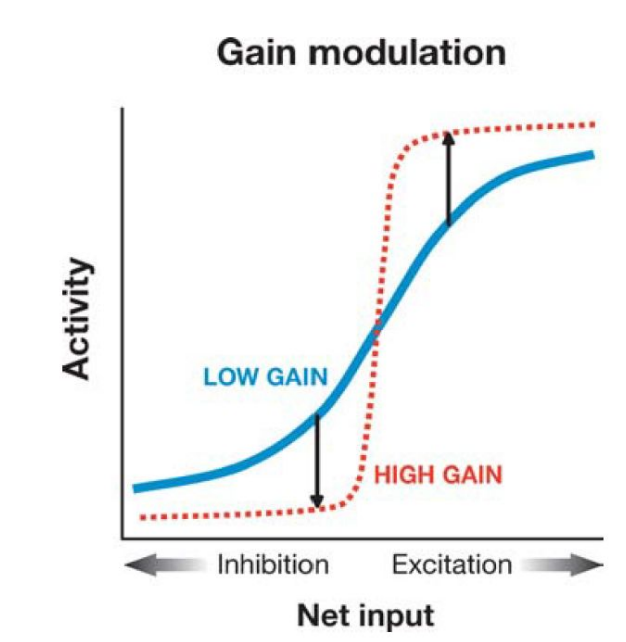
$$h(v) = Cv + (1 - C)d \tag{8}$$

When C =1: phasic mode
When C is small: tonic mode

$$g_t = G + ku_t \tag{9}$$

Modification of gain

Augmenting Model with Norepinephrine Mediated Annealing



State of the LC is given by the FitzHugh-Nagumo set of differential equations:

$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2) \quad (6)$$

Cubic Nonlinearity: $v(\alpha - v)(v - 1)$

Dampening: $-u$

$$\tau_u \dot{u} = h(v) - u \quad (7)$$

$$h(v) = Cv + (1 - C)d \quad (8)$$

When C =1: phasic mode
When C is small: tonic mode

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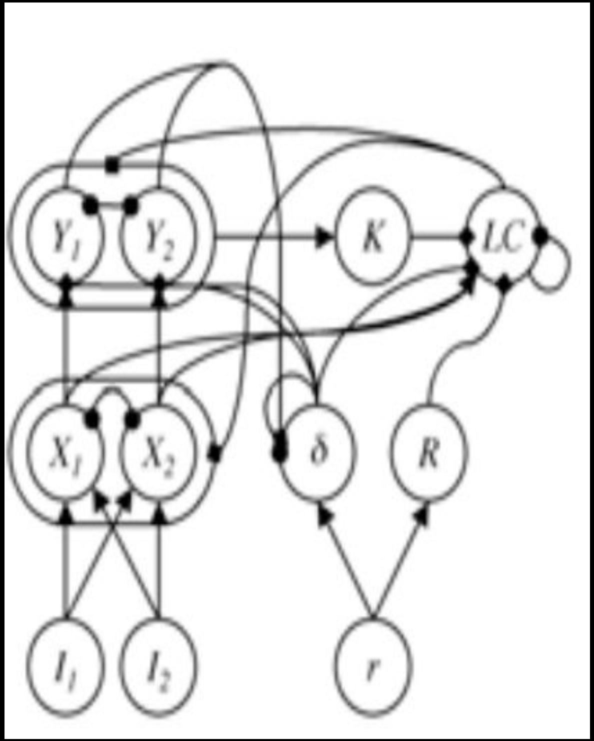
Modification of gain

Augmenting Model with Norepinephrine Mediated Annealing



$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2)$$

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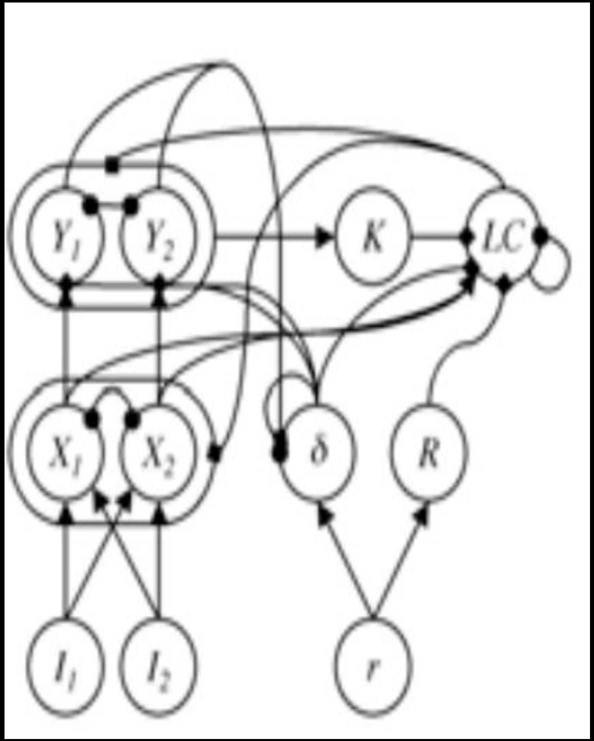
Augmenting Model with Norepinephrine Mediated Annealing

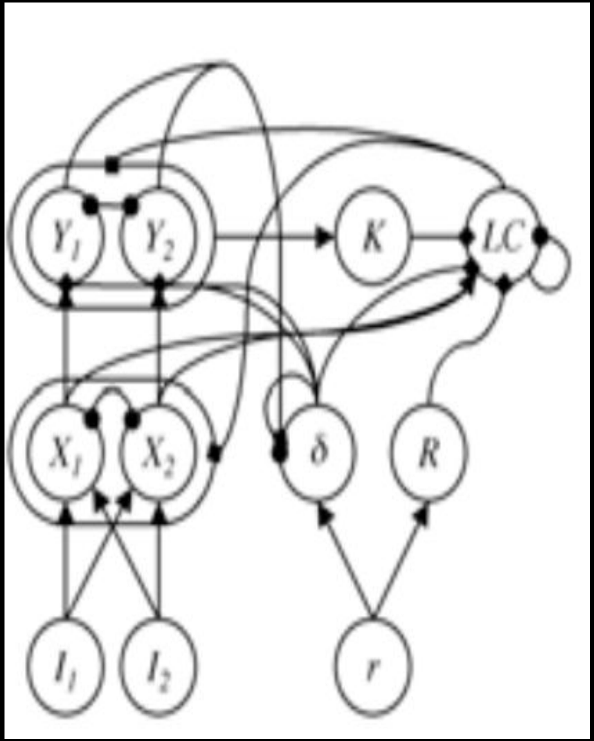


$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2)$$

$$\tau_u \dot{u} = h(v) - u \qquad h(v) = Cv + (1 - C)d \qquad g_t = G + ku_t$$

Value of C is updated after every trial by measures of response conflict and reward rate

Augmenting Model with Norepinephrine Mediated Annealing



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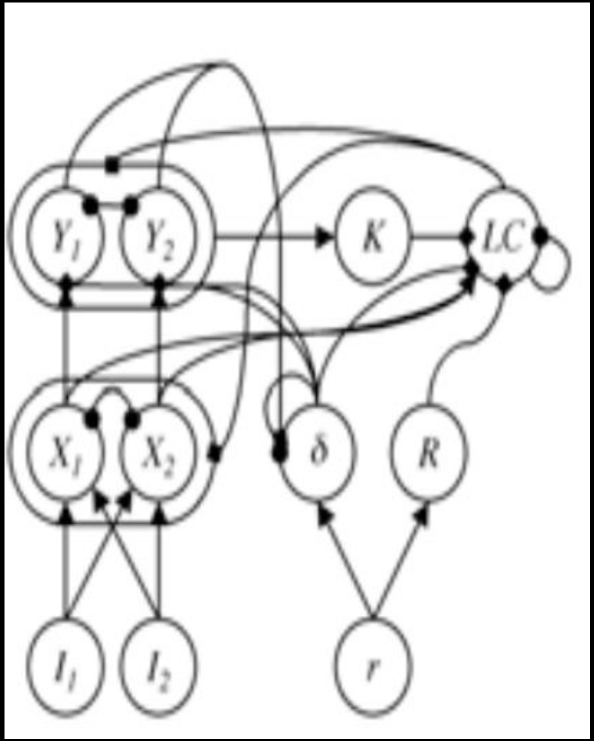
$$\tau_u \dot{u} = h(v) - u \quad h(v) = Cv + (1 - C)d \quad g_t = G + ku_t$$

Value of C is updated after every trial by measures of response conflict and reward rate

$$K = \frac{\mathbf{Y}_1 \cdot \mathbf{Y}_2}{|\mathbf{Y}_1\|\mathbf{Y}_2|} \quad (10)$$

Augmenting Model with Norepinephrine Mediated Annealing



$$\tau_v \dot{v} = v(\alpha - v)(v - 1) - u + w_{vX_1} f(X_1) + w_{vX_2} f(X_2)$$

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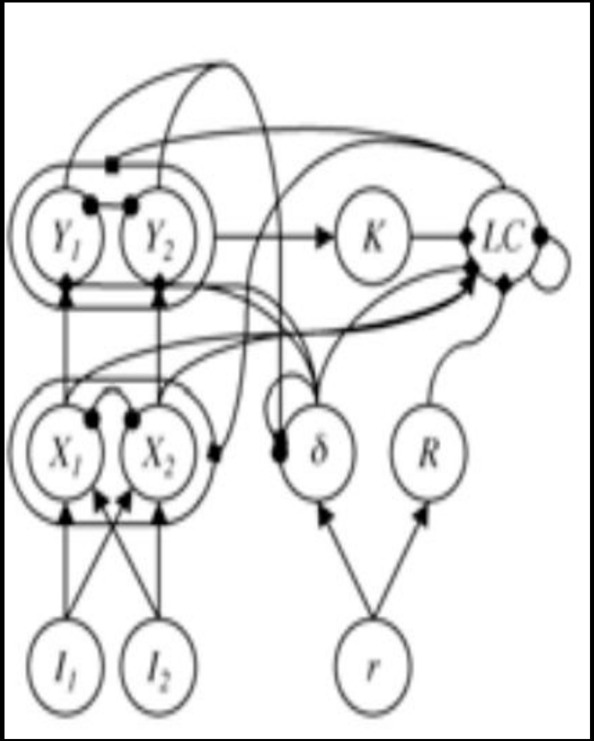
Value of C is updated after every trial by measures of response conflict and reward rate

$$K = \frac{\mathbf{Y}_1 \cdot \mathbf{Y}_2}{|\mathbf{Y}_1||\mathbf{Y}_2|} \quad (10)$$

$$K_S(T+1) = (1 - \varepsilon_S)K_S(T) + \varepsilon_S K(T) \quad (11)$$

Augmenting Model with Norepinephrine Mediated Annealing



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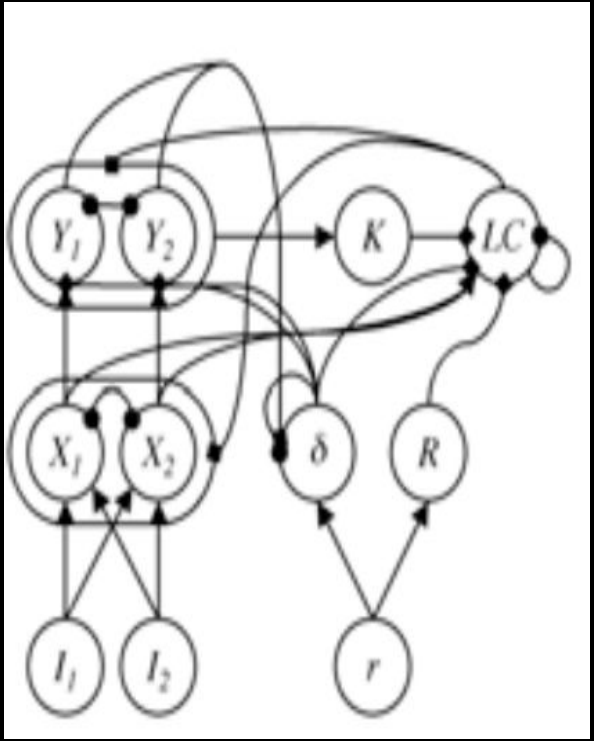
$$R(T+1) = (1 - \varepsilon_R)R(T) + \varepsilon_R r \quad (12)$$

Augmenting Model with Norepinephrine Mediated Annealing



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$$\tau_u \dot{u} = h(v) - u \qquad h(v) = Cv + (1 - C)d \qquad g_t = G + ku_t$$

Value of C is updated after every trial by measures of response conflict and reward rate

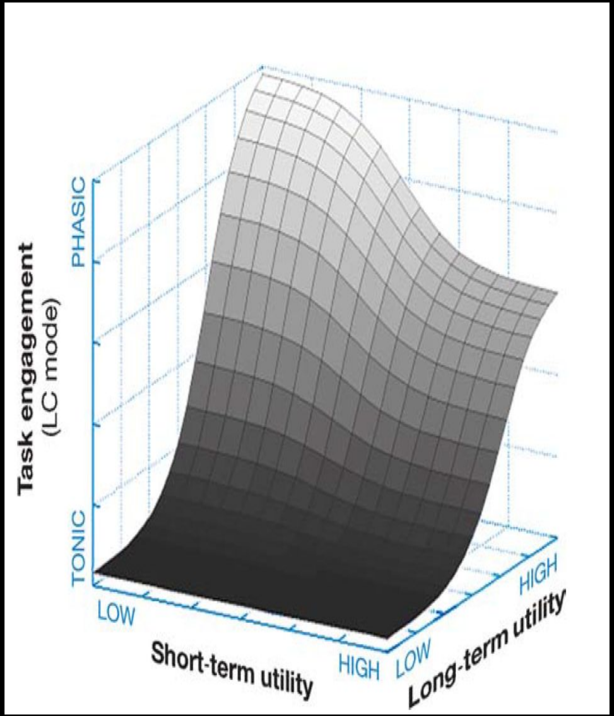
$$K = \frac{\mathbf{Y}_1 \cdot \mathbf{Y}_2}{|\mathbf{Y}_1\|\mathbf{Y}_2|} \qquad (10)$$

$$K_S(T + 1) = (1 - \varepsilon_S)K_S(T) + \varepsilon_S K(T) \qquad (11)$$

$$R(T + 1) = (1 - \varepsilon_R)R(T) + \varepsilon_R r \qquad (12)$$

$$C = \sigma(K_S)(1 - \sigma(K_L))\sigma(R) \qquad (13)$$

Augmenting Model with Norepinephrine Mediated Annealing



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Value of C is updated after every trial by measures of response conflict and reward rate

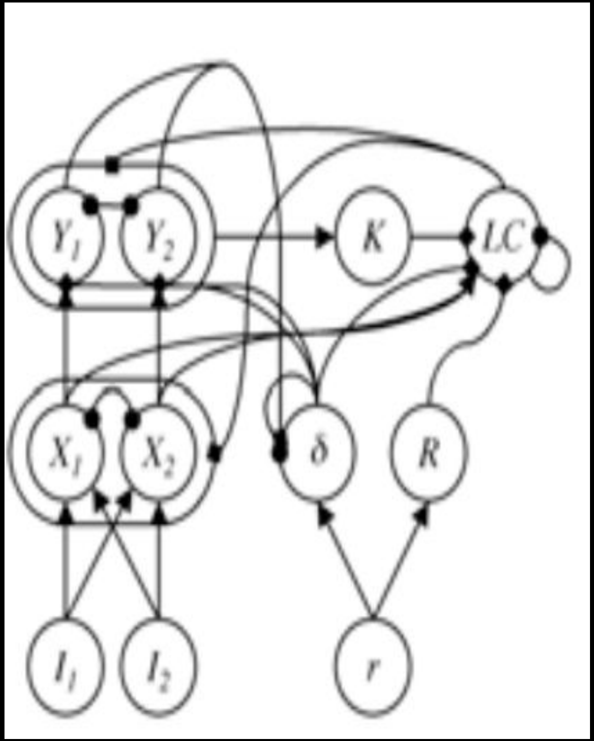
$$K = \frac{\mathbf{Y}_1 \cdot \mathbf{Y}_2}{|\mathbf{Y}_1||\mathbf{Y}_2|} \quad (10)$$

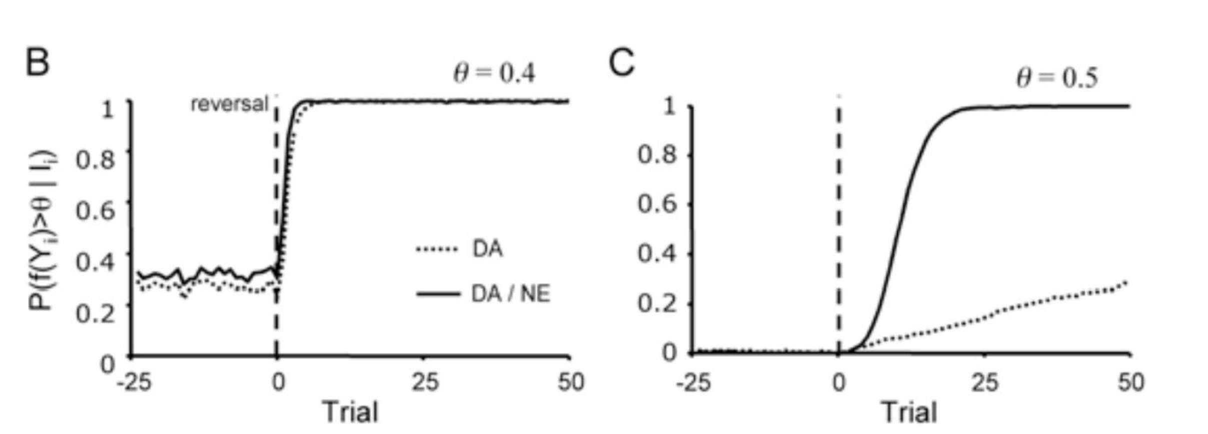
$$K_S(T+1) = (1-\varepsilon_S)K_S(T) + \varepsilon_S K(T) \quad (11)$$

$$R(T+1) = (1-\varepsilon_R)R(T) + \varepsilon_R r \quad (12)$$

$$C = \sigma(K_S)(1-\sigma(K_L))\sigma(R) \quad (13)$$

Model Performance with Dopamine and Noradrenaline





Model Performance with Dopamine and Noradrenaline