Modelling and Simulation of the Dopaminergic System

The case of Internet Addiction

Lucia Nasti - Phd Student University of Pisa

Where?

- Durham University
- Pisa University

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What is addiction?

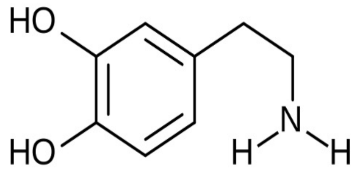
Addiction is a complex phenomenon influenced by **environmental, social** and **biological** factors.

Environmental factors:
•Education and family background
•Availability
•Economic resources
•Proved by Rat Park Experiment of Professor B.K. Alexander

Social factors:
•Consensus
•Consistency
•Distinctiveness
•Proved by Simulations

Systems involved

- **Dopamine System:** Dopamine is a neurotransmitter. **In addiction context:** at the start, dopamine level increases; later it doesn't reach anymore the initial level.



Dopamine

- **Serotonin System**: implicated in "impulse choice"
- **GABA System**: implicated in inhibition
- **Opioid System**: it consists of three receptors, that control pain, reward and addictive behaviour

Consequences

- **Craving**: compulsive desire, a sort of anticipation of positive effects
- **Withdrawal**: symptoms that occur when there is discontinuation or decrease in intake
- **Tolerance**: symptom that occurs when there is a reduced reaction to an intake, followed by increase in dose

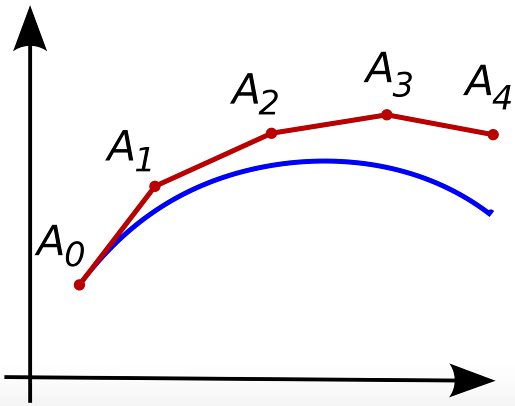
Mathematical background: differential equations

Differential equations are mathematical equations that relate some functions with their derivatives. The general first-order differential equation for the function y = F(x) is written as:

$$\frac{dy}{dx} = f(x, y)$$

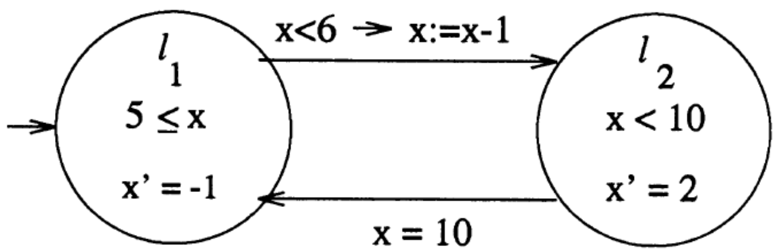
where f(x,y) can be any function of the independent variable x and the dependent variable y.

Euler's Method: resolution obtained by numerical approximation, given a known initial value. It is the simplest of the Runge-Kutta Methods.



Mathematical background: Hybrid Automata

Hybrid Automata are generalised finite-state machines for modelling hybrid system, dynamical system with both discrete (represented by jump condition) and continuous components (represented by flow conditions such as differential equations).



- Circle: state of dynamic system
- Arrow: jump transition, from one state to another
- Invariant condition: the condition to remain in the state.

Gutkin's Model

The **Gutkin's model** specifically analyses nicotine addiction.

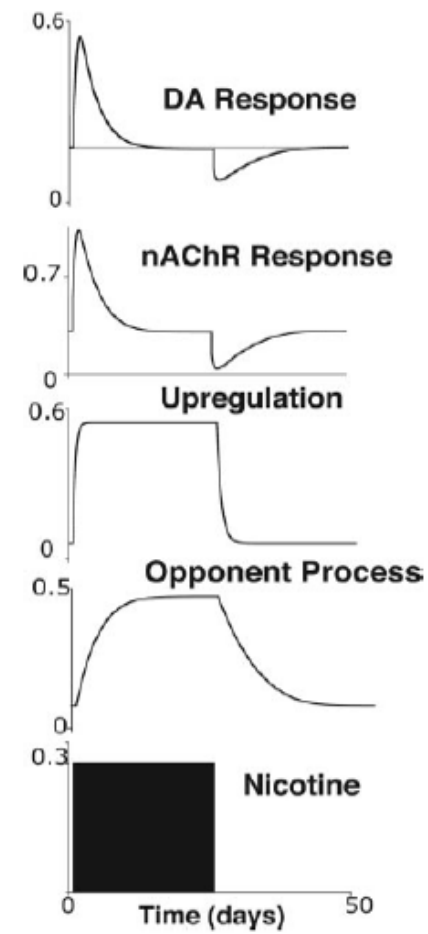
It shows how a constant stimulus causes a **consequent decrease** in neurons activity.

$$\frac{dU_{DA}}{dt} = -U_{DA} + S_{DA}\left\{\sum_i r_i; N(t)\right\}$$

$$S_{DA} = \frac{1}{2}\left(1 + \tanh\left(N(t)\sum_i r_i(t) - \theta_{DA}\right)\right).$$

$$\tau_A \frac{dU_1^A}{dx} = -U_1^A + S_A\{w_{11}^e U_1^A - w_{12}^i U_2^A - \theta_A\} + \sigma\xi \text{ and}$$

$$\tau_A \frac{dU_2^A}{dx} = -U_2^A + S_A\{w_{22}^e U_2^A - w_{21}^i U_1^A - \theta_A\} + \sigma\xi.$$



Samson's Model

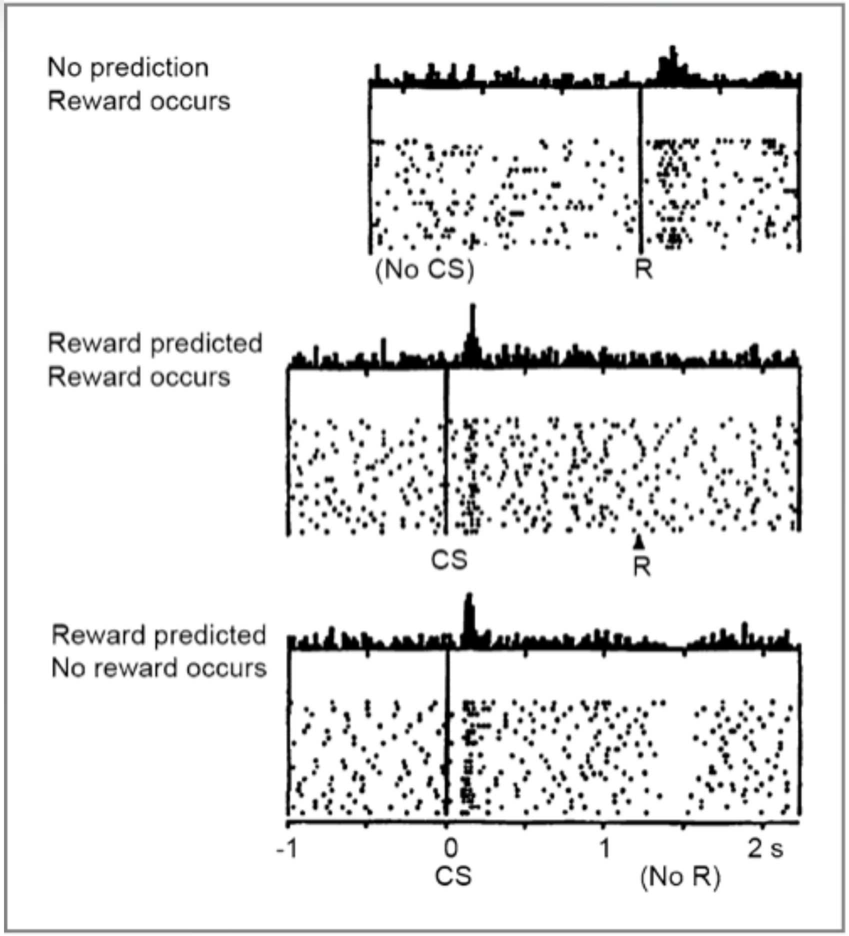
The **Samson's Model** focuses on the role of dopamine as a reward signal.

Neurons are activated when there is a reward and when reward is only predicted, but not received yet. He uses two algorithms:

- Q-learning

$$Q^{\text{new}}\left(\text{state}\left(t\right),\text{action}\left(t\right)\right)=Q^{\text{old}}\left(\text{state}\left(t\right),\text{action}\left(t\right)\right)+\alpha\delta\left(t\right)$$

- Actor-Critic



Mathematical model of Dopaminergic System

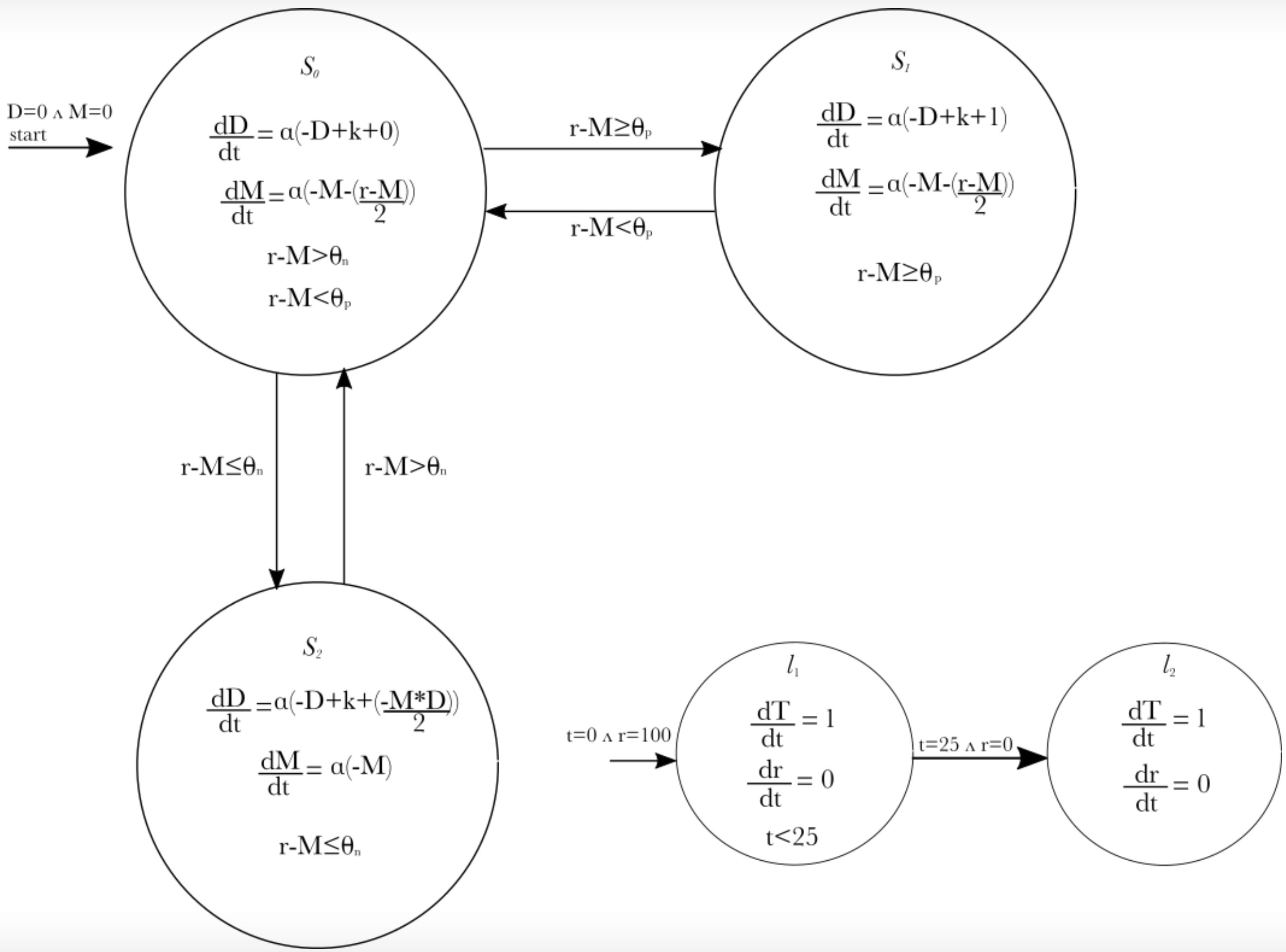
- **Equation for dopamine signalling** represents the specific neurotransmitter activity in the ventral segmental area:

$$\frac{\partial D}{\partial t} = \alpha(-D + k + \begin{Bmatrix} 1 & if \;\; r - M \geq \theta_p \\ 0 & if \;\; \theta_n < r - M < \theta_p \\ -\frac{D*M}{2} & if \;\; r - M \leq \theta_n \end{Bmatrix})$$

- **Equation for the memory activation** represents the opponent process to dopamine production (tolerance)

$$\frac{\partial M}{\partial t} = \alpha(-M + \begin{Bmatrix} -\frac{r-M}{2}, & if \;\; r > M \\ 0, & otherwise \end{Bmatrix})$$

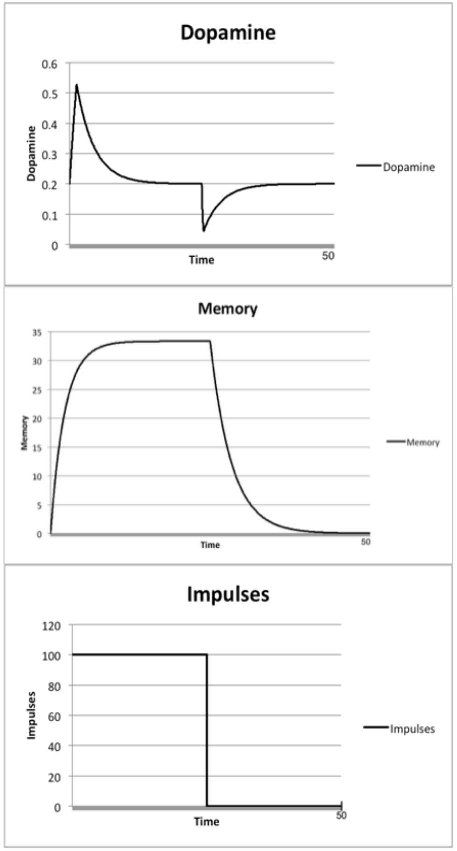
At constant pulse



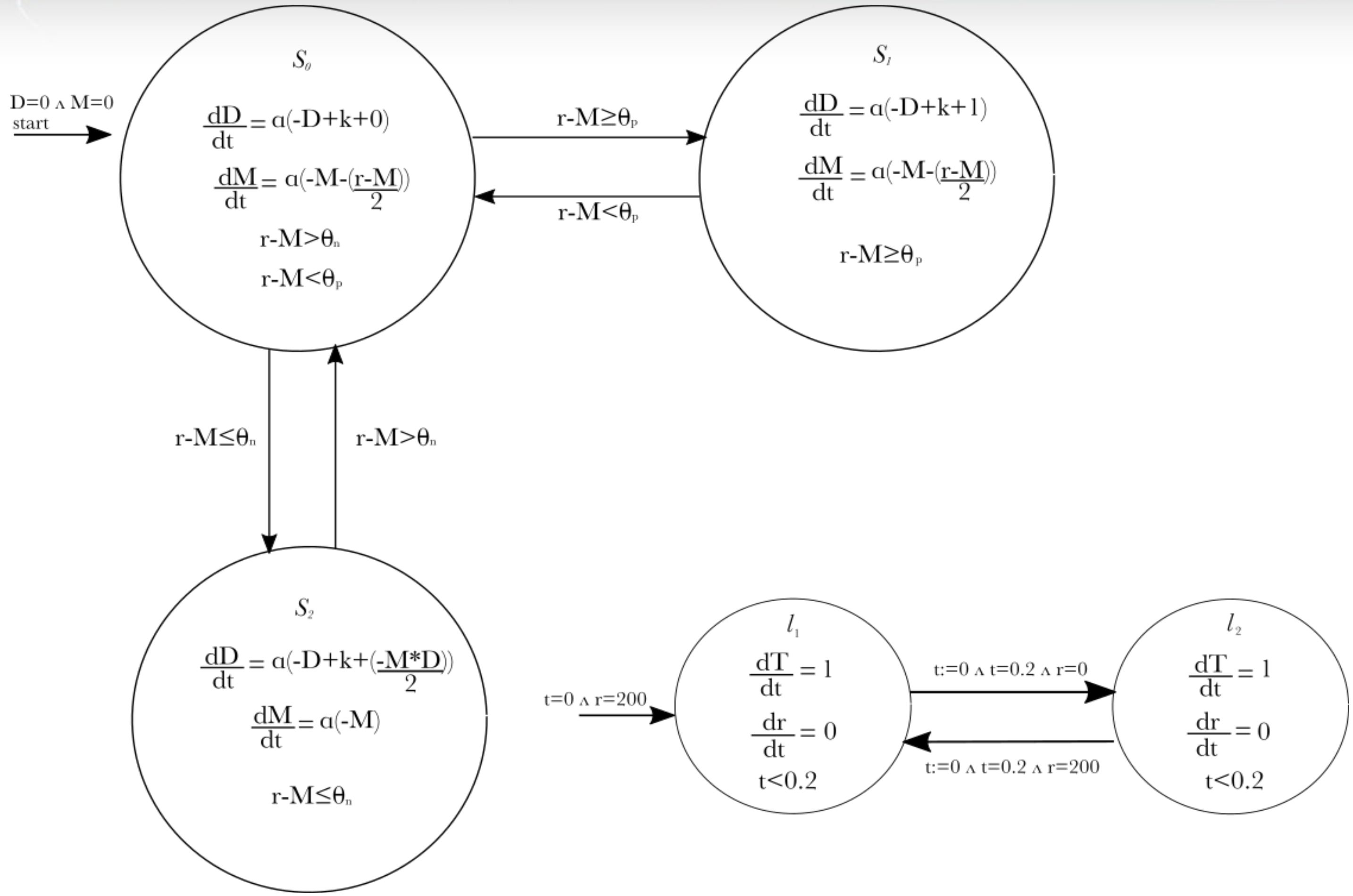
Simulation results

The **trend of dopamine**, similar to the graph obtained by Gutkin, shows an initial peak which results in a withdrawal symptom, previous to the interruption of the stimulus itself.

The performance of the memory, however, corresponds to the **opponent process**.



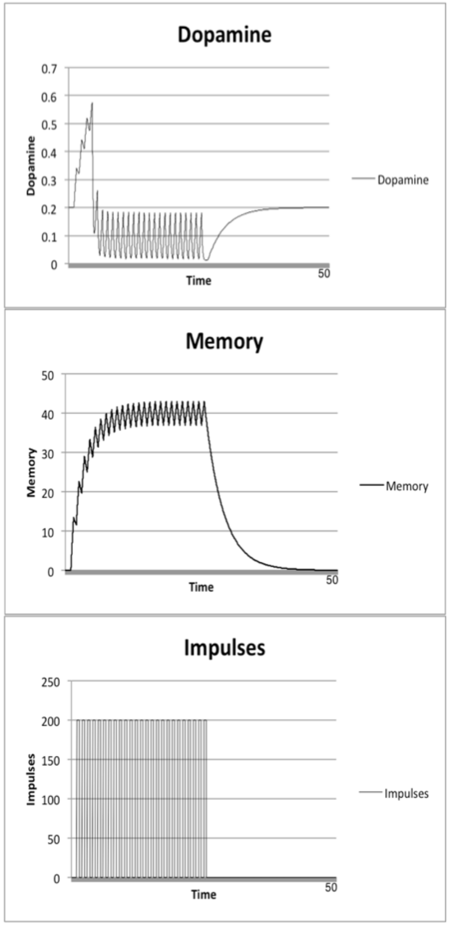
At close frequency pulses



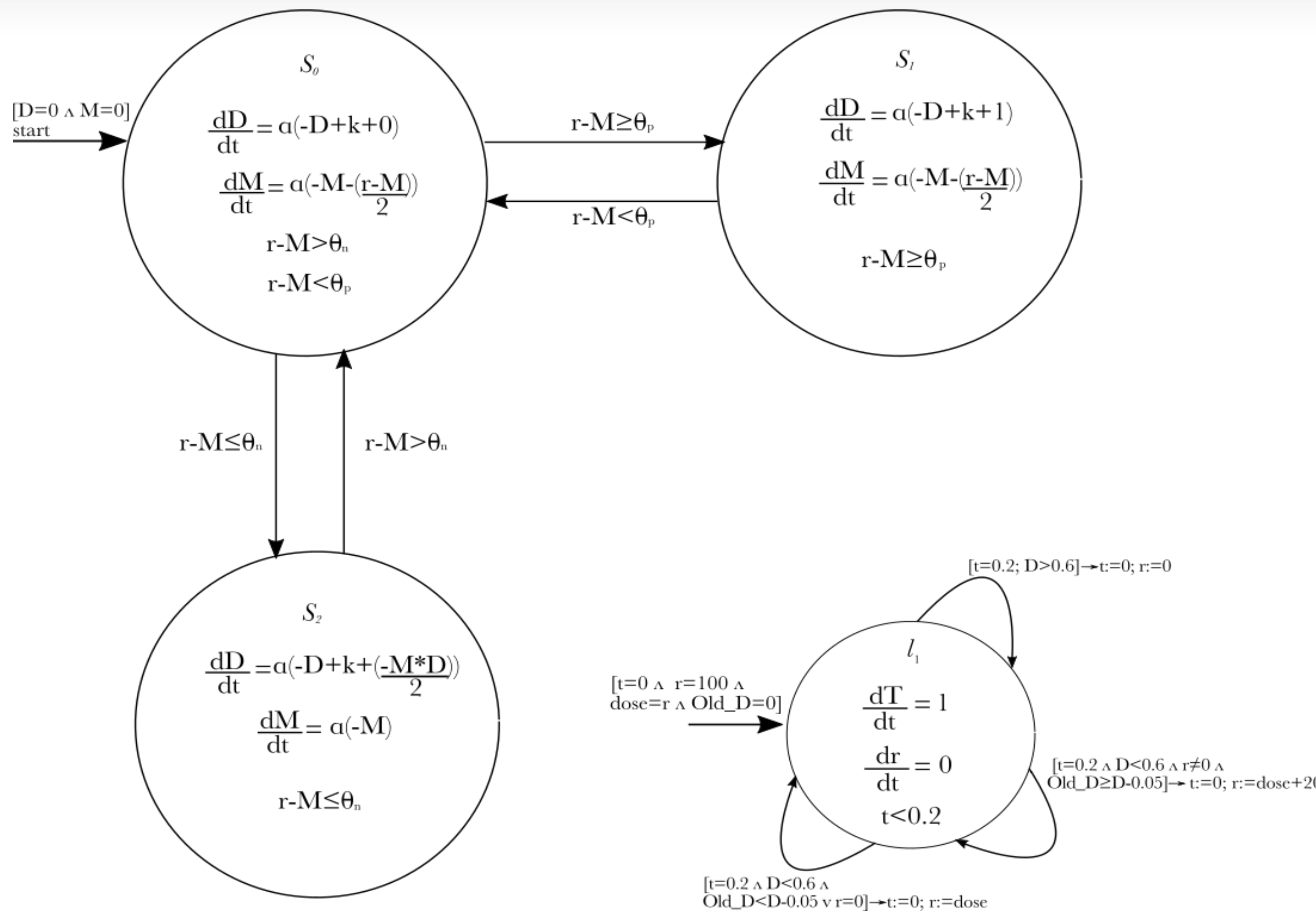
Simulation results

Also when there are **multiple impulses**, there is a situation of dependence.

Dopamine has frequent initial peaks, but, later on, can not achieve the same **initial levels**, because the stimuli do not increase in intensity.



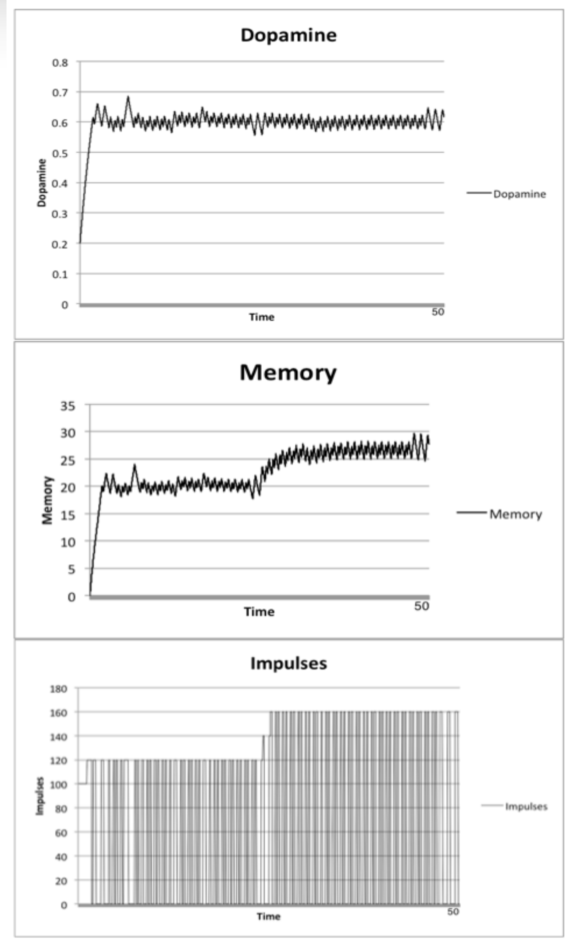
At increasing intensity and frequency pulses



Simulation results

When neurotransmitter decreases, the user feels the need to **increase the dose** and the frequency of the pulses.

The effect of **tolerance**, in fact, reduces both the perceived intensity pulse and the time between one administration and another.

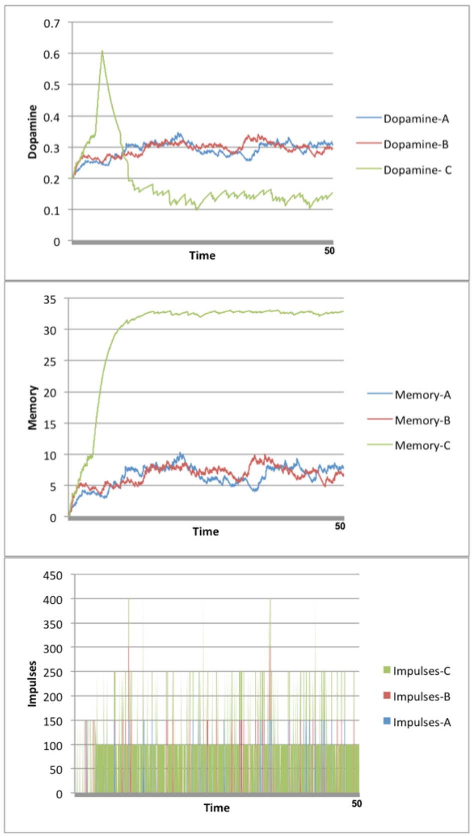


Simulation with different propensity factors

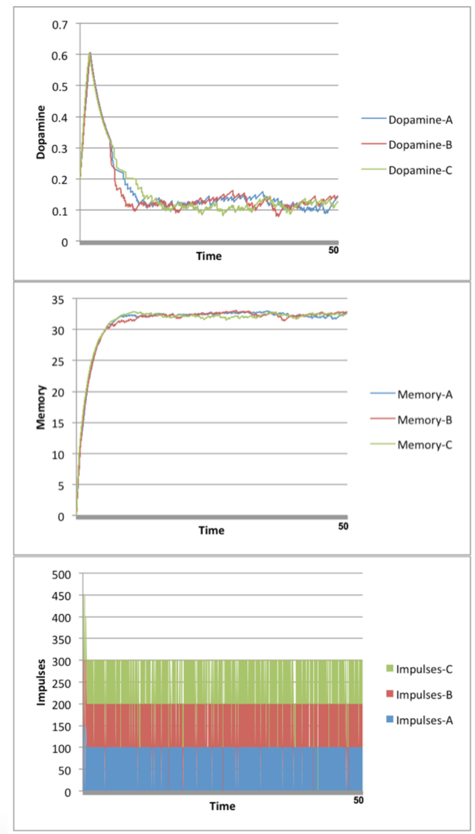
- Every time t=0.2, communication between users starts;
- At the beginning, users can only send a spontaneous message, considering their own propensity factor;
- If a user received a message, he can answer or not;
- During the interaction, some vectors are updated to keep track of the users that participate to interaction;
- The impulses are generated in according with the kind of interaction;
- For every group of users, a sample of 1000 simulations are run to find the percentage of addiction inclination, and that is when their tolerance level is high ($M \geq 15$).

Simulation results

- One user with high propensity

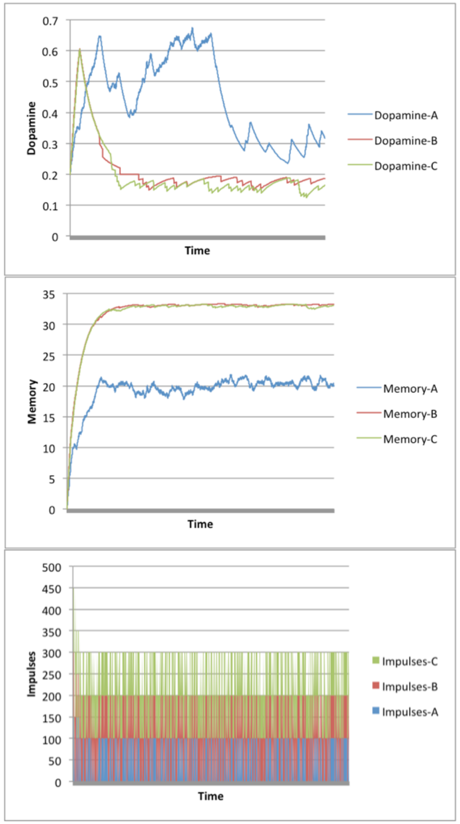


- Three users with high propensity

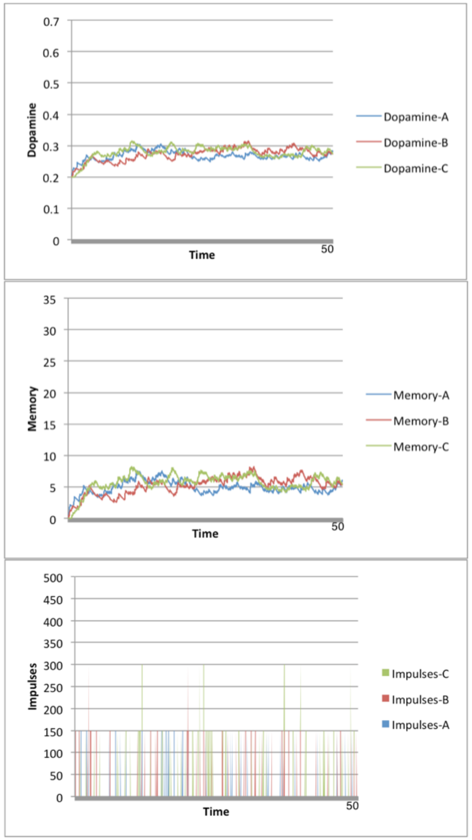


Simulation results

- Two users with high propensity



- Three users with low propensity



Conclusion

In conclusion, **achieved objectives** are:

- To isolate the source of pulses
- Abstracting the functioning of the Dopaminergic System
- To investigate the principle of emulation
- To investigate the importance of contextual factors

Future work

Research:

- Obtain a variant of Hybrid Automata augmented with discrete probability distributions
- Implement conditions in Hybrid Automata with different data structures
- Implement Compositionality to analyse more neurological structures

Application:

- Study brain diseases
- Improve reinforcement learning algorithms

Questions?