Evolving Social Structure: From Neurons to Networks with Agent-Based Models

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1 Introduction

Topologies of social networks across cultures, and sometimes across species, present a remarkable similarity. At the lowest level of sociality are structures such as herds – where social behavior is an emergent aggregate of a individual decision-making and copying the behavior or neighbors. Further up in complexity are hierarchies, with beginnings of a complex signaling system to enable communication between *alpha* individuals and subordinates – starting with dominance and submission signals, and rising in complexity with increase in size and complexity of the animals' brains.

Fowler, et al[10] demonstrate that political affiliation, social network structure and genetic makeup of the dopamine receptors are interlinked. A similar result was found in relation to propensity to obesity[4].

Dunbar[6] states that mammals can only handle a limited number of social connections (i.e. *the Dunbar Number*) where the mean number of ties is closely related to the size of the individual's prefrontal cortex – the location of long-term memory and conscious reasoning circuitry. In a competing argument, Bickart, et al[1] state that social network size in humans is mediated by the size of the amygdala – otherwise known as our "reptilian brain". In related work, dopamine (DA) receptors are linked to introversion or extraversion as well as seeking and tolerating novelty[9] – both concepts directly mapping to individual's ability to build and maintain social networks.

In short, mounting evidence is pointing to biological roots of social construction. In this paper, we present a biologically-inspired agent-based model that attempts to illustrate emergence of sociality and simple forms of communication from neuro-biological roots, specifically dopamine signaling and dopamine-mediated learning. This model is somewhat simplified, as it does not take into account the subtleties of dopamine release and reuptake, nor does it concentrate on the details of the memory system. In this paper, we show that complex sociality and communication can arise from biological roots even in absence of a well-developed reasoning ability.

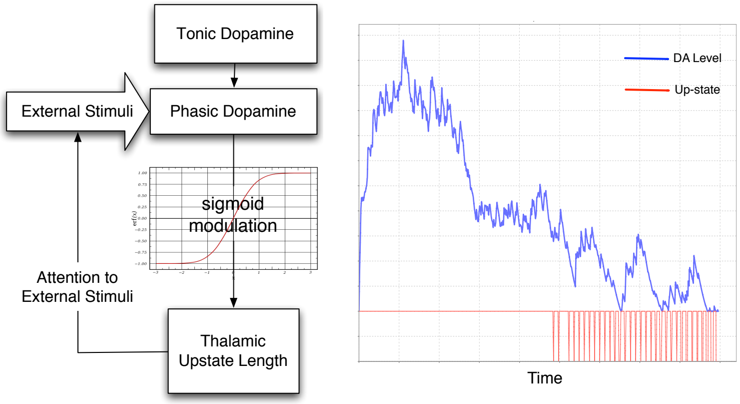

Figure 1: Model of coupled dopamine and attention up- and down-states

2 Conceptual Model

We are building a first-of-a-kind computational model that spans the unit-of-analysis spectrum from activation of dopaminergic neurons in the prefrontal cortex(PFC), to co-evolution of language, complex social structures, and cultural variation. Our objectives are:

- Model how dopamine can focus attention and facilitate recognition of the presence of a critical stimuli from an environment with a great many stimuli.
- Model how a semantic representation of the world can emerge inside an agent's mind purely as a result of interaction with the lower levels of cognition.
- Model how a group of agents such as described above can develop a society with constantly changing groups of similarly-minded agents – i.e. how social structure emerges from a biological substrate.

2.1 Modeling Dopamine and Attention

Our first objective is understanding and modeling the processes of dopaminergic regulation of cognitive functions, such as attention, filtering of incoming stimulus stream, and extraction of relevant features leading to recognition of familiar stimuli and learning of novel stimuli.

In our model, dopaminergic neurons spike proportionally to *salience* of a change in organism's state[9] from time $t-1$ to current time t. The function determining size of spike is defined as a *sigmoid* mapping stimulus to a percentage change in DA. The DA activity of a simple organism presented with a set of salient stimuli is shown on figure 1.

Durstewitz and Seamans[5] report that is a dopamine-mediated trade-off between goal-directed behavior and the ability to respond flexibly to novel behavioral demands. This behavior presents a mapping to Simon's notion of *exploration vs. exploitation*[11] in individual learning, where an individual or a social group must choose between incremental improvements to the current state and search for potential higher-payoff tasks.

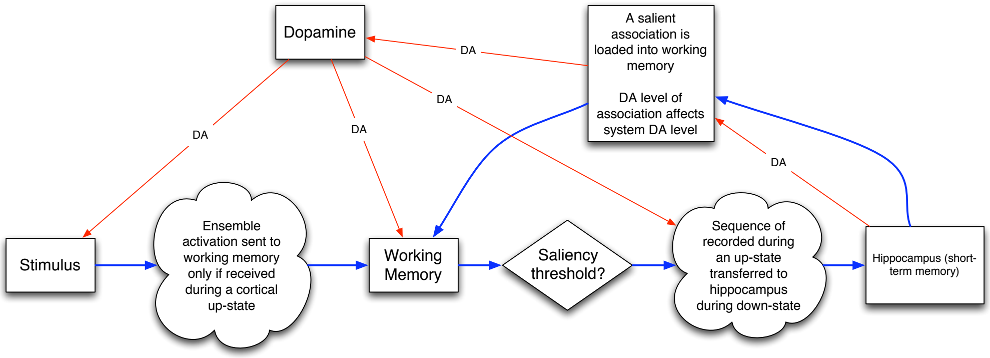

Figure 2: Working memory model subsystem

2.2 Emergence of Semantics

It is currently believed that neurophysiological mechanisms encompassing alterations in neural synaptic number, weight, strength, and efficacy within hippocampal and cortical networks underly associations necessary for short-term memory[3]. Our model aims to capture and model network properties driven by dopamine's known actions on memory.

In our model (see figure 2), stimuli are processed in working memory (WM), where high-saliency stimuli persist until transferred to the short-term memory (STM). As a result, stimuli that arrive during the duration of an attention period can be treated as co-occuring. Thus, two stimuli that repeatedly co-occur in time can be linked in a Hebbian fashion in the short-term memory[7]. The strength of association is thought of as being proportional to saliency of the stimuli, and decay over time at a constant rate.

When a familiar stimulus or part of a stimulus is encountered, an agent retrieves a relevant set of associations from memory and replays them through the working memory. Retrieval is modeled as stochastic, loading the most salient associations with highest probability, while all other choices receive exponentially decaying probabilities of loading. Thus, new stimuli are always experienced in the context of familiar stimuli, and forming associations with new incoming stimuli. As a result of accumulation of associative links, each agent builds a private ontology of stimuli, sequences of stimuli (narratives) and their interconnections. Each new incoming stimulus generates a traversal through this structure, maintaining a constant "train of thought" in the working memory.

Figure 3 shows such semantic networks in (left) a lone agent randomly exploring a complex environment, (center) a social agent in a uniform environment, and (right) a social agent in a uniform environment with predators. Grey dots are abstract concepts in agent's mind, purple dots are other agents of the same species, and yellow dot is a predator

2.3 Primitive Behaviors

These behaviors are physically expressed and we can think of them as hard-wired into the agents. We will use two types of primitive behaviors: movement and sound. They are

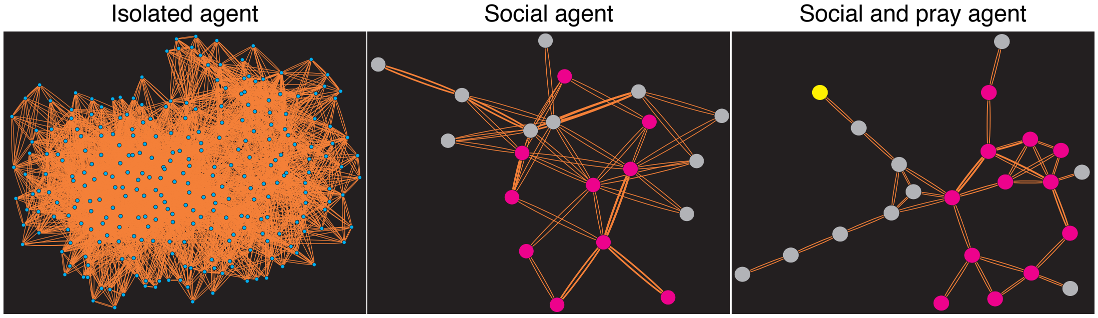

Figure 3: Semantic networks emergent in an agent's mind under various conditions.

primitive because, initially, they do not require of elaborate cognitive processes (although later on, they can be the product of higher cognitive processes). Their motivation can be rather simple, for example, an instinctive reaction to a stimulus.

2.4 Stimuli and Experiences

Agents can perceive, remember and process multiple kinds of stimuli. These range from environmental features (i.e. goodness of a particular square in the environment), to "sounds" made by self or other agents, to perception of another agents' pain or pleasure[2]. Any percieved object is treated in the same manner by the agents' brain – therefore, any object defined in the model can be memorized.

"Sounds" are a special kind of stimulus. They are emitted by the agents, and at first have no meaning assigned to them. However, as the agents learn, they gradually begin to associate sounds with other agents (i.e. naming their friends) or predators (i.e. producing a "danger" signal). Essentially, agents evolve a simple language.

2.5 Internal State

The processes through which real world stimuli influence the neuro-biological and cognitive processes are highly complex. A simplification that helps us to motivate how the stimuli affect the dopamine dynamics of an agent is the concept of internal state. The internal state is used by the agent to internalize the stimuli from the real world and produce behaviors. It also communicates with the physiological world (the internal system) of the agent to transfer the internalized stimuli to the cognitive system, so that they process it and turn into memories and behavior.

We assume that the stimuli have a direct effect on the wellness levels. In the same way, the levels of wellness will have an effect on the generation of dopamine. Higher dopamine spikes are activated when agents perceive stronger stimuli. Therefore, those experiences that produce extreme reactions in the internal state of agents (positive or negative) will induce higher dopamine levels. Stimuli that are in more salient experiences will be remembered with a higher likelihood.

Internal states can also be treated as stimuli. This allows agents to associate environments, sounds, or other agents to internal states. Through this mechanism, associative memories are reinforced.

3 Implementation

The model was written in Java, using the MASON Toolkit[8]. Agents live in a toroidal grid. Each cell in the grid represents a natural environment with a fitness level associated at startup. Agents explore the landscape and perceive its stimuli. As agents encounter different experiences that induce high dopamine levels, they build their associative memory.

Baseline: Isolated Agent We start with a single agent. This agent explores the landscape and perceives by moving through the neighboring cells where she is located. Each step of the model, the agent perceives one neighboring cell. The neighborhood is composed of all surrounding cells (von Neumann neighborhood) within a given radius (we can think of this as its vision). When an attention cycle has been completed, the agent will move one cell towards the cell that produced the highest salience. We assume that there are no negative fitnesses, so high saliences are associated with high fitness.

Different fitnesses from the cells in the landscape produce variations in the dopamine levels of the agent. Through these variations, the agent constructs associative memories of the places she has visited (figure 3(a)).

Social Agent The next step is to instantiate the model with a population of agents that exhibit social behavior. Initially, agents are randomly distributed throughout the landscape. Agents' movements are no longer motivated by the surrounding natural environments, but by other agents. This means that the natural environments that affect the internal state of an agent in only the one that is in the same cell as the agent (not the neighboring ones). Additionally, agents can perceive other agents. Therefore, during each step, each agent perceives all the stimuli that are located in a neighboring cell (natural environment, agents, and their respective sounds).

The way in which agents explore the world captures a key feature of social behavior: agents get information about the world through the experience of other agents. Recall that an agent's internal state is the interface between the external world and the agent's internal world. Hence, if agent A perceives that agent B's internal state has a high level of wellness, B's location will produce a higher salience in A's dopamine level, increasing the likelihood that A moves toward B's location. The result is that agents form herds around high-fitness locations on the map.

Predators So far, agents' movements are only motivated by high wellness levels of neighboring agents. We introduce predators as another type of agents that motivate the primitive behavior of moving away. Predators roam the world in random directions until they find

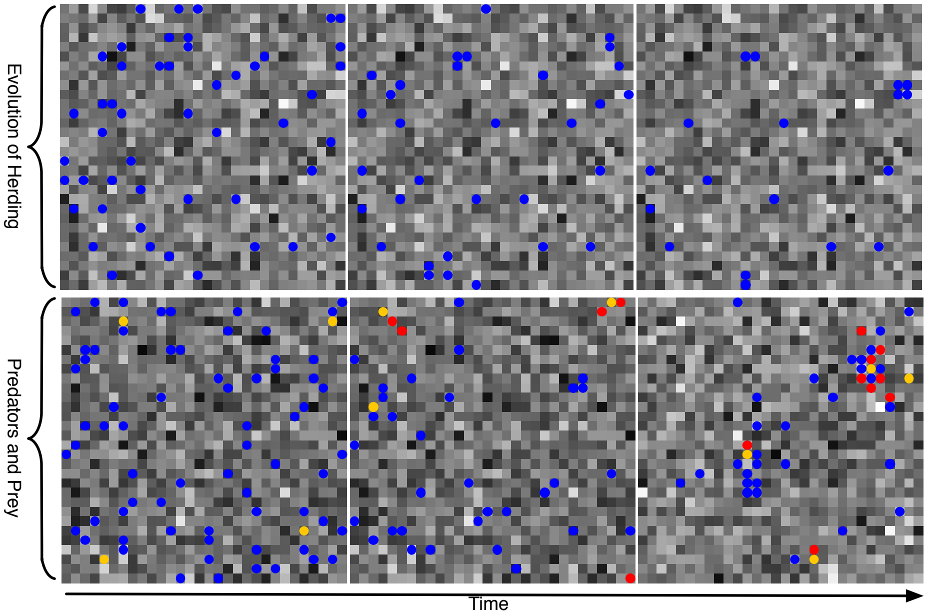

Figure 4: Top: Herding (high-density concentrations of agents in the same area) emerges over time, Bottom: Behavior in presence of a predator. Predators are orange; healthy agents are blue, agents in danger are red

another agent that is not a predator. Once its pray is located, a predator moves towards it in every step of the simulation. Once in the same cell as the pray, the predator attacks. An attack on an agent shoots her wellness levels to the lowest possible. It also triggers the primitive behavior of moving away of the predator.

The social aspect of this addition is that agents can get information about these attacks when they witness them. If agent B is attacked by a predator and agent A perceives B's internal state, A can adopt such internal state too. This produces A to move away from the cell where B is, and associated all the stimuli in the scene in her memory, with high saliency. We start by looking at the social dynamics. Without predators, agents only move towards those other agents that have a high wellness level. As shown in figure 4(top), agents tend to cluster in different groups. Once the clusters have been formed, they are stable.

4 Results

When predators are introduced, social dynamics exhibit panic waves and punctuated equilibria. As shown in figure 4(bottom), when a predator attacks a member of a cluster, all agents that witness such attack enter into a low wellness internal state. This is perceived by other agents in the outer layers of the cluster, propagating a panic wave where all agents move away of the "danger zone". These dynamics exhibit punctuated equilibria in the sense that clusters are formed and stabilized until a predator comes in and disrupts such state.

Now we look into the internal dynamics of an agent. Figure 5 shows the dynamics of

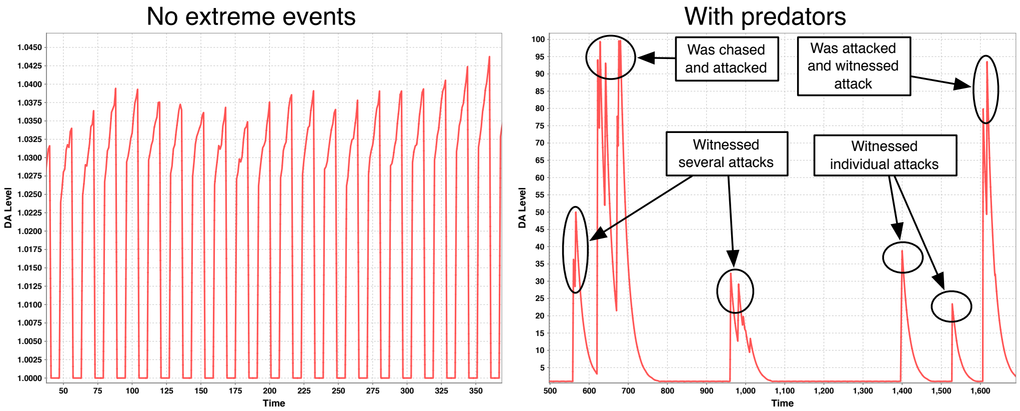

Figure 5: Dopamine levels (left) in absence of predators, (right) when predators are present in the environment. Note that spikes caused by predator attacks are an order of magnitude higher then these observed from the environment

the dopamine levels in the agents' brains. In the absence of predators, dopamine levels oscillate in regular levels, as dictated by the attention upstates. Differences in the spikes are directly related to differences in the fitness levels of the natural environments. When predators exist, large dopamine spikes are triggered due to their attacks. When an agent is attacked, her dopamine level peaks at its maximum. When an agent witnesses an attack, she adopts wellness levels almost as low as the victim's ones, triggering dopamine spikes. Witnessing a panic wave will trigger a chain of dopamine spikes. If extreme events are perceived consecutively, they can produce an escalating effect in the levels of dopamine. Thus, achieving high levels even if the agent was not directly attacked by a predator. This is an important feature since it means that agents do not need to experience predators' attacks directly to memorize them with a high saliency, it is enough to perceive other agents' experiences.

As shown in figure 3, semantic networks emerge form the agents' experiences. These networks vary according to the agent's history. When an agent is isolated, all her memories are about the natural environments she has perceived. When there are multiple agents, these memories also include other agents and sounds. Finally, with extreme events, the concept of a predator can be included in the agent's memory, and associated to certain sounds and other agents with high salience (due to the high dopamine levels that are triggered). These semantic networks allow the agent to reinforce certain associations as her experiences are repeated.

5 Conclusions and Future Directions

In this paper, we presented a highly stylized model where simple sociality emerges directly from biological concepts such as dopamine-regulated associative memory. We intend to push the model to an increased complexity of communication and language, leading to geographically separated populations of agents that develop distinct “cultures”.

At the same time, we shall work on increasing the fidelity of our biological models, docking our computational model with studies of pheromone communication of drosophila (fruit fly) under influence of nicotine and other dopamine-altering drugs. As a result, we shall be able to model both ”normal” and drug-addicted populations simultaneously *in vivo* and *in silico*.

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