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Activity Report 2016

Project-Team MNEMOSYNE

Mnemonic Synergy

RESEARCH CENTER
Bordeaux - Sud-Ouest

THEME
Computational Neuroscience and Medecine

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Project-Team MNEMOSYNE

Creation of the Team: 2012 February 01, updated into Project-Team: 2014 July 01

Mnemosyne hosted by Institut des Maladies Neurodégénératives, IMN, Bordeaux NeuroCampus.

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Computer Science and Digital Science:

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2. Overall Objectives

2.1. Summary

At the frontier between integrative and computational neuroscience, we propose to model the brain as a system of active memories in synergy and in interaction with the internal and external world and to simulate it *as a whole and in situation*.

In integrative and cognitive neuroscience (*cf.* § 3.1), on the basis of current knowledge and experimental data, we develop models of the main cerebral structures, taking a specific care of the kind of mnemonic function they implement and of their interface with other cerebral and external structures. Then, in a systemic approach, we build the main behavioral loops involving these cerebral structures, connecting a wide spectrum of actions to various kinds of sensations. We observe at the behavioral level the properties emerging from the interaction between these loops.

We claim that this approach is particularly fruitful for investigating cerebral structures like the basal ganglia and the prefrontal cortex, difficult to comprehend today because of the rich and multimodal information flows they integrate. We expect to cope with the high complexity of such systems, inspired by behavioral and developmental sciences, explaining how behavioral loops gradually incorporate in the system various kinds of information and associated mnesic representations. As a consequence, the underlying cognitive architecture, emerging from the interplay between these sensations-actions loops, results from a *mnemonic synergy*.

In computational neuroscience (*cf.* § 3.2), we concentrate on the efficiency of local mechanisms and on the effectiveness of the distributed computations at the level of the system. We also take care of the analysis of their dynamic properties, at different time scales. These fundamental properties are of high importance to allow the deployment of very large systems and their simulation in a framework of high performance computing (*cf.* § 6.1). Running simulations at a large scale is particularly interesting to evaluate over a long period a consistent and relatively complete network of cerebral structures in realistic interaction with the external and internal world. We face this problem in the domain of autonomous robotics (*cf.* § 3.4) and ensure a real autonomy by the design of an artificial physiology and convenient learning protocoles.

We are convinced that this original approach also permits to revisit and enrich algorithms and methodologies in machine learning (*cf.* § 3.3) and in autonomous robotics (*cf.* § 3.4), in addition to elaborate hypotheses to be tested in neuroscience and medicine, while offering to these latter domains a new ground of experimentation similar to their daily experimental studies.

3. Research Program

3.1. Integrative and Cognitive Neuroscience

The human brain is often considered as the most complex system dedicated to information processing. This multi-scale complexity, described from the metabolic to the network level, is particularly studied in integrative neuroscience, the goal of which is to explain how cognitive functions (ranging from sensorimotor coordination to executive functions) emerge from (are the result of the interaction of) distributed and adaptive computations of processing units, displayed along neural structures and information flows. Indeed, beyond the astounding complexity reported in physiological studies, integrative neuroscience aims at extracting, in simplifying models, regularities at various levels of description. From a mesoscopic point of view, most neuronal structures (and particularly some of primary importance like the cortex, cerebellum, striatum, hippocampus) can be described through a regular organization of information flows and homogenous learning rules, whatever the nature of the processed information. From a macroscopic point of view, the arrangement in space of neuronal structures within the cerebral architecture also obeys a functional logic, the sketch of which is captured in models describing the main information flows in the brain, the corresponding loops built in interaction with the external and internal (bodily and hormonal) world and the developmental steps leading to the acquisition of elementary sensorimotor skills up to the most complex executive functions.

In summary, integrative neuroscience builds, on an overwhelming quantity of data, a simplifying and interpretative grid suggesting homogenous local computations and a structured and logical plan for the development of cognitive functions. They arise from interactions and information exchange between neuronal structures and the external and internal world and also within the network of structures.

This domain is today very active and stimulating because it proposes, of course at the price of simplifications, global views of cerebral functioning and more local hypotheses on the role of subsets of neuronal structures in cognition. In the global approaches, the integration of data from experimental psychology and clinical studies leads to an overview of the brain as a set of interacting memories, each devoted to a specific kind of information processing [54]. It results also in longstanding and very ambitious studies for the design of cognitive architectures aiming at embracing the whole cognition. With the notable exception of works initiated by [50], most of these frameworks (e.g. Soar, ACT-R), though sometimes justified on biological grounds, do not go up to a *connectionist* neuronal implementation. Furthermore, because of the complexity of the resulting frameworks, they are restricted to simple symbolic interfaces with the internal and external world and to (relatively) small-sized internal structures. Our main research objective is undoubtly to build such a general purpose cognitive architecture (to model the brain *as a whole* in a systemic way), using a connectionist implementation and able to cope with a realistic environment.

3.2. Computational Neuroscience

From a general point of view, computational neuroscience can be defined as the development of methods from computer science and applied mathematics, to explore more technically and theoretically the relations between structures and functions in the brain [56], [43]. During the recent years this domain has gained an increasing interest in neuroscience and has become an essential tool for scientific developments in most fields in neuroscience, from the molecule to the system. In this view, all the objectives of our team can be described as possible progresses in computational neuroscience. Accordingly, it can be underlined that the systemic view that we promote can offer original contributions in the sense that, whereas most classical models in computational neuroscience focus on the better understanding of the structure/function relationship for isolated specific structures, we aim at exploring synergies between structures. Consequently, we target interfaces and interplay between heterogenous modes of computing, which is rarely addressed in classical computational neuroscience.

We also insist on another aspect of computational neuroscience which is, in our opinion, at the core of the involvement of computer scientists and mathematicians in the domain and on which we think we could particularly contribute. Indeed, we think that our primary abilities in numerical sciences imply that our developments are characterized above all by the effectiveness of the corresponding computations: We provide biologically inspired architectures with effective computational properties, such as robustness to noise, self-organization, on-line learning. We more generally underline the requirement that our models must also mimick biology through its most general law of homeostasis and self-adaptability in an unknown and changing environment. This means that we propose to numerically experiment such models and thus provide effective methods to falsify them.

Here, computational neuroscience means mimicking original computations made by the neuronal substratum and mastering their corresponding properties: computations are distributed and adaptive; they are performed without an homonculus or any central clock. Numerical schemes developed for distributed dynamical systems and algorithms elaborated for distributed computations are of central interest here [40], [49] and were the basis for several contributions in our group [55], [52], [57]. Ensuring such a rigor in the computations associated to our systemic and large scale approach is of central importance.

Equally important is the choice for the formalism of computation, extensively discussed in the connectionist domain. Spiking neurons are today widely recognized of central interest to study synchronization mechanisms and neuronal coupling at the microscopic level [41]; the associated formalism [46] can be possibly considered for local studies or for relating our results with this important domain in connectionism. Nevertheless, we remain mainly at the mesoscopic level of modeling, the level of the neuronal population, and consequently interested in the formalism developed for dynamic neural fields [38], that demonstrated a richness of behavior

[42] adapted to the kind of phenomena we wish to manipulate at this level of description. Our group has a long experience in the study and adaptation of the properties of neural fields [52], [53] and their use for observing the emergence of typical cortical properties [45]. In the envisioned development of more complex architectures and interplay between structures, the exploration of mathematical properties such as stability and boundedness and the observation of emerging phenomena is one important objective. This objective is also associated with that of capitalizing our experience and promoting good practices in our software production (*cf.* § 6.1). In summary, we think that this systemic approach also brings to computational neuroscience new case studies where heterogenous and adaptive models with various time scales and parameters have to be considered jointly to obtain a mastered substratum of computation. This is particularly critical for large scale deployments, as we will discuss in § 6.1).

3.3. Machine Learning

The adaptive properties of the nervous system are certainly among its most fascinating characteristics, with a high impact on our cognitive functions. Accordingly, machine learning is a domain [48] that aims at giving such characteristics to artificial systems, using a mathematical framework (probabilities, statistics, data analysis, etc.). Some of its most famous algorithms are directly inspired from neuroscience, at different levels. Connectionist learning algorithms implement, in various neuronal architectures, weight update rules, generally derived from the hebbian rule, performing non supervised (e.g. Kohonen self-organizing maps), supervised (e.g. layered perceptrons) or associative (e.g. Hopfield recurrent network) learning. Other algorithms, not necessarily connectionist, perform other kinds of learning, like reinforcement learning. Machine learning is a very mature domain today and all these algorithms have been extensively studied, at both the theoretical and practical levels, with much success. They have also been related to many functions (in the living and artificial domains) like discrimination, categorisation, sensorimotor coordination, planning, etc. and several neuronal structures have been proposed as the substratum for these kinds of learning [44], [37]. Nevertheless, we believe that, as for previous models, machine learning algorithms remain isolated tools, whereas our systemic approach can bring original views on these problems.

At the cognitive level, most of the problems we face do not rely on only one kind of learning and require instead skills that have to be learned in preliminary steps. That is the reason why cognitive architectures are often referred to as systems of memory, communicating and sharing information for problem solving. Instead of the classical view in machine learning of a flat architecture, a more complex network of modules must be considered here, as it is the case in the domain of deep learning. In addition, our systemic approach brings the question of incrementally building such a system, with a clear inspiration from developmental sciences. In this perspective, modules can generate internal signals corresponding to internal goals, predictions, error signals, able to supervise the learning of other modules (possibly endowed with a different learning rule), supposed to become autonomous after an instructing period. A typical example is that of episodic learning (in the hippocampus), storing declarative memory about a collection of past episods and supervising the training of a procedural memory in the cortex.

At the behavioral level, as mentionned above, our systemic approach underlines the fundamental links between the adaptive system and the internal and external world. The internal world includes proprioception and interoception, giving information about the body and its needs for integrity and other fundamental programs. The external world includes physical laws that have to be learned and possibly intelligent agents for more complex interactions. Both involve sensors and actuators that are the interfaces with these worlds and close the loops. Within this rich picture, machine learning generally selects one situation that defines useful sensors and actuators and a corpus with properly segmented data and time, and builds a specific architecture and its corresponding criteria to be satisfied. In our approach however, the first question to be raised is to discover what is the goal, where attention must be focused on and which previous skills must be exploited, with the help of a dynamic architecture and possibly other partners. In this domain, the behavioral and the developmental sciences, observing how and along which stages an agent learns, are of great help to bring some structure to this high dimensional problem.

At the implementation level, this analysis opens many fundamental challenges, hardly considered in machine learning : stability must be preserved despite on-line continuous learning; criteria to be satisfied often refer to behavioral and global measurements but they must be translated to control the local circuit level; in an incremental or developmental approach, how will the development of new functions preserve the integrity and stability of others? In addition, this continous re-arrangement is supposed to involve several kinds of learning, at different time scales (from msec to years in humans) and to interfer with other phenomena like variability and meta-plasticity.

In summary, our main objective in machine learning is to propose on-line learning systems, where several modes of learning have to collaborate and where the protocoles of training are realistic. We promote here a *really autonomous* learning, where the agent must select by itself internal resources (and build them if not available) to evolve at the best in an unknown world, without the help of any *deus-ex-machina* to define parameters, build corpus and define training sessions, as it is generally the case in machine learning. To that end, autonomous robotics (*cf.* § 3.4) is a perfect testbed.

3.4. Autonomous Robotics

Autonomous robots are not only convenient platforms to implement our algorithms; the choice of such platforms is also motivated by theories in cognitive science and neuroscience indicating that cognition emerges from interactions of the body in direct loops with the world (*embodiment of cognition* [39]). In addition to real robotic platforms, software implementations of autonomous robotic systems including components dedicated to their body and their environment will be also possibly exploited, considering that they are also a tool for studying conditions for a real autonomous learning.

A real autonomy can be obtained only if the robot is able to define its goal by itself, without the specification of any high level and abstract cost function or rewarding state. To ensure such a capability, we propose to endow the robot with an artificial physiology, corresponding to perceive some kind of pain and pleasure. It may consequently discriminate internal and external goals (or situations to be avoided). This will mimick circuits related to fundamental needs (e.g. hunger and thirst) and to the preservation of bodily integrity. An important objective is to show that more abstract planning capabilities can arise from these basic goals.

A real autonomy with an on-line continuous learning as described in § 3.3 will be made possible by the elaboration of protocols of learning, as it is the case, in animal conditioning, for experimental studies where performance on a task can be obtained only after a shaping in increasingly complex tasks. Similarly, developmental sciences can teach us about the ordered elaboration of skills and their association in more complex schemes. An important challenge here is to translate these hints at the level of the cerebral architecture.

As a whole, autonomous robotics permits to assess the consistency of our models in realistic condition of use and offers to our colleagues in behavioral sciences an object of study and comparison, regarding behavioral dynamics emerging from interactions with the environment, also observable at the neuronal level.

In summary, our main contribution in autonomous robotics is to make autonomy possible, by various means corresponding to endow robots with an artificial physiology, to give instructions in a natural and incremental way and to prioritize the synergy between reactive and robust schemes over complex planning structures.

4. Application Domains

4.1. Overview

One of the most original specificity of our team is that it is part of a laboratory in Neuroscience (with a large spectrum of activity from the molecule to the behavior), focused on neurodegenerative diseases and consequently working in tight collaboration with the medical domain. As a consequence, neuroscientists and the medical world are considered as the primary end-users of our researches. Beyond data and signal analysis where our expertise in machine learning may be possibly useful, our interactions are mainly centered on the exploitation of our models. They will be classically regarded as a way to validate biological assumptions and to generate new hypotheses to be investigated in the living. Our macroscopic models and their implementation in autonomous robots will allow an analysis at the behavioral level and will propose a systemic framework, the interpretation of which will meet aetiological analysis in the medical domain and interpretation of intelligent behavior in cognitive neuroscience.

The study of neurodegenerative diseases is targeted because they match the phenomena we model. Particularly, the Parkinson disease results from the death of dopaminergic cells in the basal ganglia, one of the main systems that we are modeling. The Alzheimer disease also results from the loss of neurons, in several cortical and extracortical regions. The variety of these regions, together with large mnesic and cognitive deficits, require a systemic view of the cerebral architecture and associated functions, very consistent with our approach.

Of course, numerical sciences are also impacted by our researches, at several levels. At a global level, we will propose new control architectures aimed at providing a higher degree of autonomy to robots, as well as machine learning algorithms working in more realistic environment. More specifically, our focus on some cognitive functions in closed loop with a real environment will address currently open problems. This is obviously the case for planning and decision making; this is particularly the case for the domain of affective computing, since motivational characteristics arising from the design of an artificial physiology allow to consider not only cold rational cognition but also hot emotional cognition. The association of both kinds of cognition is undoublty an innovative way to create more realistic intelligent systems but also to elaborate more natural interfaces between these systems and human users.

At last, we think that our activities in well-founded distributed computations and high performance computing are not just intended to help us design large scale systems. We also think that we are working here at the core of informatics and, accordingly, that we could transfer some fundamental results in this domain.

5. Highlights of the Year

5.1. Highlights of the Year

5.1.1. First PhDs defended

2016 is a very special year for our young team Mnemosyne, since our first three PhDs have been defended in October and November [1], [2], [3].

6. New Software and Platforms

6.1. Positioning

Our previous works in the domain of well-defined distributed asynchronous adaptive computations [55], [52], [57] have already made us define a library (DANA [51]), closely related to both the notion of artificial neural networks and cellular automata. From a conceptual point of view, the computational paradigm supporting the library is grounded on the notion of a unit that is essentially a (vector of) potential that can vary along time under the influence of other units and learning. Those units can be organized into layers, maps and networks.

We will also have to interact with the High Performance Computing (HPC) community, since having large scale simulations at that mesoscopic level is an important challenge in our systemic view of computational neuroscience. Our approach implies to emulate the dynamics of thousands, or even millions, of integrated computational units, each of them playing the role of a whole elementary neural circuit (e.g. the microcolumn for the cortex). Mesoscopic models are considered in such an integrative approach, in order to exhibit global dynamical effect that would be hardly reachable by compartment models involving membrane equations or even spiking neuron networks.

The vast majority of high performance computing softwares for computational neuroscience addresses sub-neural or neural models [41], but coarser grained population models are also demanding for large scale simulations, with fully distributed computations, without global memory or time reference, as it is specified in (*cf.* § 3.2).

6.2. DANA

Distributed Asynchronous Numerical & Adaptive computing framework

FUNCTIONAL DESCRIPTION

DANA is a python framework whose computational paradigm is grounded on the notion of a unit that is essentially a set of time dependent values varying under the influence of other units via adaptive weighted connections. The evolutions of a unit's value are defined by a set of differential equations expressed in standard mathematical notation which greatly ease their definition. The units are organized into groups that form a model. Each unit can be connected to any other unit (including itself) using a weighted connection. The DANA framework offers a set of core objects needed to design and run such models. The modeler only has to define the equations of a unit as well as the equations governing the training of the connections. The simulation is completely transparent to the modeler and is handled by DANA. This allows DANA to be used for a wide range of numerical and distributed models as long as they fit the proposed framework (e.g. cellular automata, reaction-diffusion system, decentralized neural networks, recurrent neural networks, kernel-based image processing, etc.).

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6.3. ENAS

Event Neural Assembly Simulation

KEYWORDS: Neurosciences - Health - Physiology

SCIENTIFIC DESCRIPTION

As one gains more intuitions and results on the importance of concerted activity in spike trains, models are developed to extract potential canonical principles underlying spike coding. These methods shed a new light on spike train dynamics. However, they require time and expertise to be implemented efficiently, making them hard to use in a daily basis by neuroscientists or modelers. To bridge this gap, we developed the license free multiplatform software ENAS (https://enas.inria.fr) integrating tools for individual and collective spike analysis and simulation, with some specificities devoted to the retina. The core of ENAS is the statistical analysis of population codes. One of its main strength is to provide statistical analysis of spike trains using Maximum Entropy-Gibbs distributions taking into account both spatial and temporal correlations as constraints, allowing to introduce causality and memory in statistics. ENAS also generates simulated spike trains. On one hand, one can draw a population raster from an user-specified Gibbs distribution. On the other hand, we have integrated in ENAS our retina simulator VIRTUAL RETINA, extended here to include lateral connections in the IPL. We hope that ENAS will become a useful tool for neuroscientists to analyse spike trains and we hope to improve it thanks to user feedback. Our goal is to progressively enrich it with the latest research results, in order to facilitate transfer of new methods to the community.

FUNCTIONAL DESCRIPTION

As one gains more intuitions and results on the importance of concerted activity in spike trains, models are developed to extract potential canonical principles underlying spike coding. These methods shed a new light on spike train dynamics. However, they require time and expertise to be implemented efficiently, making them hard to use in a daily basis by neuroscientists or modelers. To bridge this gap, we developed the license free multiplatform software ENAS integrating tools for spike trains analysis and simulation. These tools are accessible through a friendly Graphical User Interface that avoids any scripting or writing code from the user. Most of them have been implemented to run in parallel to reduce the time and memory consumption. ENAS offers basic visualizations and classical analysis for statistics of spike trains analysis. It also proposes statistical analysis with Maximum Entropy-Gibbs distributions taking into account both spatial and temporal correlations as constraints, allowing to introduce causality and memory in statistics. ENAS also includes specific tools dedicated to the retina: Receptive Field computation and a virtual retina simulator. Finally, ENAS generates synthetic rasters, either from know statistics or from the VIRTUAL RETINA simulator. We expect ENAS to become a useful tool for neuroscientists to analyse spike trains and we hope to improve it thanks to users feedback. From our perspective, our goal is to progressively enrich ENAS with the latest research results, in order to facilitate transfer of new methods to the community.

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6.4. Virtual Enaction

KEYWORDS: Neurosciences - Simulation - Health
FUNCTIONAL DESCRIPTION

VirtualEnaction: A Platform for Systemic Neuroscience Simulation. The computational models studied in our team have applications that extend far beyond what is possible to experiment yet in human or non-human primate subjects. Real robotics experimentations are also impaired by rather heavy technological constraints, for instance, it is not easy to dismantle a given embedded system in the course of emerging ideas. The only versatile environment in which such complex behaviors can be studied both globally and at the level of details of the available modeling is a virtual environment, as in video games, Such a system can be implemented as “brainy-bot” (a programmed player based on our knowledge of the brain architecture) which goal is to survive in a complete manipulable environment.

In order to attain this rather ambitious objective we have deployed an existing open-source video game middleware (Minecraft) in order to be able to shape the survival situation to be studied and we have begun to revisit some models in order to be able to integrate them as an effective brainy-bot. This was made as a platform associated to a scenario that is the closest possible to a survival situation (foraging, predator-prey relationship, partner approach to reproduction). We could integrate in the platform an artificial agent with sensory inputs (visual, touch and smell), emotional and somatosensory cues (hunger, thirst, fear, ..) and motor outputs (movement, gesture, ..) connected to a "brain" whose architecture was corresponding to the major anatomical regions studied in the team.

Nevertheless, we have seen recently that a major entertainment company (Microsoft) bought Minecraft to make similar (but larger) adaptations to what was being targeted by our VirtualEnaction project. We are currently studying the resulting product (the Malmö project) in order to adapt our strategy.

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7. New Results

7.1. Overview

This year we first explored two main loops of cerebral architecture, the limbic and motor loops, and their associated memory mechanisms. The limbic loop (*cf.* § 7.2) concerns the taking into account of the emotional and motivational aspects by the respondant and operant conditioning and their relations with the semantic and episodic memories. The motor loop (*cf.* § 7.3) considers the evolution of sensorimotor learning, from goal-directed behaviors to habitual behaviors.

We also began this year to study some characteristics of the systemic integration of our models (*cf.* § 7.4), raising the question of the conditions of autonomous learning and certain global characteristics such as neuromodulation.

Finally, we study the links between our bio-inspired modeling work and Machine Learning (*cf.* § 7.5), revisiting this latter domain in the light of the principles highlighted by our models.

7.2. The limbic loop

We explored the limbic loop by describing a series of neural mechanisms that propose how responding conditioning results from interactions between the amygdala, the nucleus accumbens and the limbic pole of the frontal cortex. In our models [1], this learning is also fed by exchanges with the hippocampus (episodic memory) and the sensory cortex (semantic memory) and we studied the major role of acetylcholine in these exchanges. This also allowed us to address the difficult question of the articulation between the respondant and operant conditioning in particular in the nucleus accumbens. We proposed an original mechanism whereby noradrenaline could modulate the balance between exploration and exploitation [12] based on an assessment of the level of uncertainty and its impact on performance [13].

Also in connection with this loop, we studied the dynamics of dopamine release in the midbrain, considered to play an essential role in the coding of the prediction error. This model developed in the framework of our collaboration with India (*cf.* § 9.3) proposes to introduce into the classical circuit, new actors (such as the pedunculopontine tegmental nucleus in the brainstem) and new functions (dissociation of amplitude and timing of the reward), that we will seek to corroborate in the future.

Lastly, we carried out a thorough study about the behavior of our model of associative memory in the hippocampus [23], and particularly about its resistance to interference.

7.3. The motor loop

The nervous system structures involved in decision making constitute a circuit formed by the basal ganglia, the cortex, the thalamus and their numerous interconnections. This circuit can be described as a set of loops operating in parallel and interacting at different points. The decisions and therefore the actions of an individual emerge from the interactions between these loops and the plasticity of their connections. These emerging behaviors and arising learning processes are addressed through a closed-loop approach in which the theoretical model is in constant interaction with the environment of the task. To this end, neural modeling and dedicated analysis software tools were developed in the laboratory, at the level of the neuronal circuit. We have explored this year the dynamics of information flows within this circuit through a computational model described at the neuron and synapse level. Taking into account previous experimental observations from primates and earlier computational models, we incrementally developed a network capable of learning to perform behavioral tasks under several protocols and conditions [5]. The development of this computational model was conducted in parallel with the development of an experimental model of decision making in the salamander (Pleurodeles waltlii) [2]. The result here is a computational model of learning and decision making in the basal ganglia that allows for the testing of experimental hypotheses and also to conduct in silico pathophysiological or pharmacological investigations at the cellular level.

7.4. Systemic integration

We have worked this year on the integration of goal-oriented and habitual behaviors, two modes of learning associated to the motor loop. There is an apparent contradiction between experimental data showing that the basal ganglia are involved in goal-oriented and routine behaviors and clinical observations. Lesion or disruption by deep brain stimulation of the globus pallidus interna has been used for various therapeutic purposes ranging from the improvement of dystonia to the treatment of Tourette's syndrome. None of these approaches has reported any severe impairment in goal-oriented or automatic movement. To solve this conundrum, we trained two monkeys to perform a variant of a two-armed bandit-task (with different reward contingencies). Bilateral inactivation of the globus pallidus interna, by injection of muscimol, prevents animals from learning new contingencies while performance remains intact, although slower for the familiar stimuli. We replicate in silico these data by adding lateral competition and Hebbian learning in the cortical layer of the theoretical model of the cortex–basal ganglia loop that provided the framework of our experimental approach [7]. These results suggest that a behavioral decision results from both the cooperation (acquisition) and competition (expression) of two distinct but entangled memory systems, the goal-directed system and the habitual system that may represent the two ends of the same graded phenomenon.

We began our first works of systemic integration associating our models developed in the limbic and motor loops, for the study of the taking into account of the uncertainty in the selection of the action [1]. This preliminary work using the VirtualEnaction platform (*cf.* § 6.4) will be continued this year with a PhD that begins.

We have more generally proposed a study [11], analyzing the role of neuromodulation in adaptation to uncertainty, whose potential systemic impact is evident, particularly because it provides precious characteristics for autonomous learning [10].

7.5. Machine Learning

In Machine Learning, we were interested this year in two phenomena for which we consider classical paradigms of modeling and for which we wonder how they could be adapted by bio-inspiration.

The first paradigm concerns the manipulation of temporal sequences. In a perspective of better understanding how brain learn structured sequences we extended a model on syntax acquisition using the Reservoir Computing framework (using random recurrent networks) [16], [9], [19], [20]. The extended model is also used in a Human-Robot Interaction architecture to enable users to use more natural language with robots [14], [15], [18]. This work will be extended with our collaborators at the University of Hamburg (*cf.* § 9.3).

In an industrial application for the representation of electrical diagrams (*cf.* § 8.1), we also study how recurrent layered models can be trained to run through these schemes for prediction and sequence representation tasks.

The second paradigm concerns the extraction of characteristics and the use of hierarchical networks, as in the case of deep networks. An industrial application whose study has just begun (*cf.* § 9.2) will lead us to revisit these models to make them more easily usable in constrained frameworks, for example with limited size corpuses.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Contract with Algotech

Participants: Frédéric Alexandre, Ikram Chraibi Kaadoud, Nicolas Rougier, Thierry Viéville.

Algotech is a SME working in the domain of CADD software edition for electrical circuit diagram interpretation and design. Its activity is interesting for our team because they are also interested in the design, by learning, of perception (for diagram identification) and action aspects of loops (for diagram genesis) with the specificity of working at a small scale, considering the variety of items to be manipulated. This is consequently a very interesting benchmark for transfering our bio-inspired models to the domain of classical machine learning, as we have begun this year.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. PsyPhINe: Cogito Ergo Es

Participant: Nicolas Rougier.

Project gathering researchers from: MSH Lorraine (USR3261), InterPsy (EA 4432), APEMAC, EPSaM (EA4360), Archives Henri-Poincaré (UMR7117), Loria (UMR7503) & Mnemosyne.

PsyPhiNe is a pluridisciplinary and exploratory project between philosophers, psychologists, neuroscientists and computer scientists. The goal of the project is to explore cognition and behavior from different perspectives. The project aims to explore the idea of assignments of intelligence or intentionality, assuming that our intersubjectivity and our natural tendency to anthropomorphize play a central role: we project onto others parts of our own cognition. To test these hypotheses, we ran a series of experiments with human subject confronted to a motorized lamp that can or cannot interact with them while they're doing a specific task. Early results (analysis not yet finished) tend to show that people have a tendency to over-interpret any kind of behavior as intentional and meaningful. We also organized our second national conference in Nancy gathering speakers from philosophy, robotics, art and psychology and hired a new post-doc to work on the new experimental setup (http://poincare.univ-lorraine.fr/fr/manifestations/psyphine-2016)

9.1.2. Project of the Aquitaine Regional Council: Decision making, from motor primitives to action

Participants: Nicolas Rougier, Meropi Topalidou.

This project has ended with the PhD defense of Meropi Topalidou on October 10th, 2016. Using a computational model, we investigated the classic hypothesis of habits formation and expression in the basal ganglia and proposed a new hypothesis concerning the respective role for both the basal ganglia and the cortex. Inspired by previous theoretical and experimental works [47], we designed a computational model of the basal ganglia- thalamus-cortex system that uses segregated loops (motor, cognitive and associative) and makes the hypothesis that basal ganglia are only necessary for the acquisition of habits while the expression of such habits can be mediated through the cortex. This work leads to several publications including an important article in "Movement disorders" [7] explaining some counter-intuitive clinical observations. Furthermore, the early work during the first year of the PhD led N.Rougier to create the ReScience journal.

9.1.3. Collaboration with the Neurocentre Magendie on parameter optimization: Neurobees

Participant: André Garenne.

The development of computational models of neurons and networks typically involves tuning the numerical parameters to fit experimental results. Parameter tuning can sometimes be manually completed, it is more convenient to use automated optimization algorithms at least for two reasons: (i) to apply an homogeneous processing to all the calculation and parameter space exploration which alleviates operator influence and (ii) to avoid a tedious and uncertain result from human operators when the dimensionality increases. A multi-agent algorithm in line with ABC (Artificial Bee Colony) paradigm has been applied to new benchmark tests in order to ensure its robustness and better performances, especially when compared to evolutionary and swarm algorithms and this has recently been confirmed, thanks to the local Plafrim computation facilities.

9.2. National Initiatives

9.2.1. FUI Sumatra

Participants: Frédéric Alexandre, Thalita Firmo Drumond, Xavier Hinaut, Randa Kassab, Nicolas Rougier, Thierry Viéville.

This FUI project, supported by the Aerospace Valley Innovation Pole, gathers two industrial groups (Safran Helicopter and SPIE), three research labs and four SME. Its goal is to provide contextualized information to maintenance operators by the online analysis of the operating scene. We are concerned in this project with the analysis of visual scenes, in industrial contexts, and the extraction of visual primitives, categories and pertinent features, best decribing the scenes, with biologically inspired neuronal models.

Firstly, this is an opportunity for us to revisit the principles of deep network architectures by adapting principles that we will elaborate from the context of the hierarchical architecture of the temporal visual cortex. Secondly, we intend to exploit and adapt our model of hippocampus to extract more heterogenous features. This project is an excellent opportunity to associate and combine our models and also to evaluate the robustness of our models in real-world applications.

9.2.2. ANR MACAQUE40

Participant: Nicolas Rougier.

Most of the theoretical models in economics proposed so far to describe money emergence are based on three intangible assumptions: the omniscience of economic agents, an infinite time and an extremely large number of agents (not bounded). The goal of this interdisciplinary study is to investigate the condition of apparition of a monetary economy in a more ecological framework provided with the assumption that the market is made up of a finite number of agents having a bounded rationality and facing a time constraint.

In this study, we propose a generic model and environment of monetary prospecting. Our first objective is to artificially identify structural (trading organisation, agents specialisation) and cognitive conditions (learning skills, memory and strategic anticipation abilities, tradeoff exploration/exploitation) that allowed money emergence. This will provide relevant environmental constraints that we will use during our manipulations in the laboratory. The agents that will be involved in these manipulations will be of two types: non-human primates (rhesus macaques) and humans.

9.2.3. Project Motus of the ANSES

Participant: André Garenne.

The MOTUS project (MOdulaTion dU Signal RF et effets sur le cerveau : approche in vivo et in vitro) is financed by the ANSES (the french national agency for health security). This 3 years project is studying the effects of GSM-RF on living matter and especially neuronal activity and development. Our main involvement concerns electrophysiological data and spike trains analysis as well as the development of pharmacological protocols to test GSM-RF effects hypotheses.

9.2.4. Project Mimacore of the CNRS Challenge Imag'In

Participants: Frédéric Alexandre, Nicolas Rougier.

Better understanding the resting states (regional interactions and corresponding functional networks in the brain when the subject is at rest) is of central interest for a systemic approach of brain understanding. As we think that this domain is not mature enough for a direct functional modeling approach, we try to get familiar with it, through this imaging study. In this exploratory study funded by the CNRS, we are associated with three teams in neuroscience developing three imaging techniques (MRS, MRI, Clarity), to explore resting states in rodents and learn more about their genesis.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Labs

9.3.1.1. Braincraft

Title: Braincraft

International Partner (Institution - Laboratory - Researcher):

University of Colorado, Boulder (United States) - Computational Cognitive Neuroscience - Randall O'Reilly

Start year: 2015

We develop with this team a computationally-based understanding of the neural circuits involved in decision making, namely basal ganglia and prefrontal cortex. More precisely, we want to understand what are the processes by which animals and humans select their actions based on their motivations and on the consequences of past actions. This is a fundamental question in neurosciences, with implications to ethology, psychology, economics, sociology and computer science. Through a unique combination of expertise in cognitive psychology, neurosciences and computer science, this associate team will foster a collaboration for developing a computationally-based understanding of the neural circuits involved in decision making, namely basal ganglia and prefrontal cortex. One of the key question is to know the overall contribution of these structures and their function in the decision process.

9.3.2. Participation in Other International Programs

9.3.2.1. Project LingoRob with Germany

LingoRob - Learning Language in Developmental Robots - is a project of the Programme Hubert Curien PHC Procope with Germany (University of Hamburg). The scientific objective of the collaboration is to better understand the mechanisms underlying language acquisition and enable more natural interaction between humans and robots in different languages, while modelling how the brain processes sentences and integrates semantic information of scenes. Models developed in both labs involve artificial neural networks, and in particular Echo State Networks (ESN), also known as pertaining to the Reservoir Computing framework. These neural models allow insights on high-level processes of the human brain, and at the same time are well suited as robot control platform, because they can be trained and executed online with low computational resources. The collaborators will also combine Deep Learning networks to the reservoir models already used in order to benefit from their very good feature extraction abilities.

9.3.2.2. Project BGaL with India

In the 3-years project “Basal Ganglia at Large (BGaL)”, funded by the CNRS and the CEFIPRA, we collaborate with the computer science department of IIIT Hyderabad and the biomedical department of IIT Madras, for the design of models of basal ganglia and for their implementation at large scale as well as for their relation with other brain structures. This year we have developed a model of a dopaminergic region, VTA, central for reinforcement learning in the basal ganglia.

9.3.2.3. Project ECOS-Sud with Chile

In the 3-years project “A network for computational neuroscience, from vision to robotics”, funded by ECOS-Sud and Conicyt, we collaborate with University Santa Maria and University of Valparaiso in Chile, and also with another Inria EPI, NeuroMathComp. The goal of the project is to rely on our experience of previous collaborations with these teams, to develop original tools and experimental frameworks to open our scientific domains of investigation to new fields of valorization, including medical (neurodegeneration) and technological aspects (robotics). This year, in addition to the visits of a Professor and a PhD student, we have written a chapter book that will be published next year and have prepared together a summer school to be held in Chile in january 2017 (http://www.laconeu.cl/).

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Prof. Palacios Adrian
  - Date: Sep 2016
  - Institution: Univ. Valparaiso (Chile)
- Ravello Cesar (PhD student)
  - Date: Nov 2016
  - Institution: Univ. Valparaiso (Chile)
- Prof O'Reilly Randall
  - Date: June 2016
  - Institution: U. Colorado Boulder (USA)
- Mollick Jessica (PhD student)
  - Date: Jul 2016 - Aug 2016
  - Institution: U. Colorado Boulder (USA)

9.4.1.1. Internships

- Kaushik Pramod
  - Date: June 2016 - Dec 2016
  - Institution: IIIT Hyderabad (India)
- Sabyasachi Shivkumar
  - Date: June 2016 - July 2016
  - Institution: IIIT Madras (India)

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

X. Hinaut : Co-organiser of the 2nd Automn Day of the Working Group (GT8) "Robotique et Neurosciences" of Groupe de Recherche (GDR) Robotique (CNRS), at LaBRI, 17th November 2016.

10.1.1.2. Member of the Organizing Committees

Projections, Interactions, Emotions - Journées PsyPhINe, 2016 (http://poincare.univ-lorraine.fr/fr/manifestations/psyphine-2016, N. Rougier)

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

F. Alexandre: SAB 2016

10.1.2.2. Reviewer

F. Alexandre reviewer for AMINA 2016; X. Hinaut for CogSci 2016.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- Frédéric Alexandre: Review Editor for Frontiers in Neurorobotics;
- Nicolas Rougier: Editor in chief for ReScience, review editor for Frontiers in Neurorobotics.

10.1.3.2. Reviewer - Reviewing Activities

- F. Alexandre: Frontiers in Human Neuroscience; npj Science of Learning; European Journal of Neuroscience; PLoS ONE;
- A. Garenne: Journal of Integrative Neuroscience
- X. Hinaut: PLoS ONE, Neural Networks, Intellectica, Frontiers in Neurorobotics, ReScience, Cognitive Computation.

10.1.4. Invited Talks

F. Alexandre: invited talk at the conference: “Modeling: success and limitations” (http://www.cnrs.fr/insmi/spip.php?article1876), Dec 6th and interview for the journal of the CNRS (https://lejournal.cnrs.fr/articles/modeliser-plus-pour-simuler-moins).

X. Hinaut: “Reservoir Computing for Robot Language Acquisition”, at IROS Workshop on Machine Learning Methods for High-Level Cognitive Capabilities in Robotics. Daejon, South Korea, October 2016 [9].

N. Rougier:

- Open Science, AdaWeek, November 2016, Paris
- ReScience, "La loi numérique, et après ?", November 2016, Meudon
- "One actor, two critics", Robotiques et Neurosciences, November 2016, Bordeaux
- "Advanced Scientific Programming in Python", July 2016, Austin, USA.
- "Computational Neuroscience", International School of Bioelectromagnetics, Erice, April 2016, Italy.

10.1.5. Leadership within the Scientific Community

X. Hinaut:

- member of the Administration Committee of Fresco association (French Federation of students in Cognitive Science)
- member of “open citizen labs” : MindLaBdx (Bordeaux), IA*lab and CogLab (La Paillasse, Paris).

10.1.6. Scientific Expertise

F. Alexandre is the french expert for Mathematics and Computer Science of the PHC (Hubert Curien Program) Utique for scientific cooperation between France and Tunisia.

10.1.7. Research Administration

- F. Alexandre is member of the Inria Evaluation Committee; Deputy Scientific Delegate and Vice-head of the Project Committee of Inria Bordeaux Sud-Ouest; Corresponding scientist for Bordeaux Sud-Ouest of the Inria COERLE ethical committee; Member of the national Inria committee for international chairs; Member of the local Inria committee for young researchers hiring; Member of the steering committee of the regional Cluster on Information Technology and Health; of the regional Cluster on Robotics; Expert of the ITMO ’Neurosciences, Sciences Cognitive, Neurologie, Psychiatrie’
- N. Rougier is vice-head of the Mnemosyne team-project; elected member of the Inria Evaluation Committee; Responsible of the local Inria committee for invited professors; Member of the steering committee for the BioComp CNRS consortium; Editor in chief and co-founder of ReScience.

- Thierry Viéville is in charge, at the Inria national level till October 2016, of the institute science outreach actions and depends on the Direction Générale Déléguée à la Science for this part of his work. He is, for Inria, in charge of the http://classcode.fr project.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Advanced scientific python summer school, University of Reading, September 2016 (N. Rougier).

F. Alexandre: Teaching at the IBRO Advanced School in Neuroscience “Basal Ganglia, Parkinson’s disease And Related Disorders”, May 9-21, 2016, Faculty of Sciences, Rabat (Morocco)

Many courses are given in french universities and schools of engineers at different levels (LMD) by most team members, in computer science, in applied mathematics, in neuroscience and in cognitive science.

Thierry Viéville is since 2009 in charge of formations of high-school teachers in popular computer science.

10.2.2. Juries

We participate to many juries each year.

10.3. Popularization

For a multi-disciplinary team as Mnemosyne, science popularization is not only a nice and useful contribution to the dissemination of scientific knowledge but also a necessity since we work with colleagues from biosciences with whom sharing profound ideas in computer science is mandatory for a real collaboration.

- Thierry Viéville is for 80% of his time involved in popularization actions.
- Frédéric Alexandre: Article in the journal La Tribune in January 2016 about robots and emotions; Article in tribute to Marvin Minsky (Blog Binaire http://binaire.blog.lemonde.fr/2016/01/29/lintelligence-artificielle-debraillee/; Bulletin of the French Society of Computer Science http://www.societe-informatique-de-france.fr/bulletin/1024-numero-8/); Article about learning in the magazine of the University of Bordeaux (http://www.u-bordeaux.fr/Universite/U-magazine)
- Xavier Hinaut: “Apprentissage de la grammaire par un cerveau positronique”. CogTalk organised by the association Ascoergo, Bordeaux, March 2016.
- Nicolas Rougier: "Le Grand Remue-Méninges", Octobrer 2016, Bordeaux; "Les neurosciences au coeur des innovations", May 2016, Lyon; Interview for the "Verge of Discovery" March 2016; Intervention for the "Artificial Intelligence forum", Bordeaux.
- For all the team: participation to the “Fête de la Science” in an exhibition in the Scientific Museum Cap Sciences: http://www.bordeaux-neurocampus.fr/fr/divers/toutes-les-communications/com-2016/fete-de-la-science.html

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