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Activity Report 2018

Project-Team MNEMOSYNE

Mnemonic Synergy

RESEARCH CENTER
Bordeaux - Sud-Ouest

THEME
**Computational Neuroscience and
Medicine**

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Project-Team MNEMOSYNE

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Keywords:

Computer Science and Digital Science:

- A1.1.12. - Non-conventional architectures
- A1.5. - Complex systems
- A3.1.1. - Modeling, representation
- A3.1.7. - Open data
- A3.2.2. - Knowledge extraction, cleaning
- A3.2.5. - Ontologies
- A3.3. - Data and knowledge analysis
- A3.3.2. - Data mining
- A3.4.1. - Supervised learning
- A3.4.2. - Unsupervised learning
- A3.4.3. - Reinforcement learning
- A3.4.4. - Optimization and learning
- A3.4.6. - Neural networks
- A3.4.8. - Deep learning
- A5.1.1. - Engineering of interactive systems
- A5.1.2. - Evaluation of interactive systems
- A5.2. - Data visualization
- A5.3.3. - Pattern recognition
- A5.4.1. - Object recognition
- A5.4.2. - Activity recognition
- A5.7.1. - Sound
- A5.7.3. - Speech
- A5.7.4. - Analysis
- A5.8. - Natural language processing
- A5.9.1. - Sampling, acquisition
- A5.10.5. - Robot interaction (with the environment, humans, other robots)
- A5.10.7. - Learning
- A5.10.8. - Cognitive robotics and systems
- A5.11.1. - Human activity analysis and recognition
- A7.1. - Algorithms
- A9.2. - Machine learning
- A9.5. - Robotics

Other Research Topics and Application Domains:

- B1.2. - Neuroscience and cognitive science
- B1.2.1. - Understanding and simulation of the brain and the nervous system
- B1.2.2. - Cognitive science
- B2.2.6. - Neurodegenerative diseases

- B8.5.2. - Crowd sourcing
- B9.1.1. - E-learning, MOOC
- B9.5.1. - Computer science
- B9.6.8. - Linguistics
- B9.7. - Knowledge dissemination
- B9.8. - Reproducibility
- B9.11.1. - Environmental risks

1. Team, Visitors, External Collaborators

Research Scientists

- Frédéric Alexandre [Inria, Team leader, Senior Researcher, HDR]
- Xavier Hinaut [Inria, Researcher]
- Randa Kassab [Inria, Advanced Research Position, until Aug 2018]
- Nicolas Rougier [Inria, Researcher, HDR]
- Thierry Viéville [Inria, Senior Researcher (part-time (50%) in the project-team), HDR]

Faculty Member

- André Garenne [Univ de Bordeaux, Associate Professor]

PhD Students

- Ikram Chraïbi Kaadoud [Univ. Bordeaux, PhD Student, granted by CIFRE, until Feb 2018]
- Thalita Firmo Drumond [Inria]
- Pramod Kaushik [Inria, from Oct 2018]
- Bhargav Teja Nallapu [Inria]
- Guillaume Padiolleau [CEA, from Sep 2018]
- Silvia Pagliarini [Inria]
- Remya Sankar [Inria, from Oct 2018]
- Anthony Strock [Univ de Bordeaux]

Interns

- Edwige Cyffers [Inria, from Jun 2018 until Jul 2018]
- Romain Ferrand [Inria, from Jun 2018 until Jul 2018]
- Basile Garcia [Inria, from Feb 2018 until Jul 2018]
- Pierre Marcus [Inria, from Jun 2018 until Jul 2018]

Administrative Assistant

- Chrystel Plumejeau [Inria, Assistant (part time in the team)]

External Collaborator

- Arthur Leblois [CNRS, HDR]

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 mnemonic 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. 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 protocols.

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 [49]. 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 [46], 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 undoubtedly 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 [51], [40]. 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 heterogeneous 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 mimic 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 homunculus or any central clock. Numerical schemes developed for distributed dynamical systems and algorithms elaborated for distributed computations are of central interest here [37], [45] and were the basis for several contributions in our group [50], [47], [52]. 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 [38]; the associated formalism [43] 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 [35], that demonstrated a richness of behavior [39] 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 [47], [48] and their use for observing the emergence of typical cortical properties [42]. 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. 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.

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 [44] 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 [41], [34]. 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 episodes and supervising the training of a procedural memory in the cortex.

At the behavioral level, as mentioned 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 continuous re-arrangement is supposed to involve several kinds of learning,

at different time scales (from msec to years in humans) and to interfere 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 protocols 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* [36]). 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 mimic 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 mnemonic 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 undoubtedly 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

We published this year an important article [3], together with neuroscientist colleagues in our laboratory. We are particularly proud of this paper because it illustrates a very fruitful cooperation between modeling and experimental analysis, particularly allowing to revisit current views about a dogma in neuroscience, concerning the place where habits are learned and their role in cognition.

6. New Software and Platforms

6.1. DANA

Distributed Asynchronous Numerical and Adaptive computing framework

KEYWORD: Neural networks

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.).

- Participant: Nicolas Rougier
- Contact: Nicolas Rougier
- URL: <http://dana.loria.fr/>

6.2. Virtual Enaction

KEYWORDS: Neurosciences - Simulation - Health

FUNCTIONAL DESCRIPTION: VirtualEnaction: A Platform for Systemic Neuroscience Simulation. The computational models studied in this project 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 both (i) deploy an existing open-source video game middleware in order to be able to shape the survival situation to be studied and (ii) revisit the existing models in order to be able to integrate them as an effective brainy-bot. It consists of a platform associated to a scenario that is the closest possible to a survival situation (foraging, predator-prey relationship, partner approach to reproduction) and in which it is easy to integrate 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 will correspond to the major anatomical regions involved in the issues of learning and action selection (cortex areas detailed here, basal ganglia, hippocampus, and areas dedicated to sensorimotor processes). The internal game clock can be slowed down enough to be able to run non trivial brainy-bot implementations. This platform has already being used by two students of the team and is now a new deliverable of the KEOpS project.

- Participants: André Garenne, Frédéric Alexandre, Nicolas Rougier and Thierry Viéville
- Contact: Frédéric Alexandre

6.3. Mnemonas

KEYWORDS: Recurrent network - Manifold

FUNCTIONAL DESCRIPTION: This source bundle provides source files of the: - Manifold representation of ontology for machine learning (in progress). - Recurrent neural network weight estimation though backward tuning publication.

- Contact: Thierry Viéville

6.4. ReservoirPy

KEYWORDS: Recurrent network - Artificial intelligence - Reservoir Computing - Multi-label classification - Timeseries Prediction - Time Series - Machine learning - Classification

FUNCTIONAL DESCRIPTION: This toolbox provides a class of Echo State Networks that can be used with Python and its scientific libraries like Numpy, Scipy and Matplotlib. It includes useful expertise to train recurrent neural networks of ESN architecture kind.

ESN is a particular kind of recurrent neural network (RNN) with or without leaky neurons. The input stream is projected to a random recurrent layer and a linear output layer (called "read-out") is modified by learning (which can also be done in an online fashion).

Compared to other RNNs, the input layer and the recurrent layer (called "reservoir") do not need to be trained. For other RNNs, the structure of the recurrent layer evolves in most cases by gradient descent algorithms like Backpropagation-Through-Time, which is not biologically plausible and is adapted iteratively to be able to hold a representation of the input sequence. In contrast, the random weights of the ESN's reservoir are not trained, but adapted to possess the "Echo State Property" (ESP) or at least suitable dynamics (e.g. 'edge of chaos') to generalize, which includes a non-linear transformation of the input that can be learned by a linear classifier. The weights are adapted by scaling the weights based on the maximum absolute eigenvalue (also called spectral radius), which is a hyperparameter specific to the task. The states of the reservoir are linearly separable and can be mapped to the output layer by a computationally cheap linear regression, as no gradient descent is necessary. The weights of the input layer can be scaled by the input scaling hyperparameter, which also depends on the nature of the inputs.

- Partners: Université de Hamburg - University of Hamburg
- Contact: Xavier Hinaut
- URL: <https://github.com/neuronalX/reservoirpy>

7. New Results

7.1. Overview

This year we have explored the main cortico-basal loops of the cerebral architecture and their associated memory mechanisms. The limbic loop (*cf.* § 7.2) concerns the taking into account of the emotional and motivational aspects by the respondent and operant conditioning and their relations with the semantic and episodic memories. The associative loop (*cf.* § 7.3) is about mechanisms of working memory. Concerning the motor loop (*cf.* § 7.4), we have studied mechanisms of song acquisition and production in birds.

We have also worked on the systemic integration of our models (*cf.* § 7.5), raising the question of the conditions of autonomous learning and certain global characteristics such as the transition from goal-directed to habitual behaviors.

Finally, we study the links between our bio-inspired modeling work and Machine Learning (*cf.* § 7.6), revisiting this latter domain in the light of the principles highlighted by our models.

7.2. The limbic loop

We have continued to explore the mnemonic characteristics of the main information flows and cerebral structures interacting with the limbic loop. This is the case with the main learning paradigms associated to the involvement of the amygdala in respondent conditioning [16]. We have also continued our work on the hippocampus and particularly its function of pattern separation [7].

7.3. The associative loop

The prefrontal cortex is known to be involved in many high-level cognitive functions, in particular working memory. In [23], we studied to what extent a group of randomly connected units (namely an Echo State Network, ESN) can store and maintain (as output) an arbitrary real value from a streamed input, i.e. can act as a sustained working memory unit. Furthermore, we explored to what extent such an architecture can take advantage of the stored value in order to produce non-linear computations. Comparison between different architectures (with and without feedback, with and without a working memory unit) shows that an explicit memory improves the performances. This property of the model can be considered as a gated memory: a value enters the memory at the moment of the (input) trigger and is kept constant in face of incoming distractors (the continuous streamed input).

7.4. The motor loop

Sensorimotor learning represents a challenging problem for artificial and natural systems. Several computational models try to explain the neural mechanisms at play in the brain to implement such learning. These models have several common components: a motor control model, a sensory system and a learning architecture. In S. Pagliarini's PhD, our challenge is to build a biologically plausible model for song learning in birds including neuro-anatomical and developmental constraints.

We made a review on a specific type of sensorimotor learning referred to as imitative vocal learning and exemplified by song learning in birds or human complex vocalizations. We aim to compare the various approaches used in existent sensorimotor models relevant for our purpose and to place them in a common framework. We propose a bio-inspired model for an imitative sensorimotor learning, which aims at building a map between the sensory representations of gestures (sensory targets) and their underlying motor pattern through random exploration of the motor space. An example of such learning process occurs during vocal learning in humans or birds, when young subjects babble and learn to copy previously heard adult vocalizations. Previous work (by Hahnloser and Ganguli) has suggested that a simple Hebbian learning rule allows perfect imitation when sensory feedback is a purely linear function of the motor pattern underlying movement production. We aim at generalizing this model to the more realistic case where sensory responses are sparse and non-linear. To this end, we explore the performance of various learning rules and normalizations. Importantly, the proposed model is robust whatever normalization is chosen. We showed that both the imitation quality and the convergence time are highly dependent on the sensory selectivity and dimension of the motor representation.

On this topic, X. Hinaut is also collaborating with Catherine del Negro's team (CNRS, University of Paris-Sud, Orsay) on the representation of syntax in songbird brains. In particular, the project aims at (1) linking the neural activity of a sensori-motor area (HVC) to syntax elements in the songs of domestic canaries ; (2) analysing the audio files and transcripts of canary songs in order to find syntax cues and higher order representations (graph properties of songs, evaluate Markovian forward and backward transition probabilities of various orders). The song analyses part has been performed with the help of a L3 intern, Pierre Marcus.

7.5. Systemic integration

This year, we have considered characteristics of interactions of cortico-basal loops [32], firstly to continue the development of a software environment based on the Minecraft videogame allowing for the survival behavior of an autonomous agent [25], [24] and secondly to revisit the principles of habits formation.

The dorsal pallium (a.k.a. the cortex in the mammals) makes a large loop circuit with the basal ganglia and the thalamus known to control and adapt behavior but the who's who of the functional roles of these structures is still debated. Influenced by the Triune brain theory that was proposed in the early sixties, many current theories propose a hierarchical organization on the top of which stands the cortex to which the subcortical structures are subordinated. In particular, habits formation has been proposed to reflect a switch from conscious on-line control of behavior by the cortex, to a fully automated subcortical control. We have proposed in [3] instead to revalue the function of the network in light of the current experimental evidence concerning the anatomy and physiology of the basal ganglia-cortical circuits in vertebrates.

This theory is supported by a model [11] that includes interactions between the cortex, the basal ganglia and the thalamus based on a dual competition. We hypothesize that the striatum, the subthalamic nucleus, the internal pallidum (GPi), the thalamus, and the cortex are involved in closed feedback loops through the hyperdirect and direct pathways. These loops support a competition process that results in the ability of basal ganglia to make a cognitive decision followed by a motor decision. Considering lateral cortical interactions, another competition takes place inside the cortex allowing the latter to make a cognitive and a motor decision. We show how this dual competition endows the model with two regimes. One is driven by reinforcement learning, the other by Hebbian learning. The final decision is made according to a combination of these two mechanisms with a gradual transfer from the former to the latter. We confirmed these theoretical results on primates (*Macaca mulata*) using a novel paradigm predicted by the model.

7.6. Machine Learning

In this section, we report on some neuronal adaptive mechanisms, that we develop at the frontier between Machine Learning and Computational Neuroscience. Our goal is to consider and adapt models in Machine Learning for their integration in a bio-inspired framework.

Concerning the manipulation of temporal sequences, we have proposed an original algorithm for the extraction of sequences from LSTM, a major class of recurrent neural networks [1]. These sequences are then interpreted as rules representing implicit knowledge within electrical diagrams (*cf.* § 8.1).

Concerning our work on reservoir computing, X. Hinaut is collaborating with Michael Spranger (Sony Lab, Tokyo, Japan) on grounding of language, adapting Hinaut's previous Reservoir Language Model (RLM) with the representational system of Spranger: IRL (Incremental Recruitment Language). He is also collaborating with Hamburg on the use of reservoir models for robotic tasks (*cf.* § 9.3). In this work, we have shown that the RLM can successfully learn to parse sentences related to home scenarios in fifteen languages [6]. This demonstrates that (1) the learning principle of our model is not limited to a particular language (or particular sentence structures), and (2) it can deal with various kinds of representations (not only predicates), which enable users to adapt it to their own needs.

Regarding the extraction of characteristics from and the use of hierarchical networks, as in the case of deep networks, we have been able to consider how to deal with not-so-big data sets, and target the notion of interpretability of the obtained results which is a key issue: since deep learning applications are increasingly present in the society, it is important that the underlying processes be accessible and understandable to every one. In order to target these challenges, we have analyzed how considering prototypes in a rather generalized sense (with respect to the state of the art) allows to reasonably work with small data sets while providing an interpretable view of the obtained results. Some mathematical interpretation of this proposal have also been discussed. Sensitivity to hyperparameters is a key issue for reproducible deep learning results, and has been carefully considered in our methodology. Performances and (even more interesting, in a sense) limitations of the proposed setup have been explored in details, under different hyperparameters sets, in an analogous way as biological experiments are conducted. We obtain a rather simple architecture, easy to explain, and which allows, combined with a standard method, to target both performances and interpretability [4].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Contract with Algotech

Participants: Frédéric Alexandre, Ikram Chraïbi 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 transferring our bio-inspired models to the domain of classical machine learning. Particularly, during the PhD of Ikram Chraïbi Kaadoud (defended this year), we have worked on the extraction of implicit knowledge, from the learning of sequences, extracted from diagrams.

8.1.2. Contract with CEA Cesta

Participants: Frédéric Alexandre, Guillaume Padiolleau.

In the context of the PhD of Guillaume Padiolleau, we are working with the CEA on possible interactions between model-based and model-free approaches of reinforcement learning, based on cognitive consideration. Particularly, to decrease the complexity of exploration of a large data space in model-free approaches, we aim at considering introducing a priori knowledge coming from a model and we also propose to consider motivation as another way to orient the search in the learning space. This is applied in the robotic domain to manipulations by a robotic arm.

8.1.3. *Contract with Ubisoft*

Participants: Frédéric Alexandre, Pramod Kaushik.

Together with the Inria Project-team Flowers, we are working with the video game editor Ubisoft to define original bio-inspired learning methods, to qualify the behavior of human players observed during runs of games. Such learning algorithms will be specifically considered in the PhD of Pramod Kaushik.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. *PsyPhINe*

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 at exploring 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. We've organized our third national conference in Nancy gathering speakers from philosophy, robotics, art and psychology and closed a three years cycle. The group now aims at publishing a book gathering text from all the invited speakers.

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 describing 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 SOMA (PRCI)*

Participants: Nicolas Rougier, Remya Sankar.

This project is a convergence point between past research approaches toward new computational paradigms: adaptive reconfigurable architecture, cellular computing, computational neuroscience, and neuromorphic hardware:

1. SOMA is an adaptive reconfigurable architecture to the extent that it will dynamically re-organize both its computation and its communication by adapting itself to the data to process.
2. SOMA is based on cellular computing since it targets a massively parallel, distributed and decentralized neuromorphic architecture.
3. SOMA is based on computational neuroscience since its self-organization capabilities are inspired from neural mechanisms.
4. SOMA is a neuromorphic hardware system since its organization emerges from the interactions between neural maps transposed into hardware from brain observation.

This project represents a significant step toward the definition of a true fine-grained distributed, adaptive and decentralized neural computation framework. Using self-organized neural populations onto a cellular machine where local routing resources are not separated from computational resources, it will ensure natural scalability and adaptability as well as a better performance/power consumption tradeoff compared to other conventional embedded solutions.

9.2.3. 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.

9.2.4. 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. Altogether, our experimental findings provide evidence for dose-dependent effects of RF signals on the bursting rate of neuronal cultures and suggest that part of the mechanism is nonthermal (publication in Journal of Neurophysiology). In an attempt to elucidate the depressing effect of GSM on in-vitro neuronal activity, pharmacological studies have also been realized on cortical cells.

9.3. International Initiatives

9.3.1. Participation in International Programs

9.3.1.1. 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.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Chair of Conference Program Committees

X. Hinaut: organisation of the Workshop on Language and Robotics (follower of the ML-HLCR workshop at IROS 2017), at IROS, 1st of October 2018, Madrid, Spain, <http://iros2018.emergent-symbol.systems/>. <http://iros2018.emergent-symbol.systems/>.

10.1.1.2. Member of the Conference Program Committees

F. Alexandre: TAIMA'18; SAB'18; X. Hinaut: ICDL-Epirob'18; N. Rougier: WSOM'18;

10.1.1.3. Reviewer

X. Hinaut: ICDL-epirob'18; CogSci'18; IJCNN'18; ESANN'18;

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

- Frédéric Alexandre: Academic Editor for PLOS ONE; Review Editor for Frontiers in Neurorobotics;
- Nicolas Rougier: Editor in chief for ReScience, Academic editor for PeerJ, review editor for Frontiers in Neurorobotics.
- Xavier Hinaut: guest editor in the Journal Advanced Robotics of a special issue on "Machine Learning Methods for High-Level Cognitive-Capabilities-in-Robotics"

10.1.2.2. Reviewer - Reviewing Activities

- F. Alexandre: Elife; EMBC; Frontiers in Neurobotics; Neurobiology of Disease; PLoS ONE
- André Garenne: Journal of Integrative Neuroscience
- Xavier Hinaut: Adaptive Behavior; Applied Science; Cognitive Computation; Cognitive Systems (CogSys); Neural Networks; ReScience; Transactions in Human-Robot Interaction (THRI); Transactions in Cognitive Developmental Systems (TCDS);
- Nicolas Rougier: Frontiers in Neuroinformatics, Frontiers in Neurobotics, Frontiers in Computational Neuroscience, PLOS Computational Biology, PeerJ;
- Thierry Viéville: Frontiers in Neuroinformatics, Frontiers in Neurobotics, Frontiers in Computational Neuroscience

10.1.3. Invited Talks

F. Alexandre:

- "When cognitive neursciences revisit Artificial Intelligence", Big Data Seminar of the Labri, February 8 and 22 (in two parts);
- "Understanding or transforming the human being ?", Annual meeting of the International Catholic Center for cooperation with UNESCO, Paris, May 4;

- “Modelling the medial prefrontal cortex for the motivated behaviour of an autonomous agent in the Minecraft video game”, Symposium «Frontiers in medial prefrontal cortex research», Bordeaux, September 6;
- “Modeling the functional organization of the medial and ventral prefrontal cortex”, Symposium on Cognitive Systems, Chemnitz (Germany), September 13;
- “Does Artificial Intelligence learn from its errors ?”, Colloquium Cathy Dufour on Artificial Intelligence, University of Lorraine, November 16;
- “The contributions of Machine Learning to research on neurodegenerative diseases”, in the annual meeting of the Bordeaux Initiative for Neurodegenerative Disorders (BIND), about Technological Innovations and Neurodegenerative Diseases (November, 23);

Ikram Chraïbi Kaadoud: La Grande Jonction (Bordeaux);

Silvia Pagliarini at the European Birdsong Meeting, Odense, Denmark;

N. Rougier:

- Berstein Conference / PhD symposium (Berlin);
- ICML, Workshop on reproducibility in Machine Learning (Stockholm);
- Loria (Nancy);
- Digital Aquitaine / Club Commerce Connecté (Bordeaux);
- Phiteco conference (Compiègne);

10.1.4. Leadership within the Scientific Community

X. Hinaut:

- President of the association MindLaBDX: “open citizen lab” in Cognitive Sciences and Artificial Intelligence in Bordeaux.
- member of the Administration Committee of Fresco association (French Federation of students in Cognitive Science)

Nicolas Rougier: Editor in chief for ReScience

10.1.5. 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. He is also an expert for the Association Robert Debré for Medical Research.

Nicolas Rougier: UNESCO; Engineering and Physical Sciences Research Council (UK); Assistance Publique Hopitaux de Paris; Eurostars program (Eureka).

10.1.6. 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 (until september2018); member of the Inria monitoring and forecasting cell; 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; IES referent for Inria Bordeaux Sud-Ouest; Member of the committee for researcher recruitment; Member of the steering committee for the BioComp CNRS consortium; Editor in chief and co-founder of ReScience.

- Thierry Viéville is in charge of the <http://classcode.fr> project and in charge, for Inria, of the creation of a Master SmartEdTech at UCA within the scope of his mission for the Inria Sophia Antipolis - Méditerranée direction.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

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 teaching computer thinking in the Msc #CreaSmartEdtech ("Digital Expertise", "Educational Informatics" including Artificial Intelligence and Ontologies, "Digital Intedisciplinary Project ") and is co-organizing this Master of Science [29]. In addition, this year, N. Rougier gave tutorials to the Advanced Python Programming for Science summer school (Camerino, Italy) and a Digital Typography course (SIGGRAPH, Vancouver, Canada). In May, X. Hinaut gave an invited course on Echo State Networks in the Neural Networks lecture of the Master of Science on Intelligent Adaptive Systems of the University of Hamburg. F. Alexandre, X. Hinaut and N. Rougier have been participating and teaching to the "Robotics and Social Interactions" summer school (October 1-4, Moliets-et-Maa). We can also mention that S. Pagliarini (PhD student) was selected to participate to the OIST Computational Summer Course (June 24-July 15, Okinawa, Japan).

10.2.2. Juries

In addition to several juries in France, we can note a reviewing and participation to a PhD defense in Germany (F. Alexandre)

10.3. Popularization

10.3.1. Internal or external Inria responsibilities

Thierry Viéville is in charge of mission regarding e-education in particular the collaborations with the UCA university on these subjects, more precisely the LINE laboratory ESPE of Nice where he is affected at 20%, for the creation and co-direction of the MSc and the relation with EducAzur, and the actions within the Class Code project.

10.3.2. Articles and contents

- For online publications: F. Alexandre in Usbek & Rica (June 8) and Inriality (May 17): <https://usbeketrica.com/article/2067-la-singularite-empire-des-machines> and <https://www.inriality.fr/informatique/informatique-ia-intelligence-artificielle/2067-la-singularite-ou/>;
- Interviews in order to popularize: F. Alexandre in La Tribune newspaper (September 10): <https://objectifaquitaine.latribune.fr/innovation/2018-09-10/inria-bordeaux-10-ans-de-recherches-a-la-pointe-du-numerique-789911.html>; I. Chraïbi Kaadoud and A. Garenne in blog scilogs about neural networks: <http://www.scilogs.fr/intelligence-mecanique/architecture-reseaux-de-neurones-de-choix/>; <http://www.scilogs.fr/intelligence-mecanique/architecture-des-reseaux-de-neurones-reseaux-de-neurones-artificiels-classiques-2-3/> and <http://www.scilogs.fr/intelligence-mecanique/architecture-des-reseaux-de-neurones-reseaux-de-neurones-impulsionnels-3-3/>; X. Hinaut about organizing a Hackathon in <https://pixees.fr/hack1-cerveau/>; N. Rougier in CNRS website (September 21): <http://www4.cnrs-dir.fr/insb/recherche/parutions/articles2018/t-boraud.html> and in Le Monde newspaper (September 19): https://www.lemonde.fr/sciences/article/2018/09/19/les-emotions-au-coeur-de-l-apprentissage_5357127_1650684.html; Thierry Viéville is co-editor and/or co-author of about two papers per month on <http://binaire.blog.lemonde.fr>.

10.3.3. Education

F. Alexandre: Teaching to the high-school professors in Philosophy of the academy of Poitiers about Artificial Intelligence (April, 25); Thierry Viéville has realized more than ten session of formation (over 400 teachers involved) within the scope of the Class Code project, and co-organized two of them.

10.3.4. Interventions

- National events: participation of the team on the NeuroCampus to the Week of the Brain (Semaine du Cerveau: March 19-23); to the Declics program for high-schools (<http://www.cerclefer.org/fr/declics/>, Nov. 22); Fête de la Science at Inria Bordeaux and Cap Sciences in October: The humanoid Nao robot was listening to the instructions and learning names of objects. This demo was performed by X. Hinaut and A. Strock with a German collaborator from the University of Hamburg (J. Twiefel).
- Public exhibitions:
 - “Brain and Artificial Intelligence” at Regional Headquarters in Limoges (Feb. 2);
 - “What is the usefulness of Artificial Intelligence ?” at Café des Sciences in Soustons (Dec. 12) (F. Alexandre);
 - Science pour tous (Bordeaux), Machine learning (Communauté Urbaine de Bordeaux), AI Unplugged (Bordeaux), Déambulation autour de l’IA (Bordeaux), L’intelligence artificielle en question (Paris) (N. Rougier);
 - Participation to the Neurocampus Day (S. Pagliarini, poster “Learning an inverse model for vocal production: toward a bio-inspired model”);
 - Thierry Viéville: Interventions on artificial Intelligence and the development of critical thinking on large audience popularization events (Universcience, Médiathèque de Bordeaux, Semaine du Cerveau, Fête de la Science, Select Sophia-Antipolis, more than 200 persons involved) and three interactive talks in high-school (more than 150 students involved).
 - T. Firmo Drumond and B. Teja Nallapu prepared and presented a demo for the 10 years of the Bordeaux Inria Centre (September 27).
 - N. Rougier and X. Hinaut participated to a theater performance on AI, showing the state of work of an artistic residence in November.

10.3.5. Internal action

- Internal meetings: T. Firmo Drumond presented Deep Learning to the Inria Bordeaux Café des Sciences (March 22);
- Nicolas Rougier gave a talk about scientific fraud and misconduct at the institute of neurodegenerative diseases.

10.3.6. Creation of media or tools for science outreach

Thanks to fundings from the Bordeaux Museum of Science Cap Sciences (<http://www.cap-sciences.net/>) and from the Foundation Blaise Pascal (<https://www.fondation-blaise-pascal.org/>), we have begun to design a software tool to run small demonstrative scenarios, to help everyone discover the brain functions at the origin of our sensorimotor and vital cognitive behaviors (instinctive and motivated behavior, selection of embodied action, emotional decision-making, seat of self-awareness, etc.). This resource is for a wide audience to whom we can show scenarios, but also co-build multi-media resources to share methods and knowledge (participatory scientific mediation approach) and to discuss these topics. It is also at the disposal of scientific mediators (researchers and beyond) who wish to co-construct such resources, or to present research results involving the animation of anatomy of the nervous system as well as of users or authors of computer code who want to reuse shared technologies to derive other applications, in particular become familiar with the specification languages (here JSON and markdown).

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