RESEARCH CENTRE

Bordeaux - Sud-Ouest

IN PARTNERSHIP WITH:

Université de Bordeaux, CNRS, Institut Polytechnique de Bordeaux

2021
ACTIVITY REPORT

Project-Team
MNEMOSYNE

Mnemonic Synergy

IN COLLABORATION WITH: Laboratoire Bordelais de Recherche en Informatique (LaBRI)

DOMAIN

Digital Health, Biology and Earth

THEME

Computational Neuroscience and Medicine

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Project-Team MNEMOSYNE

Creation of the Project-Team: 2014 July 01

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1 Team members, visitors, external collaborators

Research Scientists

- Frédéric Alexandre [Team leader, Inria, Senior Researcher, HDR]
- Amélie Aussel [Inria, from Nov 2021, Starting Faculty Position]
- Xavier Hinaut [Inria, Researcher]
- Nicolas Rougier [Inria, Researcher, HDR]
- Thierry Viéville [Inria, Senior Researcher, HDR]

Post-Doctoral Fellow

- Jianyong Xue [Inria]

PhD Students

- Naomi Chaix-Eichel [Univ de Bordeaux, from Oct 2021]
- Hugo Chateau-Laurent [Inria]
- Snigdha Dagar [Inria]
- Fjola Hyseni [Univ de Bordeaux]
- Chloe Mercier [Inria]
- Subba Reddy Oota [Inria]
- Guillaume Padiolleau [CEA]
- Silvia Pagliarini [Univ de Bordeaux, until Feb 2021]
- Axel Palaude [Inria, from Oct 2021]
- Remya Sankar [Inria]
- Nikolaos Vardalakis [Univ de Bordeaux]

Technical Staff

- Cyril Regan [Inria, Engineer, until Sep 2021]
- Nathan Trouvain [Inria, Engineer]

Interns and Apprentices

- Lola Denet [Inria, from Feb 2021 until Aug 2021]
- Gabriel Doriath Dohler [Inria, from Jun 2021 until Jul 2021]
- Ali Issaoui [Inria, Jan 2021]
- Ammar Kheder [Inria, Apprentice, from Oct 2021]
- Quentin Lanneau [Inria, from Mar 2021 until Aug 2021]
- Bastien Lhopitallier [Inria, from May 2021 until Jul 2021]
- Tanguy Pemeja [Inria, from Mar 2021 until Aug 2021]

- Bhushan Rugbursing [Université de Bordeaux, from Jun 2021 until Jul 2021]
- Karen Sobriel [Inria, from Apr 2021 until Jun 2021]
- Theophane Vallaeys [Ecole normale supérieure Paris-Saclay, from Jun 2021 until Jul 2021]
- Quan Zhang [Inria, from Apr 2021 until Aug 2021]

Administrative Assistant

- Chrystel Plumejeau [Inria]

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 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

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 [64]. 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 [59], 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 [66, 57]. 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 [53, 52] and were the basis for several contributions in our group [65, 61, 67]. 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 [58]; the associated formalism [68] 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 [62], that demonstrated a richness of behavior [63] 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 [61, 60] and their use for observing the emergence of typical cortical properties [55]. 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 [56] 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 [54, 50]. 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* [51]). 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

Modeling the brain to emulate cognitive functions offers direct and indirect application domains. Our models are designed to be confronted to the reality of life sciences and to make predictions in neuroscience and in the medical domain. Our models also have an impact in digital sciences; their performances can be questioned in informatics, their algorithms can be compared with models in machine learning and artificial intelligence, their behavior can be analysed in human-robot interaction. But since what they produce is related to human thinking and behavior, applications will be also possible in various domains of social sciences and humanities.

4.2 Applications in life sciences

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. 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 and related domains like for example educational science.

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.

4.3 Application in digital sciences

Of course, digital 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 undoubtly 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.

4.4 Applications in human sciences

Because we model specific aspects of cognition such as learning, language and decision, our models could be directly analysed from the perspective of educational sciences, linguistics and economy. Because we manipulate such concepts as embodiment of cognition, theory of mind and emotions, we could also participate in debates in philosophy and ethics.

Futhermore, our implication in science outreach actions, including computer science teaching in secondary and primary school, with the will to analyse and evaluate the outcomes of these actions, is at the origin of building a link between our research in computational learning and human learning, providing not only tools but also new modeling paradigms.

5 Social and environmental responsibility

5.1 Footprint of research activities

As part of the Institute of Neurodegenerative Diseases that developed a strong commitment to the environment, we take our share in the reduction of our carbon footprint by deciding to reduce our commuting footprint and the number of yearly travels to conference. In 2021, this collided again with the sanitary crisis that de facto reduced our travel capacity. But beyond the crisis, we aim at enforcing this policy.

5.2 Impact of research results

We're engaged in the EcoMob regional project in collaboration with the University of Bordeaux and the University of La Rochelle to study and model the behavior of individuals during their daily trips to and from work places. In this context and based on our previous work on decision making, our team is interested in elucidating how habits are formed and more importantly, how can they be changed. This year, we participated to an activity of dissemination on this topic (and were awarded for that, *cf.* § 11.3.3).

6 Highlights of the year

6.1 Awards

X. Hinaut was awarded a young investigator ANR grant for the project DeepPool: "Hierarchical reservoirs to model language processing and production". This will enable to extend our studies on hierarchical reservoir computing [3] and sensorimotor models [25].

F. Alexandre and **N. Rougier** were awarded a Talents U 2021 for their active participation to the Climackathon initiative of university of Bordeaux that took place on March 12 and 13, 2021. During two half days, 30 students, scientists and staff co-created solutions to the following problem: how to engage the university community on climate change and motivate behavioral change ?

6.2 Recrutiment and promotions

A. Aussel has been recruited on an ISFP position.

N. Rougier has been promoted to a research director position.

6.3 Events

N. Rougier co-organized the first edition of a recurrent Science & Fiction festival (Hypermondes) mixing literature and sciences. The topic of the first edition was about Robotics. It gathered more than 40 SF authors, 15 scientists and 2500 people during the three days of the festival.

N. Rougier published an open access book on scientific visualization [4] which totaled 100,000 downloads in one week.

7 New software and platforms

7.1 New software

7.1.1 ReservoirPy

Name: Reservoir computing with Python

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

Scientific Description: Reservoirs Computing is based on random Recurrent Neural Networks (RNNs). ESNs are a particular kind of networks with or without leaking neurons. The computing principle can be seen as a temporal SVM (Support Vector Machine): random projections are used to make dimensionality expansion of the inputs. The input stream is projected to a random recurrent layer and a linear output layer (called "read-out") is modified by learning. This training is often done offline, but 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 representaion of the input sequence. In contrast, the random weights of the ESN's reservoir are not trained, but are often adapted to possess the "Echo State Property" (ESP) or at least suitable dynamics to generalize. The reservoir activities include non-linear transformations of the inputs that are then exploited by a linear layer. The states of the reservoir can be mapped to the output layer by a computationally cheap linear regression. The weights of the input and recurrent layer can be scaled depending on the task at hand: these are considered as hyperparameters (i.e. parameters which are not learned) along with the leaking rate (or time constant) of neurons and the random matrix densities.

Functional Description: This library provides implementations and tools for the Reservoir Computing paradigm: a way of training Recurrent Neural Networks without training all the weights, by using random projections. ReservoirPy provides an implementation only relying on general scientific librairies like Numpy and Scipy, in order to be more versatile than specific frameworks (e.g. TensorFlow, PyTorch) and provide more flexibilty to build custom architectures. It includes useful and advanced features to train reservoirs. ReservoirPy especially focuses on the Echo State Networks flavour, based on average firing rate neurons with tanh (hyperbolic tangent) activation function.

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News of the Year: The last stable release (0.3.0) has been launched. It enables the creation of complex architectures (deepESN, Hierarchical ESN, coupled reservoirs...). It features online and offline learning rules, feedback connections, optimisation of training and running for Echo State Networks (parallelisation, improved memory efficiency), ready-to-use benchmark timeseries. Implementation of models from literature. Redaction of documentation, tutorials and examples. Presentation of the tool in several conferences and workshops.

URL: `https://github.com/reservoirpy/reservoirpy`

Publication: hal-02595026

Contact: Xavier Hinaut

Participants: Xavier Hinaut, Nathan Trouvain, Nicolas Rougier

7.1.2 Neurosmart

Name: Neurosmart

Keywords: Science outreach, Web Application, JavaScript, JSon, Cognitive sciences, Neurosciences

Functional Description: The software consists of a web interface allowing to run the scenario of a presentation of cognitive functions while visualizing the brain areas involved. It's made of : - a 3D brain model - an interactive visualization module of this brain model with low computation consumption - a command language in JSON syntax to drive the display of the model and interactive multi-media content, which can be extended - an "indulgent" JSON syntax analyzer, i.e., allowing to build the data structure with a minimum of control characters, all is programmed in Javascript to run in any browser.

Release Contributions: Initial version

URL: `https://gitlab.inria.fr/mnemosyne/neurosmart`

Contact: Thierry Viéville

Partners: Fondation Blaise Pascal, EchoScience

7.1.3 AIDElibs

Name: Artificial Intelligence Devoted to Education

Keywords: Cognitive sciences, Neurosciences, Educational Science, C++, JavaScript, Python, Connected object, Automatic Learning, Learning

Functional Description: This library includes - a set of C/C++ routines for basic calculations, with the portions of code executed on connected objects which allow measurement of learning traces, and the control of experiments, - C/C ++ or Javascript tools to interface the different software modules used, and a Python wrapper to develop above these functionalities.

Release Contributions: Initial version

URL: `https://gitlab.inria.fr/line/aide-group/aide`

Contact: Thierry Viéville

Partners: Laboratoire LINE, Université Côte d'Azur, PoBot

8 New results

8.1 Overview

This year we have addressed several important questions related to our scientific positioning. Central to this positioning, we have studied and modeled bio-inspired learning mechanisms and collaborative mnesic functions (*cf.* § 8.2). We have also studied higher cognitive functions, related to cognitive control (*cf.* § 8.3) and have also considered how important characteristics can be associated to this framework, like symbolic abstract knowledge (*cf.* § 8.4), and oscillations (*cf.* § 8.5). Endly, we have also pursued our work on language processing in birds and robots (*cf.* § 8.6).

8.2 Learning mechanisms and collaborative mnesic functions

This year, we have published a paper summarizing our general approach and proposing a global framework integrating the various mnesic functions and their interactions [1]. We have been working on several bio-plausible learning mechanisms like hebbian learning, contrastive divergent learning (CDL) and reinforcement learning and their combination in different frameworks. This is the case for the development of original versions of Restricted Boltzmann Machines in robotic applications (*cf.* § 9.1.1) and for the development of Reservoir Computing. Within the ReservoirPy library (developed in the team) we have included several offline and online learning mechanisms, parallel implementation and various advanced features. We worked on the parallelisation with the HiePACS project-team. This new release of ReservoirPy (v0.3.0) enables to build complex reservoir architectures (we give some examples as python notebooks). We demonstrated the training speed of the parallel implementation in a study on birdsong decoding [26]: we included a comparison with LSTMs which should to be much slower and perform worse on few data than reservoirs. Additionally, we proposed a general method to search reservoir hyperparameters for any task, using visual tools proposed in ReservoirPy [21].

We've also investigated the development of automatized skills, such as song production in the songbird that is driven by the basal ganglia through dopamine-modulated reinforcement learning in order to guide learning in a parallel "cortical" pathway, which eventually governs the production of the skill [6]. From a theoretical perspective, this can be considered as a dual learning system, one being reactive and dependent on instantaneous reward (reinforcement learning) while the other being much slower and independent of reward but being able to strongly bias the output. This hypothesis is now tested in the newt where the absence of a proper cortex should prevent such dual learning.

Due to the parallel development of a reservoir canary decoder [26] and a canary syllable GAN generator [34], it enables to build a full vocal sensorimotor model for songbird imitation learning [25]. It enables a model to create real canary syllables of high quality (most were indistinguishable from real canary sounds). This enables the sensorimotor model to learn from its own real sounds produced.

8.3 Cognitive control

In cognitive control, the working memory in the prefrontal cortex and the episodic memory in the hippocampus play a major role in inhibiting the dominant behavior and replacing it with contextual rules in a flexible way, as we have studied in [20]. This year, we have pursued or work on the definition of a flexible switching between rules, thus stressing the difference between simple and abstract rules, and we have begun to develop a model of the hippocampus to better understand the role of episodic memory in cognitive control [18], including its role for creativity [19].

8.4 Integrating abstract symbolic knowledge

Within the AIDE AEx (*cf.* § 10.3.3), we introduced the idea of a symbolic description of a complex human learning task, in order to contribute to better understanding how we learn [23], in the very precise framework of a task, named #CreaCube, related to initiation to computational thinking presented as an open-ended problem, which involves solving a problem and appealing to creativity. We also proposed to map an ontology onto a SPA-based architecture with a preliminary partial implementation into spiking neural networks [23] in order to provide an effective link between symbolic presentation of information and biologically plausible numerical implementation, including regarding representation of belief, revisiting the possibility theory [36]. We furthermore proposed to make explicit how a reinforcement learning paradigm can be applied to a symbolic representation of a concrete problem-solving task, modeled here by an ontology [22]. This work is embedded in a strong collaboration with education science collaborators [30] working on computational thinking initiation and computer science tools in education with a multi-disciplinary vision of cognitive function modeling [33].

Still at the interface between numerical and symbolic approaches, we have also proposed an original work to extract rules learned by a Long Short Term Memory model fed with sequences built from an unknown grammar [9].

8.5 Integrating oscillations

Theta-nested gamma oscillations have been reported in many areas of the brain and are believed to constitute a fundamental mechanism to transfer information across spatial and temporal scales. Such transfer is known to occur between hippocampus and prefrontal cortex and this is the reason that leads us to first investigate oscillations inside a detailed model of the hippocampus based on the model by our new colleague A. Aussel. We introduced in this model a set of Kuramoto oscillators in order to model the oscillatory properties of the medial septum. These oscillators are able to induce a theta reset in the presence of a strong sensory input as it has been observed in rodents.

8.6 Language processing

We made a hierarchical task reservoir able to parse natural language starting from speech inputs, towards several levels of abstraction (phonemes, words, part-of-speech), until the semantic role labels [3]. This demonstrate the ability of reservoirs to perform abstract complex tasks in the language domain requiring embedded levels of abstraction.

A reservoir-based syllable canary decoder was implemented using ReservoirPy [26], it enables to build a full vocal sensorimotor model for songbird imitation learning [25]. We have implemented a GAN able to generate high quality songbird sounds (canary syllables) [34]. An additional novelty is that the generator part of the GAN is low-dimensional; with as few as 2 or 3 dimensions it is able to faithfully reproduce and interpolate between canary syllables. This low-dimensional property enabled to include it in a full sensorimotor model [25]: a simple Hebbian learning mechanism is sufficient to learn the motor commands to learn to imitate canary syllables.

We build on previous cross-situational learning experiments towards robot language grounding, and made an extensive comparison on different datasets related to robot instructions, various word embedding representations, and comparing various architectures (reservoirs, LSTMs, ...) [38].

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

9.1.1 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.

9.1.2 Contract with Ubisoft

Participants: Frédéric Alexandre, Cyril Regan.

Together with the Inria Project-team Flowers, we are working with the video game editor Ubisoft to define original bio-inspired learning methods. We are more specifically interested in methods to improve representation sizes and learning times, which are generally prohibitive with classical architectures in Reinforcement Learning.

10 Partnerships and cooperations

10.1 International initiatives

10.1.1 Associate Teams in the framework of an Inria International Lab or in the framework of an Inria International Program

MENG PO

Title: Memory ENGineering for Problem sOlving

Duration: 2020 ->

Coordinator: Shan Yu (shan.yu@nlpr.ia.ac.cn)

Partners:

- Brainnetome Center and National Laboratory of Pattern Recognition

Inria contact: Frederic Alexandre

Summary: Artificial Intelligence (AI) has been built on the opposition between symbolic problem solving that should be addressed by explicit models of planning, and numerical learning that should be obtained by neural networks. But it is clear that in ecological conditions, our cognition has to mix both capabilities and this is nicely carried out by our brains. Our behavior is sometimes described as a simple dichotomy between Goal-Directed (explicit deliberation and knowledge manipulation for planning) and habitual (automatic Stimulus-Response association) approaches. Recent results rather report more general strategies, including the hybrid combinations of both. Importantly, they highlight key mechanisms, corresponding to detect explicitly contexts in which the strategy should be modified and to adapt simple Stimulus-Response associations to these contexts. We propose here to associate our experiences to develop a more general framework for adapting neural networks to problem solving, thus augmenting their usability in AI and the understanding of brain reasoning mechanisms. On the Chinese side, connectionist models like deep neural networks are adapted to avoid so-called catastrophic forgetting and to facilitate contextbased information processing. On the French side, models in computational neuroscience explore the capacity of neuronal structures like the hippocampus to categorize contexts and investigate the role of the prefrontal cortex, known to modulate behavioral activity depending on the context. The main impact of this associate team is in the better understanding of brain circuits and their relation to higher cognitive functions associated to problem solving. This might also have an impact in the medical domain, through the possibility of studying lesioned systems and their relations to dysfunctions of the brain. In addition, the new algorithms and network architecture for deep learning generated in this project promise a wide range of applications in complex and dynamic environments. Due to the Covid, we could not travel this year, but we could organize an online workshop on Problem Solving.

SARASWATI

Title: Sequential motor skills: a dual system view

Duration: 2022 – 2025

Coordinator: Nicolas P. Rougier

Partners:

- Raju Surampudi Bapi (PI) (Cognitive Science Lab, IIIT, Hyderabad, India)
- Thomas Boraud (Institute of Neurodegenerative Diseases, Bordeaux, France)
- Srinivasa Chakravarthy V. (Computational Neuroscience Lab, IIIT Madras, Chennai, India).

Inria contact: Nicolas P. Rougier

Summary: The objectives for the three years is to design a generic machine learning architecture mixing Hebbian learning and reinforcement learning and to compare this new architecture to more classical approaches (supervised learning). Based on experimental evidences on the French sides (newts, rodents and non-human primates) as well as behavioral investigation on humans (IIT-H), the two teams will explore computational models that can give account on behavior and will also confront their respective hypothesis.

10.1.2 Participation in other International Programs

PHC VAN GOGH 2021

Title: Neurocomputational modelling of bilingual sentence comprehension and production

Duration: 2021 –

Coordinator: Xavier Hinaut

Partners:
- Stefan Frank, Radboud University, Nijjmegen, NL.

Inria contact: Xavier Hinaut

Summary: When bilinguals comprehend or produce sentences, they often display language transfer (influence from the properties of one language on the other language), code switching (the spontaneous use of both languages in one utterance) and cross-linguistic syntactic priming (re-use of syntactic structures from one language in the other). Although these phenomena form a fascinating window into the multilingual mind, very little is currently understood about the neural and cognitive mechanisms that underlie them. The project will tackle this issue by answering the following scientific questions: (1) Could typical bilingual behaviours be explained by general brain mechanisms (e.g. inhibitory control) or do they depend on specifically linguistic aspects? (2) What are the features, behaviours and limits of current computational models that simulate sentence processing and/or production in at least in two languages, specifically in comparison to data from psycholinguistic experiments (e.g., eye-tracking and neuroimaging)? In particular, the project will begin by using neural network models of bilingual sentence processing, which have already been developed in the two collaborating laboratories, to explore how transfer, structural priming, and code switching could be explained by the interaction of general neural/cognitive mechanisms with the properties of the languages involved. This will lead to a novel model that integrates the insights from the two teams' current models and that will greatly increase our understanding of multilingual sentence processing.

10.2 European initiatives

10.2.1 Other european programs/initiatives

We are member of the "Communauté d'Apprentissage de l'Informatique" CAI Erasmus+ project which aims to bring teachers into a community to facilitate the discovery of computers and the tools necessary for their learning for students aged 10 to 18. A platform and digital tools will allow mutual assistance between teachers through discussions and sharing of experiences and educational resources, this part of the project being leaded by our team working in cooperation with the LINE laboratory, including large audience dissemination.

10.3 National initiatives

10.3.1 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.

10.3.2 GTnum Scolia

Participants: Frédéric Alexandre, Chloé Mercier, Thierry Viéville.

Our team is part of an international consortium selected by the French ministry of education, to investigate AI for new modes of interaction, new modes of assessment and hybridization of learning environments. Our team is more specifically in charge of the part dedicated to modeling the learner and to evaluation.

10.3.3 Exploratory action AIDE

Participants: Frédéric Alexandre, Hugo Chateau-Laurent, Chloé Mercier, Thierry Viéville.

The modelling and assessment of computational thinking (CT) skills is a challenge that has a major impact on how learning activities are integrated into the curricula of OECD countries, particularly in terms of equal opportunities. The Artificial Intelligence Devoted to Education (AIDE) Inria exploratory action (AEx)aims to help address this challenge in an innovative way by modelling computational thinking through a neuro-inspired cognitive model, allowing analysis of the learner engaged in learning activities.

It's an exploratory subject. We are taking the scientific risk of looking at things differently. For example, instead of using the so-called artificial intelligence mechanisms to try to make "assistants", i.e., algorithms to better learn, we start focusing on how formalisms from the field of "artificial intelligence" (numerical and symbolic) contribute to better understand how we learn. But it is also a research with applications. Our hope is to contribute to the reduction of educational inequalities and improve school perseverance, focusing on transversal competencies, also called 21st century competencies which include computer thinking. More details on our activities here and a public presentation here.

10.4 Regional initiatives

10.4.1 EcoMob

Participants: Frédéric Alexandre, Nicolas Rougier, Snigdha Dagar.

Project gathering researchers from: University of La Rochelle (Cerege lab in social sciences and L3I lab in computer science); University of Bordeaux (IRGO lab in organisation management); Town and suburbs of La Rochelle.

The goal of this project is to study and model user urbanmobility behaviours in an eco-responsibility context. Interactive mobile applications are used to measure the effective evolution of behaviour. Our team is in charge of studying models of decision in such complex contexts, in interaction with teams in social sciences aiming at influencing user behaviours.

10.4.2 PsyPhINe

Participant: Nicolas Rougier.

Project gathering researchers from: MSH Lorraine (USR3261), InterPsy (EA 4432), APEMAC, EPSaM (EA4360), Archives Henri-Poincaré (UMR7117), Loria (UMR7503) and 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 amotorized lamp that can or cannot interact with them while they're doing a specific task. This year, we have organized a national conference in La Rochelle, on the topic Droles d'objets.

10.4.3 Regional Research Networks

We are members of three Regional Research networks, devoted to Artificial Intelligence, Robotics and Computational Education.

11 Dissemination

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

General chair, scientific chair: F. Alexandre was in charge of the scientific organization of the one-week workshop AI for Industry AI4I20 including 350 attendees on january 18-22, with (on-line) teaching in the morning and (on-site in subgroups) hands-on experiments on industrial applications in the afternoon. N. Rougier and M. Bourdenx organized the 13th Advanced Scientific Programming in Python gathering 30 European students and 10 faculties. The school was held in Bordeaux and lasted 1 week. N. Rougier co-organized the National conference "Drôles d'Objets: un nouvel art de faire" held during 2 days in La Rochelle (2021). F. Alexandre and J. Xue organized the First online French-Chinese workshop on Problem Solving on september 14. S. Pagliarini and X. Hinaut organized the SMILES (Sensorimotor Interaction, Language and Embodiment of Symbols) workshop of the ICDL 2021 conference.

Tutorials N. Trouvain and X. Hinaut participated to the PFIA 2021 (French National conference on Artificial Intelligence) to present a tutorial on Reservoir Computing and an introduction to the team library ReservoirPy [28].

11.1.2 Scientific events: selection

Members of the conference program committees: F. Alexandre: DELTA'21, ACAIN2021
X. Hinaut: SpLU-RoboNLP 2021

Reviewer: F. Alexandre: ICANN'21
X. Hinaut: IEEE Transaction in Cognitive Developmental Systems, Frontiers in Robotics and AI, Frontiers in Neurorobotics, MDPI Applied Sciences, CogSci'21, ICANN'21, ICDL'21
J. Xue: IJCNN'21
T. Viéville: Frontiers in Neurobiotics, ICANN'2021

11.1.3 Journal

Member of the editorial boards: N. Rougier is redactor in chief for ReScience C and ReScience X, academic editor for PeerJ Computer Science and review editor for Frontiers in Neurobotics, Frontiers in Psychology and Frontier in Neuroscience;
F. Alexandre is Academic Editor for PLOS ONE; Review Editor for Frontiers in Neurorobotics;
X. Hinaut is member of the Editorial Board of Frontiers in Neurorobotics as Review Editor. He edited a special issue on "Language and Robotics" in Frontiers in Robotics and AI [17].

Reviewer - reviewing activities: F. Alexandre: IEEE Transactions on Cognitive and Developmental Systems.

11.1.4 Invited talks

F. Alexandre:

- "Ingredients for a biologically plausible AI", during the Virtual Conference conducted by the Computational Neuroscience Lab (CNSL), IIT Madras, on August 13;
- talk at the on-line Research workshop by University of Nice: Understanding creative problem solving through a computational learning sciences perspective (January 15);
- talk at the conference "Drole d'objets", La Rochelle, october 19;
- "Is the brain a good model for artificial intelligence?" during third edition of the Σ-Tech Days autumn school at university of Limoges, on october 6;
- "What cognitive neuroscience tells artificial intelligence": invited talk during the scientific days of the french GDR on Artificial Intelligence, on december 2nd;
- "What is AI ? What is Intelligence, invited talk at the Forum of Nouvelle Aquitaine on Artificial Intelligence and Robotics on december 9-11.

X. Hinaut:

- AI4industry workshop, Bordeaux (January);
- R4 "Réseau régional de recherche en robotique" network (virtual) (February);
- Loria, Inria Nancy (virtual) (March);
- NeuroFrance Symposium on "Sequence processing" at NeuroFrance conference, Marseille (virtual), (May);
- 10th Peripatetic Conference: Cognitive Systems Modelling, Kalatówki, near Zakopane, Poland, (October);
- talk and organisation of the Machine Learning session at the R4 workshop, Bidart (November);

- Radboud University, Nijmegen, Netherlands (November);

N. Rougier:

- December 2021, L'intelligence artificielle dans le domaine de la santé, Une brève histoire de l'IA
- October 2021, Journées scientifiques, Embodied Cognition
- September 2021, 8th edition of the URFIST symposium, Numerical methods and scientific practices.
- June 2021, European Neuroscience Conference by Doctoral Students, The Art of Braincrafting
- Mars 2021, Société Informatique de France, Long term reproducibility

F. Hyseni was an invited speaker to the First student conference on biological sciences, on december 17-18.

11.1.5 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. This year, he also made expertises for the Natural Sciences and Engineering Research Council of Canada (NSERC) and for the ANID (Agencia Nacional de Investigacion y Desarrollo) in Chile.

N. Rougier has been nominated permanent expert for the French Open Science initiative.

11.1.6 Research administration

F. Alexandre is member of the steering committee of Inria Bordeaux Sud-Ouest Project Committee; member of the Inria International Chairs committee; corresponding member for Inria Bordeaux Sud-Ouest of the Inria Operational Committee for the assesment of Legal and Ethical risks;

N. Rougier is the local correspondent for the IES committee.

X.Hinaut is member of the “Committee for Technological Development” (CDT), the "Committee for Research Jobs" (CER) of Inria Bordeaux Sud-Ouest, and addressee of the PlaFRIM high-performance computing cluster. He is also member of IEEE Task Forces (TF) about: "Reservoir Computing", "Cognitive and Developmental Systems Technical Committee": "Language and Cognition" and "Action and Perception". He is co-Head of the "Apprentissage et Neurosciences pour la Robotique" (GT8) CNRS Robotics Working Group.

11.2 Teaching - Supervision - Juries

11.2.1 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.

T. Viéville is teaching computational thinking in the Msc #CreaSmartEdtech ("Digital Expertise", "Educational Computing" including Artificial Intelligence and Ontologies, "Digital Interdisciplinary Project ") and is co-organizing this Master of Science.

C. Mercier teached the Education Computing II Ontology online interactive course, including student follow-up, 6 hours.

F. Alexandre and T. Viéville have been involved in the production of the "Intelligence Artificielle Intelligente" citizen formation, via the creation of a MOOC, with more than 20,000 participants after six months, allowing everyone to master these disruptive technologies by better understanding ground notions [8, 42].

T. Viéville coordinated the building of the accompanied community-based self-training of computer science and technology secondary school teachers, aiming at offering a French-speaking formation regarding the NSI and SNT teaching.

11.2.2 Supervision

C. Mercier co-supervised two six-months research Intern of the Ecole Normale Supérieure on belief representation [36] and VSA architecture implementation and one six-months research MSc Intern on intrinsic motivation and cognitive function modeling [33].

A. Palaude supervised an engineer and two students during a four-months Intern project on tangible activity learning trace online measurement.

11.2.3 Juries:

F. Alexandre: 2 PhD review teams and 1 HDR review team;

N. Rougier: Reviewer for 2 PhD and 1 HDR, examiner for 1 PhD.

This year, F. Alexandre was part of Selection Committees for hiring a Professor at Lorraine University and an Associate Professor at Bourgogne University.

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

T. Viéville is co-editor of the computer science outreach blog binaire of LeMonde.fr in link with the French Computer Science Society

11.3.2 Articles and contents

Our team is featured in a comic book about Artificial Intelligence Les défis de l'Intelligence Artificielle.

Activities of our team have been presented for the Brain Awareness Week on the Inria Website.

F. Alexandre: an article about cognitive biases and decision making in the blog Binaire of the French newspaper Le Monde, on April, 23; an article about decision making and climate changes in the journal of Economics La Tribune;

T. Viéville wrote several large audience popularization articles [45], [49], including regarding computer science teaching at school [48] and managed the edition of more than 20 of them this year.

X. Hinaut made an interactive performance at the "Drôles d'Objets" conference (La Rochelle) [27]. He invited the public to interact with tiny robots following lines and executing color code instructions, to suggest the link with the Turing Machine and Keith Haring work.

11.3.3 Interventions

F. Alexandre: "A short history of Artificial Intelligence" monthly seminar "Unithé ou Café" of Inria Bordeaux, March 02; participation to a ClassCode webinar What is an algorithm of Artificial Intelligence ?, February 4.

T. Viéville participated in several large audience conferences, popularization activities, in particular in disadvantaged estate areas.

F. Alexandre and N. Rougier participated to the theater show The trial of Artificial Intelligence, in Bordeaux on october 1st;

On march 12 and 13, F. Alexandre and N. Rougier participated to the first Climackathon of the university of Bordeaux, to discuss the role of decision making to act against climate change. Later on, on september 21, our group was awarded a trophy Talents U in the category "societal responsability" by the university for this activity.

F. Hyseni is responsible for the organization of the ReproducibiliTea journal club at the Université de Bordeaux about reproducibility and the Open Science movement.

C. Mercier and A. Palaude participated in the "ENS in Bordeaux" speed dating session for presenting Mnemosyne research to candidate students.

H. Chateau-Laurent, C. Mercier, A. Palaude and F. Alexandre participated in the large audience NAIA.R regional forum on AI and robotics (organization of a workshop to help citizens discover AI).

12 Scientific production

12.1 Major publications

[1] F. Alexandre. 'A global framework for a systemic view of brain modeling'. In: *Brain Informatics* 8.1 (16th Feb. 2021), p. 22. DOI: 10.1186/s40708-021-00126-4. URL: https://hal.inria.fr/hal-03143843.

[2] A. Nioche, N. P. Rougier, M. Deffains, S. Bourgeois-Gironde, S. Ballesta and T. Boraud. 'The adaptive value of probability distortion and risk-seeking in macaques' decision-making'. In: *Philosophical Transactions of the Royal Society B: Biological Sciences* (Jan. 2021). DOI: 10.1098/rstb.2019.0668. URL: https://hal.inria.fr/hal-03005035.

[3] L. Pedrelli and X. Hinaut. 'Hierarchical-Task Reservoir for Online Semantic Analysis from Continuous Speech'. In: *IEEE Transactions on Neural Networks and Learning Systems* (27th Sept. 2021). DOI: 10.1109/TNNLS.2021.3095140. URL: https://hal.inria.fr/hal-03031413.

[4] N. P. Rougier. *Scientific Visualization: Python + Matplotlib*. 15th Nov. 2021. URL: https://hal.inria.fr/hal-03427242.

[5] N. P. Rougier and G. I. Detorakis. 'Randomized Self Organizing Map'. In: *Neural Computation* (2021). URL: https://hal.inria.fr/hal-03017448.

[6] R. Sankar, N. P. Rougier and A. Leblois. 'Computational benefits of structural plasticity, illustrated in songbirds'. In: *Neuroscience & Biobehavioral Reviews* (2021). URL: https://hal.archives-ouvertes.fr/hal-03416314.

12.2 Publications of the year

International journals

[7] F. Alexandre. 'A global framework for a systemic view of brain modeling'. In: *Brain Informatics* 8.1 (16th Feb. 2021), p. 22. DOI: 10.1186/s40708-021-00126-4. URL: https://hal.inria.fr/hal-03143843.

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[9] I. Chraibi Kaadoud, N. P. Rougier and F. Alexandre. 'Knowledge extraction from the learning of sequences in a long short term memory (LSTM) architecture'. In: *Knowledge-Based Systems* 235 (29th Oct. 2021), p. 18. DOI: 10.1016/j.knosys.2021.107657. URL: https://hal.inria.fr/hal-03437920.

[10] B. Girau, B. Miramond, N. P. Rougier and A. Upegui. 'Self-Organizing Machine Architecture'. In: *ERCIM News* 125 (1st Apr. 2021). URL: https://hal.inria.fr/hal-03186497.

[11] A. Nioche, N. P. Rougier, M. Deffains, S. Bourgeois-Gironde, S. Ballesta and T. Boraud. 'The adaptive value of probability distortion and risk-seeking in macaques' decision-making'. In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 376.1819 (21st Jan. 2021), p. 20190668. DOI: 10.1098/rstb.2019.0668. URL: https://hal.inria.fr/hal-03005035.

[12] L. Pedrelli and X. Hinaut. 'Hierarchical-Task Reservoir for Online Semantic Analysis from Continuous Speech'. In: *IEEE Transactions on Neural Networks and Learning Systems* (27th Sept. 2021). DOI: 10.1109/TNNLS.2021.3095140. URL: https://hal.inria.fr/hal-03031413.

[13] C. Rossant and N. P. Rougier. 'High-Performance Interactive Scientific Visualization With Datoviz via the Vulkan Low-Level GPU API'. In: *Computing in Science and Engineering* 23.4 (1st July 2021), pp. 85–90. DOI: 10.1109/MCSE.2021.3078345. URL: https://hal.inria.fr/hal-03465943.

[14] N. P. Rougier and G. I. Detorakis. 'Randomized Self Organizing Map'. In: *Neural Computation* (2021). URL: https://hal.inria.fr/hal-03017448.

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[17] T. Taniguchi, T. Horii, X. Hinaut, M. Spranger, D. Mochihashi and T. Nagai. 'Editorial: Language and Robotics'. In: *Frontiers in Robotics and AI* 8 (12th Apr. 2021). DOI: 10.3389/frobt.2021.674832. URL: https://hal.inria.fr/hal-03533733.

International peer-reviewed conferences

[18] H. Chateau-Laurent and F. Alexandre. 'Augmenting Machine Learning with Flexible Episodic Memory'. In: 13th International Joint Conference on Computational Intelligence. Valletta, Malta, 25th Oct. 2021. URL: https://hal.inria.fr/hal-03359384.

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