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**Institut Polytechnique de
Bordeaux**

Université de Bordeaux

Activity Report 2019

Project-Team MNEMOSYNE

Mnemonic Synergy

RESEARCH CENTER
Bordeaux - Sud-Ouest

THEME
**Computational Neuroscience and
Medicine**

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Project-Team MNEMOSYNE

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

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

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2. Overall Objectives

2.1. Summary

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

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

We claim that this approach is particularly fruitful for investigating cerebral structures like the basal ganglia and the prefrontal cortex, difficult to comprehend today because of the rich and multimodal information flows they integrate. We expect to cope with the high complexity of such systems, inspired by behavioral and developmental sciences, explaining how behavioral loops gradually incorporate in the system various kinds of information and associated 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 [53]. It results also in longstanding and very ambitious studies for the design of cognitive architectures aiming at embracing the whole cognition. With the notable exception of works initiated by [50], most of these frameworks (e.g. Soar, ACT-R), though sometimes justified on biological grounds, do not go up to a *connectionist* neuronal implementation. Furthermore, because of the complexity of the resulting frameworks, they are restricted to simple symbolic interfaces with the internal and external world and to (relatively) small-sized internal structures. Our main research objective is 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 [55], [44]. 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 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 [41], [49] and were the basis for several contributions in our group [54], [51], [56]. 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 [42]; the associated formalism [47] 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 [39], that demonstrated a richness of behavior

[43] 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 [51], [52] and their use for observing the emergence of typical cortical properties [46]. 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 [48] that aims at giving such characteristics to artificial systems, using a mathematical framework (probabilities, statistics, data analysis, etc.). Some of its most famous algorithms are directly inspired from neuroscience, at different levels. Connectionist learning algorithms implement, in various neuronal architectures, weight update rules, generally derived from the hebbian rule, performing non supervised (e.g. Kohonen self-organizing maps), supervised (e.g. layered perceptrons) or associative (e.g. Hopfield recurrent network) learning. Other algorithms, not necessarily connectionist, perform other kinds of learning, like reinforcement learning. Machine learning is a very mature domain today and all these algorithms have been extensively studied, at both the theoretical and practical levels, with much success. They have also been related to many functions (in the living and artificial domains) like discrimination, categorisation, sensorimotor coordination, planning, etc. and several neuronal structures have been proposed as the substratum for these kinds of learning [45], [38]. 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* [40]). 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 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 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 recently considered a new domain of application for our models, educational science. In a very stimulating perspective, we wonder how our cognitive models of cerebral architectures can be used to study children performing problem solving. Our first steps in this domain concern the establishment of relations with a laboratory in educational science, designing a software platform (*cf.* § 6.4). and being associated to ongoing projects, **one project with the French ANR** regarding cocreativity and problem solving evaluation during a computational thinking initiation activity and one in the Erasmus+ CAI « Communauté d'Apprentissage de l'Informatique » 19PE0004 project, in link with the Erasmus+ **Let'Steam** project.

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. 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 librairies 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 representaion 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>

6.4. Platforms

6.4.1. Platform AIDE

Keywords : computational thinking initiation, learning analytics, machine learning

Functional description : This [package](#) provides source files to control a tabletop setup allowing to initiate learners to computational thinking using unplugged activities and connected objects, and collecting automatically learning activities including thanks to neuroinspired machine learning mechanisms, developed in collaboration with [pobot](#) and the Inria [mission of science outreach](#) and the [LINE laboratory](#).

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 and rule manipulation. 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.

Finally, we study the links between our bio-inspired modeling work and other domains like Machine Learning, computer science and educational science (*cf.* § 7.6).

7.2. The limbic loop

Our main contribution this year to advancing our view of the limbic loop is the defense of the PhD of B. T. Nallapu [1] related to the modeling of the orbital and medial loops the two main constituents of the limbic loop, as described in [33]. In short, this work proposes, instead of a global view of the orbital loop as generally proposed, a view with two loops, one corresponding to the lateral part of the orbitofrontal cortex related to respondent conditioning and one to the medial part related to operant conditioning and closely linked to the medial loop. The work shows that such a model replicates a variety of observations in neuroscience and can be used for the autonomous behavior of an agent in the Minecraft video game.

7.3. The associative loop

The prefrontal cortex is known to be involved in many high-level cognitive functions, in particular working memory. Gated working memory is defined as the capacity of holding arbitrary information at any time in order to be used at a later time. Based on electrophysiological recordings, several computational models have tackled the problem using dedicated and explicit mechanisms. We propose instead to consider an implicit mechanism based on a random recurrent neural network. We introduce a robust yet simple reservoir model of gated working memory with instantaneous updates [11]. The model is able to store an arbitrary real value at random time over an extended period of time. The dynamics of the model is a line attractor that learns to exploit reentry and a non-linearity during the training phase using only a few representative values. A deeper study of the model shows that there is actually a large range of hyper parameters for which the results hold (number of neurons, sparsity, global weight scaling, etc.) such that any large enough population, mixing excitatory and inhibitory neurons can quickly learn to realize such gated working memory. This suggests this property could be an implicit property of any random population, that can be acquired through learning. Furthermore, considering working memory to be a physically open but functionally closed system, we give account on some counter-intuitive electrophysiological recordings.

We also developed a model of working memory combining short-term and long-term components [24]. For the long-term component, we used Conceptors in order to store constant temporal patterns. For the short-term component, we used the Gated-Reservoir model [11]. We combined both components in order to obtain a model in which information can go from long-term memory to short-term memory and vice-versa.

The prefrontal cortex is also known to be the place where complex and abstract behavioral rules are implemented. In order to study the mechanisms related to the manipulation of such rules, we have begun the study of networks able to build rules to manipulate such framework as the Wisconsin Card Sorting Test, widely used in the clinical domain [3].

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[35]. Sensorimotor learning represents a challenging problem for natural and artificial systems. Several computational models have been proposed to explain the neural and cognitive mechanisms at play in the brain [34]. In general, these models can be decomposed in three common components: a sensory system, a motor control device and a learning framework. The latter includes the architecture, the learning rule or optimisation method, and the exploration strategy used to guide learning. In this review, we focus on imitative vocal learning, that is exemplified in song learning in birds and speech acquisition in humans. We aim to synthesise, analyse and compare the various models of vocal learning that have been proposed, highlighting their common points and differences. We first introduce the biological context, including the behavioural and physiological hallmarks of vocal learning and sketch the neural circuits involved. Then, we detail the different components of a vocal learning model and how they are implemented in the reviewed models.

On this topic, X. Hinaut is also collaborating with Catherine del Negro's team (CNRS, NeuroPSI, 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 transcription and analyses has been done by M1 intern (in Neuroscience) Juliette Giraudon, and preliminary work on song segmentation and classification has been done by L3 intern (ENS) Pierre Marcus.

In December, Aurore Cazala (student in the NeuroPSI collaborator team since 2014) defended her PhD at the University of Paris-Saclay on "Codage neuronal de l'ordre des signaux acoustiques dans le chant des oiseaux chanteurs"; X. Hinaut participated in studies done in this PhD.

7.5. Systemic integration

Several global approaches corresponding to the systemic integration of several loops have been studied this year. The PhD work [1] evoked in section § 7.2 for its contributions to modeling the limbic loop, has also been partly devoted to the definition of a global cognitive model and its embodiment in an agent in the Minecraft game, in order to illustrate the performances of autonomous behavior of a system endowed by such a limbic loop [33].

7.6. Association to other scientific domains

Concerning Machine Learning and 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 parser (ResPars) with the representational system of Spranger: IRL (Incremental Recruitment Language) [17]. 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 [5]. 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. Some people can mix two languages within the same sentence: this is known as intra-sentential code-switching. With M1 intern Pauline Detraz, we collected data from human subjects that were required to mix pairs of given sentences in French and English. The corpus obtained have some very complex mixed sentences: there can be until eleven language switches within the same sentence. Then, we trained our Reservoir-based sentence Parsing model, with the collected corpus. Surprisingly the model is able to learn and generalize on the mixed corpus with performances nearly as good as the unmixed French-English corpus [16]. A post-doc joined the team in Nov 2019 to work on the project HuRRiCane ("Hierarchical Reservoir Computing for Language Comprehension") project founded by Inria. This project aims at extending the ResPars model to work from speech inputs to sentence comprehension including coherency checking. In other words, the objective is to experiment how a sentence comprehension model, based on reservoir computing, can learn to understand sentences by exploring which meanings can have the sentences, implying several steps from stream of phonemes to words and from stream of words to sentence comprehension. The model will be implemented on a virtual agent first and then on the Nao humanoid robot.

This project is linked to other projects in the team on the hierarchical organization of the prefrontal cortex (including Broca's area, involved in language). This hierarchy corresponds to an increasingly higher abstraction, which is made by different sub-areas. We will therefore be able to link this post-doc project to existing projects of the team, where different levels of abstractions are necessary for sentence comprehension.

As explained in § 7.6, song segmentation and classification has been done by L3 intern (ENS) Pierre Marcus.

The on-going work on an original prototype based approach of deep-learning considering not so big data sets, and targeting also interpretability of the result, has been finalized [4], including a fine study on metaparameter adjustment in this context, while both standard learning and meta-learning paradigms have been considered. The capability to easily the "how it works" mechanism to no specialist of the field is an important outcome of the paper.

Co-led by Margarida Romero scientific director of the LINE laboratory of the UCA and researchers of our team, a preliminary work regarding artificial intelligence devoted to education (AIDE) was developed to study applications to educational science. This first year has been devoted to study to which extents the existing collaboration between Inria science outreach regarding computational thinking initiation and educational science research in order to be understand the underlying cognitive processes of the former actions and evaluate them, could be enlarged to multi-disciplinary research in both fields. The first outcome of this collaboration has been an analysis of a computational thinking unplugged activity under the perspective of embodied cognition

[9] and deep and large review in the field, analyzing how computational thinking in K-12 education could be developed [22], within the scope of studies regarding co-creativity, robotics and maker education. [20], while a qualitative analysis one very large audience (more than 18000 inscriptions) on-line course outcomes has been published [18], with some operational outcomes regarding enlarging computational thinking training from teachers to all citizens [12].

Software is a fundamental pillar of modern scientific research, across all fields and disciplines. However, there is a lack of adequate means to cite and reference software due to the complexity of the problem in terms of authorship, roles and credits. This complexity is further increased when it is considered over the lifetime of a software that can span up to several decades. Building upon the internal experience of Inria, the French research institute for digital sciences, we provide in this paper a contribution to the ongoing efforts in order to develop proper guidelines and recommendations for software citation and reference. Namely, we recommend: (1) a richer taxonomy for software contributions with a qualitative scale; (2) to put humans at the heart of the evaluation; and (3) to distinguish citation from reference.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. *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.

8.1.2. *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. *EcoMob*

Participants: Frédéric Alexandre, Snigdha Dagar, Nicolas Rougier.

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 urban mobility 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.

9.1.2. *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, 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.

9.3. International Initiatives

9.3.1. Participation in Other 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: Co-organizer of the workshop on language learning at IEEE ICDL-EPIROB 2019, Oslo, Norway, August 2019; of the "Day of the NeuroRobotics Working Group", Nov 2019, Bordeaux, France; Session chair at the CogSci conference, Montréal, Canada. Jul 2019.

N.Rougier: co-chair for the track on Neuroscience and Cognitive science during the SciPy conference (Austin, Texas, USA)

10.1.1.2. Member of the Conference Program Committees

X. Hinaut: IROS Workshop on Deep Probabilistic Generative Models for Cognitive Architecture in Robotics, Macau, China. Nov 2019. International Workshop on Cognitive and Neural Systems, Granada, Spain. Oct 2019.

10.1.1.3. Reviewer

X. Hinaut: CogSci'19, ICANN'19, ICDL-Epirob'19, IWANN'19; S. Pagliarini: ICDL-Epirob'19;

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"; guest editor for Frontiers Robotics and AI special issue on "Language and Robotics" <https://www.frontiersin.org/research-topics/8861/language-and-robotics> ; Member of the Editorial Board of Frontiers in Neurorobotics as Review Editor.

10.1.2.2. Reviewer - Reviewing Activities

- F. Alexandre: Elife; EMBC; Frontiers in Neurobotics; Cognitive Computation; PLoS ONE
- Xavier Hinaut: Cognitive Computation, Entropy, Front. in Neurorobotics, Neural Networks, PeerJ, ReScience, IEEE Transactions in Cognitive Developmental Systems (TCDS).
- N.Rougier: Current Biology, PLoS Computational Biology, Journal of Open Science Software, PeerJ

10.1.3. Invited Talks

F. Alexandre:

- Invited speaker at the joint workshop between Inria and LIAMA (The Sino-European Laboratory of Computer Science, Automation and Applied Mathematics), Paris, April 3rd, for the talk: "Setting the basis of a bio-inspired Reinforcement Learning";
- talk to the Interdisciplinary and Translational Neuroscience research network (IT-Neuro) of the University of Lorraine, Nancy, April 25th: "Modeling the frontal cortex for motivated decision making";
- Invited talk "A computational model to study the dynamics of representations of rewards in the orbital and medial frontal cortex", on October 2nd to the 2019 Bordeaux Neurocampus Conference on Reward <http://brainconf.u-bordeaux.fr/>;
- Invited talk "Trusted AI in medicine" and participation to a round table on december 11th in Merignac at MediSpace congress on transfers of technologies and best practices between space, aeronautical and medical industries <https://www.medispace2019.com/en/presentation-2/>

X. Hinaut:

- "How to ground sensorimotor sequence of symbols ? From robot learning languages to songbirds", ICDL- Epirob workshop on Language Learning (M. Spranger), Oslo, NW, Aug 2019.
- "Random recurrent networks for language and bird song learning", B. Golosio, Physics dept., University of Cagliari, IT.
- "Modélisation de l'encodage neuronal pour l'apprentissage de séquences complexes : applications à l'interaction homme-robot et aux chants des oiseaux". LIRIS, Lyon, June 2019.
- "Modèles Neuronaux Récurrents pour le Traitement de Séquences Complexes", Journée GT-ACAI-Neurorobotique: Neuroscience et multimodalité dans les interactions humain-humain, humain-agent ou humain-robot, ACAI-GT8 common working group day, Telecom ParisTech, Paris, FR.
- "Modélisation de l'encodage neuronal pour l'apprentissage de séquences complexes", "Acoustic Perception" seminar from ETIS lab, University of Cergy-Pontoise, FR. March 2019.
- "Little Mechanisms of AI: from Ants to Language", PhD Retreat of Center for Research and Interdisciplinarity of Paris. Arcachon, June 2019.
- "How to ground sensorimotor sequences of symbols? From robot learning languages to songbirds", ICDL-epirob workshop on Language learning, Oslo, Aug. 2019.
- Symposium organised by regional chair on technological systems for human augmentation, March 28—29, 2019, Bordeaux, France.
- "Echo State Networks", invited lecture at the International MSc "Intelligent Adaptive Systems", KT lab, University of Hamburg, Germany, June 2019.

N.Rougier: Invited talk at the “Robotics, development and neurosciences” conference (Cergy, France)

10.1.4. Leadership within the Scientific Community

X. Hinaut:

- Co-Head of the "NeuroRobotics" CNRS Working Group Organisation of several workshops throughout the year
- IEEE Task Force (TF) member: "Reservoir Computing", "Cognitive and Developmental Systems Technical Committee": "Language and Cognition" TF and "Action and Perception" TF.
- President of the association MindLaBDX: “open citizen lab” in Cognitive Sciences and Artificial Intelligence in Bordeaux.

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.

Thierry Vieville has been required as expert to review a large neuroscience lab by the HCERES agency. He has also contributed to a large audience report on « AI in the media and creative industries » [25].

10.1.6. Research Administration

- F. Alexandre is member of the steering committee of Inria Bordeaux Sud-Ouest Project Committee; Corresponding scientist for Bordeaux Sud-Ouest of the Inria COERLE ethical committee; Member of the national Inria committee for international chairs; 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'
- X. Hinaut: Member of the “Committee for Technological Development” of Inria, Bordeaux, FR
- 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 involved in the <http://classcode.fr> project and in charge, for Inria of the **MSc SmartEdTech** at Univ. Cote d'Azur (UCA).

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 computational 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. He has been involved in the production of the "Science Numérique et Technologie" (SNT) new high-school course teacher formation, via the creation of a MOOC, with more than 18000 inscriptions, and has collaborated to the qualitative analysis of the course outcomes [18].

In addition, this year, F. Alexandre gave a lecture at the Barcelona Cognition, Brain and Technology Summer School <https://bcbt.specs-lab.com/bcvt19/>.

10.2.2. Juries

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

10.3. Popularization

10.3.1. Articles and contents

- F. Alexandre published an article about AI and neuroscience in The Conversation <https://theconversation.com/de-quelles-facons-lintelligence-artificielle-se-sert-elle-des-neurosciences-124402>
- N. Rougier published article: Pourquoi votre chat est nul aux échecs et pourtant plus intelligent qu'une IA, The Conversation (FR); article: Why your cat is lousy at chess yet way smarter than even the most advanced AI, The Conversation (US); Interview: Et le cerveau dans tout ça ? U magazine (Univ. Bordeaux)

10.3.2. Education

F. Alexandre: A lesson about AI (2 hours) and an unplugged activity about learning and memory (1 hour) given to a high-school class of 2nd on november 14th in Dax for the "1 scientist 1 class : Chiche !" MENJ program.

N. Rougier: Science outreach day at the Montendre high-school on unplugged AI (Montendre, France)

Several people in the team (F. Alexandre, T. Firmo-Drumond, N. Rougier, T. Vieville) participated (talks and demonstrations) to the Day "Activities for teaching AI" organized between Inria Bordeaux and LINE laboratory in Sciences of Education in Nice, June 21st;

10.3.3. Interventions

F. Alexandre:

- Intervention at the annual conference of the Bishops of France (Lourdes, April 2nd), with a conference ("What can medicine expect from AI") and the organization of a workshop on Robotics for AI;
- Participation to a round table discussion at the Robot Makers Day Festival, Talence, April 12th: "AI: threats and opportunities for our companies: what training for tomorrow's engineers?"
- conference to the ESME-Sudria School of Engineers, Bordeaux, May 21st: "Is the brain a good model of intelligence ?"
- Conference "Should we be afraid of artificial intelligence?", at the "Université de tous les savoirs" in Saint Jean de Luz on November 13th http://www.utl-luz.fr/index_002.htm
- Conference: "What can we expect from AI ?", in the special day "AI and me" organized on November 15-16 by the city of Pontonx-sur-Adour <https://www.pontonx.fr/Pontonx-sur-l-Adour/Agenda-et-actualites/Toutes-les-actus-de-Pontonx/L-intelligence-artificielle>

A. Garenne: intervention about "Artificial Neural Networks and Machine Learning" at a club of companies, Pessac, decembre 12

X. Hinaut:

- "Pint of Science" invited talk, Bordeaux, FR, May 2019.
- "Les petits mécanismes de l'IA", invited talk at the Library of "Le Haillan", FR, April 2019.
- Invited jury member of the world scale hackathon "Créathon", Poitiers, FR, May 2019.
- Invited talk at the Science Fest Day, Cap Sciences, Bordeaux, FR, Oct 2019.

N. Rougier:

- Reboot conference "Will robots dominate us ?" (Bordeaux, France)
- Discussion with the general public about science, fiction and AI at Cap-Sciences (Bordeaux, France)

Thierry Viéville is an active member of [Femmes et Sciences](#), has been invited speaker at [Un rêve pour les filles et les garçons : LA SCIENCE](#) and is involved in dedicated science outreach actions [15].

Several people in the team (F. Alexandre, T. Firmo-Drumond, N. Rougier) participated to the “Trial of AI” on november 20, in the project “The controversy of Bordeaux Macropole” during the festival Facts, program Arts and Sciences of University of Bordeaux. <https://www.youtube.com/watch?v=UI4B4TteRmA> and <https://twitter.com/bdxmacropole>

Intervention by A. Garenne and T. Firmo-Drumond at the inter-university seminar "artificial intelligence and clinical sense", Bordeaux, march 11-12

10.3.4. 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 designed 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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Invited Conferences

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