APPLICATION FORM (full project proposal)

2021 Interdisciplinarity call for projects

Application form

Deadline for submission of complete proposals:

28 FEBRUARY 2022, 12-noon (Paris)

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Instructions for preparation and submission of your application

All the information relative to the modalities for submission and the people to contact for any questions are indicated in the framework text for the call, available through: https://www.univ-amu.fr/fr/public/lancement-de-lappel-projets-interdisciplinarite-2021

Your submission should be written to allow its assessment according to the assessment criteria and sub-criteria defined in the framework text.

Your application must include the following elements:

1. The application form below, completed (without modifications to the template).
2. The budget (use the Excel template supplied in the appendix, the file is locked so you only need to fill out some parts).
3. A letter from the STL of the institute presenting how the project will contribute to the community, along with a description of its interdisciplinary aspects.
4. A letter of commitment from the director of the scientific and technical leader's research unit attesting the capacity of the research unit to undertake the administrative management of the project and detailing how the application contributes to the research unit's overall strategy.
5. A letter of commitment from each partner.

Other documents in support of the project may also be included as appendices, in French or English (letters of support, other requests for funding/funding awarded, etc.).

How to fill out this application:

- The template of the present Word document must not be modified
- Font size: Calibri at least 11 (excluding appendices)
- Page format: A4
- Maximum page limit, exclusive of appendices: no overall limit
- The application must be provided as a Word or PDF file, not scanned, without protection
- **Appendices should be combined in a single PDF file**[1]**,** not scanned, without protection with the exception of the budget (Excel file).
- The document must be written in English.

[1]To combine PDF files, free sites and software can be used

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1. General information

1.1 Project identification

Project title	**Temporal spiking motifs in neurobiological and neuromorphic data**	
Project acronym	*Polychronies*	
Keywords (maximum 10)	spiking neural networks, machine learning, event-based representations, neuromorphic computing, neurobiology, sequence learning, development.	
Planned schedule for the project (start and end)	01/10/2022	30/09/2024
Duration of the project (in months)	24	

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1.2 Scientific and technical leader for the project (STL) and internal structure with which they are affiliated

Surname	PERRINET
First name	Laurent
Role (e.g.: MCF, PR, CD, DR, etc.)	DR2 CNRS
Contact details (E-mail + Tel)	Laurent.Perrinet@univ-amu.fr 0619478120
Research unit (Name + Acronym) *Unit with which the STL is affiliated*	Institut de Neurosciences de la Timone, INT
Research team (Name + Acronym) *Team within the unit of which the candidate is a member*	NEuronal OPerations in visual TOpographic maps (NeOpTo)
Learning and teaching department (Name + Acronym) *Only for personnel affiliated with a learning and teaching department within the University* *If affiliated with Ecole Central or Science Po Aix: also add this information here*	
Employed by (e.g.: AMU, CNRS, AP-HM, etc.)	CNRS

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1.3 Partner(s) in implementation

Partner 1	
Type of partner (1 answer only)	☒ Aix-Marseille site research unit[2] ☐ AMU learning and teaching department or school on the Aix-Marseille[2] site (Science Po Aix, Centrale Marseille) ☐ Aix-Marseille-affiliated institute ☐ Other internal structure (Doctoral schools, etc.) ☐ Organisation outside the Aix-Marseille[2] site
Name (full + Project acronym)	Institut de Neurosciences de la Timone, INT
If the organisation is outside the Aix-Marseille[1] site:	
Type of organisation (1 answer only)	☐ Association ☐ Company ☐ Cultural institution ☐ Foundation ☐ Research organisation ☐ University / Grande Ecole (school of engineering) ☐Other (please specify:)
Country	
Field of specialisation	Computational Neuroscience, neuromorphic computing
Contact person for the project (Full name, Contact e-mail + tel)	Laurent PERRINET Laurent.Perrinet@univ-amu.fr, +33-619478120

[2] The Aix-Marseille site - within A*Midex - includes AMU and the 7 IDEX partners: CNRS, INSERM, CEA, IRD, Centrale Marseille, Sciences Po Aix, and AP-HM

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Partner 2	
Type of partner (1 answer only)	☒ Aix-Marseille site research unit[3] ☐ AMU learning and teaching department or school on the Aix-Marseille[2] site (Science Po Aix, Centrale Marseille) ☐ Aix-Marseille-affiliated institute ☐ Other internal structure (Doctoral schools, etc.) ☐ Organisation outside the Aix-Marseille[2] site
Name (full + Project acronym)	Institut de Neurobiologie de la Méditerranée, INMED
If the organisation is outside the Aix-Marseille[1] site:	
Type of organisation (1 answer only)	☐ Association ☐ Company ☐ Cultural institution ☐ Foundation ☐ Research organisation ☐ University / Grande Ecole (school of engineering) ☐Other (please specify:)
Country	
Field of specialisation	Neurobiology
Contact person for the project (Full name, Contact e-mail + tel)	Rosa COSSART rosa.cossart@inserm.fr, tel: +33-491828131 (lab)/491828110 (dir)

[3] The Aix-Marseille site - within A*Midex - includes AMU and the 7 IDEX partners: CNRS, INSERM, CEA, IRD, Centrale Marseille, Sciences Po Aix, and AP-HM

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Partner 3	
Type of partner (1 answer only)	☒ Aix-Marseille site research unit[4] ☐ AMU learning and teaching department or school on the Aix-Marseille[2] site (Science Po Aix, Centrale Marseille) ☐ Aix-Marseille-affiliated institute ☐ Other internal structure (Doctoral schools, etc.) ☐ Organisation outside the Aix-Marseille[2] site
Name (full + Project acronym)	Laboratoire d'Informatique et Systèmes, LIS
If the organisation is outside the Aix-Marseille[1] site:	
Type of organisation (1 answer only)	☐ Association ☐ Company ☐ Cultural institution ☐ Foundation ☐ Research organisation ☐ University / Grande Ecole (school of engineering) ☐Other (please specify:)
Country	
Field of specialisation	Machine learning and computational modeling of behavior
Contact person for the project (Full name, Contact e-mail + tel)	Thomas SCHATZ thomas.SCHATZ@univ-amu.fr, +33-632011660

[4] The Aix-Marseille site - within A*Midex - includes AMU and the 7 IDEX partners: CNRS, INSERM, CEA, IRD, Centrale Marseille, Sciences Po Aix, and AP-HM

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1.4 Disciplines and interdisciplinarity

Disciplinary field(s)	☐ Human and Social Sciences ☒ Life Sciences ☐ Physics ☒ Computing ☒ Engineering ☐ Environmental science ☐ Chemistry ☐ Planet and Universe ☐ Mathematics ☒ Cognitive sciences ☐ Statistics ☐ Economics and quantitative finance ☐ Non-linear science
Discipline(s)	Depending on the discipline(s) indicated above, select the sub-discipline(s) from the list published at: https://hal.archives-ouvertes.fr/browse/domain • Computer Science [cs] / Machine Learning [cs.LG] • Neurons and Cognition [q-bio.NC] / Neurobiology • Cognitive science / Neuroscience • Cognitive Science / Computer Science • Neurons and Cognition [q-bio.NC] / Psychology and behavior • Neurons and Cognition [q-bio.NC] / Cognitive Science • Computer Science [cs] / Signal and image processing • Engineering Sciences / Signal and image processing • Cognitive Science / Psychology
Indicate the name and acronym for the Aix-Marseille-affiliated institute to which you belong	NeuroMarseille Institute
AMU interdisciplinary research direction (1 answer only)	☐ Humanities ☐ Energy ☐ Environment ☐ Science & Advanced Technology ☒ Health & Life Sciences

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1.5 Budget

Overall budget for the project (€) *(A + B)*	**100 k€**
Assistance requested from A*Midex (€) *(A)*	**100 k€**
Other income and funding (€) *(B)*	**000 k€**

1.6 Confidentiality

Specific confidentiality requirement?	☐ Yes ☒ No
If yes, reason and details of requirements	

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2. Abstract

This (non-confidential) abstract may be communicated in the context of the selection process when seeking experts (Recommendation: max. 1500 characters including spaces)
It is recommended that you take particular care when presenting the objective of the project in order to:

- *Encourage the acceptation of role of expert by the people contacted so as to allow your proposal to be appropriately assessed.*
- *(If the project is retained) be able to publish it for communication and mediation ends, for reading by audiences outside the project's disciplinary field. The text must therefore be as clear as possible, indicating the societal and/or technical challenges targeted.*

French version

Pour quelle raison les neurones communiquent-ils par le biais de potentiels d'actions ? Un potentiel d'action est un événement binaire —il a lieu ou non, sans plus de détails— et asynchrone, c'est-à-dire qu'il peut survenir à n'importe quel instant. Dans le monde du vivant, les neurones utilisent presque systématiquement ce format de représentation dit *impulsionnel*, sans que l'on sache exactement pourquoi. Mieux comprendre ce phénomène reste un enjeu fondamental en neurobiologie pour mieux interpréter les masses de données enregistrées. C'est aussi un défi naissant en informatique pour permettre l'exploitation efficace d'une nouvelle classe de senseurs et calculateurs impulsionnels, dits *neuromorphiques*, qui pourraient permettre des gains importants en temps de calcul et consommation d'énergie —des enjeux sociétaux majeurs à l'heure du numérique et du réchauffement climatique.

L'objectif de ce projet est d'apporter un éclairage inter-disciplinaire sur l'avantage computationnel des représentations impulsionnelles pour le cerveau et pour les machines traitant de l'information. Notamment, nous allons étudier mathématiquement comment des motifs d'événements arrangés dans le temps de manière très précise (que nous appellerons *motifs polychrones*) peuvent être détectés plus efficacement à l'aide de réseaux impulsionnels, et ce même lorsque de nombreux motifs se superposent dans le temps. Ce problème formel de détection des motifs polychrones est directement motivé par des observations neurobiologiques, notamment dans l'hippocampe, et son aspect novateur est d'élargir les capacités des représentations analogiques basées sur la fréquence de décharge pour considérer un codage basé sur la répétition de motifs polychrones à des temps précis d'occurrence. Cette formalisation s'adapte particulièrement bien au calcul neuromorphique, et permet en général un apprentissage supervisé ou auto-supervisé de ces motifs dans toute donnée de type événementiel.

En étendant ce paradigme à une hiérarchie, nous envisageons des applications pratiques de cette approche dans le domaine du traitement du signal audio, vidéo ou neurobiologique. De façon cruciale, l'éclairage croisé de la neurobiologie et de l'approche neuromorphique sera déterminant pour comprendre le développement typique ou pathologique de tels réseaux de neurones impulsionnels.

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English version

Why do neurons communicate through action potentials, or *spikes*? An action potential is a binary event —it can occur or not, without further details— and asynchronous, i.e. it can occur at any time. In the living world, neurons almost systematically use this so-called *event-based* representation, though we do not yet have a clear idea why. A better understanding of this phenomenon remains a fundamental challenge in neurobiology in order to better interpret the masses of recorded data. It is also an emerging challenge in computer science to allow the efficient exploitation of a new class of sensors and impulse computers, called *neuromorphic*, which could allow significant gains in computing time and energy consumption —a major societal challenge in the age of the digital economy and of global warming.

The goal of this project is to bring an interdisciplinary perspective on the computational advantage of time series representations for the brain and for information processing machines. In particular, we will formalize mathematically a representation in an assembly of neurons based on a set of patterns of different relative spike times called *polychronous* groups. This hypothesis is directly inspired by neurobiological observations in the hippocampus, and the innovative aspect is to expand the capabilities of analog representations based on the firing rate by considering a representation based on repetitions of these polychronous groups at precise times of occurrence. This formalization is particularly well suited to neuromorphic computing, and allows for supervised or self-supervised learning of polychronous groups in any event-driven data.

By extending this paradigm to a hierarchy, we envision practical applications of this approach in audio, video or neurobiological signal processing. The cross-fertilization of neuroscience and neuromimetic approaches will be instrumental in understanding the typical or pathological development of such spiking neural networks.

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3. Quality and ambitions of the project

3.1. Context

Briefly present the general context and the challenges to which the project relates, in scientific terms. Present how the project contributes to the dynamics of the institute in terms of returns for the site (impact in scientific, pedagogical, international and innovation terms).

Neuroscience has recently undergone a scientific and technological revolution and the scales at which neuronal activity can be experimentally sampled has considerably expanded. One striking example is the use of imaging approaches to simultaneously sample the activity of thousands of neurons *in vivo*. This is concomitant with the transition of the research community to openly provide access to huge amounts of data. Interestingly, these experimental advances are occurring in concert with the emergence of new foundations for modern computer vision through deep learning methods. In particular, feed-forward, step-by-step convolutional neural network architectures were initially inspired by biological visual pathways. However, experimental evidence shows that information processing in the brain is not a purely feed-forward process but instead relies on internally generated activity in recurrent networks forming complex dynamical systems in which most information is carried by way of time series of action potentials (or *spikes*).

Remarkably, novel neuromorphic chips use a representation similar to that of real neurons (Rasetto et al., 2022). For example, event-based cameras provide a stream of binary asynchronous events signaling detectable changes in luminance, and information is represented by these spike-based temporal motifs, hence their name "silicon retinas" (see Figure 1). For such devices, it is crucial to better understand the potential of using such event-based representations in order to devise novel algorithms.

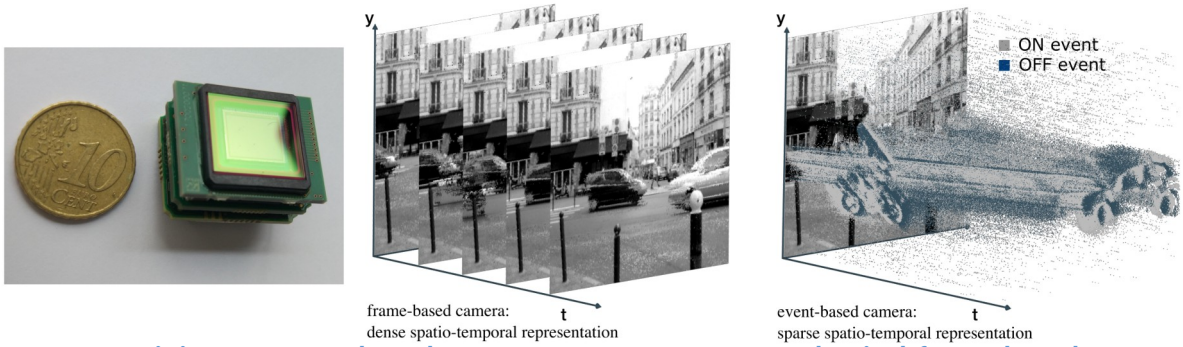

FIGURE 1: A miniature, event-based ATIS sensor. Contrary to a classical frame-based camera for which a full dense image representation is given at discrete, regularly spaced timings, the event-based camera provides with events at the micro-second resolution. These are sparse as they represent luminance increments or decrements (ON and OFF events, respectively).

Currently, few interdisciplinary research projects take full advantage of event-based representations in computational and biological neuroscience. Nevertheless, there is a substantial literature in neurobiology indicating that brain dynamics often organize into stereotyped sequences (like synfire chains (Ikegaya et al., 2004), packets (Luczak et al., 2007) or hippocampal sequences (Pastalkova et al., 2008; Villette et al., 2015) and on the role of such precise spike timing in downstream information transfer and coding (Branco et al., 2010; Buzsáki & Tingley, 2018; Luczak et al., 2015). In particular, one theoretical viewpoint considers *synfire braids* (Bienenstock, 1995), where a precise sequential motif of spikes will synchronize as it reaches the soma of a neuron for which synaptic delays are adequately tuned. In particular, computational modeling shows that at the scale of neurons, an efficient neural code can emerge where spike times are organized in prototypical, precise temporal motifs (Izhikevich, 2006) which he defined as *polychronous groups*.

Stereotyped sequences of neuronal activation have been particularly well described in the adult hippocampus and related to its function in mental travel in time and space (Buzsáki & Tingley, 2018). These sequences can be internally generated (Pastalkova et al., 2008; Villette et al., 2015) and are formed by the chained activation of orthogonal assemblies, themselves organized as sequence packets (Malvache et al., 2016). Thus, hippocampal sequences are formed by the ordered activation of smaller sequence motifs. They are stereotyped and robust, since neurons can be activated in the same order across days (see Figure 2 of (Haimerl et al., 2019)). As a consequence, hippocampal sequences may rely on an internally hardwired structure and form the functional building blocks for encoding, storing and retrieving experience.

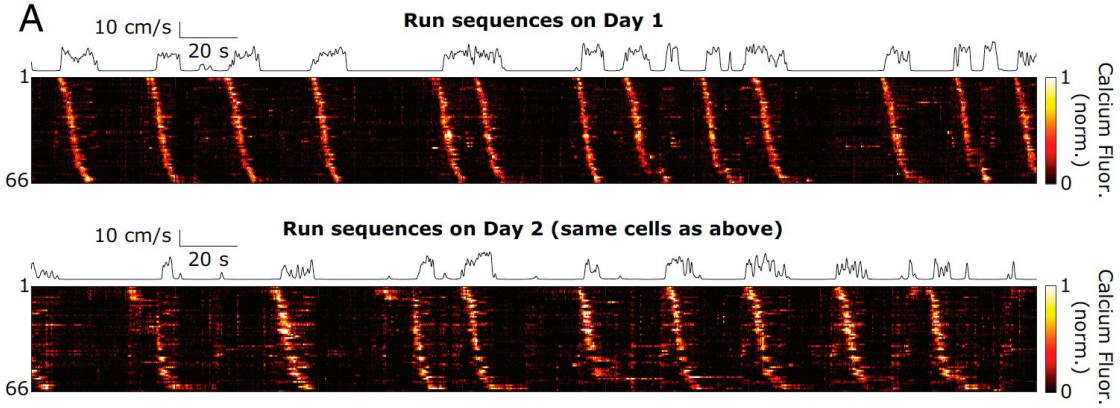

FIGURE 2: An example of a polychronous group seen in cortical slices. In this study by (Haimerl et al., 2019), an analysis of the raster plot shows repetitions of precise spiking motifs with a time scale of the order of seconds.

In this context, our concept and aim is to develop a theoretical framework to integrate this novel biologically-inspired dimension, or "*polychrony*" into artificial machine learning algorithms and to better understand the computational principles of spiking (event-based) representations. Such ambitious program involves different disciplines and we will bring together partners with that interdisciplinary expertise from three institutes from AMU: Institut de Neurosciences de la Timone, INT and Institut de Neurobiologie de la Méditerranée, INMED (from the NeuroMarseille Institute) and Laboratoire d'Informatique et Systèmes, LIS. Our objective within that focused consortium is to validate and improve event-based algorithms (partner INT) in neurobiological data (partner INMED) but also to benchmark this event-based approach in neuromorphic machine sensing applications, for instance applied to audition or vision (partner LIS). This core theoretical paradigm will bring together these different actors to bring novel insights into the development of natural and artificial intelligent learning processes.

3.2. Concept and aims of the project

Present the overall objectives of the project, describe any novel aspects with respect to the topic addressed.

The central objective of our project is to model the ability of a given neuron to encode precise temporal motifs of spikes that we will define as *polychronous groups* (see Figure 3). As spiking events are binary all-or-none events, an optimal detection model can be mathematically expressed as an artificial neural network using a similarly structured motif of synaptic delays (see Figure 3). We have shown in preliminary results that **this machine learning algorithm outperforms classical covariance-based methods in retrieving the timing and identity of *polychronous groups* (PGs)**. It is a powerful tool even in the case of a large number of overlapping PGs, in particular as we increase the temporal depth of the motifs (that is, the range of possible synaptic delays). In particular, this machine learning algorithm may therefore provide a powerful tool to detect sequential activity in neurobiological data. As observed in neurobiological data, such sequences may be intermingled but are functionally orthogonal (Malvache et al., 2016). In practice, this algorithm can be applied to neurobiological raster plots but also to data from event-driven cameras. Moreover, since it is expressed in terms of classical machine learning blocks, we efficiently implemented it using the *pyTorch* deep-learning library that currently adapts well to high-performance computing architectures such as GPUs or in the future to neuromorphic chips. Interestingly, the model may be extended to an online algorithm (i.e., which processes event-based data as it flows in) but also to a recurrent neural network architecture.

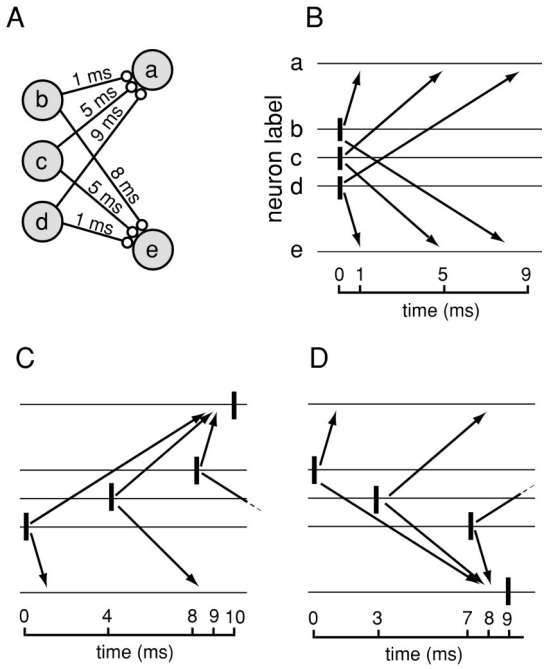

FIGURE 3: *Polychronous groups* as defined by (Izhikevich, 2006) . (A) In a population of 3 neurons (b), (c) and (d) connecting to 2 neurons (a) and (b), these connections will de defined by weights and delays. In B, a synchronous volley will be distributed at different delays on the output. In (C), a specific sequence of input sequence will converge at the same time on (a), and reach a threshold sufficient to emit a spike at time 10ms. In (D), the same volley of spikes but in a different order will not elicit a spike in (a), but one in (e).

An added value of the project is that **this algorithm allows to *learn* polychronous groups** in an unsupervised way. Preliminary results show that a gradient descent scheme can learn to retrieve these motifs in synthetic data for which the ground truth is known. A first important application would be to apply this learning on raster plots obtained in experimental recordings. A crucial aspect

is to validate this scheme using different neural sizes (number of PGs) and different temporal depths for each given dataset. By extending the framework using spatial convolutions, we will also be able to apply it to event-driven cameras, a missing tool for efficient processing of these event-driven representations. We will also test if our learning algorithms is able to explain behavioral data from auditory noise learning experiments (Agus et al., 2010; McDermott et al., 2011) and compare it to alternatives based on sparse predictive reservoir coding (Buonomano & Maass, 2009).

Finally, the most audacious aspect of our project is to consider that the timing of the different PGs can itself be temporally structured into repeating temporal motifs (like the cortical songs in Ikegaya et al. 2004 or the chains of cell assemblies in Malvache et al. 2016) and therefore that **the *polychrony* model naturally extends to a hierarchy**. As such, our machine learning algorithm will be able to extract temporal sequences at larger time scales, which will, importantly, enable confronting it with further biological knowledge. In particular, given the importance of sequential activity for hippocampal function and its prevalence in hippocampal dynamics, our INMED partner will provide us with multi-neuron in vivo calcium imaging datasets imaged from developing mouse pups in order to try extracting such polychronous groups and in particular time the emergence of hippocampal sequences and assemblies during brain development (Dard et al., 2021). This interdisciplinary cross-talk will help us to improve our understanding of sequence learning in biology but also, in turn, to refine our theoretical models.

3.3. Presentation of the scientific and technical leader and of the project team

Briefly present the scientific and technical leader of the project, the laboratory with which they are affiliated and the key lecturer-researcher(s) / researcher(s) / personnel involved. Any CVs should be included in the appendices.

The STL, **Laurent Perrinet**, is a researcher in computational neuroscience at INT (UMR 7289, AMU). He holds an engineering degree from SUPAERO and has developed models of spiking neural networks as part of his PhD in cognitive neuroscience (2003) before joining the CNRS (with Dr. Masson, INT). He further developed predictive coding models of visual processing with Karl Friston (UCL). Recently, he has focused on porting these models to neuromorphic hardware, notably through an interdisciplinary grant on neuromorphic computing for biorobotics (with Stéphane Viollet, ISM-AMU). Moreover, the STL has a long experience in bringing together computational and biological neurosciences (with Dr. Chavane, INT), both in his scientific publications and in the development of interdisciplinary collaborative networks. He coordinates the recently-created CONECT group, a center for computational neuroscience at INT.

*The role of **Laurent Perrinet** in this project is to coordinate the consortium and to act as the main supervisor of the post-doctoral researcher. An important role of partner INT is to ensure the mobility of the post-doctoral researcher within the consortium and to provide with an efficient collaboration environment. This includes the construction of the inter-disciplinary dataset consisting of the experimental data obtained by partners INMED and LIS, but also by collating the neuromorphic datasets obtained by partner INT's neuromorphic cameras and by existing collaborations. Partner INT will also be responsible for coordinating the effective implementation of the project in terms of scientific impact and outreach (see section 4.4).*

3.4. Presentation of the partner(s) involved

Briefly present the external organisation(s) involved in the project - if applicable - along with their role and the teams involved in the partnership. Provide the necessary elements to allow others to grasp what these partners contribute to the project, and their role(s) in the project.

Rosa Cossart is the Director of the Institute of Mediterranean Neurobiology (INMED, INSERM U1249, AMU), affiliated to INSERM and Aix-Marseille University, a pioneering Institute in the field of Systems Developmental Neuroscience. After graduating in Mathematics and Physics from the Ecole Centrale Paris, she studied the functional rewiring of GABAergic circuits in epilepsy during her PhD with Drs. Bernard and Ben-Ari. As a postdoctoral fellow with Pr. Yuste at Columbia University, she pioneered the use of calcium imaging to study cortical circuit function. Her lab made seminal contributions to the understanding of how development scaffolds hippocampal circuits. They discovered "hub cells" and more recently "assemblies" forming the functional building blocks of hippocampal function. Her work has been rewarded by several prizes, including the INSERM Research Prize and the CNRS Silver Medal. She has been awarded three times a European Research Council grant.

*The role of **Rosa Cossart** in this project is to co-supervise the post-doctoral researcher. In particular, she will be involved in the use of the computational algorithm developed in this project to extract sequences from biological datasets. These datasets will mostly be comprised of raster-plots describing in vivo hippocampal dynamics obtained with calcium imaging in the adult and developing mouse brain. She will be involved in selecting the datasets and in providing the information needed to interpret the findings. An asset of the project would be to allow the mobility of the post-doctoral researcher to allow for a continuous interaction with partner INMED. Moreover, we anticipate that the results obtained on neurobiological data will bring useful data on the structure of the PGs or with regard to development which would in return allow to improve the machine learning algorithms. A role would be to supervise one master student on this task (see work-package wpD below). A further role of partner INMED is to facilitate the integration of this neurobiological knowledge into the theoretical framework.*

Thomas Schatz is an assistant professor at AMU in the Computer Science and Systems Laboratory (LIS, UMR 7020) and the Language Cognition and the Brain Institute (ILCB). He studies learning in animals as well as in machines, with a focus on understanding how human infants learn to perceive the world and how that might inspire the design of less costly, more capable and more reliable artificial learning systems. After being admitted to the Ecole Normale Supérieure de Cachan in Computer Science, he studied for his PhD with Emmanuel Dupoux and Francis Bach at the Ecole Normale Supérieure, where he introduced a novel method to evaluate unsupervised speech representation learning systems that has since become widely used in speech technology. As a postdoctoral fellow with Naomi Feldman at the Massachusetts Institute of Technology and the University of Maryland, he contributed to our understanding of the development of speech perception in human infants.

*The role of **Thomas Schatz** in this project is to co-supervise the post-doctoral researcher. In particular, partner LIS will lead the investigation of the formal benefits of neuromorphic implementations of the proposed PG detection and learning schemes from the point of view of computer science. A role would be to supervise one master student on this task (see work-package wpA below). The post-doctoral researcher would also be granted regular access to the partner's lab at Centrale Marseille as well as to the computational resources of the LIS laboratory. Partner LIS will also be the lead advisor to assess the proposed schemes' ability to account for observed human behavior in noise learning experiments and for the evaluation of the schemes' performance on standard information-retrieval benchmarks in machine learning.*

The consortium leading this project forms a focused team with a broad expertise, an extensive network of collaborations within and beyond AMU with a solid inter-disciplinary experience.

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4. Implementation modalities

4.1. Plan of action

Present activities in terms of objectives, tasks, deliverables, and criteria to measure success that can be used to evaluate the results at the end of the project. Add as many Work Packages as necessary. The schedule for the various tasks and their interdependencies may be presented in graphical form (e.g., Gantt diagram).

Work-packages: The project will last 24 months and will start immediately as it does not require new experimental data at its onset. We will start by setting up an agile collaborative environment for communication, computer code and data sharing.

The recruitment of the post-doctoral researcher will allow to kick-off the project which is organized in progressively more complex work-packages that we will develop from month 1 (M01-10/2022) to month 24 (M24-09/2022).

	M01-M03	M03-M09	M09-M12	M12-M15	M15-M21	M21-M24
wpA	DETECTION OF PGs					
		Master 2 #1				
wpB		BAYESIAN UNSUPERVISED LEARNING				
wpC			HIERARCHICAL MODULES			
wpD				DEVELOPMENT		
					Master 2 #2	

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Title of Work package A (WP-A): Asynchronous	
Start[5]: M01 (10/2022)	End[3]: M09 (06/2023)
Objectives: The first work-package consists in exploring the theoretical foundations of asynchronous coding and in particular the **detection of PGs**. We will explore the theoretical possibilities of this framework through 1/ simulations with synthetic data (lead: INT) and 2/ formal comparisons of possible implementations over neuromorphic vs conventional hardware (lead: LIS). A useful extension to this detection model would be to extend the network model from a feed-forward to a recurrent model using an online formulation of the detection problem (Alemi et al., 2018).	
Description of the activity: The detection of a pattern in a generic signal should be adapted to the nature of the signal. For instance, using a correlation-based computation is optimal when detecting an analog pattern in Gaussian noise. In the case of an event-based signal, we will devise a novel metric adapted to such sparse, binary data. Thanks to our preliminary work, we will first validate this metric on synthetic data for which the ground truth is known. We will also control the efficiency of this measure compared to classical correlation-based metrics and study how to efficiently implement our solution on neuromorphic hardware.	
Resources involved (including human, material, technical, financial, contributions of partners, etc.) This work-package will involve the post-doctoral researcher which would need to take over our existing preliminary work and make sure the resources will be available to the whole consortium, especially when collecting neuromorphic or biological data. Moreover, partner LIS will recruit a first master 2 student (from M03 to M09) to develop formal comparisons of neuromorphic vs conventional implementations of the proposed PG detection scheme.	
Expected results (deliverables, indicators): We will provide with a core library which should extend our preliminary code (using pyTorch on dedicated GPUs) and optimize its computational speed and energy savings using the binary nature of the data and the sparseness of connections. In particular, we will benchmark this core library in order to be competitive for high-throughput of both neuromorphic and neurobiological data.	
Comments / Analysis: This work-package is expected to be of low risk thanks to our preliminary work. The extension to detection using a recurrent network is theoretically feasible (for instance by using back-propagation through time), yet it has still to be validated experimentally on our synthetic data.	

[5]Example. M1, M6 etc. for month 1, month 6.

APPLICATION FORM (full project proposal)

Title of Work package B (WP-B): Bayesian	
Start[3]:M03 (01/2023)	End[3]:M21 (06/2024)

Objectives:

The second work package will explore how we can use the detection model developed in *wpA* and its corresponding metric to l**earn the structure of unknown PGs**. This unsupervised learning algorithm will first be tested and validated on synthetic data. It will then be applied on data from neuromorphic cameras (DVXplorer camera from Inivation©, partner INT) and experimental neuroscience (existing data from two-photon imaging, partner INMED). The analysis of the emerging PGs will allow to refine the detection (*wpA*) and learning (*wpB*) models. The refined model's ability to account for behavioral observations in humans will be tested and compared with alternatives by partner LIS.

Description of the activity:

While we have shown in preliminary data that one can learn PGs from neuromorphic silicon retina data using supervised learning using standard gradient descent, it remains a challenge to implement a self-supervised clustering algorithm on generic event-based data. Thanks to our expertise in machine learning (partner LIS), in modeling SNNs (partner INT) and in the neurobiological recordings (partner INMED), we will integrate useful *a priori* information to allow the algorithm to converge on the different datasets. In particular, we will include priors on the sparseness of the latent variables.

Resources involved (including human, material, technical, financial, contributions of partners, etc.)

The resources will be first devoted to collect the different datasets and will require for all members of the consortium to participate to the consolidation of a common database of neuromorphic and neurobiological data. Our first results should compare the resulting PGs obtained in supervised and self-supervised learning. This task will require technical skills for the elaboration of the computer framework to maintain the high-throughput capabilities of the detection paradigm (*wpA*).

Expected results (deliverables, indicators):

We will learn PGs for both neuromorphic and neurobiological data, allowing us to better understand the determinants of these emerging structures. This should help the tuning of the learning algorithms, notably to choose for each dataset the size of the PGs (notably their temporal depth and the size of assemblies) or the number of kernels necessary to explain most of the signal.

Comments / Analysis:

This work-package is expected to be of medium risk thanks to our preliminary work. In particular, by controlling the way we provide with labels, we may progressively transition from supervised to self-supervised learning.

APPLICATION FORM (full project proposal)

Title of Work package C (WP-C): CorticalSongs	
Start[6]: M09 (06/2023)	End[3]: M24 (09/2024)

Objectives:

We will develop a model as **a hierarchy of polychrony modules** as developed in *wpB*. While this is a natural and common extension in machine learning (especially deep learning, see (LeCun et al., 2015) for a review), we will carefully consider the implications of architectural choices in the design of the hierarchy at each layer, including the layer-by-layer complexity of the representation (number of PGs) and temporal depth of the PGs (lead: INT). Neuromorphic and biological data will constrain the types of invariance functions (such as max-pooling) to match timing accuracy with experimental data from partner INMED. The resulting algorithm will be tested and compared with state-of-the-art in relevant machine sensing tasks, such as information retrieval from auditory and/or visual cues (lead: LIS).

Description of the activity:

As we have previously seen, the detection model transforms an input raster plot into a raster plot representing the identity and timings of PGs. This operation can therefore be chained such that each module is a node on a larger scale graph. As the learning will be implemented by a gradient descent, a similar learning can be applied given some conditions on the graph.

Resources involved (including human, material, technical, financial, contributions of partners, etc.)

This work package will be a core outcome of the project and will involve resources from all partners. In particular, we will validate our framework on the datasets provided during *wpB* for the neuromorphic (partner INT and LIS) and neurobiological (partner INMED) data.

Expected results (deliverables, indicators):

In particular, we expect first to replicate the detection of higher-order temporal motifs of PGs in neurobiological data, and to be able to analyze the structure of the emergent PGs. Second, we expect to explore the relevant parameters to successfully achieve an efficient learning paradigm. An indicator of success would be to be able to provide with a real-time solution for the detection of multi-layered PGs in both neuromorphic and neurobiological data.

Comments / Analysis:

This work-package is clearly expected to be of higher risk than *wpA* and *wpB*. This risk will be first mitigated by progressively increasing the number of layers, but also by using progressively more difficult tasks starting from synthetic data to then switch on neuromorphic and neurobiological data. We also expect to mitigate risks thanks to the knowledge acquired in *wpD*.

[6]Example. M1, M6 etc. for month 1, month 6.

APPLICATION FORM (full project proposal)

Title of Work package D (WP-D): Development	
Start[3]: M12 (10/2023)	End[3]: M24 (09/2024)
Objectives: The *wpC* work-package provides an audacious framework for **temporal sequence detection**. Learning such a network involves a large number of parameters and is generally known to be difficult. We will draw on studies regarding the development of predictive maps (for instance spatial navigation), both neurophysiological and behavioral, to understand how the convergence of the algorithm developed in *wpC* can be improved to be more stable on our different datasets defined in *wpA* (synthetic, neuromorphic, biological). This part will rely crucially on partner INMED's expertise on the scaffolding of neural assemblies, notably in the hippocampus, as well as on partner LIS expertise regarding human behavioral development.	
Description of the activity: We anticipate that the learning paradigm introduced in *wpC* will be subject to instabilities when applied to real data. These are common in the machine learning community and our objective here is to take advantage of the interdisciplinary approach to translate the knowledge gained from the development studies in the hippocampus (partner INMED) to the way we train machines.	
Resources involved (including human, material, technical, financial, contributions of partners, etc.) This worpackage led by partner INMED will involve all partners. It will involve a master 2 student (months M15 to M21) at INMED co-supervised by the post-doctoral researcher that will take advantage of the existing scientific knowledge in the hippocampus and its potential transfer to machine learning.	
Expected results (deliverables, indicators): We will synthesize and quantitatively validate development patterns observed in neurobiology in machine learning, notably on the scaffolding of neural assemblies or the existence of critical periods (Dard et al, 2021). Of particular interest would be the potential predictive power of such theoretical results regarding neurological disorders and pathologies.	
Comments / Analysis: This workpackage is more exploratory and risky, yet it constitutes a high potential impact of this interdisciplinary project to the whole community from computational neuroscience to neurobiology.	

APPLICATION FORM (full project proposal)

Summary :

For each WP, and as detailed in the Comments / Analysis sections, we have considered a mitigation scheme: To summarize, while *wpA* and *wpB* are respectively of low and medium risk and feasible thanks to our preliminary studies, *wpC* is a challenging task. We will mitigate this risk by starting with a two-level hierarchy and then leverage the results of *wpD* to address potential convergence issues of the algorithms developed in *wpC*.

4.2. Steering and administrative management

Indicate which resources will be mobilised within the research unit's administrative team, after consultation of the management

Experience of the research unit in project management (European, A*Midex, ANR, etc.): The research unit of partner INT has a longstanding experience in managing European-wide projects (ITN, CHISTERA, …) and to develop interactions within AMU. The project will take advantage of research unit's administrative team organization, following existing experience on similar projects.

Administrative contact person (if applicable)

Surname	CHASSAING
First name	Jean-Louis
Role	***Administrative manager***
Contact details (E-mail + Tel)	jean-louis.chassaing@univ-amu.fr
Estimation of the level of experience in management of research projects:	☐ Beginner ☐ Intermediate ☒ Confirmed

Financial manager

Surname	SALOMONI
First name	Hélène
SIFAC accreditation level	☐ Polyvalent ☐ SIFAC Web ☐ SIFAC Qualified
Role	***Financial manager***
Contact details (E-mail + Tel)	helene.salomoni@univ-amu.fr
Estimation of the level of experience in management of research projects:	☐ Beginner ☐ Intermediate ☒ Confirmed

4.3. Scientific and strategic management of the project and the partnership

Describe the modalities of coordination, the principles of organisation, and the resources allocated to ensure monitoring and implementation of the project.

The STL (Scientific and Technical Leader) will coordinate the scientific and strategic management of the project, notably by proactively integrating the core members of the consortium – Rosa Cossart and Thomas Schatz. The STL, with his engineering background and more than 20 years of expertise in the field of neural networks, has a long experience at the intersection of theoretical, computational and biological neuroscience, ans in particular in interdisciplinary programs.

To implement an efficient management of the project, we will keep regular interactions during the duration of the project. These will be coordinated by the STL and will first take the form of regular monthly meetings. These meetings will be the opportunity to validate the inter-disciplanary nature of the project by presenting different scientific outcomes in front of the consortium. Second, we envision the joint participation to AMU events (summer-schools, hackathons) by presenting specific projects directly related to this project (see section 4.4). This will be essential to motivate the regularity of the monthly meetings.

4.4. Communication and dissemination

Describe the communication and dissemination plan, in particular the actions aiming to improve visibility of the project at the relevant scales (schedule, communication supports, networking, etc.).

During the project, we will strive to foster further development of such inter-disciplinary approaches at the interface between computational and biological neuroscience, machine learning and developmental sciences through training actions. These will be directed directly to AMU students through existing venues (M2 Computational Neuroscience for partner INT with NeuroMarseille, M2 IAAA (machine learning), M2 MASCO (cognitive science) and ILCB Summer School for partner LIS, CENTURI Summer School organized by partner INMED), but also through broader actions (such as the Marseille brainhack or dedicated seminars).

One of the fundamental commitments of the project is to further open it to the AMU community. Indeed, the objective of the project is to confront the theoretical model with real data. The dialogue with the CIRCUITPHOTONICS Equipex project will be useful to obtain more high-quality experimental data and provide with efficient high throughput analysis algorithms. The partnership with CENTURI will be essential to develop collaborations with biological neuroscience. On the other hand, the CONECT collaboration network will promote interactions with theoreticians (at INT, INS or LIS), but also with roboticians (Stéphane Viollet, ISM) and neurobiologists. This will take the form of targeted meetings and workshops.

Following the FAIR principles, we will ensure the openness and accessibility of datasets, publications and code. We already have a longstanding experience in sharing our scientific knowledge, notably by using international preprint servers (arXiV, biorXiV) or locally (HAL-AMU). We also have an established experience in sharing code (gitHub, packaging) but also to share tutorials or course material, for instance in the form of Jupyter notebooks. This project will be also the occasion to foster such FAIR initiatives in our collaborative network by taking advantage of the tools provided by AMU.

APPLICATION FORM (full project proposal)

5. Expected impact and returns

Describe the perspectives for scientific, pedagogical and technical returns, and the potential in terms of novel interdisciplinary approaches; the perspectives for adoption of the project within the Institute and/or the site, returns for the site in terms of visibility, synergy and partnerships; leverage effect on new funding (national and European) for:

- *The scientific and technical leader*
- *The partner(s)*
- *The Aix-Marseille site*

The core of the project is first motivated by our understanding of the spiking nature of information transmission across neural assemblies. The project involves a unique *pluridisciplinary consortium* spanning across machine learning, neuromorphic computing and biological neuroscience, from neurons to behavior: Partner LIS has a distinguished expertise in both machine learning and behavior and partner INMED is an expert in neurobiological recordings. Partner INT has a long-standing experience in the theory of spiking neural networks applied to event-based cameras and neuromorphic chips (notably SpiNNaker).

Our first goal is to design an *interdisciplinary project* to derive new machine learning algorithms tailored to handle data encoded as a stream of spikes. An important objective from the point of view of machine learning will be to characterize formally the properties of the resulting algorithms and to compare them to the classical alternatives which usually apply to signals uniformly sampled in time. We will benchmark the algorithms to neurobiological and behavioral data, which will synergistically drive further mathematical model refinements and new model-driven experimental designs.

At this level of the project, we will foster a cross-fertilization of the different disciplines, especially regarding the role of development in biological and artificial systems. The construction of deep hierarchies for polychrony detection will in particular provide new methods for theoretical neuroscience but also innovative algorithms for robotics, signal processing and high throughput analysis of neuroscience using low-energy neuromorphic chips, an audacious *trans-disciplinary solution* to important societal problems.

In particular, we have identified the following persons as potential researchers within AMU that declared to be interested in using our computational framework :
- Arnaud J Noreña (Laboratoire de Neurosciences Cognitives) by applying on recordings related to audition in the mouse,
- Rochelle Ackerley (Laboratoire de neuro-sciences sensorielles et cognitives) applied to the human in vivo technique of microneurography to investigate how touch and muscle afference is encoded and interpreted
- Stéphane Viollet - biorobotics team (ISM)
- Jérôme Epsztein and Roustem Khazipov at INMED

This network of collaborators will help develop practically the use of our framework within AMU.

APPLICATION FORM (full project proposal)

6. Budget

6.1. Detailed presentation of the budget for the project

Include the Excel document as appendix 1. ***This document must be filled out with the help of the financial manager selected to monitor the project if this option is retained, or an administrative manager from the research unit.*** *This person will help the applicant scientific and technical leader to link each expense to a broader category of costs.*

6.2. Overall justification of the budget

*In addition to the table, provide any general comments to justify the projected use of the financial resources and the links between A*Midex funding and other sources of funds.*

The budget reflects the main resources of the project which are centered on the recruitment of a post-doctoral researcher. Further resources required involve a High-Performance Computing server with a specialized GPU card, but also to provide with the right scientific environment, including resources for the dissemination of the scientific outcomes (publications). The gratification for master 2 students will complement that budget in order to train future early researchers.

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7. Appendices

Appendix 1 (required): Excel version of budget

APPLICATION FORM (full project proposal)

Appendix 2 (required): Letter of commitment from the scientific and technical leader of the Aix-Marseille-affiliated institute

APPLICATION FORM (full project proposal)

Pascale Durbec
Directrice NeuroMarseille

Institut NeuroMarseille
Aix*Marseille Université

Marseille, February 26, 2022

Letter of support – interdisciplinary call A*MIDEX

Title of the project: "Temporal spiking motifs in neurobiological and neuromorphic data"
Acronym : Polychronies
Project leaders Dr Laurent Perrinet (Institut de Neurosciences de la Timone (INT UMR 7289, AMU)

Polychronies submitted by the project leader Dr Perrinet has been selected by the scientific committee of the NeuroMarseille institute.

This innovative project addresses a fundamental question in neurobiology: why brain communication based on "spikes", a binary phenomenon, is so efficient. An applicative corollary is whether one could implement this efficiency in neuromorphic devices such as digital cameras or microphones. To address these two questions, the aims to develop a numerical framework for analysing and modelling timing patterns in both biological and artificial neuronal networks. More specifically, the objective is to understand how precisely timed neuronal activity patterns can be detected more efficiently using computational biology. This problem of temporal pattern detection is directly motivated by neurobiological observations, notably in the hippocampus but also has direct technological implications for neuromorphic devices. Its innovative aspect is to consider a hierarchy of temporal patterns across scales, allowing to build much richer information contents.

In order to reach this goal, this interdisciplinary project will foster the collaboration of one neurobiology team (Rosa Cossart at INMED), one computational biology team (Laurent Perrinet at INT) and one young assistant professor at AMU specialized in Machine learning and computational modelling of behaviour (Thomas Schatz at LIS). These teams and scientists are leading experts in their domain, have international visibility, and are highly complementary.

NeuroMarseille fully supports this project, fostering the local community's interactions and providing essential data to understand temporal spiking motifs in neurobiological data.

Pascale Durbec
DR1 CNRS
Directrice de NEUROMARSEILLE

NeuroMarseille – Institut d'Etablissement
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Aix*Marseille université

APPLICATION FORM (full project proposal)

Appendix 3 (required): Letter of commitment from the director of the research unit

APPLICATION FORM (full project proposal)

Dr Guillaume MASSON
Directeur

A :

Mr le Président
Comité Scientifique
Programme Interdisciplinarité – Fondation AMIDEX
Aix-Marseille Université

Marseille, le 22 février 2022

Monsieur le Président

Laurent PERRINET propose un projet intitulé « *POLYCHRONIES/ Temporal spiking motifs in neurobiological and neuromorphic data* » dans le cadre de l'AAP Interdisciplinarité. Ce projet est construit en collaboration avec Rosa COSSART (INMED) et Thomas SCHATZ (LIS) et un donc un projet interdisciplinaires entre Neurobiologie, Neurosciences computationnelles et Mathématiques Appliquées. Il est déposé sous couvert de l'Institut NeuroMarseille.

POLYCHRONIES est un nouveau projet, réunissant des scientifiques intéressés dans l'étude des patterns d'événements discrets et de leurs structures temporelles, dans les systèmes biologiques et artificielles. Ils posent une question de très forte actualité scientifique : quel est l'avantage computationnel des représentations impulsionnelles pour le codage de l'information ? Il faut souligner que cette démarche se distingue des approches théoriques dominantes en apprentissage automatique et en codage neuronal où les cascades de réseaux de neurones traitent uniquement des informations spatiales dans des systèmes synchrones, sans références au codage temporel. Mieux comprendre la nature et la richesse de ce codage temporel, notamment dans des réseaux polychrones, a donc des retombées théoriques en neurosciences mais également sur des applications comme la robotique, les systèmes neuromorphiques ou encore les systèmes d'analyse automatique comme la vision par ordinateur.

L'AAP Interdisciplinarité d'AMIDEX vise à l'émergence de nouvelles collaborations interdisciplinaires. POLYCHRONIES répond à cet enjeu en associant des scientifiques ayant démontré leur capacité à mener à bien des projets collaboratifs et interdisciplinaires mais n'ayant jamais collaboré entre eux. Par ailleurs, il s'inscrit dans une dynamique du site Aix-Marseille rapprochant neurosciences expérimentales, théorique neuronale et sciences de l'information (Mathématiques Appliquées, Informatique). Il est important de doter la communauté des neurosciences d'une plus grande force et visibilité autour de ces interactions centrées sur l'étude du cerveau.

L'*Institut de Neurosciences de la Timone* soutient donc fortement ce projet et s'engage à en assurer la bonne gestion. Il accompagnera les scientifiques dans la bonne conduite du projet POLYCHRONES.

Le projet est classé en 1er priorité parmi les projets de NeuroMarseille dans lesquels l'INT est impliqué. Il va renforcer encore un peu plus les liens entre l'INT, l'INMED et le LIS.

J'espère donc vivement qu'AMIDEX soutiendra ce projet interdisciplinaire.

Cordialement

Institut Neurosciences Timone
Directeur
Guillaume Masson

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APPLICATION FORM (full project proposal)

Appendix 4 (required): Letter of commitment from each partner

APPLICATION FORM (full project proposal)

Marseille, 28 Février 2022

À qui de droit,

Je soussignée Rosa Cossart, Directrice de recherche (DR1) CNRS à l'Institut de Neurobiologie de la Méditerranée, INMED, affirme par la présente ma volonté de contribuer activement au projet Polychronies : « Temporal spiking motifs in neurobiological and neuromorphic data » porté par Laurent Perrinet et que nous soumettons au titre du « 2021 Interdisciplinarity call for projects d'A*MIDEX ».

Cordialement,

Dr R. COSSART
Directrice
Inmed UMR 1249

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APPLICATION FORM (full project proposal)

Laurent Perrinet - *Researcher*
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https://laurentperrinet.github.io/ - Laurent.Perrinet@univ-amu.fr – tel: +33 619478120

Marseille, 28 Février 2022

À qui de droit,

Je déclare, soussigné Laurent Perrinet, Directeur de recherche (DR2) CNRS à l'Institut de Neurosciences de la Timone, INT mon intention de participer activement au projet « *Polychronies : Temporal spiking motifs in neurobiological and neuromorphic data* » que nous soumettons au titre du « *2021 Interdisciplinarity call for projects* » d'A*MIDEX.

Cordialement,

Laurent Perrinet, INT

APPLICATION FORM (full project proposal)

Marseille, le 24 février 2022

À qui de droit,

Je soussigné Thomas Schatz, Maître de conférences à l'Université Aix-Marseille (AMU) au Laboratoire d'Informatique et Systèmes (LIS UMR 7020 AMU/CNRS/UTLN), affirme par la présente ma volonté de contribuer activement au projet Polychronies : « Temporal spiking motifs in neurobiological and neuromorphic data » porté par Laurent Perrinet et que nous soumettons au titre du « 2021 Interdisciplinarity call for projects d'A*MIDEX ».

Thomas Schatz