

**15th International Workshop on
NEURAL CODING 2023**

Book of Abstracts

Piriápolis, Uruguay
27 February – 4 March 2023

15th International Workshop

NEURAL CODING 2023

27 February – 4 March / Piriápolis, Uruguay

<http://neuralcoding.net/nc2023>

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Foreword

The 15th International Workshop on Neural Coding is held 27 February to 4 March 2023 at the historic beach town of Piriápolis, Uruguay. Since 1995, this biennial event provides for multidisciplinary efforts of neurophysiologists, computer scientists, biophysicists, mathematicians, engineers, cognitive neuroscientists and others, bringing them to share their expertise towards outstanding issues in solving the neural code. This year we are especially keen to be back as an in-person event!

The workshop typically consists of single track multi-disciplinary sessions with topical areas that have typically covered diverse aspects of brain-computer interfaces, coupled oscillators, information theory, network architecture and dynamics, probabilistic models, sensory systems, and spike train analysis. Special emphasis is placed on exchange leading to fruitful collaborations between attendees. These may be further fostered by social and cultural events integrated into the meeting. Previous meetings have been hosted in Prague (1995), Versailles (1997), Osaka (1999), Plymouth (2001), [Aulla](#) (2003), Marburg (2005), Montevideo (2007), Tainan (2009), [Limassol](#) (2010), [Prague](#) (2012), Versailles (2014), [Cologne](#) (2016), [Torino](#) (2018), and [Seattle](#) (2021, online). Selected presentations have also been published in workshop [Special Issues](#) over the years.

This austral summer season is intended for a lively meeting aiming to facilitate discussion across all functional levels of the nervous system – from sub-cellular to systems levels and behavior-, and to work out important implications for sensory, cognitive, motor, autonomous and control processes.

Piriápolis, February 2023

The NC2023 Team

Neural Coding 2023
Piriápolis, Uruguay, 27 February – 4 March 2023

	Monday, 27 Feb	Tuesday, 28 Feb	Wednesday, 1 Mar	Thursday, 2 Mar	Friday, 3 Mar
Starting time					
09:00		LIF models	Poster session	Cognitive functions	
09:30					
10:00		Coffee break	Excursion	Coffee break	Business meeting
10:30					
11:00		From channels to networks			Neural code
11:30					
12:00		Lunch			Lunch
12:30					
13:00					
13:30					
14:00					
14:30		Associative networks			Oscillatory processes
15:00					
15:30		Coffee break		Coffee break	
16:00					
16:30					
17:00		Sensory systems		Network characterization	
17:30	Neuroscience in Uruguay				
18:00					
20:00	Welcome dinner			Farewell dinner	

MONDAY, 27th FEBRUARY

17:30 Registration, Neuroscience in Uruguay
Casa de la Cultura de Piriápolis

20:00 -Welcome dinner-
Restaurante Meridiano 58

TUESDAY, 28th FEBRUARY
Salón Dorado, Argentino Hotel

Leaky integrate and fire models

09:00 *Laura Sacerdote and Giuseppe D'Onofrio*
Jacobi processes with jumps as neuronal models - Part 1 1

09:30 *Giuseppe D'Onofrio and Laura Sacerdote*
Jacobi processes with jumps as neuronal models - Part 2 3

10:00 *Cristina Zucca and Laura Sacerdote*
Quickest detection in neuronal modelling 5

10:30 -Coffee break-

From channels to networks

11:00 *Sabrina Camargo, Daniel Martin, Eyisto Aguilar Trejo, Aylene de Florian, Maciej Nowak, Sergio Cannas, Tomás Grigera, and Dante Chialvo*
Scale-free correlations in the dynamics of a small ($N \sim 10000$) cortical network 6

11:30 *Antonella Dapino, Federico Davoine and Sebastian Curti*
Contribution of the D-type K^+ current to the operation of networks of electrically coupled neurons 7

12:00 *Christine Pedroarena*
A slow gain control mechanism 9

13:00 -Lunch at Argentino Hotel-

Associative networks

14:30 *Roseli S. Wedemann and Angel Ricardo Plastino*
Multidimensional representation of neurons in associative memory networks 10

15:00 *Andrés Pomi*
Statistical learning of autoassociations of population vectors with overlapping tensor contexts provides a natural neural basis for Bayesian computation 12

15:30 *Pawel Herman, Rohan Raj, Nikolaos Chrysanthis, Thomas Hörberg, Robert Lindroos, Anders Lansner and Jonas Olofsson*
Learning and recalling odour names in an associative cortical memory network model 13

16:00 -Coffee break-

Sensory systems

16:30 *Cornelius Schwarz*
The Slip hypothesis: Temporally Local Coding and Perception of Tactile Stimuli in Rodents and Humans 15

17:00 *Tadeo Neyen Segovia, Inés Samengo and Nicolás Vattuone*
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17:30 *Jonathan Victor, Aaron True and John Crimaldi*
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WEDNESDAY, 1st MARCH
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Pietro Vischia and Angel Ariel Caputi
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Ana Carolina Pereira, Alejo Rodriguez-Cattáneo, Pedro Aguilera and Angel Caputi
The receptive field organization of the electro-sensory lobe neurons of *Gymnotus omarorum* 23

Tamara Liberman, Martín Bidegain and María Castelló
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THURSDAY, 2nd MARCH
Salón Dorado, Argentino Hotel

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09:30 *Alessandra Lintas*
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10:00 *Angel Caputi and Marcela Piffaretti*
How does the brain evaluates logical propositions? 31

10:30 -Coffee break-

Neural code

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11:30 *Alessandro Villa*
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12:00 *Barry Richmond and Rossella Falcone*
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13:00 -Lunch at Argentino Hotel-

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15:00 *Santiago Castro, Joaquin Gonzalez and Pablo Torterolo*
Top-down directionality of gamma band (≈ 40 Hz) functional interactions during wakefulness, sleep and drugs that affect consciousness 40

15:30 *Joaquin Gonzalez, Pablo Torterolo and Adriano Tort*
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16:30 *Tatyana Turova Schmeling*
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17:00 *Lucas Diaz Celauro, Bautista Arenaza and Inés Samengo*
A formal framework to construct simplified models of probabilistic descriptions of neuroanatomical data 44

17:30 *Eyisto Aguilar, Daniel Martin, Dulara De Zoysa, Zac Bowen, Tomas Grigera, Sergio Cannas, Wolfgang Losert and Dante Chialvo*
Monitoring the state of a neural network via spatial scaling of correlations 45

20:00 *-Farewell dinner-
Kraken Restaurante*

FRIDAY, 3rd MARCH

10:00 *Business meeting (on-site + virtual)
Casa de la Cultura de Piriápolis*

Outreach activities

2 March 2023 11:00-17:00 *Exhibit: Biofeedback, Salón Dorado annex room*

3 March 2023 11:00-13:00 *Family workshop, Casa de la Cultura*

ABSTRACTS

Jacobi processes with jumps as neuronal models

Part 1*

Laura Sacerdote¹ and Giuseppe D’Onofrio²

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(2) – Dipartimento di Scienze Matematiche “G.L. Lagrange”
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The number of neuronal models is very high and their complexity ranges from oversimplified to highly realistic biophysical models ([1]). The leaky integrate and fire concept is considered a good compromise between tractability and realism. The basic idea of such models goes back to Lapique ([2]) and all the most used models can be considered variants of the stochastic version presented in the seminal paper by Stein [3]. There, the membrane potential of a neuron, in absence of spikes, is described through the process $X(t)$, solution of the stochastic differential equation

$$dX(t) = -\frac{X(t)}{\theta} + \alpha_e dN^+(t) + \alpha_i dN^-(t); \quad X(0) = 0, \quad (1)$$

where θ is the membrane potential time constant ($\theta = RC$, where R is the membrane resistance and C its capacitance), α_e and α_i are the mean amplitudes of excitatory and inhibitory postsynaptic potentials as they contribute to the membrane potential at the trigger zone, $N^+(t)$ and $N^-(t)$ are two independent Poisson processes with intensities λ_e and λ_i , respectively. Then, a threshold was superimposed to mimic the spiking activity of the neuron. The interspike intervals are identified with the first-passage time T , of the stochastic process X across a threshold S .

Since for some types of neurons the incoming inputs are frequent and relatively small, a diffusion limit over the discrete process describing the membrane potential evolution was performed to gain the higher mathematical tractability of the Ornstein-Uhlenbeck process ([4]). Different variants of the Ornstein-Uhlenbeck model have appeared in the literature, considering different diffusion processes or different types of thresholds (see [5] for a review).

The two main lacks of the Ornstein-Uhlenbeck model can be listed:

- The pure-diffusion models do not account for the spatial geometry of the neurons and do not discriminate among different sources of incoming inputs.
- The state space of the Ornstein-Uhlenbeck model is the real line and reversal potentials are disregarded.

Different variants of the Ornstein-Uhlenbeck model tried to overcome the second problem, for example switching from the Ornstein-Uhlenbeck model to the Feller one, also known as Cox–Ingersoll–Ross model ([5]). This choice allowed to account for an upper reversal potential, without introducing insurmountable mathematical difficulties. Recent papers ([6, 7]) propose the

*Joint work with Pierre Patie, Cornell University.

use of the Jacobi process to model the membrane potential evolution. The Jacobi process has a bounded state space, that is the value of the membrane potential is confined below and above by two fixed values that account for the reversal potentials. Moreover, the change in the membrane potential determined by an incoming input depends on the distance between its actual state and the two reversal potentials. As far as the first listed difficulty of the Ornstein-Uhlenbeck model is concerned, some Jump-diffusion models appeared in the literature. In particular, in [9] two very simple jump-diffusion variants of the Ornstein-Uhlenbeck model were studied by adding to the process large jumps determining the attainment of the threshold or introducing jumps towards the resting potential. In both the models the jumps times were exponentially distributed. Furthermore, a multivariate Ornstein-Uhlenbeck process with jumps is proposed in [8] to model a network. Here, we propose a more complex jump-diffusion model. We start from the Jacobi diffusion process and we allow inhibitory jumps whose size and frequency are state dependent. At the price of an heavier mathematical formalism, analytical results are obtained for the first passage time of this process. These results will be presented in the part 2 talk.

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Jacobi processes with jumps as neuronal models

Part 2*

Giuseppe D’Onofrio¹ and Laura Sacerdote²

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Among the models used for the description of single neuron’s activity the *leaky integrate-and-fire* (LIF) model is still an extremely useful tool, despite its age and simplicity [5, 7]. To overcome some limits of these neuronal models (see **Part 1** for more details), we propose a generalization of the classical model based on Jacobi processes ([2, 6]) by introducing inhibitory jumps to describe the activity of a single neuron. The statistical analysis of inter-spike intervals is performed by studying the first-passage times of the proposed Markovian Jacobi process with jumps through a constant boundary. In fact, the model describes the time evolution of the voltage across the membrane of the neuron until it reaches a certain threshold. This event is called action potential (or spike) and it is believed that the distribution of these spikes encodes the information that the neurons transfer. It is assumed that the neuron under study is point-like and receives inputs from the surrounding network of neurons that are summed up (*integrate*) producing a change in the voltage value. The term *leaky* indicates that, in the absence of input, the membrane potential decays exponentially to its resting value. In accordance with the model, the spikes are instantaneous events that are generated as soon as the voltage reaches a certain value for the first time (*fire*). After the spike, the process is reset instantaneously to the starting position, ready to start its evolution over again. This renewal condition guarantees that the inter-spike intervals, i.e. the time between two consecutive spikes, are independent and all identically distributed as the first inter-spike interval described by the random variable first-passage time.

We treat the problem mathematically characterizing its Laplace transform which is expressed in terms of some generalization of hypergeometric functions that we introduce, and, deduce a closed-form expression for its expectation, i.e. the firing rate. Our approach, which is original in the context of first passage time problems, relies on intertwining relations between the semigroups of the classical Jacobi process and its generalization, which have been recently established in [1]. A numerical investigation of the firing rate of the considered neuron is performed for some choices of the involved parameters and of the jumps distributions.

Among the strengths of the presented model we have that on one hand the good properties of the classical Jacobi process are preserved: the state space is limited and the frequency and the amplitude of the jumps are state-dependent. On the other hand it also accounts for inputs that prevent the diffusion limit due to their amplitudes and/or to their frequencies. Moreover these downward jumps are able to reduce the firing rate and introduce saturation in the “firing rate vs input” curve even in the absence of a refractory period. This constitutes a novelty

*Based on a joint work with *Pierre Patie*, Cornell University [3].

compared to other LIF models for which the firing rate increases linearly (and unbounded). The feature that the model accounts possibly large downward jumps suggests its use for describing the contribution of a strong internal inhibitory input or the effect of an external factor, like a pharmacological treatment or the intake of drugs and alcohol that interfere with the standard activity of the neuron. The tuning of this quantity can also help the investigation of the role of inhibition in the information transmission. Finally, the high degree of freedom in the choice of the jump distribution and the relatively easy numerical implementation ([4]) permit the description of multiple different situations.

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Quickest detection in neuronal modelling

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One of the most important issue in applications is the problem of detecting abrupt changes in the behavior of a signal as quickly as possible after they occur. Here we assume that the signal evolution can be modeled by an Ornstein Uhlenbeck (OU) process with a drift changing from 0 to μ at some random unobservable time θ and we approach the problem by applying the quickest detection method.

From the observed signal data, we build a process called $\{\Pi(t), t \geq 0\}$, which represents the a posteriori probability that the original OU process has changed its initial zero drift by time t , given the process history up to time t . The optimal stopping time corresponds to the time at which the process $\Pi(t)$ first hits the boundary A , connected with the probability of the false alarm $(1 - A)$. For our analysis, the time when the process $\Pi(t)$ hits the boundary A indicates the change in drift of the frequency data to a positive trend.

After describing the method, we apply it to neuronal data. We measure the brain activity with the local field potential (LFP) and we model it through an Ornstein Uhlenbeck process. We use the quickest detection method to identify the moments when there is a response to a stimulus.

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Scale-free correlations in the dynamics of a small ($N \sim 10000$) cortical network

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(Dated: November 15, 2022)

The advent of novel opto-genetics technology allows the recording of brain activity with a resolution never seen before. The characterisation of these very large data sets offers new challenges as well as unique theory-testing opportunities. Here we discuss whether the spacial and temporal correlation of the collective activity of thousands of neurons are tangled as predicted by the theory of critical phenomena. The analysis shows that both, the correlation length ξ and the correlation time τ scale as predicted as a function of the system size. With some peculiarities that we discuss, the analysis uncovers new evidence consistent with the view that the large scale brain cortical dynamics corresponds to critical phenomena.

Contribution of the D-type K⁺ current to the operation of networks of electrically coupled neurons¹

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Relevant brain functions, such as perception, organization of behavior, and cognitive processes, are the outcome of information processing by neural circuits. Within these circuits, communication between neurons carried out by electrical synapses has been recognized as a major contributor, even in the mammalian brain. These intercellular contacts support the direct spread of ionic current from one neuron to another coupled partner, by means of intercellular channels, typically organized in clusters known as gap junctions. Thus, electrical synaptic transmission is characteristically fast, bidirectional, continuous and deterministic in nature. The strength of transmission is determined by both the junctional resistance and the input resistance of the postsynaptic cell, implying that electrophysiological properties of coupled neurons are of great relevance. By working in the mesencephalic trigeminal (MesV) nucleus, a brainstem structure composed of primary afferent neurons whose cell bodies are electrically coupled mainly in pairs through soma-somatic gap junctions, we show that these contacts can support relevant functional operations which are critically shaped by voltage-dependant conductances. Our comparative study between rats and mice revealed that spike-evoked coupling potentials are far more efficient in recruiting postsynaptic coupled neurons in rats, thus supporting lateral excitation in these animals. Interestingly, the higher efficacy in postsynaptic activation does not result from any difference in the coupling strength between these animals, as its determinants, the junctional resistance and the input resistance, do not show statistical difference. This suggests that efficacy in postsynaptic recruitment might be determined by the active electrophysiological properties of coupled neurons. Confirming this hypothesis, MesV neurons from rats are significantly more excitable than its counterparts from mice, as indicated by its lower threshold current for activation, more hyperpolarized firing level as well as its higher ability to generate repetitive discharges. Voltage clamp experiments indicate that, while the persistent Na⁺

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current (I_{Nap}) and the A-type K^+ current (I_{A}) do not show any difference between these species, the D-type K^+ (I_{D}) current density in MesV neurons from mice is significantly higher. Our results support the notion that the I_{D} plays a critical role in determining the waveform of coupling potentials, mainly due to its fast activation kinetics and its subthreshold voltage range of activation. In summary, network operations, like lateral excitation, are critically shaped by the intrinsic electrophysiological properties of coupled neurons, emphasizing the relevance of neuronal excitability for the many functional operations supported by electrical transmission in mammals.

A slow gain control mechanism

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Synaptic and intrinsic properties, in particular short-term synaptic plasticity, critically determine how and which information is transferred from presynaptic to the postsynaptic neurons, eventually routing different aspects of the information encoded in the presynaptic spike trains to different targets. The sensitivity to different types of presynaptic signals in different timescales can be enhanced by the presence of different types of short-term plasticity in single synapses. In the cerebellum the inhibitory Purkinje cells, which carry the output of the cerebellar cortex to deep cerebellar nuclei neurons, are spontaneously active, even at rest, and changes in firing activity associated to cerebellar controlled behavior are embedded in this background activity. PC background activity has received much less attention than the behavior-driven signals, although background rate is highly variable and it has been shown to be altered in a number of disease models, including ataxias, autismus and schizophrenia. In addition, although persistent or background activity is present during diverse brain processes and functions, such as working memory, the relevance for synaptic processing is unclear.

First, using appropriate stimulation paradigms we identified at Purkinje to excitatory deep cerebellar nuclear neurons synapses (PC-DCN) a slow form of short-term depression, in the timescale of tens of seconds, that renders these synapses sensitive to the PCs background activity. Experimental and modeling results show S-STD is based on a presynaptic mechanism, plausibly a reduction in the number of active release sites. In shorter timescales the output of PC-DCN synapses is frequency invariant, due to the combined effect of fast short term depression and facilitation, supporting linear rate encoding (Turecek et al., 2017). Our modeling and experimental results show how combination of slow and fast forms of plasticity at a single synapse support a slow-gain control mechanism that enables faithful linear encoding of presynaptic rates in the timescale of common behaviors (e.g., reaches, steps) and gain adaptation according to the preceding background activity at longer timescales. I propose that control of PC background activity could be a mechanism to allow flexible selection, in the timescale of tens of seconds, of the right ensemble of Purkinje cells to control excitatory DCNs. Furthermore, excitatory DCNs, but not inhibitory ones, display an intrinsic adaptation to simulated repetitive inhibitory inputs, further supporting the idea that the PC background activity is not transferred to the excitatory DCNs, but play a role in modulating their responses to more transient PC signals.

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Multidimensional representation of neurons in associative memory networks*

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In 1943, McCulloch and Pitts argued that the discrete, binary activity of neurons connected by a network of synapses produces events that can be mathematically represented by propositional logic. Logical expressions and memory functioning can then be reproduced by the behavior of these kinds of networks, and they are therefore powerful computational devices. Hopfield later proposed a model where the states of neurons assume continuous values and these types of interconnected neurons behave as an associative memory, similarly to the network model composed of McCulloch-Pitts neurons. Artificial neurons with continuous state values more closely resemble biological neurons. In these models, neurons are characterized by one real state variable adopting a continuous range of values that determine whether a neuron fires at a certain time or not. The Hopfield associative memory model has been used to represent an approximation of human memory functioning, and also as an artificial storage device.

The capacity of human memory to store and retrieve information is central to many mental processes, be they normal, pathological, conscious or unconscious and these have been widely studied by the fields of psychiatry, psychoanalysis, neuroscience and computational science. As examples of the application of associative memory neural networks to the study of mental phenomena, we mention our own efforts in recent years, to develop schematic simulation models that represent aspects of some mental processes such as neurosis, creativity, and the interaction between consciousness and unconsciousness, as described by psychoanalysis [2, 3]. Hopfield-like networks and generalizations have also been used in many artificial intelligence tasks. These considerations have motivated us to investigate basic aspects of artificial associative memory models [4, 5, 6], which we continue to develop in the present work.

Most fundamental models in theoretical biology exhibit a dissipative dynamics. Important examples are given by the Lotka-Volterra models in biological population dynamics, the continuous, Hopfield and Cohen-Grossberg neural network models and various mathematical models for biological, evolutionary processes. In particular, all biologically inspired models supporting universal computation are nonconservative or, in the case of discrete models, nonreversible.

The continuous models mentioned above, besides being non-conservative, exhibit a modular structure. They consist of a set of interacting units, each one characterized by an intrinsic dissipative dynamics. In the Hopfield model, the units are the neurons, each one represented by a simple, one-dimensional, dissipative dynamics. Real biological neurons are more complex

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than those appearing in the Hopfield model. It is generally believed, however, that the Hopfield model captures some essential aspects of real biological neural networks. Nervous systems over all the biological kingdom *Animalia* consist of neurons exhibiting similar, basic features. Intriguing theoretical arguments have been advanced suggesting that this remarkable feature of animal life might hold even within astrobiological scenarios [1]. In spite of the uniformity of biological, neuronal systems, there exist valid motivations to investigate new or alternative biologically-inspired, mathematical models of computation. First, it is possible that new models may better explore the richness and complexity of biological computation (even if neurons are everywhere more or less alike). Second, there are also a variety of theoretical reasons for the exploration of other models of computation. For instance, the Cohen-Grossberg family of models are closely related to mathematical models in other areas of biology, and they include, as particular cases, various mathematical models in population dynamics. It is very natural to consider extensions of these models where the basic interacting units are characterized by multi-dimensional, dynamical systems. For instance, effects of time-delay lead to multidimensional dynamics. It is thus theoretically appealing to formulate a family of neural network models, with multi-dimensional neurons, encompassing other biological models with nonconservative dynamics, and a modular structure based on multi-dimensional units.

The aim of the present effort is to explore a general framework for constructing modular, dynamical systems, akin to associative memory neural networks, that consist of interacting units, each one described by a multi-dimensional, dissipative, dynamical system. We show that it is possible to implement an interaction scheme leading to the kind of dynamical behavior that characterizes an associative memory neural network. The family of generalized networks we advance here admit, as particular cases, the continuous, neural models of Cohen and Grossberg, as well as the continuous, Hopfield model.

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Statistical learning of autoassociations of population vectors with overlapping tensor contexts provides a natural neural basis for Bayesian computation

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Bayes' formula has been used in medical diagnosis for decades. On the other hand, within Computational Cognitive Science, Bayesian models have been used as a paradigm of rationality and as the ones that best adapt to a large part of cognitive phenomenology. The extent to which humans are Bayesian has been widely debated, but there seems to be at least some agreement that, in some way, our brains do something close to Bayesian reasoning. However, the neurocomputational mechanisms that could underpin this behavior are unknown. The scarce bibliography on the subject has been directed fundamentally to single neuron models. In this communication we show that the associative storage of the activity of large groups of neurons in an autoassociative memory with overlapping tensor contexts gives rise, implicitly, to Bayesian computation. The effect of frequency on statistical learning of exemplars of a given class with different sets of (potentially overlapping) contextual items constructs, at the same time, both the prior probability distribution and its associated likelihoods for each context. Querying the memory with a certain set of contextual items, produces the posterior probabilities of classification classes. We discuss the significance of this result and the links to related topics are explored.

Learning and recalling odour names in an associative cortical memory network model*

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Odour memory has not only been a subject of wide-ranging cognitive and psychological research but it has also fascinated poets, novelists because of its associative nature facilitating recreation of significant past episodes in our life. At the same time, our ability to recall odours or rather conjuring up olfactory sensations themselves seems rather average at least when compared to images or sounds [1]. For writers, just mentioned, recalling an odour implies an ability to describe it in words. Similarly, in olfactory studies tests for odour identification, beyond just a sense of recognition, typically involve an assessment of an individual's ability to correctly name an odour. Consequently, recalling odour names evoked by a perceptual experience constitutes a complex cognitive phenomenon and probes reciprocal interactions between olfactory memory and the brain's neural resources underlying our capacity to use language. Despite previous neuroimaging studies on neural correlates of odour identification and a vast body of behavioural data, our insights into network-level mechanisms and into the role of synaptic plasticity in shaping the associative power of odour memories is limited, particularly in relation to odour names.

In this work the aim has been to propose a hypothesis about Hebbian-like synaptic basis for the memory associations between odour percepts and olfactory word labels. In particular, we have the ambition to contribute to the understanding of rather commonly observed behavioural outcomes of odour naming tasks such as odour misidentification (providing an incorrect label) and omission of language responses. To this end, inspired by our previous work on item-in-context associations [2], we have built a two-network computational model that accounts for an odour perceptual memory system and a language reservoir of odour labels (Fig.1a). The two associative memory networks encode memory patterns, which manifest themselves as attractor states, by means of Bayesian-Hebbian learning apparatus (Bayesian Confidence Propagating Neural Network, BCPNN [3]). Since the focus in this computational study is on capturing behavioural effects and due to a rather intrinsically high level of abstraction in describing network interactions between olfactory and language systems, the model is composed of abstract computational units describing the population firing rates of superficial layers of cortical columns. Both networks are trained using BCPNN rule to form and store distributed long-term memory representations of odour percepts and labels, respectively. The recurrent connections between the two networks are also incrementally trained to simulate the process of encoding and then recalling the associations between odours and their names. To operationalise these perceptual-cognitive processes we consider the successful odour identification (recalling a correct label) as the convergence of the olfactory language network to the attractor state. This is reflected in the activation of a distributed memory representation, corresponding to the memory object - odour label, associated during the learning process with the cued olfactory representation in the odour network.

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Importantly, to validate our computational hypotheses about synaptic basis for odour misidentification and omissions in language response we used a subset of data collected as part of a population-based longitudinal Swedish National Study on Aging and Care in Kungsholmen (SNAC-K), where 2569 subjects underwent an odour naming test [4]. We also conducted a follow-up study, where 37 participants were asked to rate the level of similarity between pairs of the odours exploited in the SNAC-K. The resulting average perceptual similarity matrix (Fig. 1b) was used as the target for building distributed overlapping odour percept representations in the olfactory network space. Language network representations of odour labels were derived from the cosine distance matrix obtained for Word2Vec embeddings of the original odour names. The SNACK-K olfactory experiments simulated in this work consisted mainly of a free recall of odour names as a response to an olfactory stimulus (Fig. 1c).

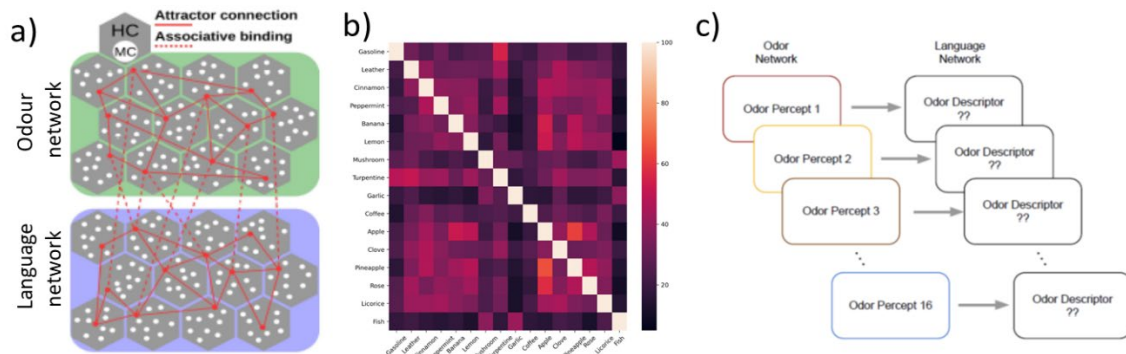


Fig.1 Modelling framework: a) schematics of recurrent connectivity in two-network memory model, b) odour perception similarity matrix used to construct odour memory representations, c) recall paradigm.

Our simulation results suggest that one of key mechanisms underlying the omission phenomenon can be attributed to weakening inter-network associative weights between odour percept and name representations. This effect is due to a specific paradigm for learning odour percept-name associations where some olfactory stimuli are matched with multiple different names during consecutive training trials. This variability of odour labels decontextualises a given percept leaving it without any strong label binding. We can observe a similar trend in data, where the variability of odour names freely recalled by SNAC-K participants partly explains the omission rates. As for the odour misidentification, we are investigating the relative impact of the similarities in the odour percept vs odour name representations. Our preliminary data suggest that the representational overlap in the language network tends to first cause confusion in odour perception (via reciprocal inter-network connectivity), which then may lead to the activation of an incorrect odour name at the cost of the original label.

In conclusion, we have proposed an attractor memory model consisting of two reciprocally connected recurrent networks, long-term olfactory memory and olfactory language memory, to study network and synaptic learning mechanisms supporting human odour naming capabilities. The model helps us validate computational hypotheses for behaviourally reported examples of cases for odour misidentifications and omissions during free recall. Our next step is to systematically evaluate the impact of network parameters including the network scale and synaptic time constants among others as well as training paradigms in relation to the available data. A particular asset of the current modelling framework is an opportunity for testing the emerging model predictions in the experimental setting.

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The Slip hypothesis: Temporally Local Coding and Perception of Tactile Stimuli in Rodents and Humans

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Perceptual systems may have evolved to employ specific physical features characteristic or even unique of the sensory signal at hand, rather than implement generic mathematical analysis of sensory data. Further, perceptual computation may involve neural as well as pre-neuronal elements, the latter based in the physics of the world. In the touch system, one such specific, pre-neuronal element is the phenomenon of biomechanical, frictional events, which are generated by the relative movement of the integument in touch with object surfaces. These short, high amplitude, vibrotactile events are called stick-slip movements ('slips'). Biomechanical evidence from the rodent whisker system showed that the kinematic outlay of slips carries rich information about the objects touched. Neurophysiological evidence from recordings of primary afferents and the first synaptic station in the brain stem, showed that the early whisker-related tactile system responds in an utmost precise fashion to the kinematics of short vibrotactile events, and that there is almost no integration of the vibrotactile signal beyond the typical duration of slips. In S1, the neuronal population responds very well to changes in the kinematic outline of vibrotactile events, but rather poorly to event rate changes. Matchingly, psychophysical results, which we carried out in rodents as well as the fingertip system in humans, indicate that local kinematic shape of short events dominates perception while integration of event rate has a comparatively poor perceptual effect. In summary, the available data suggests an alternative possibility to think about tactile (neuronal) coding, compared to the one the field has followed as its dominant theory for decades: the tactile system may detect local (shorter than 10 ms) kinematic patterns in the vibrotactile signal, rather than doing extensive integration across time to come up with 'intensity' (sum of signal), or 'frequency' (sum of spectral components).

Theoretical and experimental description of chromatic induction*

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Chromatic induction is the effect by which the perceived color of a stimulus is modified due to the introduction of a chromatic surround [2]. For example, a green stimulus looks yellowish when surrounded by cyan, and bluish when surrounded by orange. Here we develop a linear theoretical description of chromatic induction, in which the receptive field has a characteristic length. This length stems from the anatomical and physiological properties of the underlying neural network, most likely related to the length of horizontal connections or the degree of convergence in feedforward integration. The theory is most conveniently formulated in the so-called *perceptual coordinates*, in which the Euclidean distance between colours is proportional to the degree of dis-similarity with which they are perceived [1]. According to the proposed theory, color discrimination is optimal when the spatial frequency of the chromatic modulation is equal to the inverse of the characteristic length of the receptive field. We designed and carried out preliminary experiments on two volunteers and observed the presence of an optimal spatial frequency, obtaining characteristic distances around 2° which, for stimuli at a distance of 1 m , correspond to objects around 3 cm long.

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Efficient coding and active sensation in olfactory navigation

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Olfactory navigation is a sensorimotor behavior that enables organisms to find food and mates, and to avoid predators. While it is a behavior that is often critical for survival, it is also a highly challenging one, owing to the turbulent nature of natural plumes. Because of the complex nature of plume statistics, olfactory navigation provides a unique window on how the efficient coding principle applies in a scenario in which sensation subserves a specific task – locating the source of the odor. Additionally, since plume sensation is intrinsically linked to motor activity such as sniffing or antennal movement, olfactory navigation is a behavior in which active sensation is expected to play an important role. To understand how neural coding strategies may be optimized for olfactory navigation and the contributions of active sensation to this task, we performed an information-theoretic analyses of plume statistics obtained from planar laser-induced fluorescence measurements of odor concentrations in realistic plumes [1].

Since evolutionarily successful organisms accomplish olfactory navigation by making decisions on a moment-by-moment basis, we began by analyzing the information about plume source that can be gleaned by encoding a single odor sample. Single samples have only limited information about source location, and this limited information can be captured by coarsely resolving odor concentration, e.g., in 8 to 16 levels [2]. This leads to the question of how these levels should be allocated to the concentration range. If the goal of encoding were to reconstruct odor concentration, then the optimal strategy would be histogram equalization, i.e., to divide the odor range into segments of equal probability. However, using a novel dynamic programming algorithm to determine the optimal allocation, we showed that information about source location is maximized by a different strategy: one that emphasizes resolution at higher odor concentrations, even though they occur only rarely. This indicates that the filaments of high concentration that occur in turbulent plumes provide disproportionate information about location. Interestingly, the theoretically-optimal strategy for encoding the gamut of odor concentrations is closely approximated by the Hill nonlinearity of receptor binding – the ubiquitous first stage in olfactory transduction -- followed by linear encoding of the fraction of bound receptors [3].

Most animals have paired olfactory sensors, suggesting that joint coding of a pair of samples is advantageous. Moreover, even before sensory transduction, an organism can modify the statistics of the olfactory environment via motor activity: sniffing in the case of mammals, and antennal movements in the case of insects. These forms of active sensation can influence the region of space that is sampled, and can result in a local mixing of odor concentrations within the sampled regions. To explore the utility of these strategies for olfactory navigation, we extended the information-theoretic analysis to joint coding of odor concentration, and modeled the effect of active sensation by Gaussian spatial mixing. These analyses were carried out for a range of inter-sensor spacings, mixing radii, and plume

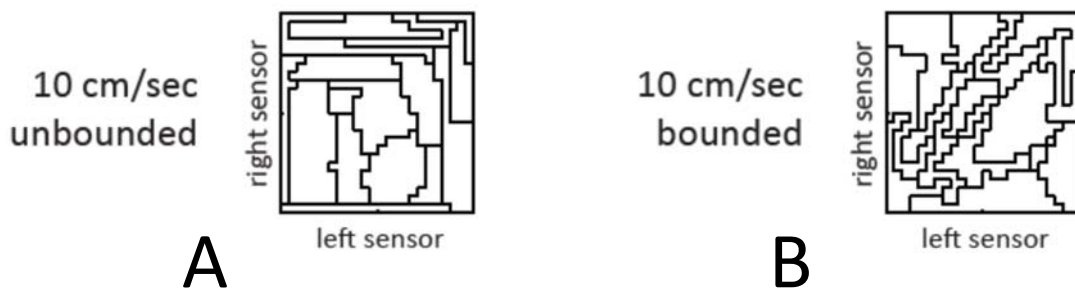
characteristics.

We found that sensing plume concentration at two locations provided more information about source location than a single sample, and the amount of information typically increased with increasing sensor separation and degree of local mixing. Moreover, the analysis showed that the optimal strategy for encoding a pair of concentrations depended on the plume characteristics. For more turbulent plumes (panel A), the optimal coding strategy focused on the presence of a high concentration at either sensor, with little information lost if sensor identity (left vs. right) is ignored. For more diffusive plumes (panel B), information about odor source was maximized by joint encoding that focused on small differences in concentration at the two sensors, with substantial loss of information if sensor identity is ignored. These findings make intuitive sense in terms of plume structure. In the diffusive plumes, the instantaneous plume structure closely resembles the mean structure, and has well-defined spatial gradients. So in these plumes, coding small differences in concentration across sensors (i.e. resolving spatial gradients) is highly advantageous. In contrast, turbulent plumes have no well-defined spatial gradients in the instantaneous plume structure and there are intermittent encounters with odor filaments. So in these plumes, it is less advantageous to encode differences (spatial gradients) and more advantageous to encode the “hits” of high odor concentration at either sensor.

These computational experiments demonstrate the advantages of binaral (or bi-antennal) sensing strategies, and make predictions about active sensing in real-world plumes.

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Encoding paired samples of odor concentrations to maximize information about source location. **A.** For the unbounded-flow (turbulent) environment, many code word boundaries delineate high odor concentrations in left or right sensors, indicating that intermittent high-concentration transients are informative. **B.** For the bounded-flow (diffusive) environment, code word boundaries lie primarily along the diagonal, indicating that the side-to-side difference in odor concentration is informative. Axes indicate odor concentration in quantiles.

Neural encoding of sound azimuth shown by the interaural time and level differences – stochastic analytical model*

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Sound enters the cochlea, the vibrations are converted into spike trains and the auditory nerve relays the spike trains further to be processed in the peripheral auditory pathway. The first neurons (spiral ganglion neurons) and second neurons (neurons of cochlear nuclei) only process mono-aural information. Binaural processing of spike trains starts at the third neurons (in the medial nucleus of the trapezoid body and foremost the complex of superior olives) of the auditory pathway and takes place at all the subsequent processing stages. The spike trains of the left and right sides are compared and processed in the auditory periphery to yield sound localization information. Two different sound localization encoding mechanisms are employed in the two centers of the superior olives: the lateral superior olive processes the interaural intensity difference [2] and the medial superior olive deals with the interaural time difference [4]. For the frequency range between the ranges of the two different circuits (two olives) also the used mechanisms overlap.

The presentation contains a stochastic model of computations with spike trains. Based on previous work, we demonstrate that a coincidence detection mechanism has to be implemented somewhere in the neural circuits of the auditory periphery, but it is not known to date, whether it is the input, processing, or output part of the auditory periphery, there is no definite evidence. Ultimately, the outputs of these computations are interpreted by the neural circuit realizing the function of the ideal observer [5].

A novel contribution to the sound localization model presented here is in the systematic replacement of the numerical components of our previous sound localization descriptions by analytical estimates of individual transfer functions of the individual parts of the auditory periphery.

Our model spike trains are based on electrophysiological recordings. Most of the biophysical constants in the model are taken from the literature on mammalian physiology and human psychoacoustics [3]. Some of the remaining constants are simple functions fit to match the other parameters in the circuit [1]. The inaccuracies in our model are mostly based on difficulties and variations in the electrophysiological measurement and variability of individual neural responses

We arrive at the best estimates for neuronal signaling. We also use a concept of the just noticeable difference of values registered by the ideal observer. The stochastic parameters of the model are given by the random patterns of neural responses. We describe the spike timing jitter and its role in spike train processing. All sets of plausible parameters are subsequently subject to discussion of their effect on the processing precision of the circuit. Also, the role of the inherent noise in the neural circuit is discussed. Intervals bounding all the parameters and computational implementation of all the mechanisms used are among the main results of this study.

Keywords

binaural hearing; coincidence detection; ergodic hypothesis of equivalent processing in neural circuits; ideal observer; interaural time difference; interaural level difference; just noticeable difference; lateral and medial superior olive; neuronal arithmetic; psychoacoustics; sound localization; spike trains; spike timing jitter.

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Modelling the neurons of the electrosensory lobe in *Gymnotus omarorum* with differentiable programming

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Nervous systems are complex structures in which one can identify different organization levels, from the molecular and subcellular to those describing the whole animal behaviour. One of the challenges of present neuroscience is to understand how different organization levels influence each other, to reach a solid understanding on how the brain works. Formal computational models are powerful tools to bridge the gaps between levels. Taking into account the characteristic features observed in one level they allow to predict the behaviour of the superior level or hypothesize sets of combination factors that explain the emergence of such characteristic features. Here we present ongoing work aiming to construct a model that bridges the gap between the intrinsic properties of the neurons and the circuit behaviour of the electrosensory lobe of the weakly electric fish *Gymnotus omarorum*.

These fish evaluate their environment and communicate using electric images carried by electric discharges of a specialized electrogenic organ. These images are originated on the heterogeneous distribution of impedance on the fish's surrounds and are sensed by cutaneous electroreceptors, each of which provides local information to the electrosensory lobe through a single primary afferent fiber. The electrosensory lobe contains two independent electrosensory paths, called *fast* and *slow* somehow analogously to those observed in the auditory system. The fast path is represented by a single type of spherical neurons that receive primary afferent calices making synaptic contact through electrical and chemical synapses and project to a mesencephalic nuclei where a Jeffress-like circuit (Jeffress, 1948) compares the latency between different incoming inputs. The slow path is represented by a cerebellum-like circuit receiving feed-forward and feed-back connections: such a circuit has two types of output neurons with different intrinsic properties and dynamical responsiveness to changes in the electrosensory image (for details on this system see Caputi et al., 2020).

We focussed first on spherical cells, because their round shape and small number of afferent contacts simplify the modelling and understanding their role in the circuit. These neurons were previously characterized by intracellular recordings in vitro (Nogueira et al., 2006) and their behaviour was studied in freely moving fish (Castelló et al., 1998). Taking into account the previous data (Nogueira et al., 2011, 2014), we used the formalism introduced by Hodgkin and Huxley, including a fast Na^+ , two K^+ currents (high and low threshold) and a mixed cation resonant current. We built a differentiable parametric simulation, and found the set of parameters values that best reproduce the experimental results obtained in vitro and the response of the fast electrosensory path in vivo by means of a gradient-descent-powered maximum likelihood fit.

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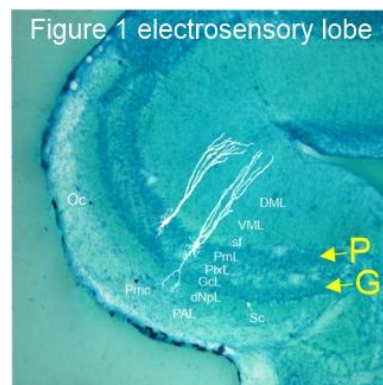
The receptive field organization of the electro-sensory lobe neurons of *Gymnotus omarorum*

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Introduction. The concept of receptive field was introduced as a space entity while studying vision and touch [1, 2]. The study of audition, electro-reception, and chemical senses releases the restriction of the term “receptive field” to a given region of the sensory mosaic where a given region of space is mapped. This is evident when considering odor as an almost pure qualitative dimension of olfactory neurons receptive field [3]. Moreover, while primary auditory afferents encode a particular frequency band of sound [4], some central neurons encode the direction to the source of sound [4]. Feeding back the ideas to vision, touch and other senses the concept of receptive field can be generalized as a multidimensional framework representing spatial and qualitative aspects of the stimulus to which a sensory neurons respond.

Each central neuron’s receptive field results from the combination of fields of all of the neurons providing input to it and, the receptive field increases in complexity with the synaptic distance from the periphery and the intricacy of the synaptic organization of the structures through which the information is previously processed. Therefore, one can hypothesize that receptive field of a neuron results not only from its intrinsic properties but also on its context including the specific imaging system and the specific neural networks linking the neuron with the stimulus source and its study is a necessary step for understanding how a sensory modality encodes reality. Here we address this problem using as a model of study the first sensory relay of the homeo-active electro-sensory system exhibited by weakly electric fish. This nucleus, the electro-sensory lobe, is a cerebellum-like structure layered which has at least 4 types of efferent neurons, 5 other types of inter-neurons and two other types of neurons projecting internally on the same and also on the contralateral electrosensory lobe besides the afferent fibers. Most cell bodies are grouped in two layers referred to as granular and pyramidal (G and P in yellow, Fig. 1).

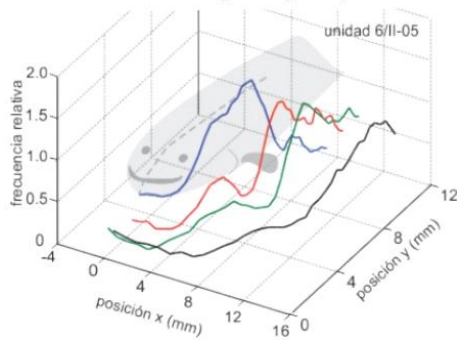


Methods. Using 16 channels multitrodes connected to a multiplexed differential amplifier we recorded the activity of 137 units in acute decerebrated fish in the absence of objects. After digitizing and unit discrimination, we used hierarchical cluster analysis of the post-EOD intervals histograms to classify them into six different categories. Data obtained by observing the distance of the best recording electrode (62 units) and the effect of metallic and plastic objects (103 units) was independently evaluated but not considered in cluster analysis. In 50 of the 137 units we recorded the while moving a vertical cylindrical copper object (9 mm diameter, 40 mm length) parallel to the skin on rostral to caudal and caudal to rostral directions over the most rostral zone of the fish where more than 90% of electro-receptors are located. In 10 of these neurons the object was moved at 1 mm/s at

different distances (1, 4, 8, 15 mm away). In the other 40, the object was moved at 1 mm distance at different speeds (1, 3, 5, 8, 13 and 21 mm/s).

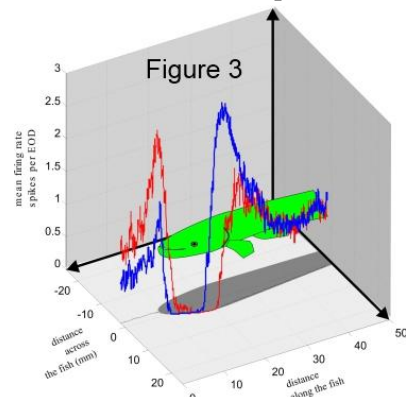
Results and Discussion. Firstly, we found that units contained in the same cluster shared their position in the ELL layers and their responsiveness (“on” and “off”) to metal objects indicating that they probably correspond to different unity types. Secondly, we found that the spike rate depends on

Figure 2. Spike rate as a function of object trajectory



the position of the moving object and shows a) one to three alternating in direction peaks when plotted as a function of object position suggesting a center surround structure of the receptive field ; b) the ratio between the central and surround peaks, and also the ratio between surround peaks varied depending on the distance, the central peak followed the curvature of the field lines when the object was moved at different distances, and the

modulation fade away at about 20 mm from the fish, confirming the importance of the imaging system on the receptive field (Fig. 2). Thirdly, we found a shift in the central effect region and a reversal in the surround peaks of the spike rate when the object moves in opposite directions (Fig 3, blue: rostral to caudal, red: caudal to rostral). Besides these asymmetry in some neurons these profiles were observed in one moving direction while flat depression were observed when the object moves in the contrary direction, suggesting a movement detection circuit (compare Fig 4A1 with A2 and B1 with AB2 obtained from



two different neurons); this might correspond to an adaptation process either at the level of receptors or at the ELL circuit [5]. Finally, while some units were scarcely depending on speed

(Fig. 4A1), other units decreased their modulation when the same object moves at subsequent trials of higher speed (Fig. 4B2) suggesting the ability of these neurons to encode the relative speed of the object with respect to the fish’s body.

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Psychological and electrophysiological effects of a virtual Mindful Self-Compassion training in Uruguayan primary school teachers.

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Teaching is one of the most demanding professions. Teachers are expected to have social and emotional skills that promote optimal classroom climates and support students, and frequently suffer from work-related stress and burnout. Uruguayan teachers have the highest rates of burnout syndrome in Latin America (Silva et al 2015) and express the need for more skills aimed at reducing their stress and increasing their well-being while enhancing social and emotional competences (INEEd, 2021b). Secular contemplative practices are increasingly implemented worldwide due to the reported beneficial effects in clinical and non-clinical populations. Mindfulness, conceived by Kabat Zinn (1994) as the awareness that arises through paying attention, on purpose, in the present moment, non-judgementally, decreases negative psychological symptoms and emotional reactivity and increases behavioral regulation and well-being. In teachers Mindfulness training promotes of pro-social skills, improves emotional regulation and well-being, and reduces stress. Neff and Germer and (2013) developed a Mindful Self-Compassion (MSC) program oriented towards promoting the capacity of mindfulness as well as self-compassion, but its neurobiological and psychological effects haven't been quantitatively investigated in teachers.

Considering the antecedents on contemplative practices, the Uruguayan teachers' need of socioemotional skills, and the gap of knowledge on the effects of MSC in teachers, in this work we studied in a group of Uruguayan female primary schoolteachers the effects of the MSC program. on mindfulness, self-compassion, empathy, well-being, and stress.

We used a pre-test post-test quasi-experimental design with an intervention (MSC training) and an active control group (KY training). After recruitment, selection, and signature of consent, female teachers were randomly assigned to either MSC or KY trainings. The effects of 9-week virtual MSC training (consisting of virtual synchronous formal and asynchronous informal activities) were assessed by means of online self-reported online psychometric tests focused on mindfulness (FFMQ test), self-compassion(SCS test), empathy (IRI test), global stress (PSS) and well-being (WHO-5). Data were collected at pre, post-training and follow-up (three months later). At the same times, two in-person empathy for pain experimental tasks according to Baez et al., (2017; (EPT1) and Jackson et al. (2005; EPT2, during which EEG and ECG recordings were acquired).



Figure 1. Experimental design

At post-test time teachers also performed a social stress test (TRIER) during which it ECG recordings were acquired. From 48 participants that met the selection criteria, 37 completed the trainings and the online psychometric tests at pre-and post-training (MSC: n=19, mean age 38 SD= 6.9 years; KY: n=18, mean age 41.2, SD= 7,2 years) and 23 at follow-up. Due to the pandemic induced drop out, 28 teachers completed the EPT at pre-and post-training.

At pre-training, MSC and KY groups showed moderate values in all the studied dimensions of mindfulness, self-compassion, empathy, stress, and well-being, without differences between groups. Virtual training on MSC and KY impacted similarly the studied dimensions at post-training. Both MSC (Fig.1) and KY (Fig. 2) increased 3 out of 5 dimensions of mindfulness; MSC increased 4 and KY 3 out of 6 dimensions of self-compassion, increased subjective well-being, and reduced stress perception. Only MSC training modified empathy, increased perspective-taking, and reduced personal distress. Several findings remained 3 months later. Concerning the EPT1, at post-training, MSC did not modify the decreased personal distress for intentional harm. MSC but not KY improved cognitive empathy as it increased the accuracy in the intentionality comprehension of intentional

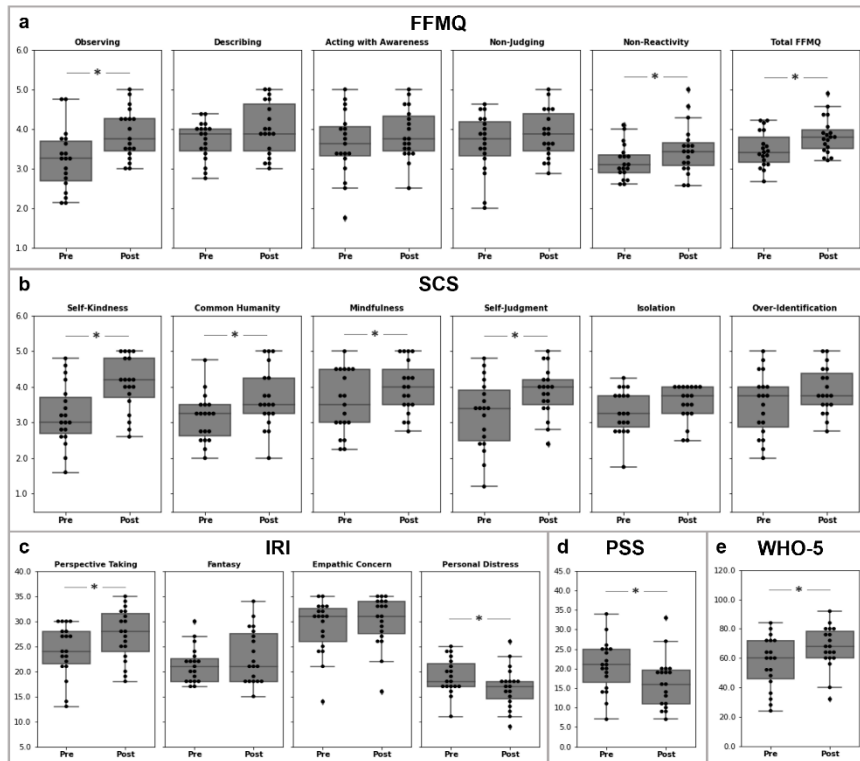


Figure 2. Effects of Mindful Self-Compassion training (n=19) on psychometric data assessed with online versions of a) Five Facet Mindfulness Questionnaire (FFMQ); b) Self-Compassion Scale (SCS); c) Interpersonal Reactivity Index (IRI); d) Perceived Stress Scale (PSS); and e) Well-Being Index (WHO-5). Significant differences between pre- and post-training. Asterisks indicate significant differences ($p<0.05$).

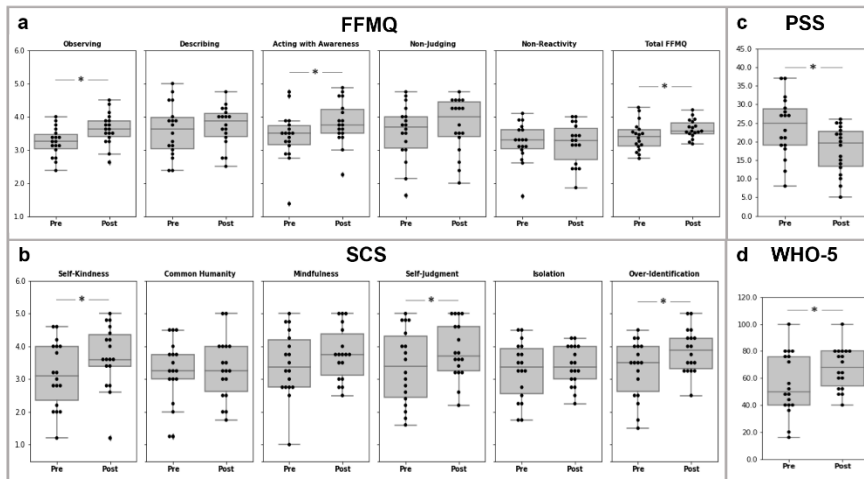


Figure 3. Effects of Kundalini Yoga training (n=18) on psychometric data assessed with online versions of a) Five Facet Mindfulness Questionnaire (FFMQ); b) Self-Compassion Scale (SCS); c) Perceived Stress Scale (PSS); and d) Well-Being Index (WHO-5). Significant differences between pre- and post-training. Asterisks indicate significant differences ($p<0.05$).

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harm. No statistical differences in any of the dimensions were found at pre-, post-training, or follow-up between MSC and KY. For EPT2, ECG data are being analyzed in time and frequency domains to study several parameters of heart rate variability (HRV), and EEG heart-evoked potentials (HEP) are being analyzed to evidence neural responses to others' perceived pain.

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Decoding the neural representations of multidimensional vocal features*

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Human voice contains rich spectrotemporal information that conveys important speaker identification cues to listeners. The acoustic envelope of speech, on the other hand, is a key feature that relays information about acoustic energy changes, and reflects no vocal spectral modulations. Slow modulations of the envelope can be reliably decoded from auditory cortical networks[1]. Importantly, the quality of such ‘envelope tracking’ during speech can be sensitive to cognitive operations such as selective attention[2] and speech intelligibility[3]. Recent work has shown evidence of similar tracking in the auditory cortex of listeners in response to changes in the fundamental frequency (f0) timeseries, arising during vocal production[4]. The f0 broadcasts information from modes of vibration by the vocal chords while, in parallel, formant modulations are defined by the speaker’s laryngeal system configuration. It is currently unclear whether formant information can be also tracked by, and reliably decoded from, cortical networks during speech listening. More so, how does any such encoding impact listener behavior.

Here, we investigate whether time-varying spectral modulations imposed by the speech production systems emerge in cortical activity as indexed by the electroencephalogram (EEG). Using the stimulus reconstruction technique, we decode how well can slow spectral modulations of f0 as well as formant (F1 to F5) and formant dispersion measures can be reflected in the EEG signals. Participants ($N=73$) listen to brief (~9 s) independent solo speech presentations from a variety of speakers while undergoing EEG. The neural representation of vocal modulations is addressed by measuring how well are these features decoded from the EEG headset. Our data suggest, similarly to envelope decoding, above-chance performance of listener decoders in the slow (1-8 Hz) temporal range for the vocal spectral features. A multidimensional index of performance measures, constructed across all these spectral features, serves to characterize individuals’ general ability to track these modulations in solo speech. In preliminary analyses we find that this multidimensional index predicts listeners’ ability to track one target speaker when a listener has to select speech in ‘cocktail-party’ settings. We propose that decoding of these important vocal identity-related modulations from electrophysiological activity may add to the battery of objective measures of speech listening, in naturalistic conditions.

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Brain dynamics of willingness-to-share studied by Event Related Optical Signals (EROS) and Event Related Potentials (ERP) *

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According to Game Theory a human subject playing the Ultimatum Game (UG) should make the most advantageous selection for oneself and offer the least possible amount to the other player (assumption of selfish rationality) [2]. However, experimental results show non-rationality of the human behavior and fairness-based (greedy versus generous offers) amplitude differences in the event-related potentials (ERPs) of Responders during UG [1, 4]. We have replicated these findings with concurrent recordings of event-related optical signals (EROS) by frequency-domain functional Near InfraRed Spectroscopy (FD-fNIRS) [3]. Our previous study [5] showed that the medial frontal negativity (MFN) occurred earlier and with greater amplitude when selfish participants rejected less favorable endowment shares. In this case, all players received zero payoffs, which showed that MFN in selfish participants was associated with a spiteful punishment. At posterior-parietal sites (CPz and Pz), we found that the greater the selfishness, the greater the amplitude of the late positive component. Based on these results, our working hypothesis is that frontal regions closer to ACC, dlPFC, and vlPFC (electrode sites Fz, FCz, and Cz) elicit differences in neural activity occurring approximately 250-550 ms after presentation of the offer. These differences should be larger for less generous, i.e., more unfair, offers. More importantly, we expect to see similar differences in both the EEG and EROS signals. Our study allowed to determine the spatial contributions of frontal brain activity during specific time windows of the decision-making process and, in particular, that frontal regions closer to dlPFC elicited increased patterns of activity based on fairness compared to a control site (temporal parietal junction). These are new evidence of the existence of specific somatic markers associated with the activation of distinct cerebral circuits by the evaluation of fair and unfair proposals in participants characterized by different expressions of perceived willingness-to-share.

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How does the brain evaluates logical propositions?

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Several mathematical models for logical decision-making by humans have been proposed in last 150 years. Models differ in their different algebras, and elementary operators. For example Boolean logic is based on operating elemental concepts through negation, conjunction and disjunction. Later work shows that Boolean logical operations can be derived from a single one and that such an elementary operation can take more than one form. More recently, it was shown the congruence between Boolean logic and learning ability and the role of negation. The issue of exclusive disjunction as an elementary operation has been discussed, but it can be shown that this operation could be inconsistent with reality when evaluating a chain of uneven decisions.

Here we assume that the probability of errors and the time taken by a decision on the truth value of a proposition based on perceptual information will increase with the underlying complexity of the decision process. The complexity of an algorithm can be measured as the length of the shortest possible description of the string in a universal language. However, the description language and in consequence the formalism, may heavily depend on the physical device that analyses the data and takes the decision. Within this context emerges the question: What is the formalism used by our brain? To search for a model that reproduces better the formalism used by the brain, we contrasted the complexities corresponding to different models on a set of logical decisions with the decision times and error probabilities obtained when human subjects experimentally decided on the truth of a proposition on the basis of a visual stimulus.

At present 56 right handed humans older than 18 years, of either sex, participated in decision making experiments. In all experiments, subjects had to use color proposition under a go (true) /no-go (false) random presentation protocol. Subjects were seated in a dim-lightened cabin looking at a computer screen (48 x 26 cm, 1680 x 1050 pixels, 60 Hz, maximum screen illumination) where a colored circle was displayed on a black background. Stimulus images consisted of three non-contiguous identical and homogeneously colored (blue, yellow, green, violet, cyan and red) 60° circle sectors centered at clock dial positions 12, 4 and 8 separated by a randomly pixelated color pattern in which every mentioned color was equally present. Subjects had to fix their sight on a central spot, to respond as soon as possible by pressing a mouse button when the colors in homogeneous sectors of the stimulus image truly verified the proposition (e.g. “a blue sector is present”, “a blue sector is not present”) and should not respond in the opposite case. Eighteen proposition were evaluated

We found that the decision time and errors increase linearly with the number of affirmed items, with the number of negated items and also with the number of exclusive disjunctions to be judged. Taking into account these findings we constructed a model that explain human decision behavior in most of the tested propositions. A single proposition, $(A \& \sim C) \mid (\sim A \& \sim B)$ did not fit the heuristic model. Different possible explanations are discussed.

On the approximation of the ISI distribution from spike train data using generalized Laguerre polynomials

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The first-passage-time (FPT) problem arises in many applications in which a stochastic process $X(t)$ starting in x_0 at time τ evolves in the presence of a threshold $S(t)$ [5]. The mathematical study of the FPT problem consists in finding the probability density function (pdf) $g[S(t), t|y, \tau] = \frac{d}{dt}\mathbb{P}\{T < t\}$ of the random variable T (see [6]), defined by¹

$$T = \inf_{t \geq \tau} \{X(t) > S(t)\}, \quad X(\tau) = x_0 < S(\tau). \quad (1)$$

There are several strategies to approach this problem, whose effectiveness depends on the formulation of a suitable model for $X(t)$ and on its properties. But when a random sample of FPTs is analyzed without any prior information on the stochastic dynamics generating the data, the identification of a model could be difficult to implement. In many applications the only available data consist in the direct observation of the FPT variable. This can happen, for instance, in the case of computational neuroscience where, in the popular *leaky integrate and fire* models, the stochastic process $X(t)$ describes the time evolution of the voltage across the neuronal membrane [4]. In this context the FPT data represent the time between two consecutive spikes (ISI) performed by a neuron and their distribution is essential since it is believed to enclose the neural code. In general, classical tools as histograms or kernel density estimators are the first choice aiming to postulate a shape of the FPT pdf and then a model.

This contribution introduces a general method which fits into the broad framework of strategies for the approximation of FPT density on a random sample of FPTs through a constant boundary and, of course, is intended for the cases in which the closed form expression of g is not available. The proposed approximation is of Laguerre-Gamma polynomial type and belongs to the class of generalized Fourier series expansions. This proposal have been successfully applied to Feller processes [1] and Inhomogeneous Geometric Brownian Motion [2] for which no closed form expressions of the FPT pdf are available. Moreover, to check the feasibility of the method both in fitting the density and in estimating the parameters, the GBM FPT has been considered in [3]. All these processes are widely used in the context of the modeling of single neuron or small networks [4].

Differently from other methods, the approximating function results to be a pdf whatever order of approximation is reached. Indeed the proposed method iteratively looks for the best degree

¹Similarly $T = \inf_{t \geq \tau} \{X(t) < S(t)\}$, when $X(\tau) = y > S(\tau)$.

of the approximating polynomial such that the normalization condition is preserved. Numerical investigations have confirmed that this stopping criterion is accurate, robust and independent on the shape of the pdf. Moreover, the implemented algorithm relies on simple and new recursion formulae involving FPT moments or cumulants, depending on the treatability of their expressions. Note that it is possible to recover cumulants up to order k from moments up to the same order (and viceversa), using the general partition polynomials [1]. Therefore, from a theoretical point of view, there is a duality between these two numerical sequences and the choice depends on which one has a simpler expression. When they are estimated from data, κ -statistics might be used as free-distribution estimators of cumulants. Indeed they are symmetric functions of the random sample with minimum variance when compared to all other unbiased estimators.

In the end, this approximation has a twofold advantage. If the FPT moments/cumulants are not known, the special feature of this approach is the chance to recover an approximation of the FPT pdf starting from a sample of FPT data like the classical density estimators. If the FPT moments/ cumulants are known or can be recovered from the Laplace transform of the FPT random variable T , the method is essentially a way to find an approximated analytical expression of g . The method turns to be useful also if the model is known but the knowledge of the FPT moments is limited, as usually happens. In such a case, the approximation might be carried out by simulating the trajectories of the process through a suitable Monte Carlo method. If, in addition to data, the FPT moments or cumulants were known analytically, it's possible to implement a maximum likelihood procedure to carry out estimates of the parameters involved in the model since the approximated function is a pdf. In the neuronal modeling context this strategy allows to obtain expression of the moment or other statistical quantities of the ISIs and enables the estimation of the parameter of the process (and then of the characteristic of the neuron) starting from the spike train rather than observing the trajectories as it is commonly done.

To explain the feasibility of the method, results are presented on comparisons between approximated expressions (obtained analytically or estimated through) related to the GBM FPT in two instances: known and unknown FPT moments.

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Neural coding across interacting cortical columns *

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Local field potentials are produced by the synchronized activity of large sets of neurons. This activity may propagate across large brain areas or even at the entire brain scale in reverberating circuits [3], in such a way that it contributes to the spatiotemporal dynamics of EEG signals associated with sensorimotor and cognitive processes [4]. Neural mass models of cortical columns implemented by stochastic Jansen-Rit equations are used to show that that precise temporal information [2], carried by deterministic nonlinear attractor mappings, is filtered and transformed into fluctuations in phase, frequency and amplitude of oscillatory brain activity [5]. The overall activity of cortical columns acts as a filter to a large extent, but it retains the capacity for gating a temporally driven input signal and propagate selected temporal features, thus allowing traveling waves to encode temporal information. We extend the study to a scale-free network of 50 cortical columns with bidirectional synaptic connections between interconnected columns. The analysis of bifrequencies interactions, generated by the periodic drivings of the interacting neural mass models, by higher-order spectral statistics (in particular the cross-bicoherence and spectral Granger causality) showed that quadratic phase coupling (QPC) occurred in such nonlinear interactions between cortical columns [1]. We investigated the effect of increasingly larger levels of background noise fed independently to each column on the detection of QPC. At low levels of noise, the activity was dominated by the columnar periodic drivings and no QPC could be detected. At intermediate levels of noise, we observed two distinct domains. In the first domain, the increase in noise was generally associated to an increase in detection of QPC. The second domain was highly sensitive to the initial random conditions, in such a way that for some runs no QPC was detected and some other runs QPC was very well detected. At a higher noise level the dynamics was dominated by noise and no QPC could be detected. These results suggest the occurrence of stochastic resonance characterized by optimal levels of noise to generate QPC in the network of interconnected cortical columns. We discuss the effect of local excitatory/inhibitory balance on these results [6] and how excitability in cortical columns, controlled by neuromodulatory innervation of the cerebral cortex, may contribute to set a fine tuning and gating of the information propagated across cortical columns.

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How Many Neural Codes Are There?*

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Ever since the first neuronal recordings by Adrian, the structure of the neural code has been seen as a route for learning how the brain processes. It was recognized early that the intensity of a response, that is the number of action potentials, is a code about the conditions under study, e.g., Hubel & Wiesel [1]. A question that has intrigued investigators has been whether the pattern of spikes over time is part of the code. We have found that the pattern of spikes over time might play different roles for different neurons.

Our work is centered on learning how information is converted from sensory coding to predicted outcome values; that is, how do we learn which stimuli predict a rewarding outcome and which predict an aversive outcome? We have found that the neural code is different in different brain regions in a well-defined reward prediction behavior.

We recorded neurons from rhesus monkey ventral-medial-rostral striatum and from lateral Prefrontal Cortex (IPFC) while the monkeys were shown visual cues indicating the size of an offered reward and the delay to reward delivery in successful behavioral trials. The monkeys were free to refuse the offer by failing to complete the current trial successfully. Unsurprisingly the monkeys were most likely to accept big rewards delivered immediately and least likely to accept offers of small, late rewards.

We found that a well-known but somewhat mysterious set of striatal neurons, the so-called Tonicly Active Neurons (TANS; also known as the Cholinergic Interneurons, CINs), carry information about stimulus associated outcome value in a temporal code, where the number of spikes is the same for every condition, but the distribution of spikes is governed by a sinusoidal envelope [2]. TANS are the only class of neurons that we have identified showing this sinusoidal temporal coding.

We also recorded neurons in the IPFC. Neurons in IPFC project to the rostral ventral-medial striatum, thus plausibly providing input to the TANS. Each IPFC neuron has a particular temporal pattern; that is, each neuron has its

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own distribution of spikes over time. The time window where the information is found is an essential part of the code. However, despite the patterns of firing over time differ from neuron to neuron, the information is conveyed by the spike count for each individual neuron; that is, the spike count depends on the stimulus being shown. Information is restricted to the spike count modulation in an approximately 200 ms window, but it is the timing of this information window that is idiosyncratic across neurons. The population of such neurons tiles the entire time period from the cue onset to the imperative signal. In this scenario, it is the population that holds the information about the predicted outcome for the entire cue period.

Our results seem to show that different parts of the reward circuit, at least, code for stimulus associated predicted outcome with radically different spike-based neural codes. Does this mean that each brain region, and perhaps each neuronal cell type codes information with its own coding rules? How many coding rules are there?

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EFFECTS OF HALOPERIDOL ON LOW GAMMA OSCILLATIONS OF THE EEG

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Abstract

During cognitive processes, different cortical areas interact intensely with each other and with other subcortical regions such as the thalamus (Singer and Gray, 1995; Gandal et al., 2012). It has been postulated that oscillations in the gamma band frequency (30 to 45 Hz) of the electroencephalogram (EEG) are the product of these interactions, and therefore they are involved in cognitive functions (Bressler et al., 1993; Llinás & Ribary, 1993). Both cognitive processes and the cortical gamma activity, as well as its coupling between cortical areas, are radically different between wakefulness and the different stages of sleep (Castro et al., 2013, 2014, 2018; Cavelli et al., 2015, 2018).

Numerous neuronal groups and neurotransmitters are involved in both the regulation of wakefulness, as well as in the cognitive processes associated with it (Vanini & Torterolo, 2021). The dopaminergic system is one of them. Dopamine agonists have a promoting effect on motivated wakefulness, while dopamine antagonists produce the opposite effect (Nishino & Mignot, 1997). However, it is not yet known if the dopaminergic system participates in the regulation of the gamma band.

For this reason, the goal of the project focuses on characterizing the role of the dopaminergic system in the modulation of the gamma band EEG frequency range. To carry out this purpose, the effect of high doses (4 mg/kg, i/m) of haloperidol (dopamine receptor antagonist) was studied in 4 cats chronically implanted for polysomnography. Subsequently, we analyzed the power spectral density and intercortical connectivity through the "phase lag index" (PLI) of the gamma band during wakefulness and sleep under the control situation and the effects of haloperidol.

We evidenced a displacement of the maximum value of gamma power towards lower frequency values, generating increases in power even in the beta band of EEG frequencies. Similarly, the maximum value of gamma band PLI was evidenced in lower frequency values after administration of haloperidol. It is concluded that the dopaminergic system has a modulating role of the gamma band of the EEG.

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Top-down directionality of gamma band (≈ 40 Hz) functional interactions during wakefulness, sleep and drugs that affect consciousness

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Cognitive processes and consciousness depends on large-scale thalamocortical and corticocortical recurrent interactions¹⁻³. It has been postulated that the oscillations in the gamma frequency band (30 to 45 Hz) of the electroencephalogram (EEG) are the product of these interactions and therefore are involved in cognitive functions^{4,5}. Oscillations in the gamma frequency band of the electroencephalogram are involved in the binding of spatially separated but temporally correlated neural events, which results in a unified perceptual experience^{2,6,7}.

Top-down processing is how the mind uses our expectations, attentional focus, and other cognitive variables to adaptively influence bottom-up sensory processing^{3,8}.

In our previous work, utilizing the cat as an animal model, we demonstrated that the coherence in the gamma band between intrahemispheric cortical areas is large during wakefulness (W), it decreases to moderate values during NREM sleep and reaches minimum values during REM sleep^{7,9}. Furthermore, the administration of a subanesthetic dose of ketamine (a model of psychosis), also decreases gamma coherence to a similar level than during REM sleep¹⁰. Finally, administration of atropine or scopolamine (muscarinic antagonists) produce delta waves and sleep spindles as in NREM sleep but the animals remain active. This dissociated state was accompanied by gamma power and coherence values similar to W. This high functional connectivity in the gamma band of frequencies could explain why the animals remain awake despite the presence of slow waves and spindles in the EEG¹¹.

The aim of our study is to address the sense of direction of the the gamma band functional interactions during W and sleep, as well as following the administration of ketamine (15mg/k) and scopolamine (1 mg/k). For this porpoise, five cats were chronically prepared for polysomnographic recordings, with electrodes in different cortical areas. Gamma band directionality was studied in the abovementioned conditions by two different methods. The first and simplest was quantifying the direction of the phase shifts of the amplitude envelopes of filtered gamma oscillations, The second by means of “Granger causality”¹².

We found that during W there is a predominant top-down sense of direction of gamma band functional interactions. Directionality from dorsolateral Prefrontal cortex (Pfdl) to posterior parietal cortex (Pp), from Pfdl to primary cortices such as somato-sensory cortex (S1), primary visual cortex (V1) and primary auditory cortex (A1) Predominant directionality was also from Pp to primary cortices (S1, A1, V1). This predominant sense of direction of the gamma flow of information disappeared during sleep, as well as under ketamine and scopolamine.

Our finding highlights the role of top-down processing in gamma frequencies during W when the animals are conscious; while, when consciousness is vanished or altered, this directionality is lost. Our results strongly suggest that top-down processing in the gamma frequency band is necessary for cognitive waking functions.

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Mechanisms and functions of respiration-driven gamma oscillations in the piriform cortex

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Gamma oscillations are believed to underlie cognitive processes by shaping the formation of transient neuronal partnerships on a millisecond scale. These oscillations are coupled to the phase of breathing cycles in several brain areas, possibly reflecting local computations driven by sensory inputs sampled at each breath. Here, we investigated the mechanisms and functions of gamma oscillations in the piriform (olfactory) cortex of awake mice to understand their dependence on breathing and how they relate to local spiking activity. Mechanistically, we find that respiration drives gamma oscillations in the piriform cortex, which are inhibitory and result from recurrent connections between local excitatory and inhibitory neuronal populations. Moreover, respiration-driven inhibitory gamma oscillations are triggered by the activation of mitral/tufted cells in the olfactory bulb and are abolished during anesthesia. Functionally, we demonstrate that they locally segregate neuronal assemblies through a winner-take-all computation leading to sparse odor coding during each breathing cycle. Our results shed new light on the mechanisms of gamma oscillations, bridging computation, cognition and physiology.

Keywords: neural oscillations, breathing, neuronal assemblies, sparse coding, optogenetics

Phase Transitions in Randomly Grown Neuronal Networks

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We derive equations for the probabilities of connections in a 2- and 3-dim randomly growing networks taking into account biologically justified assumptions: density of neuronal centers, the rates of outgrowth of axonal and dendrite arborizations.

The constructed graph is a function of time. Depending on the involved parameters we provide a phase diagram for the connectivity properties of the graph. In particular, we derive the critical time when the graph acquires the giant component, i.e., when a fraction of the nodes of the graph is connected. This time point, which is a function of the involved parameters, reflects a phase transition in the classical homogeneous random graph process.

Having described the underlying structure we study propagation of activity in the resulted network of synaptic connections, assuming both inhibitory and excitatory synaptic connections, and an integrate-and-fire mechanism of impulse propagation, close to the bootstrap percolation in mathematical models. We analyze the impact of the ratio between the amounts of inhibitory and of excitatory neurons on the formation of stable spatio-temporal patterns of neuronal activity.

A formal framework to construct simplified models of probabilistic descriptions of neuroanatomical data*

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In statistical mechanics, macroscopic descriptions of systems with a large number of particles can be derived from microscopic descriptions. When reducing the complexity of a model, the first step is to identify which variables to preserve and which to discard. In 2013, Machta et al [3] devised a strategy based on preserving the combinations of variables that coincide with those directions of the parameter space in which the Fisher information has eigenvectors with large eigenvalues. Here we apply this strategy to reduce the complexity of the probability distribution of a large number of variables that describe the neuroanatomical properties of the cerebral cortex of a collection of healthy individuals. In this case, the sampled data are geometric measures provided by the free software Free Surfer [2] when segmenting and characterizing a collection of MRI T1 images of 193 healthy volunteers [1], and the parameters of the model are the correlation coefficients obtained across the population between different anatomical characteristics of the images. In each of the 62 analysed cortical regions, the probability distribution describing the population variability of the anatomical properties yields a 3x3 Fisher Information matrix with one eigenvalue that is at least 30 times larger than the remaining two. The eigenvector associated with the maximally informative eigenvalue describes the degree up to which the volume of the cortical region under study can or cannot be equated with the product of the area of the region and its thickness. This eigenvector can be used to construct a simplified model that reduces the number of parameters by a factor of 3 and, as confirmed by several validation tests, still provides a good approximation of the original distribution.

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Monitoring the state of a neural network via spatial scaling of correlations*

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The dynamical state of the brain has been usually monitored from the Avalanche size distribution [1, 2], computed from the total recorded neuronal activity as a function of time, $A(t)$. Optogenetic techniques allow to record the activity and the position of hundreds to thousands of neurons. We propose to characterize the network’s dynamical state with a method that takes profit of this extra information, and computes the state from instantaneous snapshots of the system state.

We propose a metric, κ_C , to compute the dynamical state of a neuronal network, based on the scaling of the correlation length with observation size W . We compare it’s performance with observables related to avalanche size distribution κ_S [2] and the autocorrelation $AC(1)$ [3] of the activity timeseries on a numerical model of spiking neurons. We discuss the benefits and limitations of each method, and show examples of applications on datasets containing optogenetic recordings of conscious mice subject to visual stimuli, from Allen Institute [4].

We show the values of $AC(1)$, κ_S and κ_C , from the first autorrelation coefficient, avalanche size distribution, and correlation length scaling, in Fig. 1, for simulations over a neuronal model [5], this model has a control parameter T than determine the dynamical state of the system. In this model the dynamical state can be, supercritical, which means a high activity of neurons, subcritical, low activity and critical. Avalanche analysis expected results: $\kappa_S > 1$ (< 1) for supercritical (subcritical) regime, while κ_S is closest to 1 for critical regime, with control parameter $T = 0.318$ (marked with a green dot). For very subcritical values (high T), κ does not keep on

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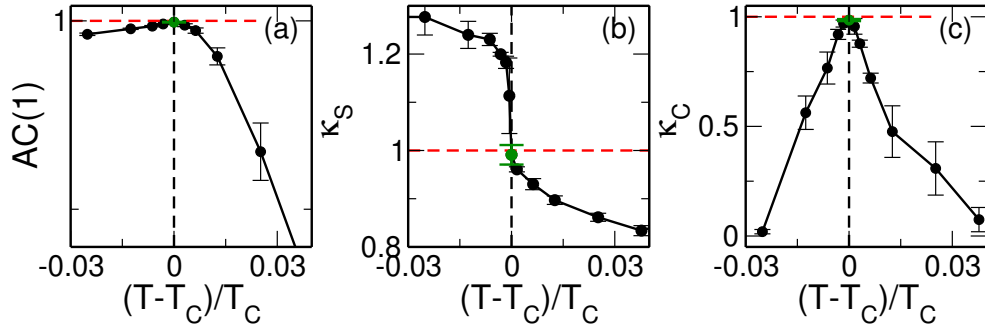


Figure 1: Behavior of the different metrics (mean $\pm SD$) as a function of T near the critical point of the neural model: $AC(1)$ in panel (a) κ_S in panel (b) and κ_C in panel (c).

decreasing, probably due to having a short range of s values captured by $P(s)$. The analysis of characteristic length collapse, κ_C , shows compatible results, see Fig. 1c. We can see how $AC(1)$ and our metric has similar results, obtaining values $AC(1) = 1$ and $\kappa_C = 1$ for critical state.

The metrics explored here yield comparable results, both in the results from numerical simulations and for the mice optogenetic data. $AC(1)$ and κ_S , being computed from 1D time series, are subject to external biases and nonstationarities. In contrast, κ_C , which uses spatial information can be computed from single snapshots and is more immune to those biases. Close to T_C both $AC(1)$ and κ_C show smaller errors than κ_S , but by themselves they cannot discriminate sub from super-critical behavior. These metrics can be useful to determine the network response to stimuli dependence on its current dynamical state. For more details about our work please read the reference: Finite-size correlation behavior near a critical point: A simple metric for monitoring the state of a neural network, Trejo et al., *Physical Review E* (2022).

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Biofeedback-Driven Sound and Image Generation

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- (4) Fibras
- (5) Rootstrap
- (6) Faculty of Arts, UDELAR

BIOFEEDBACK exhibition offers a unique experience for each visitor, combining art, neuroscience, and technology in an interactive way. Using a headband that captures bioelectric activity of the brain, the visitors are able to generate sound and images in a sequence loop, making them an integral part of the artwork. Through this interactive exhibit, visitors gain a deeper appreciation of the beauty and complexity of the brain. As a special takeaway, visitors will receive an NFT as a present, allowing them to continue their engagement with the exhibition beyond the physical space. We used EEG Biofeedback technique following a closed-loop neuroscience approach[1], capturing EEG data with Muse S[2] headband, generating in real time an audiovisual pattern stimulation. PureData is used for sound generation and Generative Adversarial Networks (GANs) [3] for image generation.

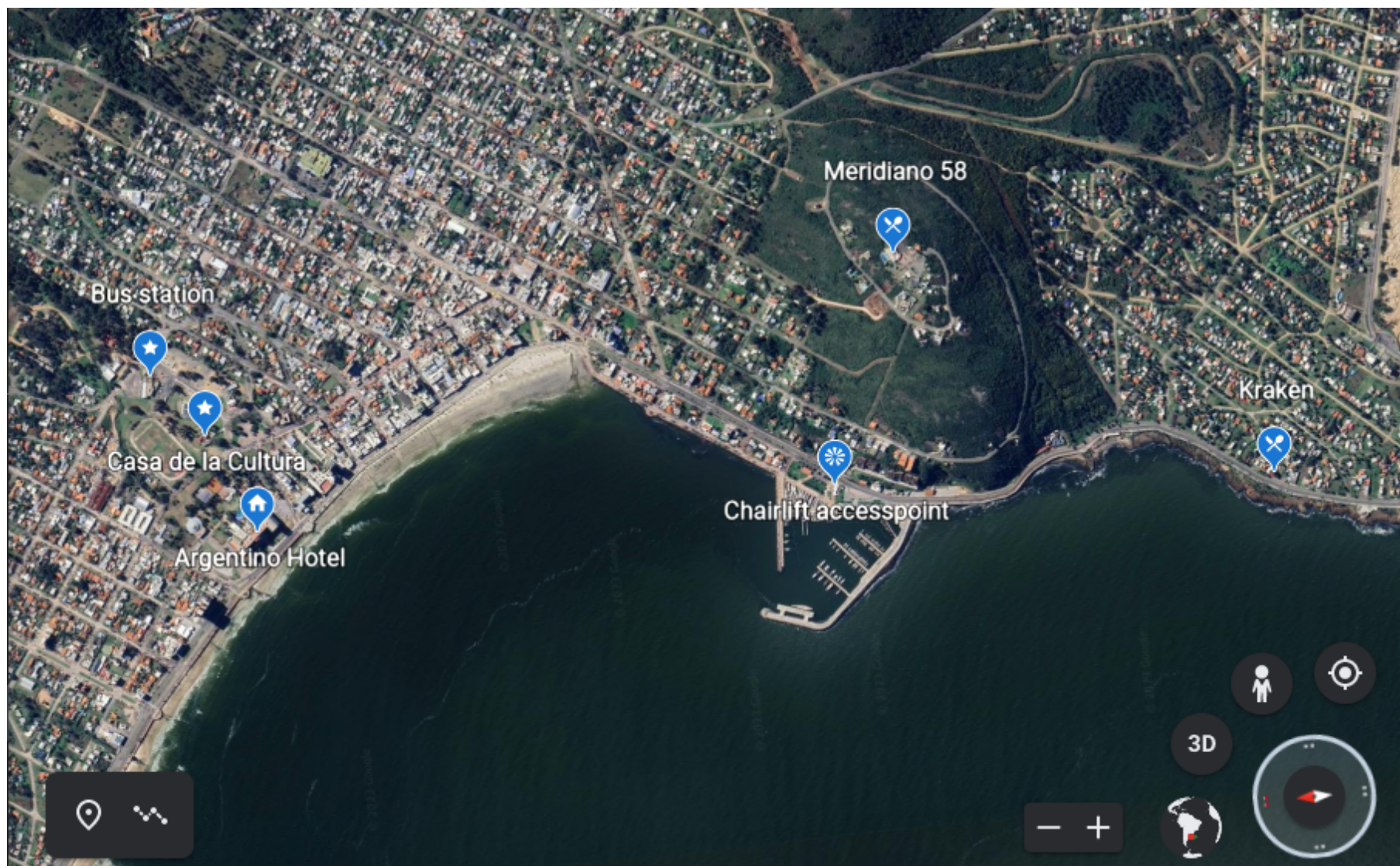
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City maps of Piriápolis



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