Proposal for PhD position

Working Group: Criticality Working Group
Members:
1. PI: Judit Gervain
team members: Jesus Encinas (co-supervised with Samir Suweis), Silvia Polver, Jessica Gemignani
2. PI: Samir Suweis
team members:
Jesus Encinas (co-supervised with Judit Gervain), Benedetta Mariani, Ramon Guevara
3. PI: Marco Dal Maschio
team members: Fabrizio Lombardi, Irem Topal
4. PI: Marco Zorzi
team members: Alberto Testolin

List of activities carried out by the Working Group and how they were communicated and promoted within the PNC from 27/2/2023 to today:

(i) joint publications by members of the working group
Mariani, B., Nicoletti, G., Barzon, G., Ortiz Barajas, M. C., Shukla, M., Guevara, R., Suweis, S.S., Gervain, J. 2023. "Prenatal experience with language shapes the brain". *Science Advances*. 9, eadj352.

(ii) joint funding
FARE Grant, Italian Ministry of Education (129 000 €; PI: Judit Gervain, co-PI: Samir Suweis)

(iii) presentations within PNC
Judit Gervain, Ramón Guevara, Samir Suweis: "Criticality in the critical period: Approaching human development through the lens of statistical physics". Talk given at the PNC Working Groups Event, Jan 31st, 2023.

(iv) joint activities
-regular meetings
-shared document reporsitory
-shared datasets

Proposal:

Title of the PhD project: Criticality as a Framework for Understanding the Brain

Abstract:

Understanding the mechanisms behind the brain's capacity for information transmission, processing, and storage remains a challenge in neuroscience. The theory of critical phenomena in physics posits that these processes may operate at a phase transition between order and chaos, in a critical state. Criticality is characterized by erratic fluctuations in a

dynamical system undergoing a phase transition. Criticalities have been used to capture a wide variety of phenomena, e.g. ferromagnets or earthquakes. Recent findings suggest that approaching neural mechanisms as critical phenomena provides novel insights into well known behavioral, perceptual, cognitive and neural processes (de Arcangelis & Herrmann, *PNAS*, 2009; Gautam et al., *PLoS Comp. Biol.*, 2015; Meisel et al., *PNAS*, 2020; Zhengyu et al, *Neuron*, 2019). However, a direct, quantitative relationship between criticality and brain function is still missing. The current project of the Criticality Working Group brings together expertise in statistical and dynamical system physics, neuroscience, psychology, and neurophysiology to break new ground in analyzing and modeling neural data from single cells to human behavior through the framework of critical phenomena.

Specifically, three lines of research are proposed. The first asks whether during human development the transition from universal to language-specific speech perception abilities may be conceptualized as a phase transition (Mariani et al., *Sci. Adv.,* 2023). Specifically, we aim to (i) lay the theoretical and methodological foundations of modeling the developing human brain as a critical system, (ii) test whether universal speech perception abilities in newborns are in a critical state, (iii) test whether language experience during the first year drives the system away from this criticality into a stable sub-critical state, (iv) test whether bilingual infants' speech perception abilities remain closer to criticality for longer than in monolinguals, (v) investigate whether healthy and pathological development differ in these dynamics.

The second line of research addresses the following questions: (i) Is processing of sensory stimuli optimal when the brain-wide network is tuned to criticality? (ii) Are dynamic range, information transfer, and information capacity maximized in the brain at criticality? Theoretical and numerical studies predict that neural networks at criticality maximize dynamic range, information transmission, and information capacity (Kinouchi and Copelli, *Nat. Physics*, 2006; Rämö et al., *Physica D*, 2006; Ribeiro et al., *Phys. Rev. E*, 2008). (iii) Is the E/I balance related to (and modulated through) tuning to criticality as proposed in modeling studies (Lombardi et al., *Phys. Rev. Lett.*, 2012; *Chaos*, 2017; Shew et al., *J. Neurosci.*, 2011) (iv) Does criticality provide measurable support for learning and memory performance, as predicted within the critical brain hypothesis (de Arcangelis & Herrmann, *PNAS*, 2009; Deco and Jirsa, *J. Neurosci.*, 2012)?

The third line of research investigates the functional role of criticality in artificial neural networks (ANNs) and generative Artificial Intelligence (AI) systems, exploring the dynamics that might lead to the emergence of critical states. We will employ a multi-disciplinary approach to investigate possible correlations between criticality and learning / inference performance of ANNs and generative AI models. The learning dynamics of deep neural networks exhibits stage-like transitions (Saxe et al., 2019), but it is currently unknown whether such transitions could be associated with critical developmental periods. Specifically, tuning to prosodic and phonological features of the native language following exposure to natural speech, as proposed in developmental psychology, can be tackled using energy-based neural networks that learn a hierarchical generative model (Zorzi et al., 2013) of child-directed speech.

[word count: 476 words excluding references]

Potential supervisors: Judit Gervain (DPSS), Samir Suweis (DFA), Marco Dal Maschio (DSB), Marco Zorzi (DPG), Alberto Testolin (DPG)

Description of the expected background of the PhD student:

The PhD student is expected to have a background in neuroscience, psychology, neurophysiology, physics, computer science, engineering, or related disciplines, with knowledge or at least a strong interest in and commitment to learning formal, computational approaches, programming and/or modelling. Similarly, familiarity with or interest in learning empirical / experimental methods is necessary. A strong motivation to meet the challenges of interdisciplinary and inter-laboratory work is expected. A working knowledge of English is a must.

Description the multidisciplinary training path planned for the student's career:

In addition to the regular training activities of the PhD program, the PhD student will spend time in the research groups of each of his/her co-supervisors, effectively gaining experience with and being involved in all aspects of the research project from planning and setting up empirical studies to data collection and data analysis. Of the three proposed lines of research, the candidate's project will be developed in an interactive way, taking into account the candidate's background and existing knowledge, his/her interests and preferences and input from the possible supervisors. The actual supervisor and co-supervisor(s) will be selected in accordance with the project. The student will attend all the (co-)supervisors' lab meetings, as well as Criticality Working Group's joint meetings, will present his/her work and will gain feedback not only from the co-supervisors, but also from all other members of the Working Group. The student will be encouraged to attend training opportunities (e.g. summer schools etc.) in all the disciplines involved as well as to present his/her work at conferences of these various areas. Publications deriving from the work will be, whenever possible, submitted to high impact generalist journals, rather than to specialist journals of a single discipline.