

Cognitive maps during group exploration

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Abstract (10 lines)*

Spatial cognition permits animals & humans to acquire knowledge about the spatial layout of their environment to navigate efficiently to locate food resources, avoid dangerous situations and find their nest. The hippocampal formation is an essential brain hub for spatial cognition. It contains a constellation of spatially modulated cells (neurons that fire preferentially at specific locations in the explored environment) such as place cells in the hippocampus and grid cells in the medial entorhinal cortex (Moser et al, 2017). The neurophysiology of space has been studied for a long time exclusively in solo travelers ('self place cells') but recent experiments on dyads have unraveled the existence of 'social place cells' that code for the position of a conspecific (Danjo et al, 2018 ; Omer et al, 2018 ; Forli et al, 2022; Zhang et al 2024). However, it is unclear how patterns of exploration and spatial coding are modulated by the presence of multiple conspecifics. This question is even more relevant since behavioral studies in animals & humans have shown that group exploration and navigation patterns are different from those of solitary travelers (Nagy et al, 2020 ; Dorfman et al, 2021). The purpose of this project is to study how place and grid cells codes for space (physical and social) during ethological group exploration of an environment. To link electrophysiological activity with dynamics of interactions between individuals in a group, we will use methods from sociophysics and network science (Génois et al, 2018). Our goal is to study how the dynamics of the socio-spatial network of the group influence spatial coding.

Keywords*

Social spatial cognition, temporal networks, social physics, electrophysiology, place & grid cells

Scientific question and Objectives (10 lines)*

The aim of the project is to study how the dynamic of the social interaction network modulates the spatial coding during group exploration of an environment.

Social animals such as mice tend to be attracted to conspecifics and stay or travel together (Dorfman et al, 2021). However, how exploratory patterns and their temporal evolution is influenced by the presence of more than one conspecific is not clear. Several questions will be assessed. First, is the exploratory pattern similar between solo and group exploration? During group exploration, do exploration patterns differ from one mouse to another? And finally, how does the interaction network

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modulate exploration patterns?

Our second objective is to study whether and how the socio-spatial network and collective exploration patterns modulate spatial coding. To do so we will record the activity of hippocampal place cells or entorhinal grid cells in one mouse during group exploration. We will leverage the socio-spatial temporal network to answer these questions: are hippocampal spatial resolution (self-place cells) modulated by the socio-spatial network? (e.g. over-representation of the location with most interactions)? are social place cells modulated by the interaction network? (e.g. preferential coding of the mouse that interacts the most with the recorded mice)? Are social place cells dynamic? (e.g. this coding evolves with the temporal network (for example, a cell that will code for the position of mouse A at one moment and mouse B at another moment)).

Proposed approach (experimental / theoretical / computational) and research plan (20 lines)*

To study how the dynamic of the social network has an influence on exploration and spatial coding, we need to get information from two different channels at the same time: individual behavior and neuronal activity. We will thus record videos of 5 to 10 mice navigating in a free-exploratory paradigm (Griebel et al, 1993). We will use SLEAP (Pereira et al, 2022), a deep learning open-source system to track the position and pose of multiple mice simultaneously. Trajectories will be analyzed with tools from statistical physics to determine their characteristics (e.g. roaming entropy as an indicator of the territorial range covered by a given mouse in a given period of time, or methods from single particle tracking to uncover change points in the trajectories), and the interactions events will be used to build temporal networks of contacts (moment by moment social context). This temporal network established in mice will first allow to help determine the roles of the mice in the group by studying the properties (degree, strength, centrality) associated with their position in the aggregated network of interactions, and the interaction patterns between them (link weights, clustering, group structures). The temporal properties, in particular the contact activity and temporal centralities, will give access to information about the evolution of behavior with time, which changes may be then correlated with modifications in the trajectory patterns. Characterizing and disentangling the coupled effects of exploration and interaction will require new methods, as trajectories are usually not available when studying contact patterns. As a side analysis, we will also be able to compare the statistics of interactions (contact durations, intercontact durations, number of contacts per link) with the ones found in human temporal networks, and test hypotheses on whether these properties are characteristic of human social mechanisms or may be more universal (Masoumi et al, 2024).

In parallel, we will chronically record hippocampal or entorhinal neuronal activity (using a high-density channels Neuropixels probe) of one mouse during solo or group exploration. This will first allow us to compare spatial coding in place and grid cells between solo and group exploration (self place-cells). Indeed, it will be interesting to know whether the spatial map of the environment is similar or different (remapping) between solo and group exploration and specially whether the temporal network of interaction modulate spatial maps (e.g. via over-representation of location with the most interaction). Next, we will analyze social place cells during group exploration by mapping the position of another mouse when a neuron fires action potentials (social place cells are neurons that fire preferentially when another mouse is at a specific position in the environment). Secondly, by aligning information from the temporal network of interactions with the neural activity, we will be able to analyze how interaction

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modulate social coding. For example, sudden changes in the network structure or contact activity may be correlated with changes in the neuronal activity. Testing the presence of such correlations could be uncovered by simple measures such as a Pearson correlation. However, the fact that we will have multiple concurring signals —interaction activity, interaction structure, position, orientation, movement, neuronal activity— will necessitate the use of advanced statistical methods —such as GLM or Bayesian inference technics— to identify the relations between all of them.

Interdisciplinarity and Implication of the two labs (15 lines)*

The main topic of this project is to explore the links between neural activity, individual and social behaviour in mice. Its main novelty is the possibility to access simultaneously electrophysiological signals of brain activity, individual trajectories in space and social interactions. As described in the precedent section, to study such data we need to combine methods and concepts from neurosciences, animal behaviour, network science and statistical physics, hence, to have an interdisciplinary approach. The experiments on mice will be conducted at INMED, which already has all the necessary equipment to carry them out (large arena and camera to track the animal's position, Neuropixels electrodes, and recording system). The neurophysiological aspect of the project will be co-supervised by 2 INMED researchers from the same team : Jérôme Epsztein & Julie Koenig Gambini, expert of spatial cognition and electrophysiological recordings of hippocampal neuronal activity in mice navigating in virtual reality. Julie Koenig Gambini is also an expert in electrophysiological recordings in freely moving animals (chronic recordings) in both hippocampus (place cells) and medial entorhinal cortex (grid cells). Preliminary experiments have already been conducted to confirm that SLEAP can effectively track 10 mice (including one mouse that was implanted and wired for electrophysiological recordings). Mathieu Génois' expertise is crucial in using statistical physics and complex network tools to study collective exploration patterns and the influence of interaction networks on these patterns and on the electrophysiological activity of the hippocampus and entorhinal cortex.

Specify with whom the person recruited will collaborate and on what aspects *

The doctoral student will be trained in mouse behavior and neurophysiological technics (chronic implantation of Neuropixels in hippocampus and/or MEC, recordings) by Julie Koenig Gambini. Theoretical and analytical training (classical analyses of individual place cells and grid cells) will be provided by Jérôme Epsztein and Julie Koenig Gambini. Mathieu Génois (CPT) will be responsible for training the doctoral student in the analytical tools (statistical physics and complex networks) essential to this project and which the two INMED researchers have not mastered. The project will be managed by the three researchers through weekly meetings.

PhD student's expected profile*

We are looking for a curious and motivated candidate with a Master's degree in Complex Systems (or a related field). An interest in neuroscience, animal behaviour and sociophysics is required, as the position lies at the interface between biological and complex systems research.

The ideal applicant should have both the willingness and ability to work with animals, as the project involves behavioural or neurobiological studies.

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A high proficiency in Python is required, particularly for data analysis and modelling; some knowledge of Matlab would be an additional asset.

We are enthusiastic researchers welcoming individuals from all backgrounds and happy to support neurodivergent and non-typical team members.

Is this project the continuation of an existing project or an entirely new one?

In the case of an existing project, please explain the links between the two projects (5 lines)*

This is an entirely new project, but it is linked to the scientific interests of the three researchers involved in this project. Jérôme Epsztein and Julie Koenig Gambini have shown that the presence of visual cues dynamically modulates spatial coding (Nordlund et al, 2025; Bourboulou et al., 2019), and they would like to extend this investigation to the presence of social cues. Mathieu Génois studies temporal interaction networks in humans navigating in several contexts (Génois et al, 2022; Kobayashi & Génois, 2021; Génois & Barrat, 2018) and is very interested in extending his findings to animals by adding a neurophysiological approach.

Two to five references related to the project*

Zhang X, Cao Q, Gao K, Chen C, Cheng S, Li A, Zhou Y, Liu R, Hao J, Kropff E, Miao C (2024) Multiplexed representation of others in the hippocampal CA1 subfield of female mice. *Nat Commun.* May 2;15(1):3702.
Génois et al. (2022) Combining sensors and surveys to study social contexts. *Personality Science*, in prod.
Dorfman et al. (2021). *Social spatial cognition. Neuroscience and biobehavioral reviews*, 121, 277–290.
Bourboulou et al. (2019). *Dynamic control of hippocampal spatial coding resolution by local visual cues. eLife*, 8, e44487.
Masoumi et al (2024) Simple crowd dynamics to generate complex temporal contact networks, arXiv:2405.06508.

Two main publications from each PI over the last 5 years*

Nordlung, Levernier, Trippa, Marti, Bourboulou, Rouault, Monasson, Epsztein & Koenig-Gambini (2022) An independent coding scheme for idiothetic distance in the hippocampus, *Current Biology*, 35, 4199–4214.
Bourboulou, Marti, Michon, El Feghaly, Nougulier, Robbe, Koenig-Gambini & Epsztein (2019) Dynamic control of hippocampal spatial coding resolution by local visual cues. *eLife*, 8, e44487.
Génois, Zens, Oliveira, Lechner, Schaible, Strohmaier (2022) Combining sensors and surveys to study social contexts: Case of scientific conferences. *Personality Science*, in prod.
Kobayashi & Génois (2021) The switching mechanisms of social network densification. *Scientific Reports*, 11:3160.



Project's illustrating image

