Application of data science to multi-brain area simultaneous recordings in the mouse during movement planning

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1 Introdution

In recent years, the field of neuroscience has seen significant progress, particularly with the increasing use of technologies designed to record neuronal activities extensively, either sequentially or simultaneously. Despite these advancements, directly observing functional interactions at the cellular level throughout the brain remains a formidable challenge. This is mainly due to the complexity of recording activities across numerous regions simultaneously [4]. Current multi-electrode and optical recording technologies have made it possible to monitor neuronal activities in the cortex and, in some cases, in deep structures. Ongoing advancements in these technologies promise to significantly increase the number of neurons that can be simultaneously recorded, potentially by orders of magnitude [2].

Previously, techniques like cross-correlation and dimensional reduction have been widely used to analyze neuronal activity[5, 4, 2]. However, these analyses were typically based on data recorded from single probes, which limited their ability to capture the full scope of neuronal interactions across different brain regions. Single-probe recordings do not allow for the simultaneous monitoring of multiple brain areas, leading to gaps in understanding how these regions interact in a coordinated manner. This limitation has made it challenging to determine the exact nature of interregional neural dynamics and their role in complex brain functions.

In contrast, multiprobe recordings surpass single probe recordings by enabling the simultaneous monitoring of neuronal activities across multiple brain regions[1]. This approach enhances spatial and temporal resolution, increases data throughput, and facilitates the study of synchronized neuronal activities, providing a more detailed and integrated perspective on brain dynamics. Such capabilities are crucial for a comprehensive understanding of neural network interactions and complex brain functions, thereby aiding in addressing our research questions more effectively.

The primary objective of this thesis is to unravel the mechanisms underlying the planning processes involved in memory-guided tasks, using state-of-the-art statistical and machine-learning methods. Specifically, it focuses on understanding the contribution of single neurons and population activity, which sheds light on the interaction of groups of neurons within the Anteromedial Prefrontal Cortex (ALM) during the execution of these tasks in mice. Additionally, the project aims to investigate the involvement of other brain regions, seeking to understand how these regions interact with the ALM during decision-making processes. The study will also consider how other information, such as the anatomical location of neurons and the hierarchical ordering of intrinsic timescales, contributes to our comprehension of brain function.

2 Aims

2.1 Problem Statement

The problem statement of this thesis is "How do the single neuron activity and the collective behavior of neuronal populations within the Anteromedial Prefrontal Cortex (ALM) contribute to decision-making during movement

planning tasks in mice, and what are the dynamic interactions between the ALM and other brain regions?

2.2 Research Objective

The objective of this research is to utilize dimensional reduction and correlation techniques to uncover brain dynamics and elucidate the role of the Anteromedial Prefrontal Cortex (ALM) in decision-making during movement planning tasks in mice.

2.3 Expected Results

- In the dimensional reduction analysis, we anticipate identifying a few vectors that can first, effectively reconstruct the original neuronal information during the memory-guided task and second, represent behaviorally relevant coding directions.
- For the correlation analysis, we expect to identify monosynaptic interaction within and across brain regions. This would indicate strong intercorrelations and interactions within the interregional loops across different brain areas, enhancing our understanding of the dynamic relationships involved in decision-making processes.

3 Methods and plan

The methodology of this thesis consists of four main steps:

Data acquisition: In this research, I will leverage the significant advancements made by the Allen Institute for Neural Dynamics and Janelia Research Campus in large-scale neural recordings. Building on their 2023 milestone of capturing neural activity across multiple brain regions simultaneously, I will analyze data derived from recordings conducted on 28 mice (Mus musculus - House mouse) during memory-guided tasks. It has anatomy-guided recordings from various interconnected brain regions, ranging from the anterior lateral motor cortex to the medulla. Multiple Neuropixels probes will be strategically inserted at different depths within various brain areas to acquire electrophysiological and behavioral data simultaneously. A key focus will be on capturing the spike times of individual neurons to gain crucial

insights into the neural dynamics associated with the observed behaviors. The dataset will include stimulus epochs lasting 0.65 seconds, delay epochs lasting 1.2 seconds, and go epochs spanning 1.5 seconds. This comprehensive data collection approach will facilitate a detailed analysis of neural activity during memory-guided tasks. Additionally, I ran different queries according to my need to separate the data further into more comprehensible and workable chunks.

Data analysis: I will start by processing the raw neural spike data, converting it into either binned data or a continuous time function using a Gaussian kernel. To manage the complexity of the large dataset, I will apply dimensional reduction techniques such as Principal Component Analysis (PCA) and Coding Direction (CD) to capture the dynamic characteristics of the underlying patterns in the neural spike data. Specifically, PCA will be applied to multi-regional data to identify principal components that reflect how different regions coordinate and contribute to complex processes. Dimensional reduction is crucial for simplifying complex, high-dimensional datasets, making it easier to identify and analyze meaningful patterns. These reduced dimensions should be able to represent actual neuronal activity and their functional interaction.

Further analysis will involve identifying the relevant neurons through techniques such as fluorescence analysis. Fluorescence analysis identifies brain regions receiving ALM input by analyzing .nii files with projection zones, enhancing the robustness of our Cross-Correlation Analysis (CCG) by selecting neurons within these zones. I will then use these identified neurons to generate cross-correlogram plots, aiming to find significant peaks between neuron pairs. We quantified functional interactions between pairs of neural units utilizing Cross-Correlograms (CCGs), which will help determine the correlation and interaction time lag between neuron pairs, providing insights into their dynamic interactions. Also, Autocorrelation and the calculation of the intrinsic time constant (τ) are important tools in neuroscience for understanding the temporal dynamics and functional properties of neuronal activity[3]. Finding the intrinsic time constant of a neuron will help us to understand how quickly its activity returns to baseline after a stimulus. A short-time constant means the neuron responds quickly and fades fast, while a long-time constant means it maintains activity longer, aiding in sustained tasks like memory.

References

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