Background

Humans and other animals exhibit complex behaviors that often consist of sequences of elementary tasks such as eye movements and motor actions. For example, during a simple task of making tea, Land et al found that this simple task involves around 400 eye fixations that are tightly coordinated with hand movements [1]. In contrast, much of neuroscience has focused on single tasks, such as visual processing, memory, and motor control. This leaves a significant gap in our scientific understanding of how humans integrate sequences of specific tasks into complex behaviors and what neural mechanisms support such integration. To address this gap, it is crucial to track these task sequences with millisecond precision while also recording neuronal responses from human subjects with high temporal and spatial resolution. Recent advances in electrode technology have enabled populations of single neurons in human subjects [2]. This offers an unprecedented opportunity to use computational approaches alongside these neural recordings to understand how complex behavior arises from neural circuits.

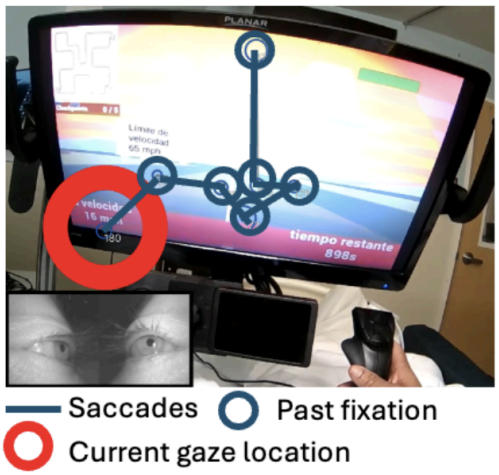
One such task is driving a car, which we will use as a "model behavior". Driving requires integrating various sources of information – a driver needs to look ahead on the road to stay in the correct lane, check the speedometer to obey the speed limit, and also follow instructions from the GPS for navigation. Such driving behavior is accomplished by rapidly switching gazes between several targets, all while coordinating hand and foot movements. Fortunately, tools from engineering that are used to build complex engineering systems, such as autonomous vehicles, are well-suited for the analysis of these types of behaviors.

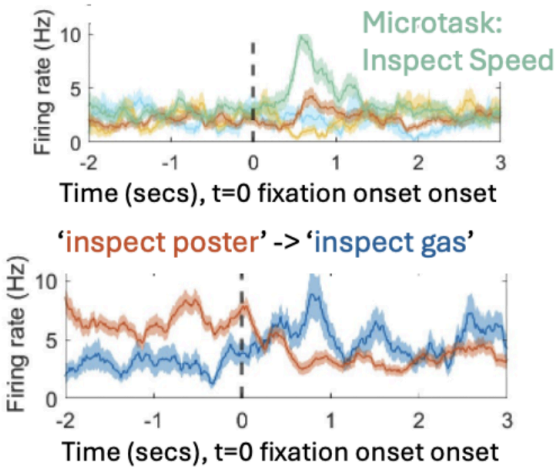
Objectives and Hypothesis

The key objective is to understand how rapid task switching is achieved by the underlying neural mechanisms. We will develop computational models that resembles rapid task switching in a driving context and determine the optimal task-switching policy through simulation and theoretical analysis. By leveraging these models, we aim to explain how flexible task-switching behavior arises from neuronal activity to acomplish the overall goal of driving. Furthermore, this approach allows us to test different hypotheses regarding how the brain controls the sequence of individual tasks. Does the brain implement a central processor where all sensory information is routed together or a distributed computing scheme where information is processed locally?

Methods

We coded a video game that requires human subjects to drive a car and complete loops on a race track. We recruit human subjects who undergo surgery and have electrodes implanted for epilepsy monitoring to play the driving game while recording behavior and neural data. While driving the car, subjects need to switch between competing mini-objectives such as steering the car, maintaining speed, checking gas, and memorizing posters on the side of the road. This gives us access to single-neuron recordings of the Hippocampus, vmPFC, Amygdala, dACC, and preSMA, which are brain regions involving memory, decision-making, emotions, and sensorimotor control. In addition, participants will be wearing an eye tracker while controlling the car using a joystick, allowing us to record eye fixations along with motor actions.





Left: A video recording of a subject playing the driving game, with gaze locations overlaid on top.
Right: Neuron firing rates aligned to eye fixations. Top panel shows evidence of a neuron that correlates with checking speed (green), bottom panel shows two neurons whose firing rates change as the subject switches gaze from poster to gas.

We first establish a simulation framework for computational modeling, supporting parallel simulations and optimization of model parameters. Taking inspiration from autonomous driving algorithms [3], we will develop computational models that replicate human task switching while taking into account human sensorimotor delays and constrained observations. We can then look into the neural data to search for evidence that the brain is implementing such models. Such evidence can stem from correlating internal variables of the model to the firing rates of neurons, which would indicate that there are neurons encoding model variables for computation. In addition, we can vary the parameters of the game to investigate the limits of performance and test whether human subjects fail in the same way as the computational models.

Significance

This project addresses fundamental questions about human behavior in naturalistic setting, focusing on how individual tasks are interleaved to form complex behaviors like driving. By combining neural recordings with computational modeling, we aim to build a bridge between neural circuits and complex behavior, and understand in what ways these complex behaviors are controlled to accomplish goals. This understanding also has important implications for designing human-machine interfaces, where it is crucial to consider the limitations of human cognitive processing.

References

[1] Land, M., Mennie, N. & Rusted, J. The roles of vision and eye movements in the control of activities of daily living. Perception 28, 1311–1328, 1999.
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[3] Rosolia, U., Zhang, X. & Borrelli, F. Data-driven predictive control for Autonomous Systems. *Annual Review of Control, Robotics, and Autonomous Systems* **1,** 259–286, 2018.