Characterizing Homebase Dynamics in Free-Roaming Rats

Through Behavioral and Robotic Interaction Analysis

Yifan Lou

Advisors: Dr. Andrea Chiba, Ian Jackson, Dr. Eric Leonardis

Department of Cognitive Science, University of California, San Diego

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Abstract

Understanding how animals regulate internal states in uncertain environments is essential to the study of adaptive behavior and social cognition. This study examined how rats balance exploration and regulation when placed in different social conditions: alone in an open field, with a familiar conspecific, or with an artificial agent called PiRat, which is a mobile robot designed to resemble a rat in size and movement.

The first part of the project focused on identifying homebase locations using behavioral tracking data. Homebases are areas that rats consistently return to in a session to self-regulate after exploring the arena. Movements of the rat are characterized in relation to homebase as excursions and incursions, and analyzed for speed and frequency. In the rat-robot condition, rats were more likely to establish homebases near the edges of the arena and exhibited shorter, faster incursions, which may reflect heightened arousal or uncertainty. The rat also tends to homebase further away from the PiRat than from a conspecific rat. The second part of the project involved analyzing local field potentials (LFPs) recorded from the main olfactory bulb, amygdala, and insula. These neural signals were aligned with moments when the rat made stops, either inside or outside of the homebase. Across all three brain regions, stops that occurred outside of the homebase were associated with higher peak frequencies, particularly in the theta band, suggesting changes in internal state or respiratory rhythm.

Together, these results suggest that both the presence and identity of a social partner, whether biological or artificial, can influence how rats navigate space and regulate internal processes. This research contributes to a growing understanding of how embodied interaction with artificial agents shapes behavior and brain activity in social settings.

Introduction

The increasing integration of artificial agents into everyday environments introduces new demands for adaptive regulation and interaction. From chatbots to mobile robots, these technologies are often designed to engage with living beings in ways that resemble social behavior. While many human-facing systems rely on language or screens, others, such as embodied animats, interact primarily through movement and physical presence. This project investigates how animals, specifically rats, respond to artificial agents that move and behave in ways resembling biological counterparts.

Rats are highly social and behaviorally flexible animals. They have evolved to navigate uncertain environments by establishing behavioral strategies for balancing exploration with regulation. One such strategy is the formation of a homebase—a spatial location within a novel environment that the animal consistently returns to and uses as an anchor point for behavior. Homebase behavior is often associated with regulatory activities such as rearing, pausing, and grooming, and is thought to reflect processes of spatial assessment, safety evaluation, and internal state regulation (Eilam & Golani, 1989). The presence and type of social agent in the environment may influence how a rat organizes its space and selects a homebase.

This study examines how homebase behavior varies across three experimental conditions: a rat exploring the arena alone (open field), with a familiar conspecific (rat–rat), or with a robotic rat (PiRat). PiRat is a mobile robot approximately the size and shape of a real rat, designed to interact with animals using movement-based social cues (Heath et al., 2018). Operated using a Wizard-of-Oz control scheme, PiRat enables real-time responses to the rat's behavior and mimics social engagement through actions like approach, retreat, and tagging. The design of PiRat allows researchers to isolate the influence of embodied behavior in a controlled environment..

The first part of this project uses pose tracking to identify homebase locations and characterize excursions and incursions—movement bouts leaving or returning to homebase. This analysis provides a behavioral lens into how the identity of a co-present agent affects exploratory dynamics. The second part of the project focuses on neural data collected from the main olfactory bulb (MOB), medial amygdala, and insular cortex. These regions are functionally connected through their roles in sensory integration, emotional processing, and interoception, and are implicated in responses to novel stimuli and social affect. Local field potentials (LFPs) recorded from these regions are time-locked to stopping behavior inside or outside the homebase to examine how neural activity reflects changes in internal state.

Together, the behavioral and neural analyses aim to clarify how rats regulate spatial and physiological responses in the presence of biological and artificial agents. This work contributes to the field of interactive neurorobotics and provides insight into how animals make sense of social others in dynamic environments, including those that are artificially constructed.

Methods

Subjects and Experimental Setup

Six adult male Sprague–Dawley rats (Rattus norvegicus) were used in this study. All procedures were approved by the Institutional Animal Care and Use Committee (IACUC) and followed institutional and federal guidelines. The rats were group housed with familiar cage-mates and maintained on a 12:12 h light-dark cycle.

The experiment was conducted in a circular open-field arena with a radius of 60.96 cm (24 inches), surrounded by opaque walls to minimize external visual distractions. Dim lighting was used to reduce potential stress for the rat. Video footage of each session was captured from an overhead camera at a resolution of 720 × 480 pixels and a frame rate of 29.97 frames per second. This behavioral video was temporally synchronized with local field potential (LFP) recordings using the Cheetah data acquisition system (Leonardis, 2022).

Each rat participated in multiple behavioral sessions across three experimental contexts. In the open-field condition, the rat explored the arena alone. In the rat–rat condition, the subject animal was accompanied by a familiar cagemate. In the rat–robot condition, the rat explored the space in the presence of PiRat, a robotic platform designed to resemble a conspecific.

Robotic Agent: PiRat

PiRat is a rat-sized mobile robot developed to support social interaction studies between animals and artificial agents. The platform features a 3D-printed shell, internal gimbal motors, and a Raspberry Pi Zero microcontroller. The system weighs approximately 0.24 kg, reaches speeds up to 1.1 m/s, and has a maximum angular velocity of 4.7 rad/s. PiRat was operated under a Wizard-of-Oz paradigm, in which a human driver remotely controlled its movements in real time via a graphical user interface. The operator adjusted PiRat's position and velocity based on the rat's ongoing behavior, with the aim of eliciting naturalistic responses such as approach, avoidance, or following. Experimenters were instructed to avoid movements that might appear aggressive or dominant and instead aimed to promote playful or exploratory engagement.

Requirement	Value	Actual
Width	< 0.10 m	0.0875 m
Length	< 0.15 m	0.123 m
Height	< 0.08 m	0.055 m
Max. Speed	$1m/s$	$1.1m/s$
Max. Angular Velocity	$\pi rad/s$	$4.7rad/s$
Weight	0.25 kg	0.24 kg
Audio frequencies	$<$ 10 dB over 25 kHz	✓
GUI	Allow selecting behaviours Use XBOX controller	✓ ✓
Autonomy	Behaviours autonomous Needs to know where rat is	✓ ✓
Cleanliness	Shell and motors cleanable	✓

Figure 1. *Illustration and physical example of the PiRat robotic platform.*

Top: Conceptual illustration of PiRat engaging in social interaction with a rat. Bottom: Photograph of the PiRat used in the experiment. PiRat is designed to approximate a rat in size and movement and is controlled using a Wizard-of-Oz framework. Right: Table summarizing the design specifications and performance metrics of the PiRat system.

Image source: Leonardis, E. (2022). Interactive Neurorobotics: Brain and Body Coupling During Interactive Multi-Agent Scenarios (PhD dissertation, UC San Diego).

Behavioral Tracking and Preprocessing

Rats' body positions were tracked using SLEAP (Social LEAP Estimates Animal Pose), a deep learning–based pose estimation tool for multi-animal tracking. Eleven body keypoints were identified for each rat (e.g., nose, mid-body, tail base), and PiRat was tracked using a single keypoint. Frames with missing or erroneous tracking data were corrected using linear interpolation. The resulting position traces were upsampled to 1010.1 Hz and smoothed using a centered moving average with a 34-frame window to align with neural data sampling.

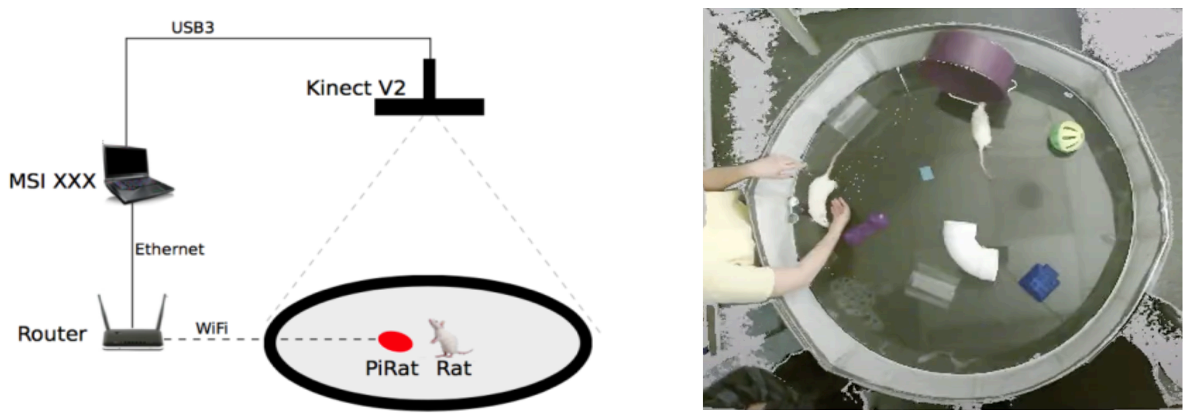


Figure 2. *Camera system setup and arena for behavioral experiments.*
Left: Schematic of the PiRat experimental setup, including components for real-time tracking and robot control, such as Kinect, router, and control laptop. Right: Overhead view of the circular arena with two rats, the experimenter, and rat toys during an enrichment session.

Homebase Identification and Movement Classification

Homebase behavior was operationalized as the tendency for a rat to return repeatedly to a specific location within the arena. To identify the homebase, the arena was divided into square grid cells (approximately 10 cm per side), and a spatial occupancy map was created by counting the number of frames the rat spent in each cell. A center-weighted 3×3 convolutional kernel was applied to the occupancy map to emphasize locally dense regions. The area with the highest cumulative occupancy was defined as the homebase centroid, and an 8-inch radius circle was drawn around the centroid to denote the homebase for that trial. The size of the homebase was approximately the size of a rat.

Stops were detected based on velocity thresholds, defined as periods when the rat's smoothed speed fell below 0.43 cm/s for a minimum duration of 0.4 seconds. To classify movement relative to the homebase, we examined the spatial location of each stop. If a movement bout began within an 8-inch radius of the homebase centroid and extended outward, it was labeled an excursion. Conversely, if the bout began away from the homebase and concluded within it, it was labeled an incursion. These movement types were used to characterize how the rat engaged with its environment and regulated its spatial behavior in different social contexts.

For each session, we quantified features of these movement bouts, including stop duration, trajectory length, average speed, and proximity to other agents and to the arena center. These behavioral features provided a foundation for comparing regulation and exploratory tendencies across experimental conditions and were used to align neural signals with behaviorally relevant events.

Neural Data Acquisition and Preprocessing

Rats were chronically implanted with electrode arrays targeting the main olfactory bulb (MOB), amygdala, and insular cortex. These regions were selected due to their roles in processing sensory inputs, evaluating emotional salience, and monitoring interoceptive states, respectively. The MOB receives direct input from the olfactory system and exhibits rhythmic activity strongly influenced by the animal's breathing (Kay, 2014). The amygdala integrates sensory and bodily inputs to rapidly assess emotional salience, such as whether an environment is safe or threatening (LeDoux, 2000). The insula serves as a hub for tracking internal bodily states and contributes to decision-making, especially under conditions of stress (Craig, 2009).

Together, these regions form a functional circuit for interpreting external cues and internal physiological responses.

Electrodes were implanted unilaterally and remained in place throughout all experimental sessions. Recordings were sampled at 1010.1 Hz and temporally aligned with positional tracking data.

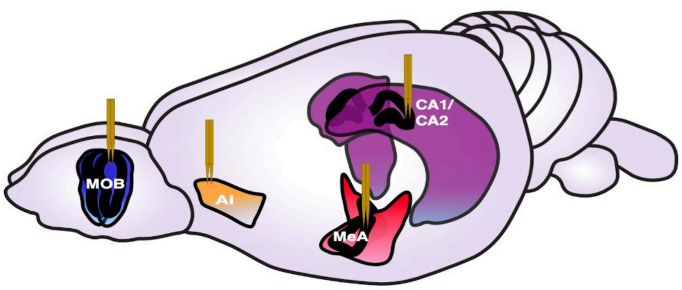


Figure 3. *Schematic of electrode implant locations for LFP recording.*
Electrodes were chronically implanted in three primary brain regions: the main olfactory bulb (MOB), amygdala , and insular cortex. Additional electrodes were positioned in hippocampal area CA2 for future analyses.

LFP Analysis

To examine neural dynamics during behavioral pauses, LFP data were segmented into time windows centered around identified stops. Each segment spanned 0.8 seconds, ranging from 0.4 seconds before to 0.4 seconds after the stop onset. Stops were categorized as either homebase or non-homebase stops based on their spatial relation to the homebase location. For each stop, the corresponding LFP signal was bandpass filtered in the theta frequency range (4–12 Hz).

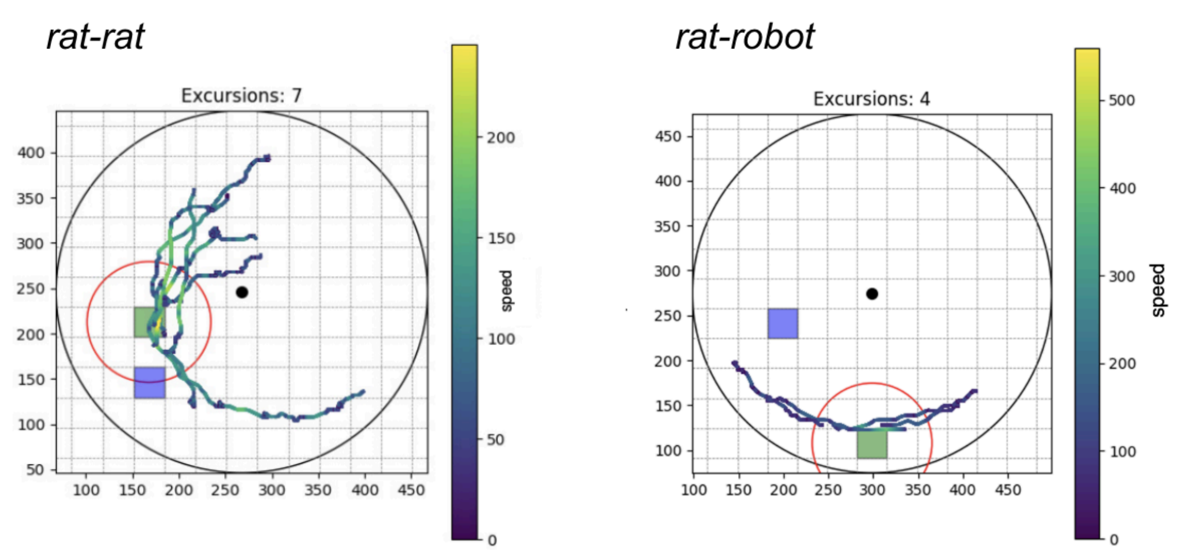
In addition to filtered time series, time–frequency representations were computed using short-time Fourier transform (STFT) with a 128-sample window and 50% overlap. Spectrograms were generated for visual inspection, and peak frequency and power values were extracted to compare across brain regions and conditions.

Neural signals during homebase and non-homebase stops were analyzed to investigate how spatial regulation and social context influence neural oscillations in regions associated with arousal, salience, and sensory integration.

Results

To characterize how social context affects homebase dynamics, video tracking data were analyzed across three experimental conditions: rat-open-field, rat-rat, and rat-robot. Each session was evaluated to determine the animal's homebase, defined as the area in which the animal spent the most time and frequently returned to. Movements away from and back to the homebase were categorized as excursions and incursions, respectively.

Across conditions, key differences in spatial behavior were observed. The distance between homebases was significantly smaller in rat-rat trials compared to rat-robot trials. In other words, rats in the presence of another rat tended to cluster more closely, forming homebases close to one another, whereas rats interacting with the robot maintained greater spatial separation. Additionally, homebases in rat-robot trials were more often located closer to the wall of the arena, which may reflect an elevated stress state and a behavioral inclination toward safety.



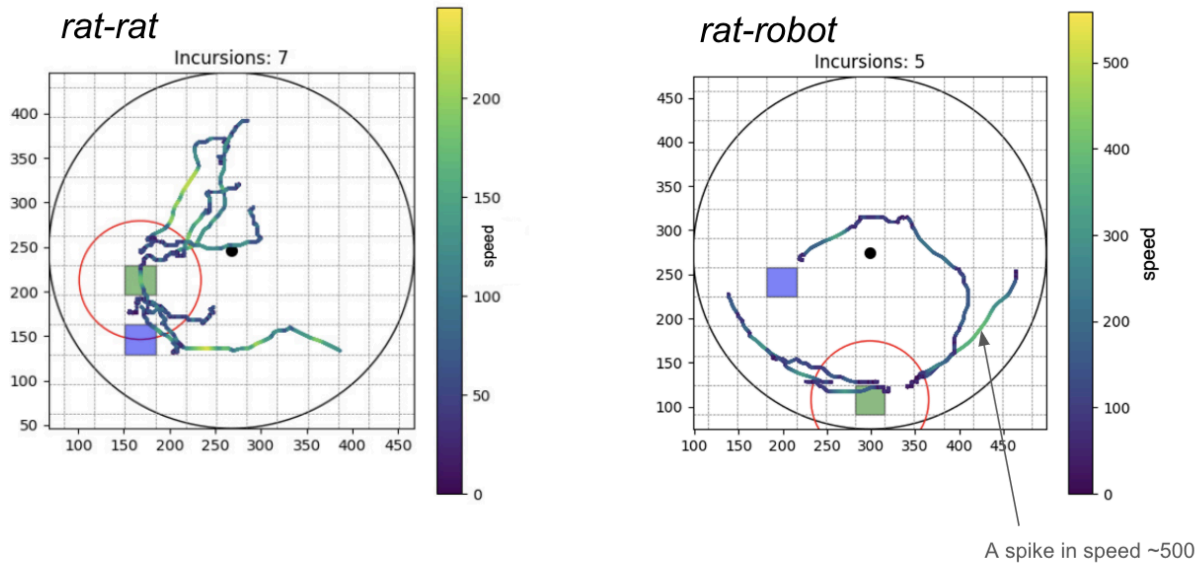


Figure 4. *Examples of excursion and incursion trajectories in rat-rat and rat-robot conditions.*
Top: Excursion trajectories, defined as movement bouts beginning within the homebase zone and ending outside it. Bottom: Incursion trajectories, defined as bouts that begin outside and return to the homebase. Squares denote the homebases of the rat being analyzed (green) and its conspecific (purple). Trajectories are colored by the rat's movement speed (cm/s), and the red circle marks the 8-inch threshold used to define homebase boundaries. Compared to the rat-robot condition, the rat-rat condition displays more frequent and variable transitions between regions, suggesting enhanced exploratory behavior in the presence of a conspecific.
Figure adapted from Jackson et al., submitted.

Movement speed analyses revealed further condition-specific differences. Incursion speeds were significantly higher in rat-robot trials than in rat-rat trials, suggesting heightened arousal or urgency when returning to homebase in the presence of the robot. Notably, both incursions and excursions in the open-field condition were significantly faster than those in rat-rat trials, and excursions were significantly faster in open-field trials compared to rat-robot trials. These findings suggest that the presence of a social agent—either a rat or robot—alters movement behavior, likely modulating arousal and perceived safety.

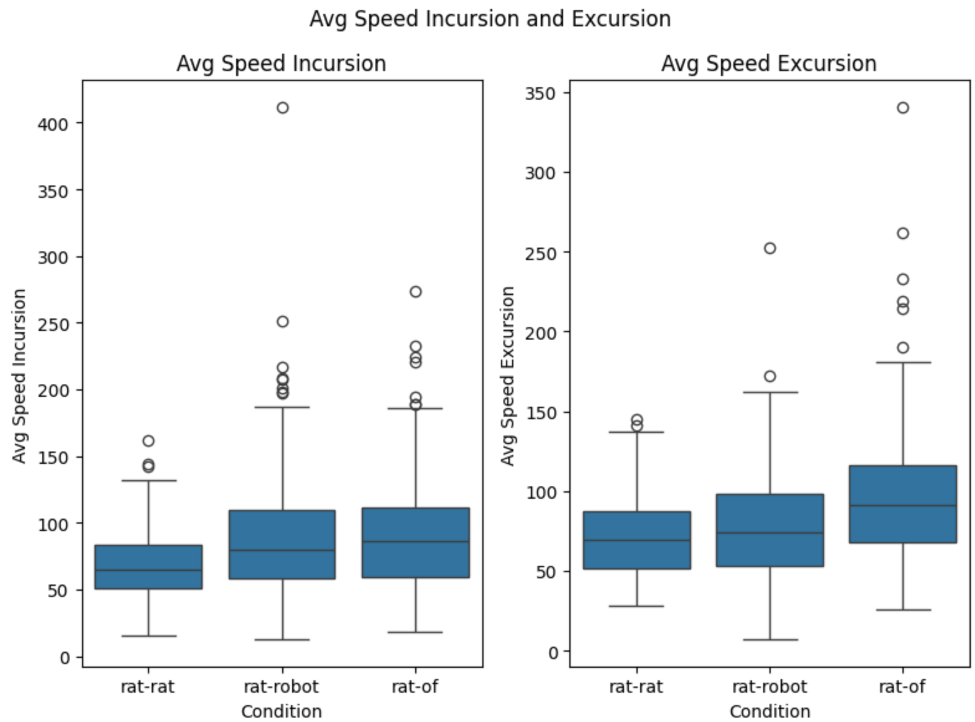


Figure 5. *Average speed duringi incursion and excursion across conditions*

The number of incursions and excursions was also quantified across conditions. Rats in rat-rat trials exhibited a higher number of both, reflecting more dynamic transitions between regulation (at homebase) and exploration (away from homebase). This may indicate a “social buffering” effect, wherein the presence of a conspecific reduces stress and promotes exploratory behavior (Kikusui, Winslow, & Mori, 2006). In contrast, rats in open-field and rat-robot conditions engaged in fewer and faster incursions and excursions, consistent with reduced exploration and higher stress levels.

To complement the behavioral findings, local field potential (LFP) recordings were analyzed to examine neural dynamics during moments of immobility. LFPs are transient electrical signals generated by the summed and synchronous electrical activity of neurons within a given region. These signals were recorded from the main olfactory bulb (MOB), amygdala, and insular cortex—three regions closely interconnected and involved in sensory processing, emotional evaluation, and interoceptive awareness.

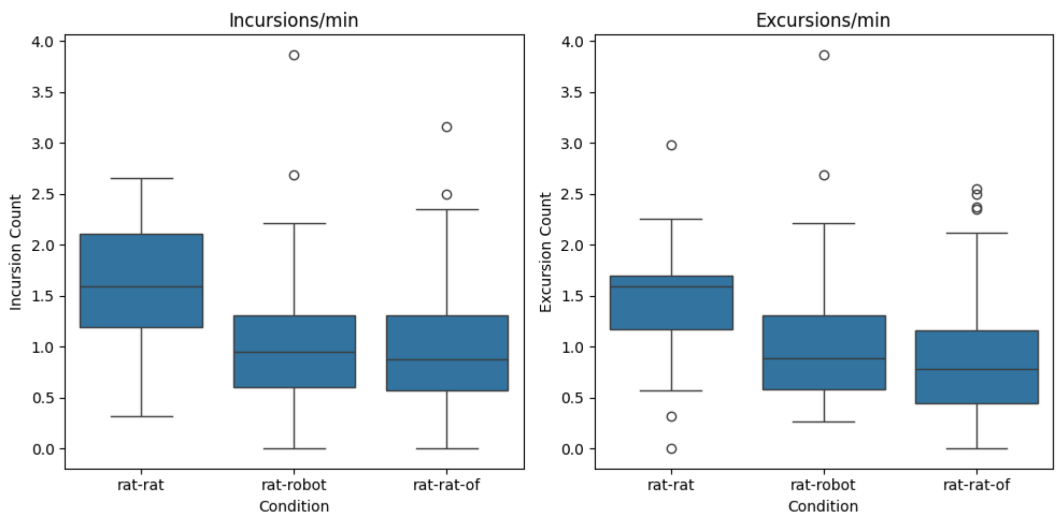


Figure 6. *Number of incursions and excursions per minute across conditions.*

Neural signals were time-aligned to immobility events—defined as episodes when the animal's speed dropped below 0.43 cm/s for at least 0.4 seconds. These stops were categorized based on location, with homebase stops occurring inside the previously defined homebase region and non-homebase stops occurring outside it.

Theta-band activity (defined here as 2–12 Hz) was extracted from the LFP signals, and both peak frequencies and theta power were analyzed across brain regions and stop types. Across the MOB, amygdala, and insula, a general trend emerged: non-homebase stops were associated with higher theta peak frequencies compared to homebase stops. Additionally, theta power exhibited a longer tail during non-homebase stops, indicating instances of elevated power during these stops.

These findings suggest heightened sensory vigilance or arousal during non-homebase stops, likely due to the animal being in a less familiar and potentially riskier location. Such states may correspond with elevated respiratory rates and increased neural synchrony. The observed similarities across MOB, amygdala, and insula may reflect their coordinated role in monitoring external cues and internal stress states.

Overall, these neural dynamics offer further insight into how homebase behavior may reflect an animal’s underlying state of engagement and stress regulation within different social contexts.

Discussion

This project explored the behavioral and neural correlates of homebase dynamics in rats across varying social conditions: open-field, rat-rat, and rat-robot. The integration of positional tracking and local field potential (LFP) recordings provided complementary insights into how spatial regulation, social context, and internal neural states interact.

Behavioral analyses revealed that homebase location, movement speed, and the frequency of excursions and incursions varied significantly depending on the presence and type of social agent. The closer spatial clustering and increased movement dynamics observed in the rat-rat condition may reflect social buffering effects, wherein the presence of a familiar conspecific reduces stress and promotes exploration (Kikusui et al., 2006). In contrast, the increased spatial separation and preference for perimeter locations in rat-robot trials suggest that the robotic agent may be perceived as unfamiliar or ambiguous, eliciting more conservative, stress-related behavioral patterns.

Neural recordings further support these interpretations. Non-homebase stops—those occurring away from the animal's preferred safe zone—were associated with elevated theta-band peak frequencies and, in some cases, increased theta power. These findings were consistent across the main olfactory bulb (MOB), amygdala, and insula, suggesting a shared pattern of heightened neural engagement during less secure states. This is in line with previous work linking theta oscillations in the MOB to respiratory rhythm and environmental vigilance, while the amygdala and insula are implicated in emotional and interoceptive processing under stress.

Importantly, the differences in theta dynamics were observed during immobility—a behavioral window often associated with internal regulation, decision-making, and monitoring of the environment. The elevated theta signatures during non-homebase stops may therefore reflect a state of increased alertness or arousal, likely modulated by both spatial unfamiliarity and social uncertainty.

Future work could expand on these findings in several directions. First, incorporating spectrograms—a visual representation of how signal frequency content evolves over time—could provide more detailed temporal profiles of LFP dynamics around behavioral events. Preliminary analyses suggest that non-homebase stops may coincide with more complex or dynamic frequency shifts, particularly in the rat-robot condition. Second, adding manual behavioral labels such as grooming, rearing, or investigatory sniffing could help identify specific behaviors that co-occur with neural signatures of regulation or arousal.

Finally, developing classifiers to distinguish LFP patterns between homebase and non-homebase stops could test the predictive power of neural features for inferring behavioral context. Including signals from the hippocampus CA2 region may further illuminate how memory-related processes contribute to spatial and social evaluation during exploration.

Taken together, these results support the idea that homebase behavior serves as a window into how animals regulate engagement, stress, and arousal. The use of robotic agents like PiRat introduces novel opportunities to systematically modulate social cues while preserving experimental control, offering a promising path toward understanding the neural basis of flexible, adaptive behavior in complex environments.

Conclusion

This study investigated how social context shapes behavioral regulation and neural dynamics in freely moving rats, focusing on homebase behavior and associated local field potentials. By comparing behavior and brain activity across solo, conspecific, and robot interaction conditions, the findings highlight the nuanced ways in which internal states and external cues co-regulate exploration and retreat.

The combination of spatial tracking and neural recordings revealed consistent distinctions between homebase and non-homebase stops, both behaviorally and neurally. Notably, differences in theta-band activity across the MOB, amygdala, and insula suggest that physiological arousal and sensory vigilance increase during moments of immobility away from the homebase. These effects were particularly pronounced in the rat-robot condition, pointing to the role of artificial agents in modulating perception and behavior, even when they are not conspecifics.

More broadly, this work demonstrates the value of integrating behavioral analysis with neural measures to understand the regulation of stress and engagement in complex, socially modulated environments. It also lays the groundwork for future use of interactive robots in neuroscience, providing a flexible tool for probing social cognition and adaptive behavior.

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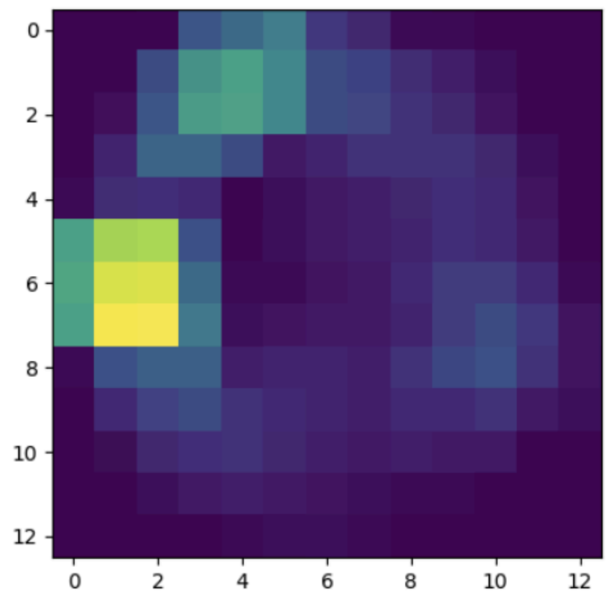
Appendix


0
2
4
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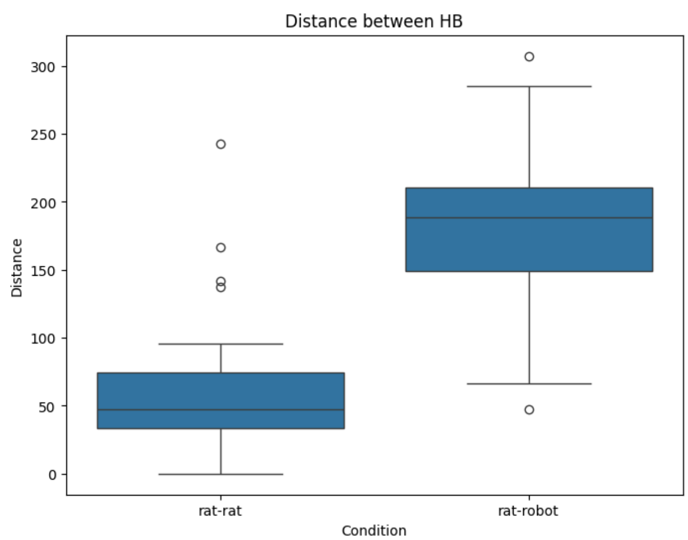
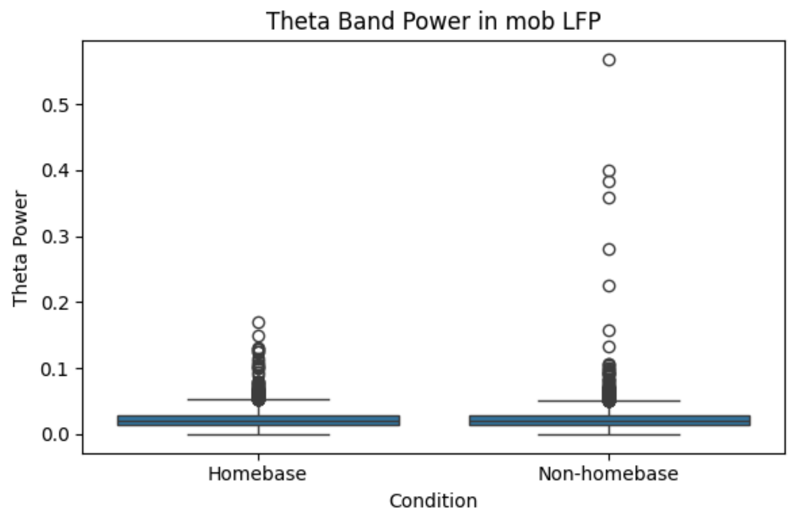
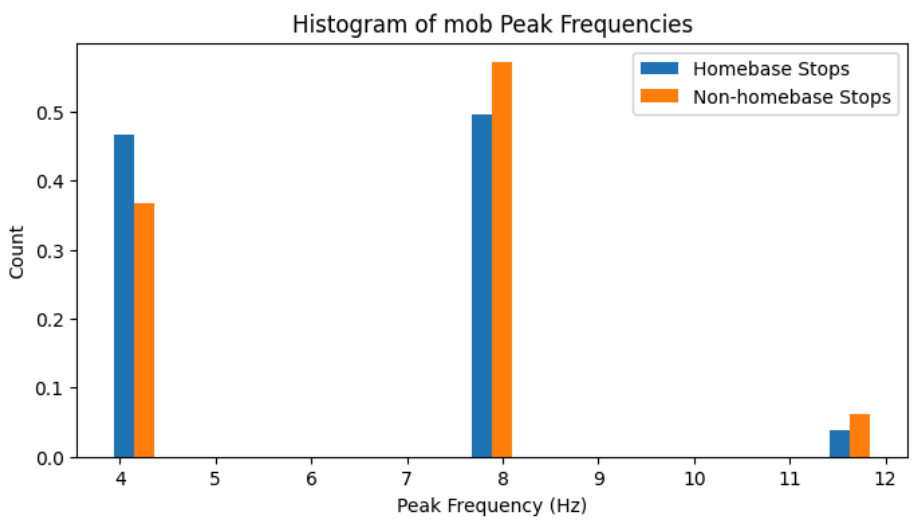
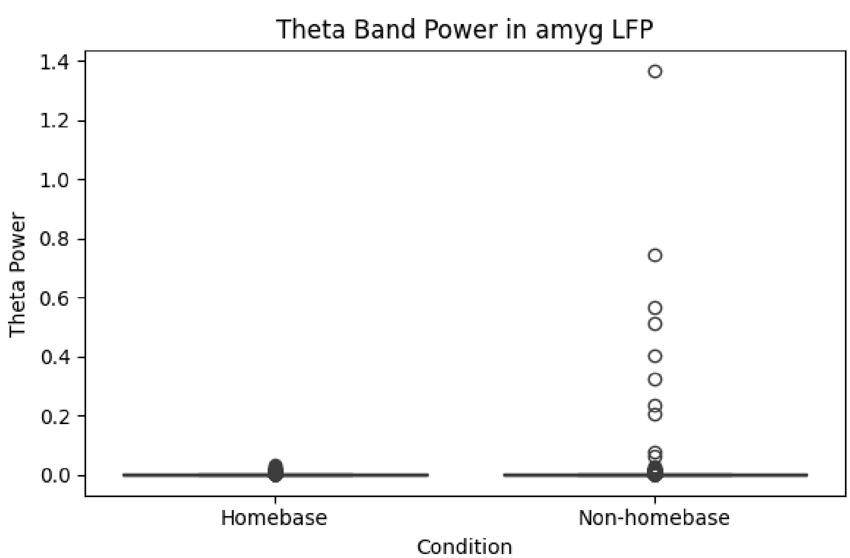
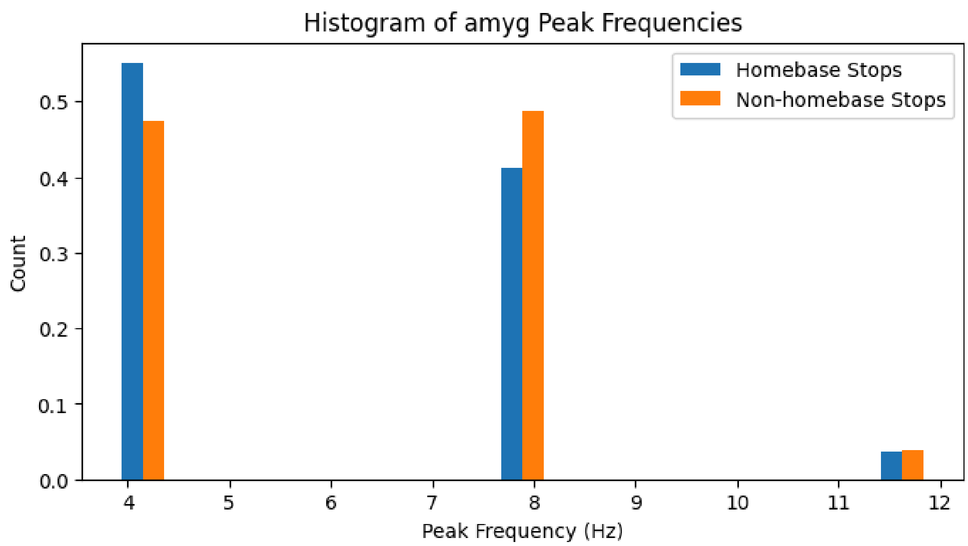
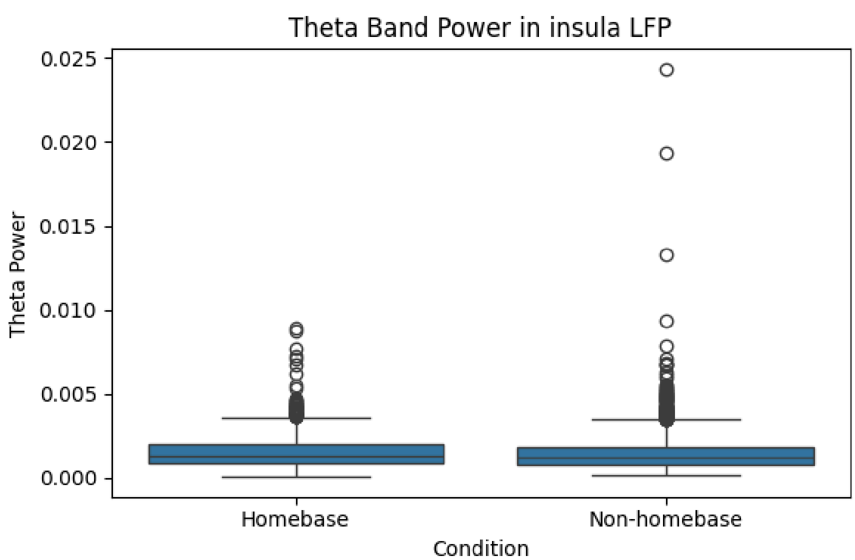

Distance between HB
300
250
200
150
100
50
0
Distance
rat-rat
rat-robot
Condition

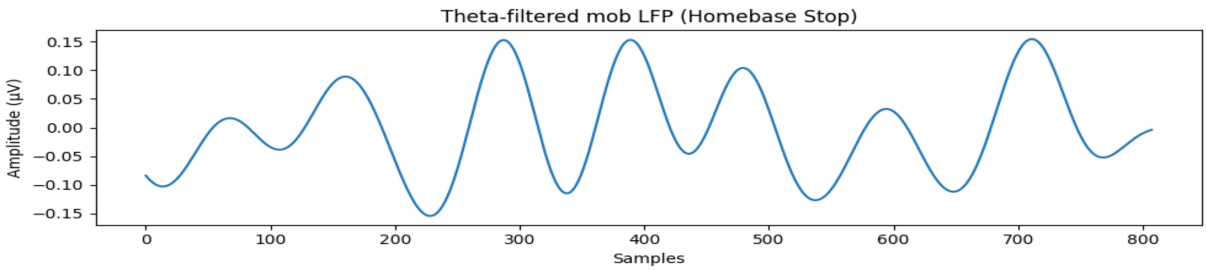

Theta Band Power in mob LFP
Theta Power
0.0
0.1
0.2
0.3
0.4
0.5
Homebase
Non-homebase
Condition

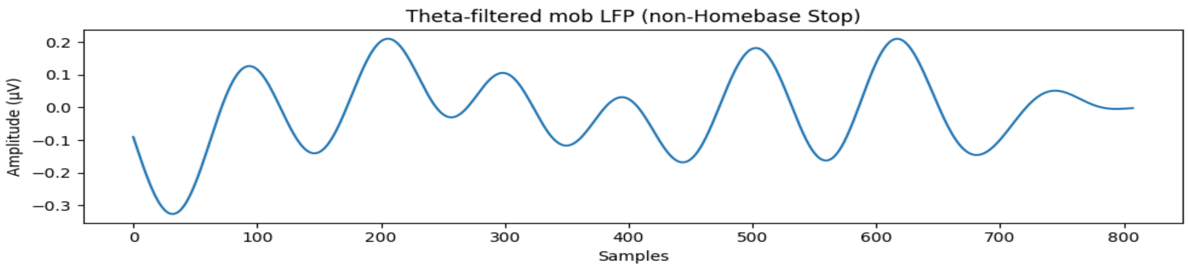

Histogram of mob Peak Frequencies
Homebase Stops
Non-homebase Stops
Count
0.0
0.1
0.2
0.3
0.4
0.5
4
5
6
7
8
9
10
11
12
Peak Frequency (Hz)


Theta Band Power in amyg LFP
Theta Power
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Homebase
Non-homebase
Condition


Histogram of amyg Peak Frequencies
Homebase Stops
Non-homebase Stops
Count
Peak Frequency (Hz)


Theta Band Power in insula LFP
Theta Power
Homebase
Non-homebase
Condition


Theta-filtered mob LFP (Homebase Stop)
Amplitude (µV)
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
0
100
200
300
400
500
600
700
800
Samples


Theta-filtered mob LFP (non-Homebase Stop)
Amplitude (µV)
0.2
0.1
0.0
−0.1
−0.2
−0.3
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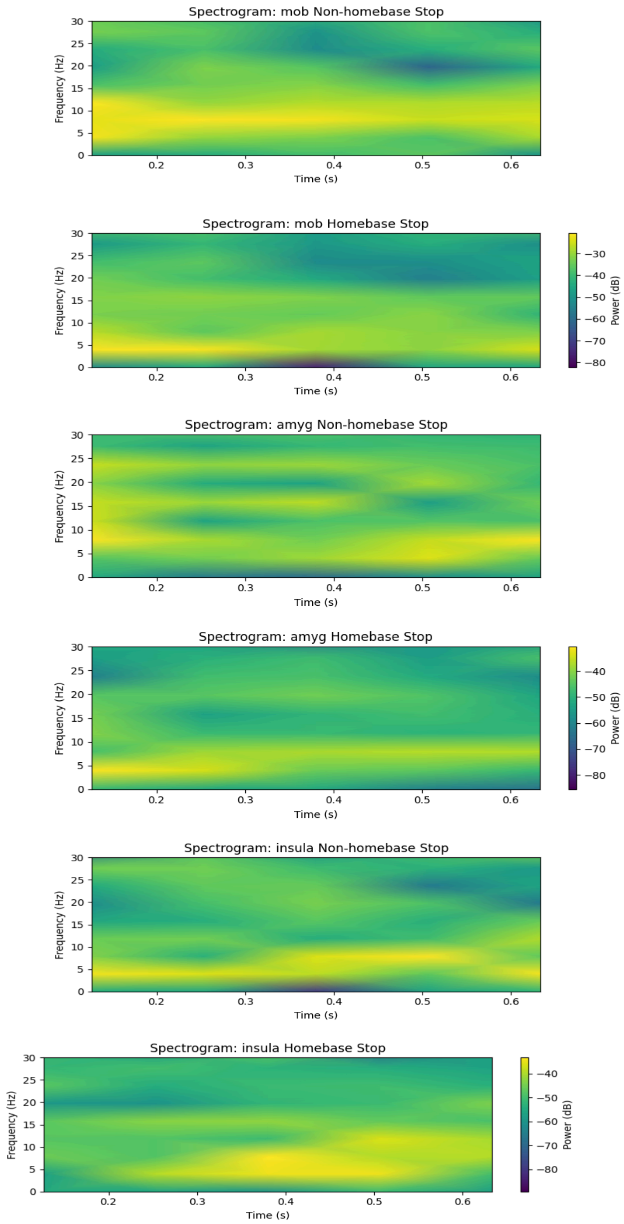
500
600
700
800
Samples


Spectrogram: mob Non-homebase Stop
Spectrogram: mob Homebase Stop
Spectrogram: amyg Non-homebase Stop
Spectrogram: amyg Homebase Stop
Spectrogram: insula Non-homebase Stop
Spectrogram: insula Homebase Stop
Frequency (Hz)
Time (s)
Power (dB)