Bridging cognitive, statistical, and neural descriptions of multi-agent bird foraging behavior

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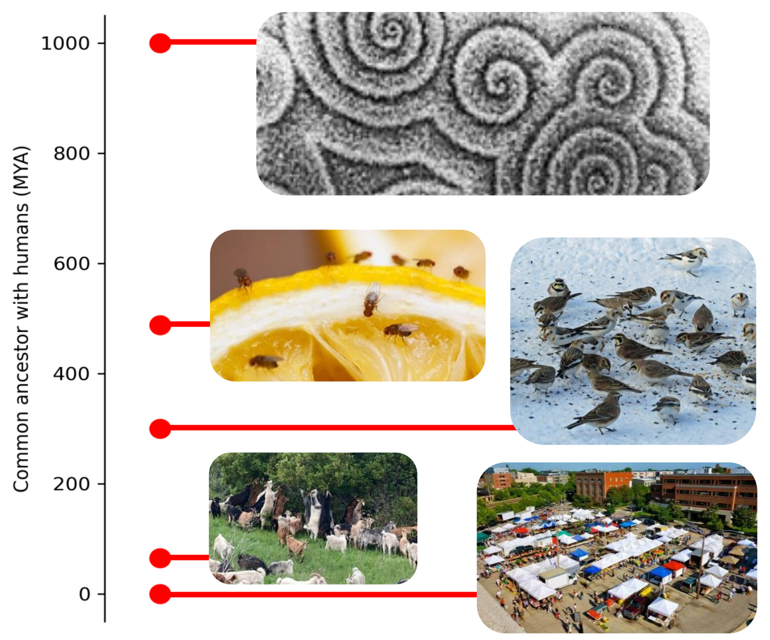
Abstract

Foraging in birds is a multi-agent social behavior that has been studied from several perspectives, including cognitive, statistical, and neural. We start from a specific type of cognitive description -- agents with an internal estimate of value that is expressed as a value function -- and translate this into a biologically plausible neural network implementation and into a statistical model where the statistical predictors correspond to components of the value function. We use the neural network implementation to simulate foraging agents in a variety of environmental conditions. In the multi-agent context, we investigate how the communication of information between different agents affects group foraging behavior. We find that communication was more beneficial in certain types of environments than others. To test the viability of the statistical approach, we simulate three different types of bird agents, and use Bayesian inference to recover what each type of agent values. Finally, we outline the main directions of future work, including new high-resolution video datasets we are collecting of multi-agent multi-species foraging behavior in the field.

Multi-agent foraging across species and communication within groups



Foraging has been studied from cognitive, neural, and statistical perspectives.

Cognitive	Statistical	Neural
Goal: Describe the computations underlying behavior in terms of goals, beliefs, and vales	**Goal:** Fit empirical behavioral data	**Goal:** Uncover brain mechanisms behind behavior
Reinforcement learning (Dayan, Niv, Gershman, Stachenfeld, Momennejad, Deepmind, …) **Optimal foraging theory** (Krebs, Charnov, El Hady, Hill, …)	**Minimal models** (Levy Flights, Boids, and random walks, Bialek, Schneidman, …) **Tracking video data** (Sun, Kennedy, Pereira, Mathis, Perona….)	**Drosophila** (Jayaraman, Ruta, …), **Nematodes** (Bargmann, Calhoun,…), **Hippocampus** (Stachenfeld, Ulanovsky, Barack, Aronov, …)

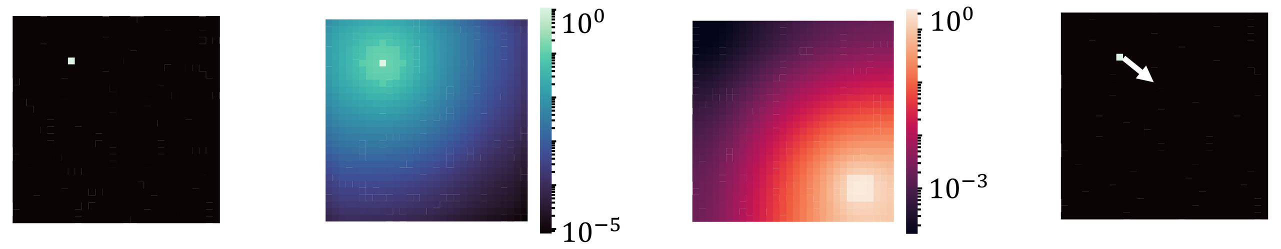
Cognitive, neural, and statistical descriptions

Cognitive

State	State (perceived)	Predictive SR representation	Value	Action

$$S \xrightarrow{N_1()} \vec{\phi}_s \xrightarrow{N_2()} M\vec{\phi}_s \xrightarrow{N_3()} \vec{w}^T M\vec{\phi}_s \xrightarrow{N_4()} A^{cog}$$

as a function of S

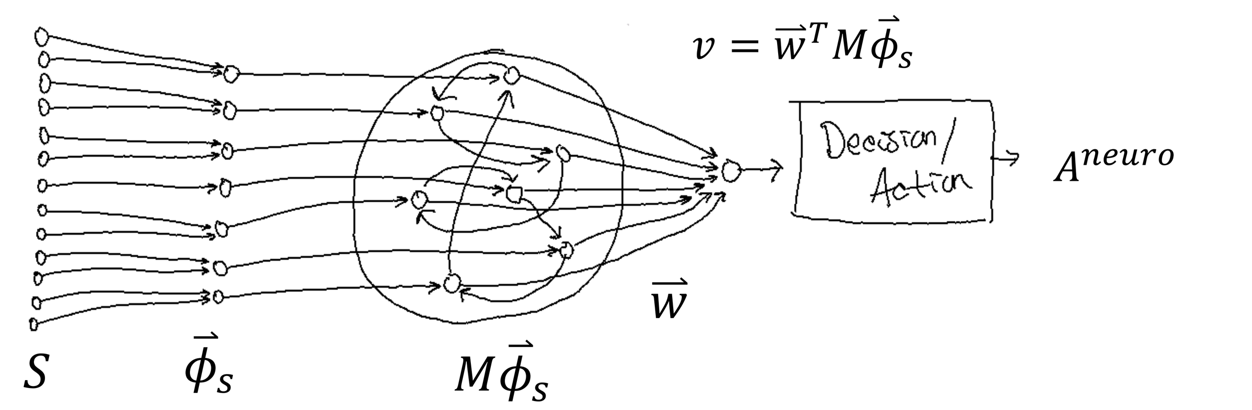


$$M = \Sigma_{t=0}^{\infty} (\gamma J)^t$$

J State transition matrix
γ Temporal discount factor
$\vec{w}$ reward prediction vector

Neural

N_1: Perception N_2: Hippocampus-like N_3: Value N_4: Motor output



Statistical

Under certain conditions, the most likely action is given by

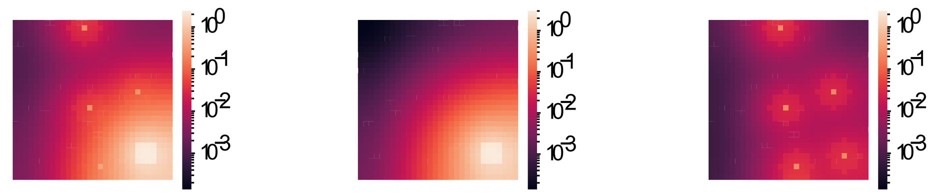
$$A_s = argmax_A\, P(A|S) = A^{cog} = A^{neuro}$$

Translation between descriptions

Decomposition of value function across different sources of reward:

$$V = c_1\vec{w}_1^T M\vec{\phi}_s + c_2\vec{w}_2^T M\vec{\phi}_s + \cdots + c_n\vec{w}_n^T M\vec{\phi}_s$$

"How much the bird values food" "How much the bird values proximity to other birds"



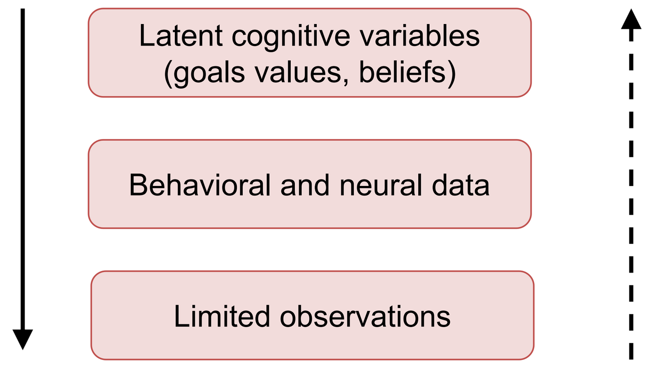
Components as statistical predictors:

$$P(A|S) = h(a_1 f_1(s) + a_2 f_2(s) + \cdots + a_n f_n(s))$$

"To what extent locations of food rewards predict the bird's behavior" "To what extent locations of other birds predict the bird's behavior"

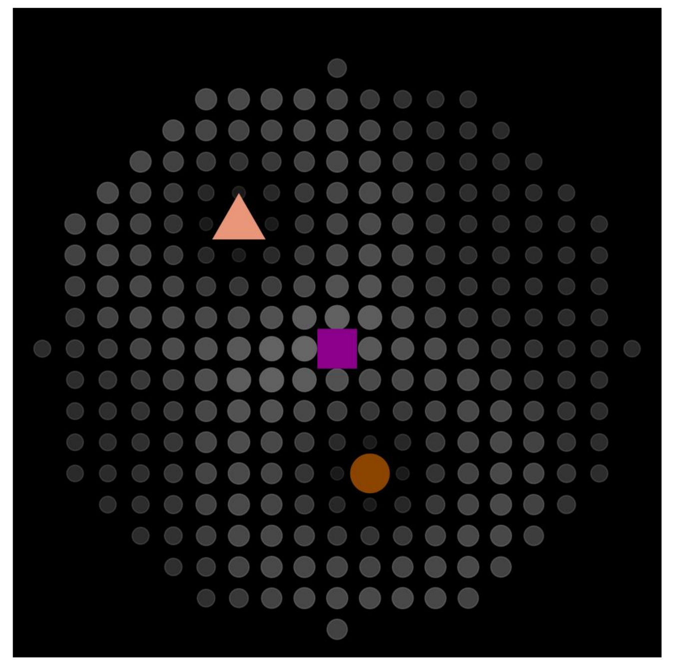
Statistical inference of foraging strategies

Goal: Infer what the agents value from observations of movements and reward locations.



Strategy:

- Simulate bird agents with different foraging strategies: follower, hungry, and random-walking birds.
- Fit a Bayesian model to infer the foraging strategy by identifying to what extent different factors predict each bird's future location.



Each bird b at time t has a visibility range specifying which locations p_i the bird can see:

$$\{p_i = \langle x_i, y_i \rangle |\ p_i \in \text{Range}(b,t)\}$$

Each point in space-time p_i is assigned two scores:

$proximity(p_i)$: a "social proximity" score representing how preferrable that point is as a function of distance to each bird.

$trace(p_i)$: based on distance to food rewards (exponential function)

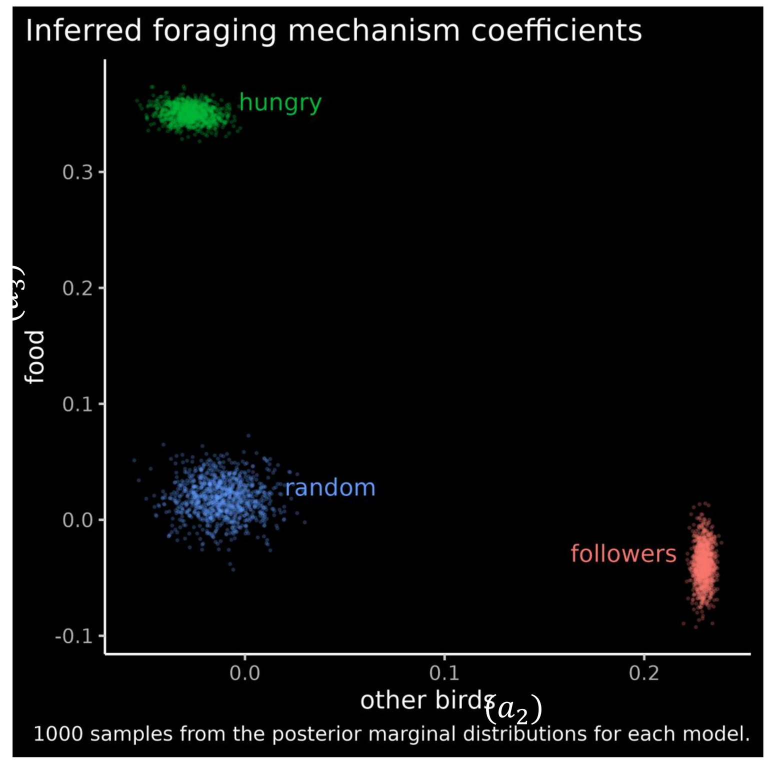
Prediction task: $accuracy(p_i)$: Euclidean distance between point p_i and bird's chosen location $p\langle b, t+1 \rangle$.

Use coefficients (a_1, a_2, a_3) to predict accuracy based on proximity and trace scores.

Bayesian model with prior distributions:

$$\begin{aligned} \text{accuracy} &\sim \text{Norm}(\mu, \sigma) \\ \mu &= a_1 + a_2\text{proximity} + a_3\text{trace} \\ (a_1, a_2, a_3) &\sim \text{Norm}(0, .4) \\ \sigma &\sim \text{Unif}(0, 1) \end{aligned}$$

Inferred coefficient values represent the contribution of that factor in predicting the bird's movements.



Toward inference of communication mechanisms in multi-agent bird flocks

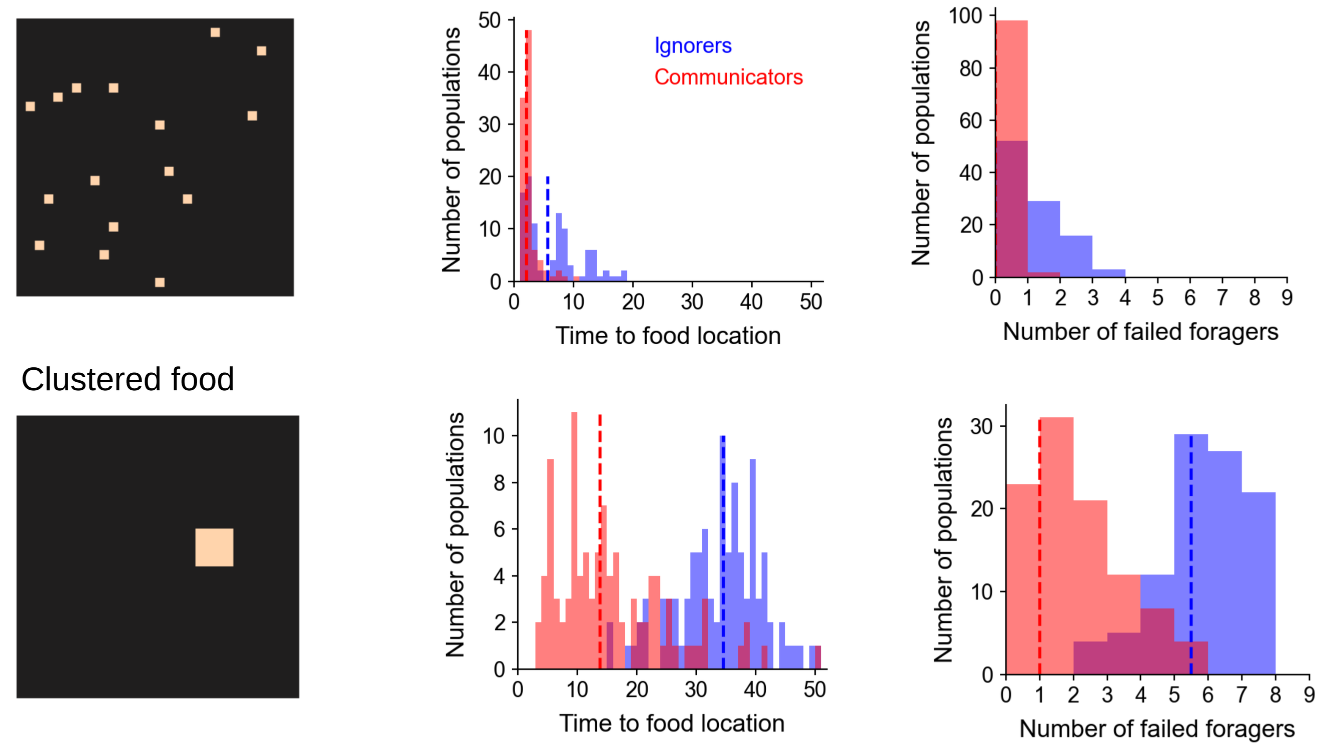
We simulated **two different foraging strategies:**

Communicators share with other birds the locations of food rewards within their visibility range, and use this information to decide where to move.

Ignorers value only food.

Question: When does communication enhance foraging success?

We compared foraging performance in **two different environments:**

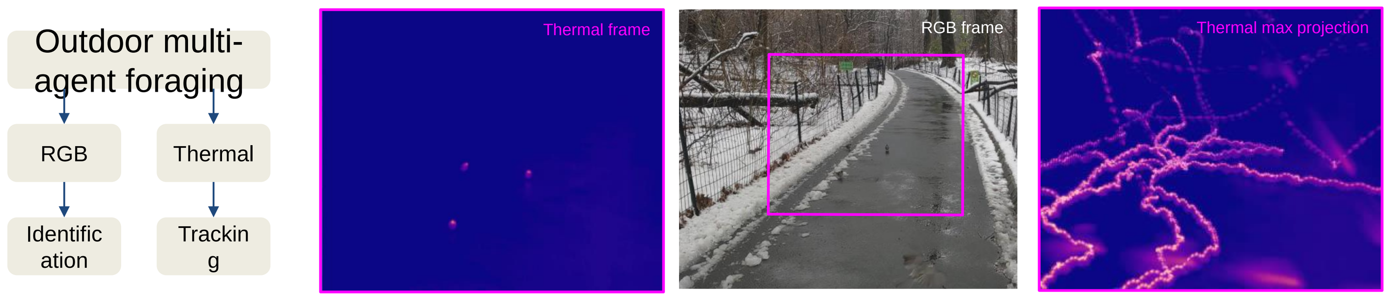


Future directions

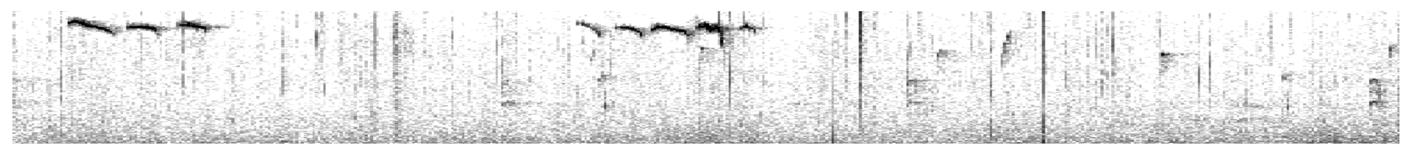
- From behavioral data, can we infer whether a group of birds is communicating?
- To what extent do birds value information about food from other birds versus from their own experience?

New datasets for multi-species bird foraging

High resolution video data



Spectrogram of vocalizations from foraging groups (10s recording)



Summary

- Framework unifying cognitive, neural, and statistical descriptions of foraging behavior
- Inference of foraging strategies from simulated data
- Role of communication in different environments
- New datasets of multi-agent bird foraging