Spatiotemporal Dynamics of Food Exchange Networks in Honeybees

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Introduction

- *Trophallaxis*, the direct transfer of food among nestmates serves not only as a feeding mechanism but also as a medium for information exchange among workers, helping them coordinate their activities within the hive [1].
- Using an integrated experimental-modeling approach, we aim to study the dynamics of food distribution among honeybees.

Question of Interest

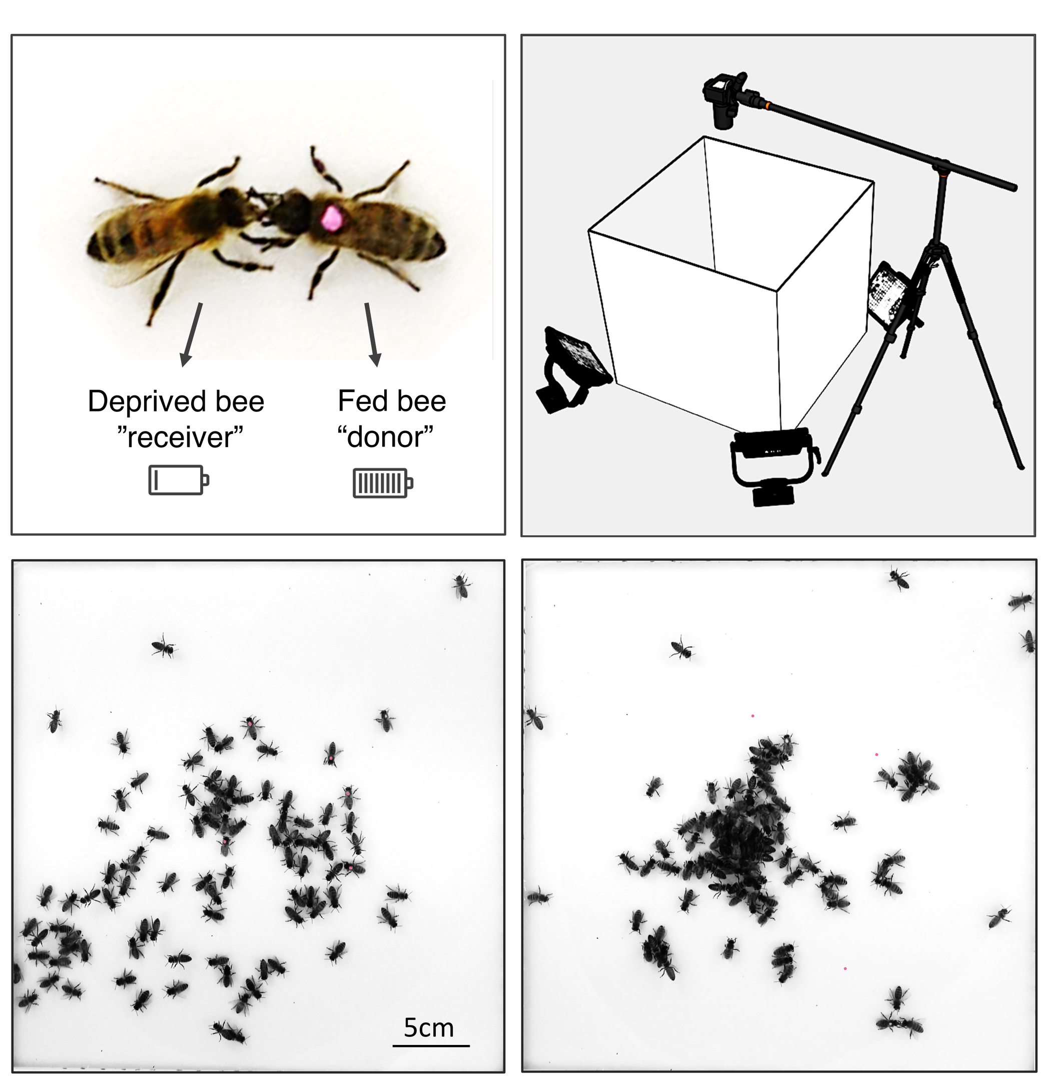
- What is the mechanism behind food exchange interactions?

Approaches

- Build a model that reproduces the food exchange dynamics
- Use topology to characterize phase changes in the collective behavior
- Study the communication mechanism among bees

Behavioral Experiments

- Six different colonies of honeybees *Apis mellifera* L. were divided into two groups.
- One group was *deprived* of food for 24 hours before each experiment, while others had constant access to food.
- These *fed* bees, which comprised $\sim 10\%$ of the whole population in each experiment, were carefully marked with a pink dot on their thorax.



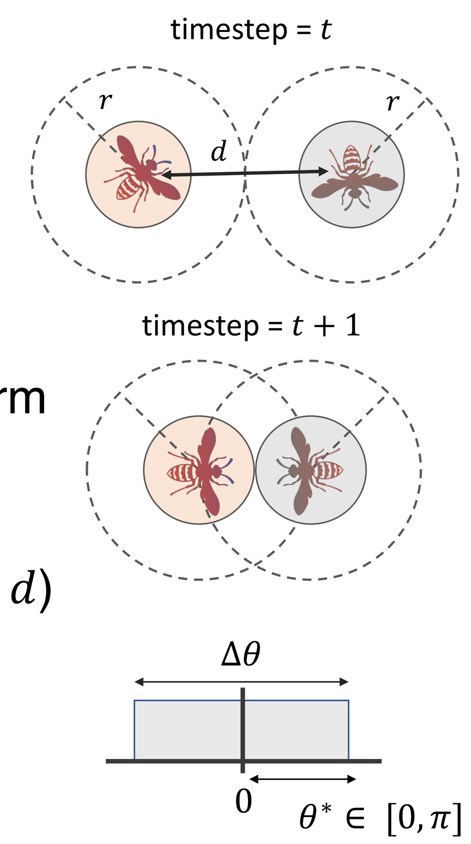
t = 0 t = 2 minutes

Agent-Based Model

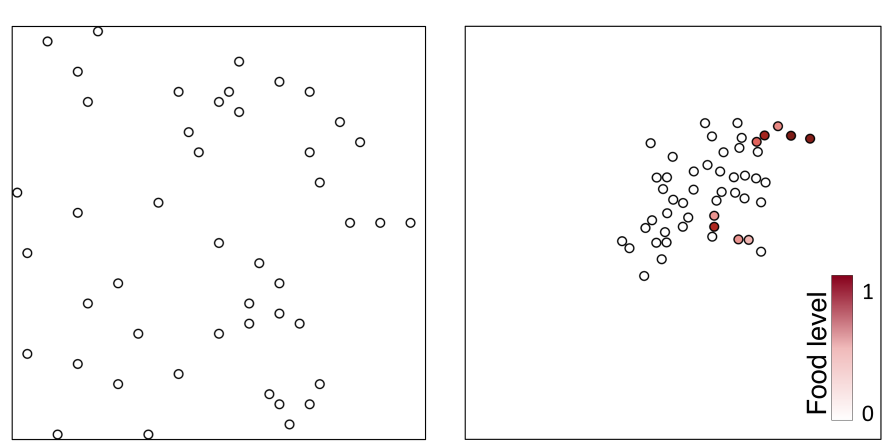
Model rules

1. Check immediate r –neighborhood, If $d \le 2r$, then agents will move one step toward each other at the next timestep (attraction parameter r)
2. Modify heading by $\Delta\theta$ drawn from a uniform distribution and take a random walk step (angle parameter θ^*)
3. Check for encounter (distance parameter d)
4. Exchange food: $f_i(t+1) = f_i(t) \pm \frac{\Delta f(t)}{2}$
5. Loop until the food distribution is uniform (variance threshold)
   - Convergence: $\sigma^2(t) \le \sigma^2_{threshold}$

$$\sigma^2(t+1) - \sigma^2(t) \le \Delta\sigma^2_{threshold}$$



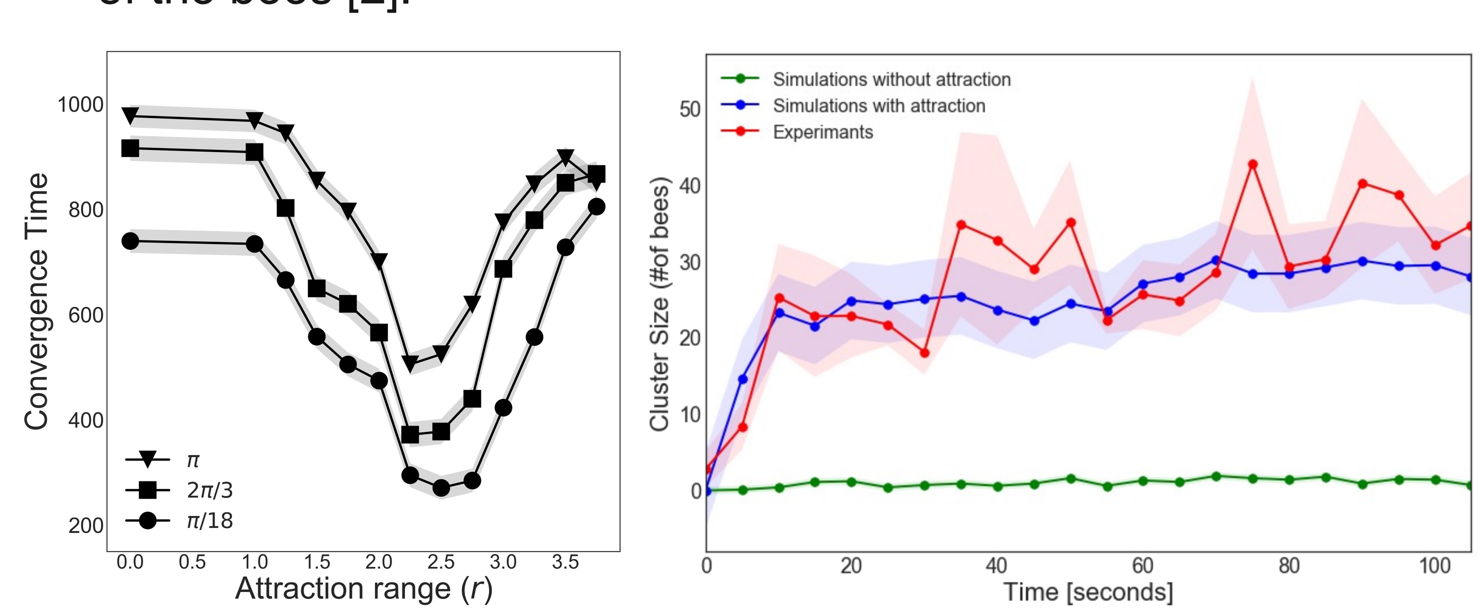
- The values of some model parameters such as trophallaxis duration are drawn from the experiments.



timestep = 0 timestep = 600

Findings

- *Short-range attractions* foster aggregation, which in turn increases the efficiency of food distribution.
- Comparing the cluster sizes across real and simulated bees show that model with attraction is a better match to the natural behavior of the bees [2].

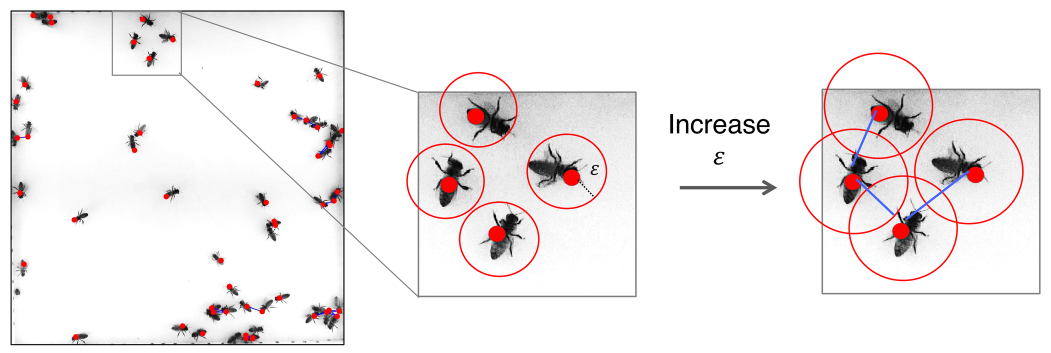


References

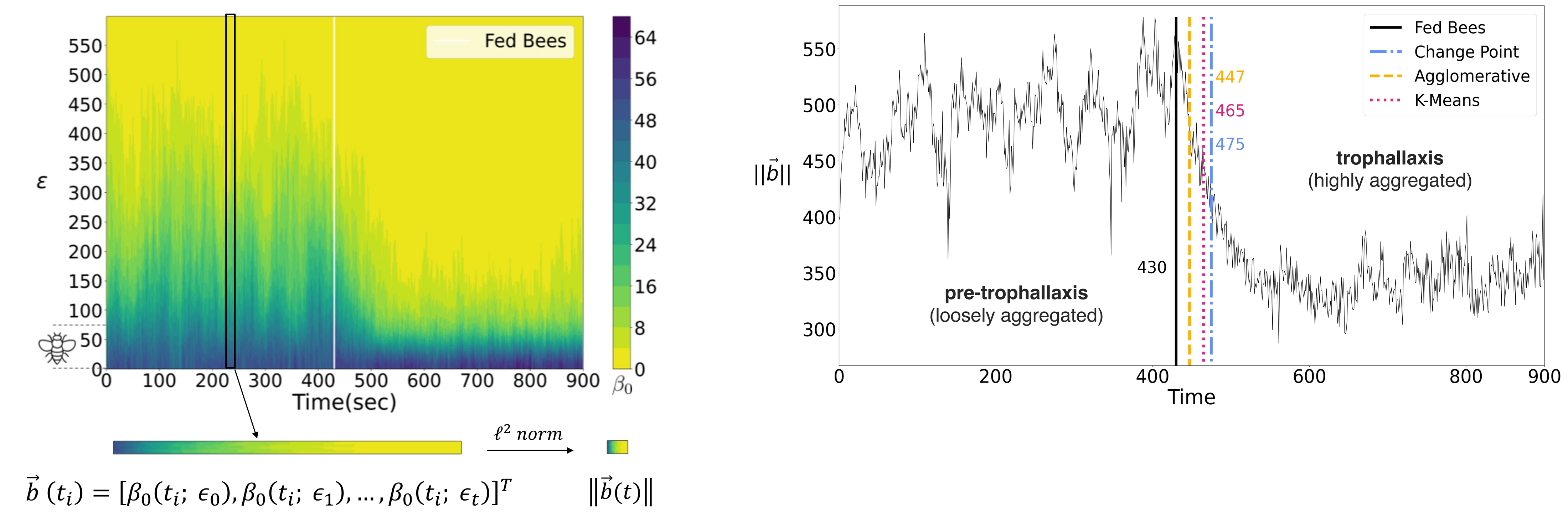
[1] Greenwald *et al. Scientific Reports*, 2015.
[2] Gharooni Fard *et al. MIT Press*, 2020.
[3] Ulmer *et al. PLOS ONE*, 2019.
[4] Gharooni Fard *et al.* To appear in *Npj Complexity*, 2024.
[5] Nguyen *et al. PNAS*, 2020.

Topological Data Analysis

- Our experimental analysis described in [2] suggests that bees aggregate to share food.
- We use TDA, a framework from applied mathematics, to analyze the morphology of the group.



- The goal is to characterize the group's dynamics via the time evolution of topological invariants called Betti (β) numbers, accounting for persistence of topological features across multiple scales. Our focus is on tracking the value of β_0 (*i.e.*, the number of connected components).
- We use the CROCKER plot [3] representation and then perform clustering on the norms of the CROCKER slices to detect any possible regime shift.



Findings

- Feeding the time-series data of the ℓ^2 *norm* of the CROCKER plots to two different clustering algorithms, we successfully detect the change in the group dynamics soon after the fed bees are introduced.
- This method works both on experimental and simulated data [4].

Outlook: Communication for Aggregation

- We train a machine-learning algorithm [5] to identify the positions and directions of *scenting events* — which honeybees use to communicate — in our experiments.
- We then correlate those events with the spatiotemporal density of bees by treating the positions $(S^p_{i,t})$ and directions $(S^d_{i,t})$ vectors as a set of gradients that define a minimal surface of height $f(x,y,t)$.
- We compute the value of normalized mutual information $MI\langle f\rangle_t$ between the attractive surface (f) and the density of the bees (ρ), averaged over 10 minutes after the introduction of the fed bees.

$$MI\big(f(x,y,t);\rho(x,y,t)\big) = \sum_{f_i\in f}\sum_{\rho_i\in\rho} P_{(f,\rho)}(f_i,\rho_i)\log\frac{P_{(f,\rho)}(f_i,\rho_i)}{P_{(f)}(f_i)P_{(\rho)}(\rho_i)}$$

Preliminary Findings

- Our preliminary results confirm that there is positive correlation, $MI\langle f\rangle_t = 0.44$, between scenting events and the location of the food exchange aggregations.