Collective response to external stimuli in social animal swarms: experiments and numerical modeling

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Abstract In this work, we study how social animals (soldier crabs) respond to external stimuli as a function of swarm size, and thus inter-individual interaction strength. Laboratory experiments using a rotating light stimulus show that the ability to self-organize and adapt to changing external conditions strongly depends on swarm size. In small swarms interactions are too weak to induce collective behavior, whereas in dense swarms strong physical interactions slow down the response to external changes. Mid-sized swarms exhibit the most efficient adaptation. To complement the experiments and explore a wider range of swarm sizes, we also introduce a mathematical model. Although the numerical results are still preliminary, the model qualitatively reproduces the main features of soldier crab motion, with a more detailed quantitative validation currently underway.

Keywords Animal swarm, External stimulus, Soldier crab, Collective motion, Social animals

Introduction

Interactions are fundamental to the collective dynamics of social animals and, more generally, of self-propelled particles and active matter. Without interactions, coordination is impossible, and without coordination, self-organized structures cannot emerge from individual motion. The nature and strength of interactions strongly influence collective outcomes. When individuals are distant, interactions are mainly cognitive, such as attraction, repulsion, or alignment mediated by sensory cues. At shorter distances, physical interactions become relevant, with animals attempting to avoid contact or minimize collisions.

In addition to internal interactions, social animals also respond to changes in the external environment. External stimuli such as predators, sudden disturbances, or changes in lighting can trigger collective responses that alter group dynamics. Thus, collective motion results from the interplay between internal interactions, both cognitive and physical, and externally induced stimuli.

Experiments and numerical model

We conducted laboratory experiments using soldier crabs (*Mictyris guinotae* [1]), a species of crabs known for forming large swarms. Crabs were placed in a circular arena where a light source rotated at different angular speeds (Figure 1, left). Swarm sizes of 3, 10, and 30 individuals were tested. Since soldier crabs are attracted to bright areas, the rotating light acted as an external stimulus affecting their collective motion. This condition was used to assess the ability of crabs to adapt to changing external inputs.

Results show that both swarm size and light rotation speed affect the ability of crabs to self-organize (Figure 1, right). When the stimulus rotates too quickly, collective alignment fails and crabs move independently. A more in-depth analysis also showed that in large swarms (30 individuals in this study), collective motion does form, but the light does not play any role in determining the direction, and changes in the rotation direction result in no change in collective motion.

Experimental results are consistent with field observations showing that large swarms respond slowly to external threats, whereas in scattered swarms crabs act individually, exhibiting little or no coordination with nearby individuals. Only in medium-sized swarms are changes quick and noticeable [2].

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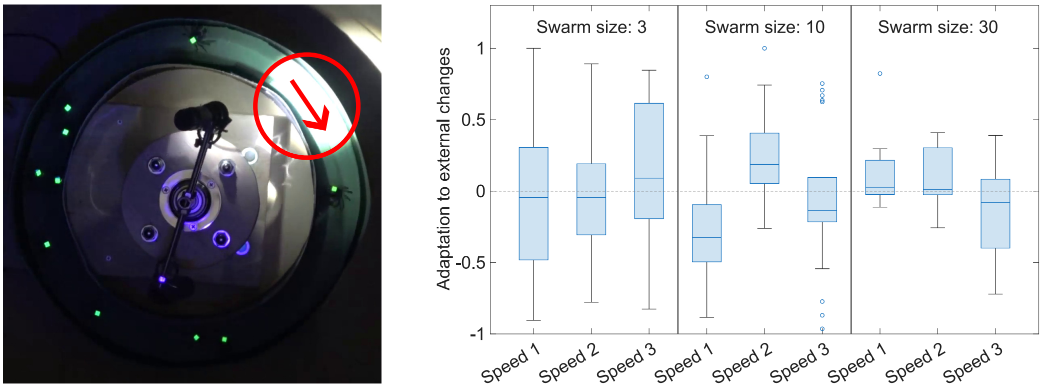

Figure 1: Left: Experimental setup; the red arrow indicates the direction of the rotating light. Crabs are tracked using UV-illuminated green markers. Right: Experimental results showing directional adaptation only for swarm size 10 and sufficiently slow light rotation. -1 and +1 indicate a prompt adaptation to external changes, 0 no adaptation at all.

In the numerical model, each crab is described by its angular position ϑ_i on a circular domain and its angular velocity ω_i ($\dot{\vartheta}_i = \omega_i$). The dynamics are given by

$$\dot{\omega}_i = f(\omega_i) + \frac{\sigma}{n} H_i + \eta, \tag{1}$$

where η is uniform noise, σ is the coupling strength, and f describes intrinsic frequency dynamics, assumed identical for all crabs:

$$f(\omega_i) = a\left(-\omega_i^5 + b\,\omega_i^3 + c\,\omega_i\right). \tag{2}$$

The interaction term

$$H_i = \sum_{j=1}^{n} e^{-\mu(\vartheta_j - \vartheta_i)^2} (\omega_j - \omega_i), \tag{3}$$

models short-range interactions that depend on spatial proximity and velocity differences.

The quintic form of f yields stable fixed points at $\omega = \pm 1$ and $\omega = 0$, corresponding to clockwise motion, counter-clockwise motion, and rest, respectively, with unstable fixed points at $\pm\tilde{\omega}$. This structure allows individuals to switch direction (after slowing down) or stop. Local interactions are strongest when nearby crabs have different velocities, allowing fast-moving crabs to influence stationary ones.

Conclusions

This study shows that the ability of social animals to adapt to external conditions depends on swarm size and, ultimately, on the strength of inter-individual interactions. More specifically, strong interactions are needed for self-organization, but they can limit adaptability and thus make a system at risk when external changes represent a threat to their safety.

The conclusions of this study, together with the numerical model under development, may help to better understand the dynamics of social animals and also contribute to the optimization of distributed systems in which negotiation among individual elements to achieve a common goal is a necessary condition.

References

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