Adaptive Dynamics in Biological Microswimmers

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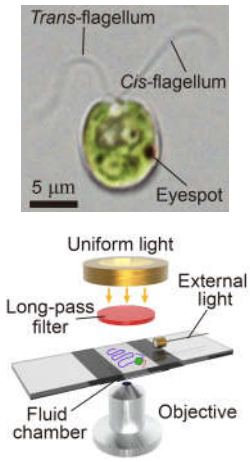
Introduction

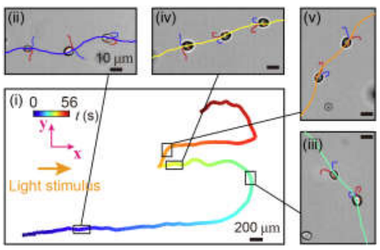
Biological microswimmers play essential roles in nutrient cycling and energy flow in ecosystems. To survive in diverse environments, they exhibit adaptive dynamics—altering behaviors in response to cues such as light, chemicals, and fluid flows. The green alga *Chlamydomonas reinhardtii* shows how rapid, flexible single-cell responses can produce complex spatial and temporal patterns. **However, the link between individual adaptive behaviors and global pattern formation remains unclear.** Understanding these dynamics offers insights into fundamental biological processes and the principles governing active matter.

Chlamydomonas reinhardtii

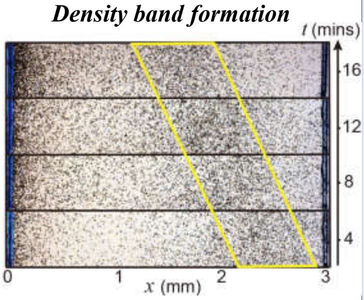


Objectives

Oscillatory phototaxis



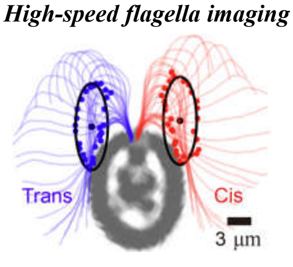
Density band formation



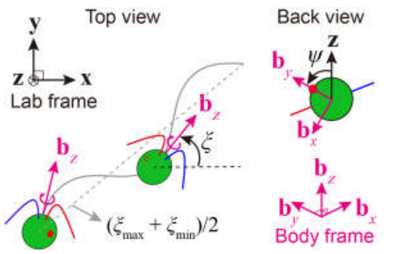
We find that *Chlamydomonas* exhibits oscillatory phototaxis—alternating swimming directions—at intermediate light intensities, unlike previously reported unidirectional responses. **This leads to a slowly propagating density band** toward the light source. These findings prompt us to explore how adaptive switching in individual behaviors drives long-term pattern formation in microswimmer populations.

Methodology

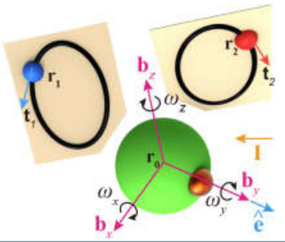
High-speed flagella imaging



Long-term cell tracking



Hydrodynamic modeling



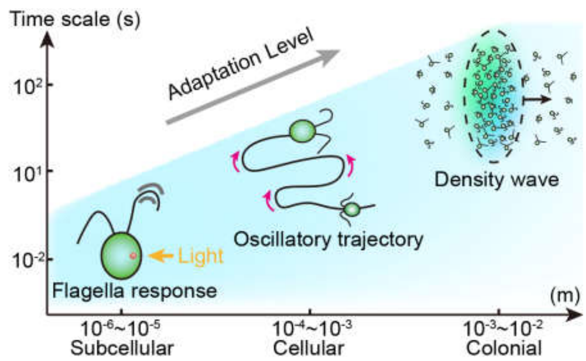
Cellular dynamics across scales were investigated through a combination of:

- **High-speed flagella imaging**
- **Long-term cell tracking**
- **Hydrodynamic modeling**

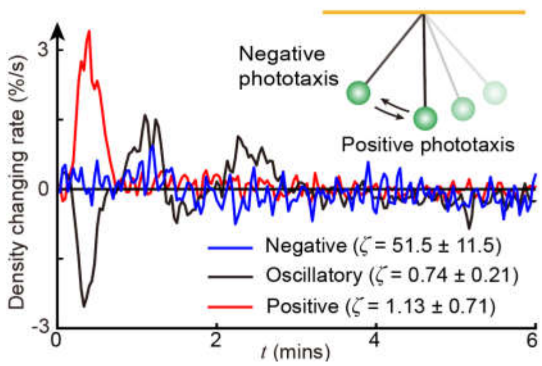
Research accomplishments

We propose an adaptive phototaxis mechanism that links fast subcellular responses to individual behavior and global pattern formation across multiple timescales.

- *Chlamydomonas* dynamically switches flagellar beat patterns and phase angles to achieve both positive and negative phototaxis.
- Oscillatory phototaxis arises from continuous switching between positive and negative phototaxis, governed by changes in the phase angle.



- The selection among positive, negative, and oscillatory phototaxis is modulated by adaptation-induced damping, shaping long-term population patterns such as density bands.



Conclusions

We uncover an adaptive phototaxis mechanism that quantitatively explains how *Chlamydomonas* transitions between phototactic behaviors, linking single-cell oscillatory responses to colony-scale density band formation. **Our work establishes a general framework for understanding adaptive sensor–actuator responses and pattern formation in microswimmers**, with broad implications for studying cellular behaviors and designing adaptive materials in both biological and synthetic systems.

References:

1. Z. Wang, and A. C. H. Tsang. **PNAS**, **2025**, 122, e2425369122.
2. A. C. H. Tsang, and I. H. Riedel-Kruse. **PNAS**, **2024**, 121, e2408082121.
3. A. C. H. Tsang *et al.*, **Nat. Phys.**, **2018**, 14, 1216-1222.