Is randomness an effective strategy (for exploration)?

Readings for today

- Huo, H., He, R., Zhang, R., & Yuan, J. (2021). Swimming Escherichia coli Cells Explore the Environment by Lévy Walk. Applied and Environmental Microbiology, 87(6), e02429-20.

- Hein, A. M., & McKinley, S. A. (2012). Sensing and decision-making in random search. Proceedings of the National Academy of Sciences, 109(30), 12070-12074.

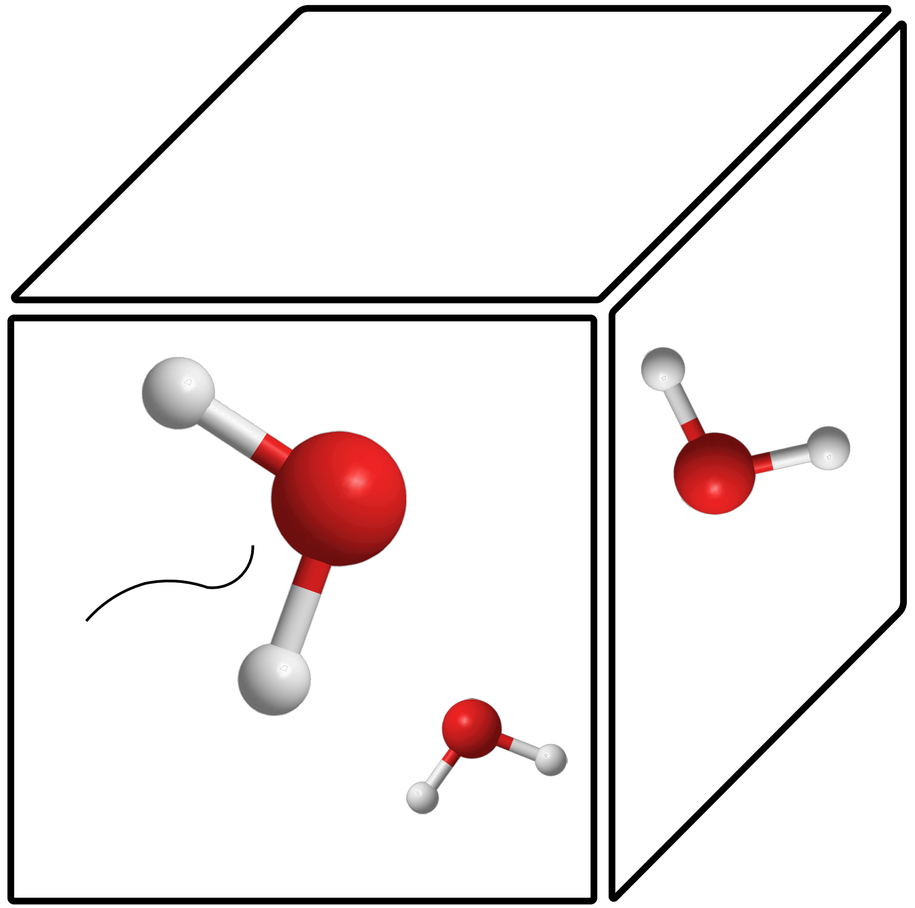
Topics

- Simple forms of exploration
- The value of simple sensing

Simple forms of exploration

What is the optimal way to explore?

An optimal exploration policy is one that samples every option at least once.



Brownian motion

In 1D space

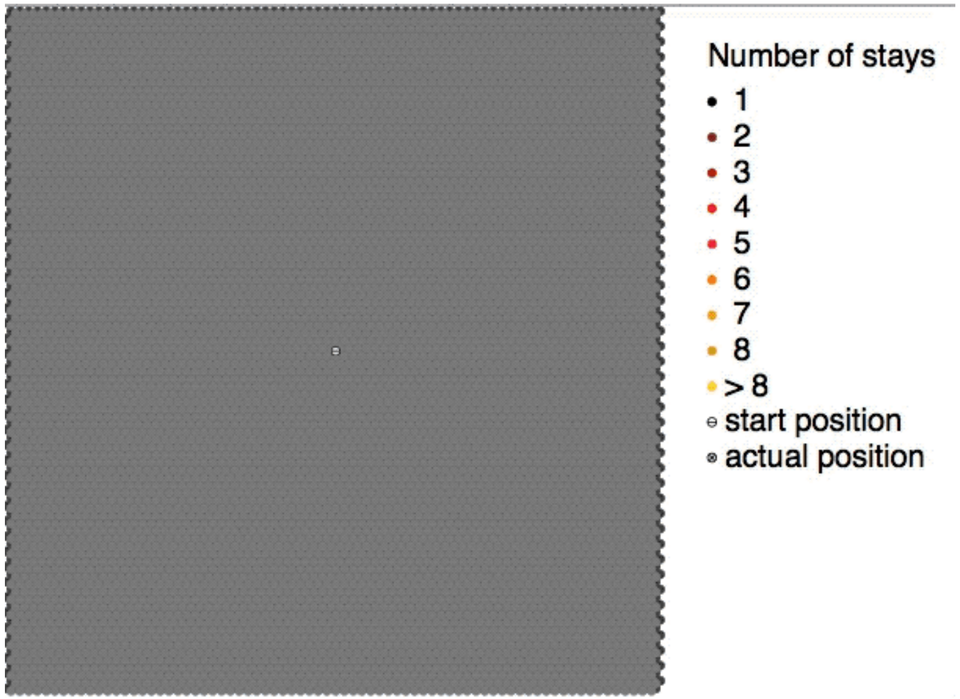
$$x_i = x_{i-1} + u_i, \quad u_i \sim N(\mu, \sigma)$$

In 2D space

$$\theta_i = v_i 2\pi, \quad v_i \sim U(-\pi, \pi)$$

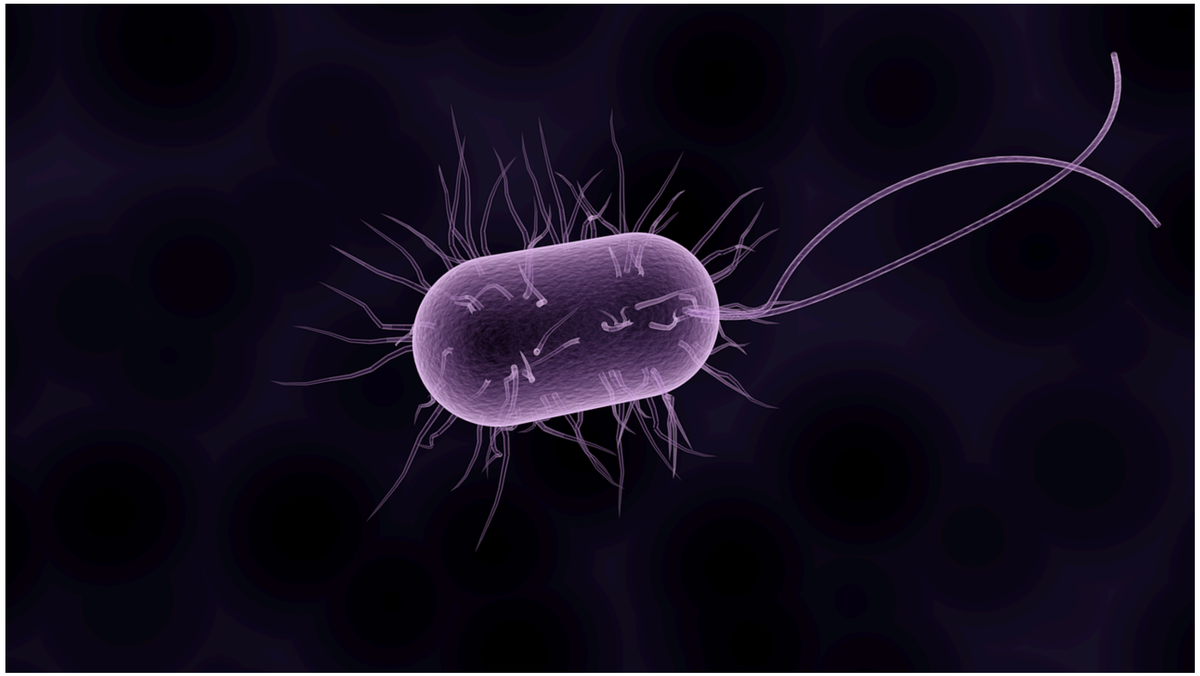
$$x_i = x_{i-1} + u_i \cos(\theta_i)$$

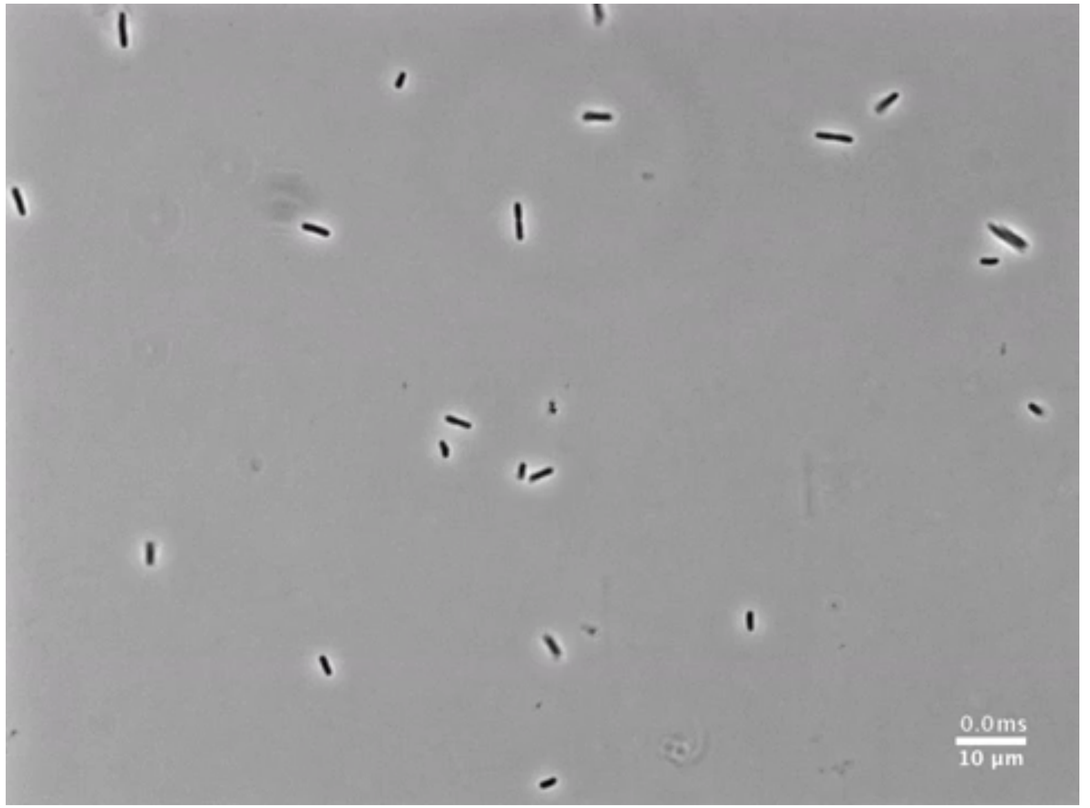
$$y_i = y_{i-1} + u_i \sin(\theta_i)$$



2D random walk of a silver adaptor on a Ag(111) surface (source: Wikipedia; Marburg et al. 2017)

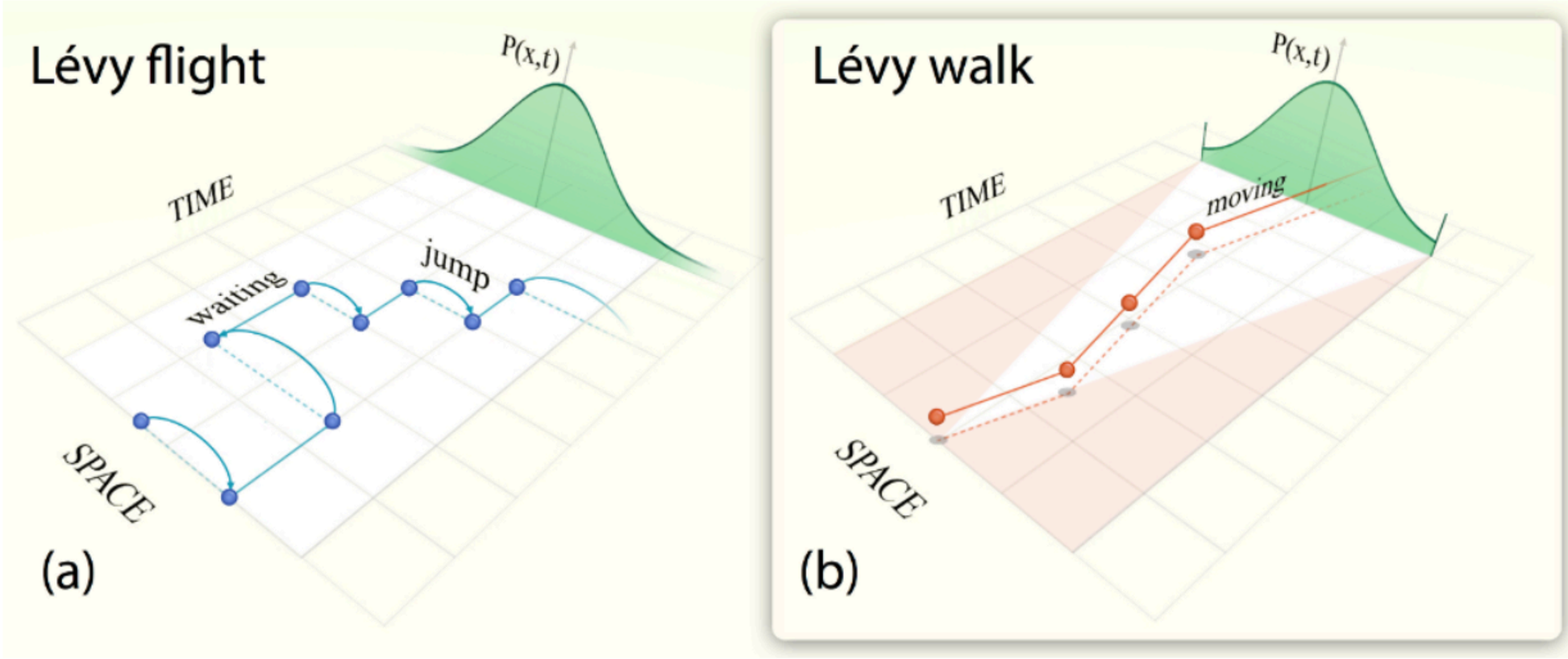
Organism: E. Coli





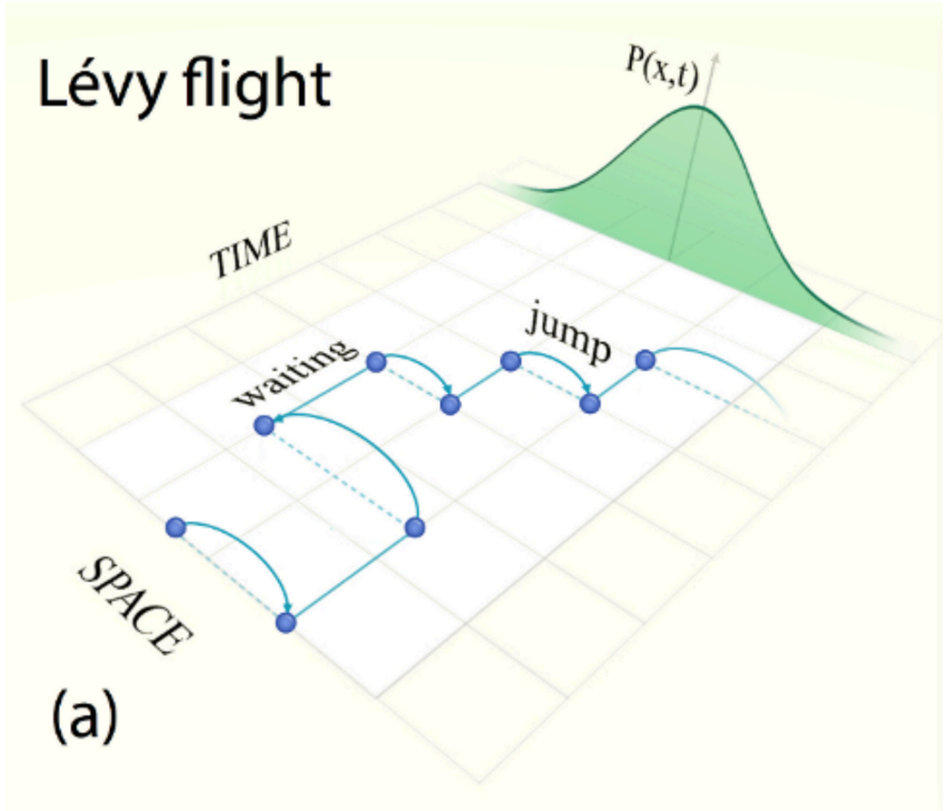
https://www.youtube.com/watch?v=CldjFTSr4fY

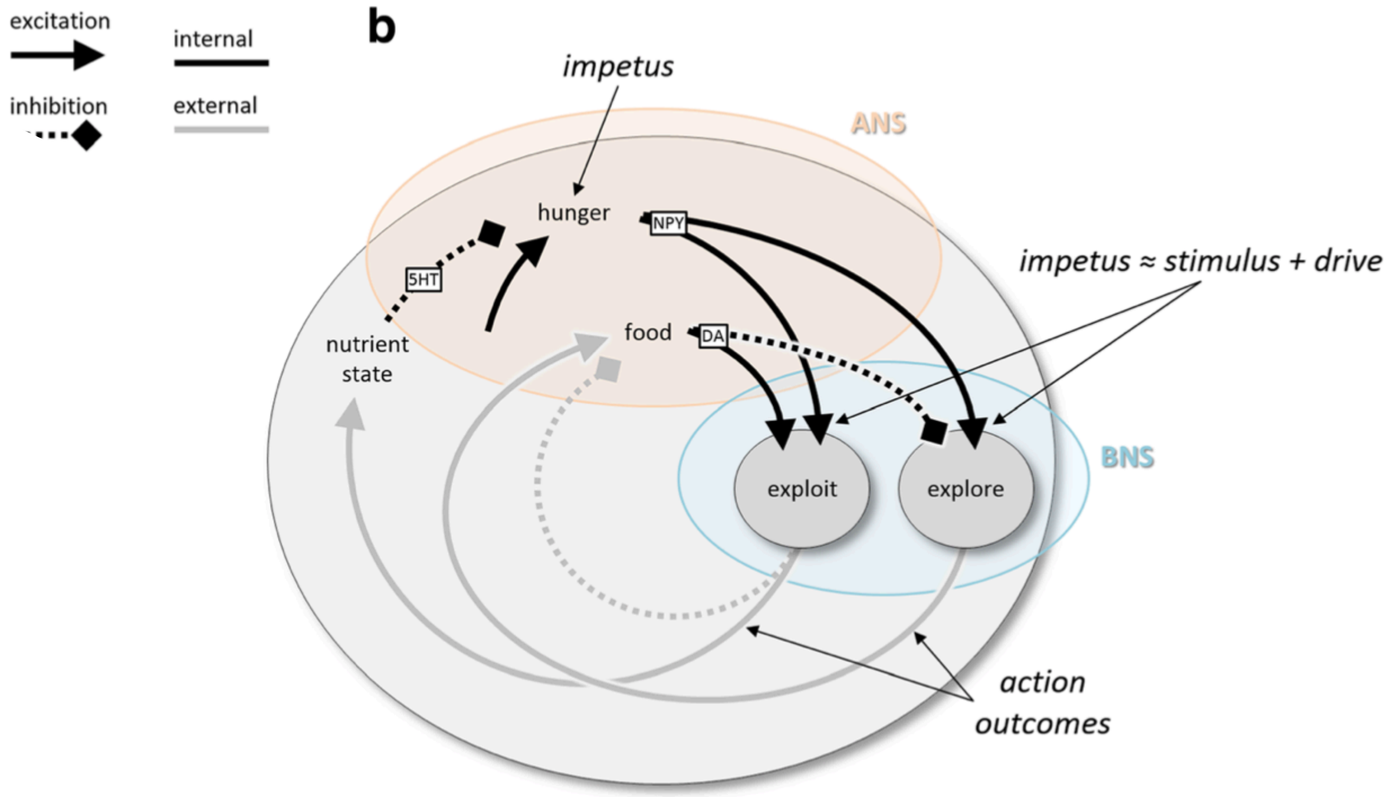
Lévy flights and Lévy walks



(Zaburdaev et al. 2015)

Lévy flights as explore-exploit processes





(Cisek 2019)

Lévy walk vs. Brownian motion

Random walk in 2D space

$$\theta_i = v_i 2\pi, \quad v_i \sim U(-\pi, \pi)$$

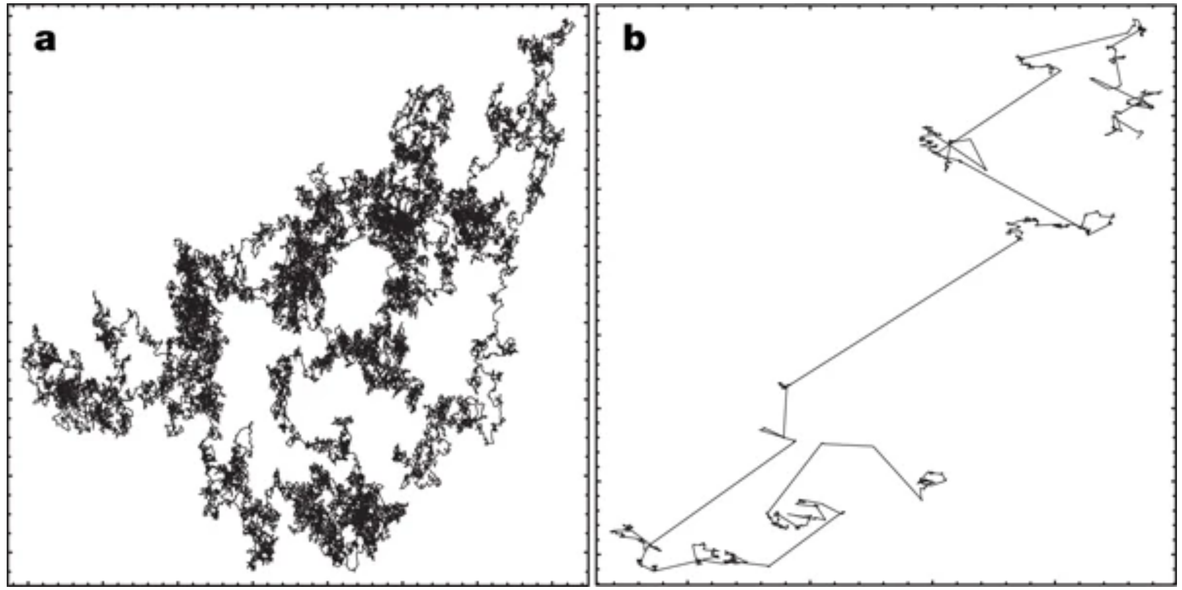
$$\delta_i = u_i^{-\frac{1}{\gamma}}, \quad u_i \sim N(\mu, \sigma)$$

$$x_i = x_{i-1} + \delta_i \cos(\theta_i)$$

$$y_i = y_{i-1} + \delta_i \sin(\theta_i)$$

Brownian motion ($\gamma = 1$)

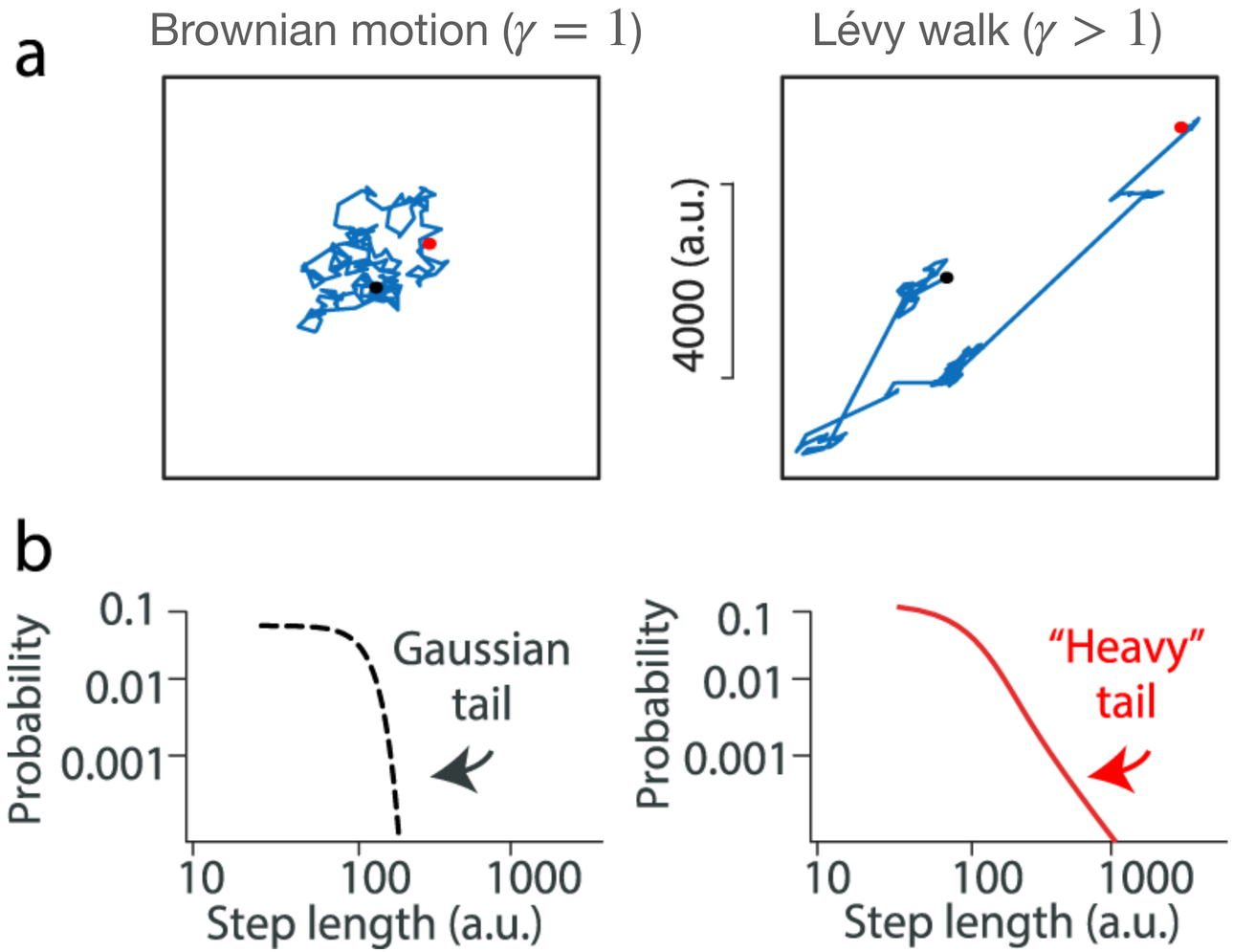
Lévy walk ($\gamma > 1$)



(Barthelemy et al. 2008)

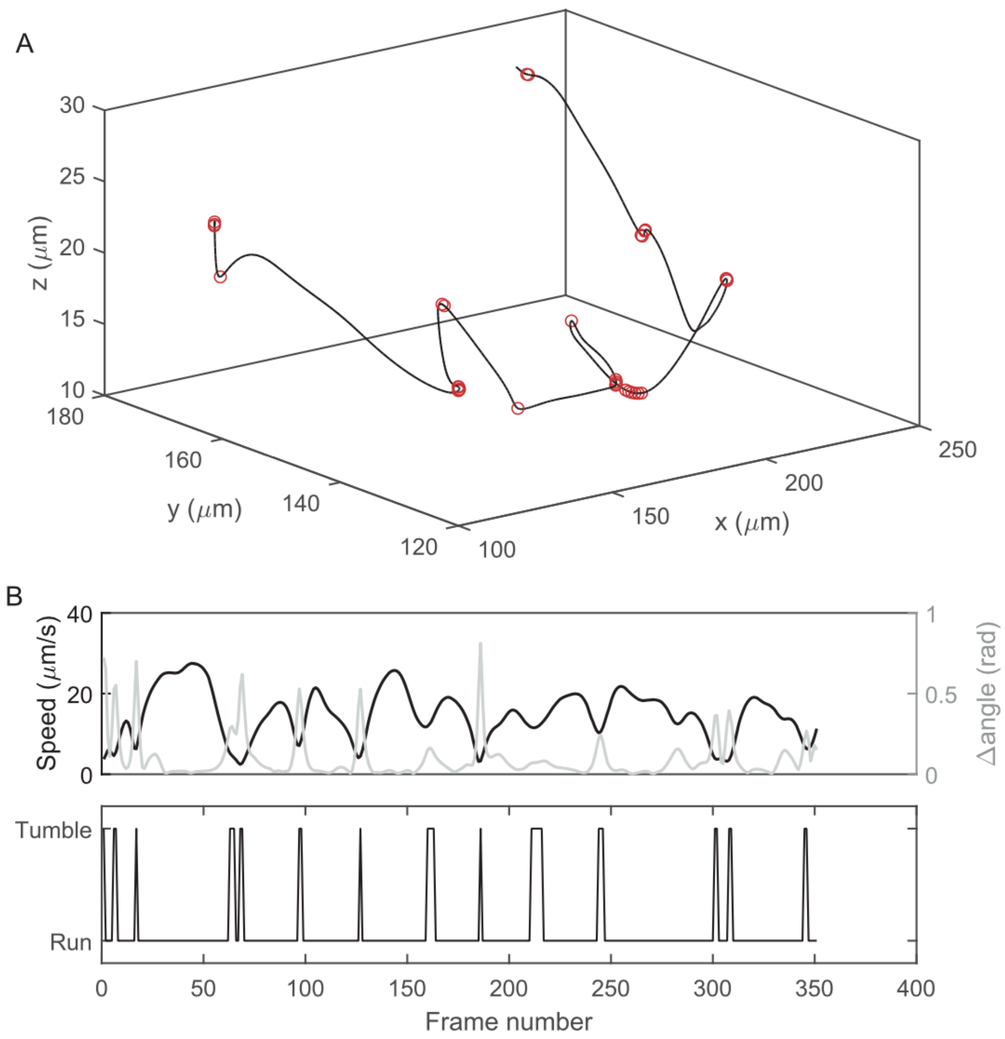
Power Law

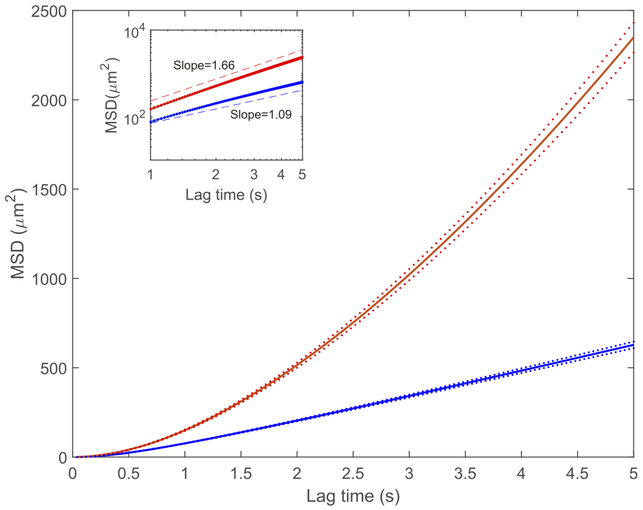
Lévy walks produce probability distributions with “heavy” (aka- long) tails, compared to Brownian motion.

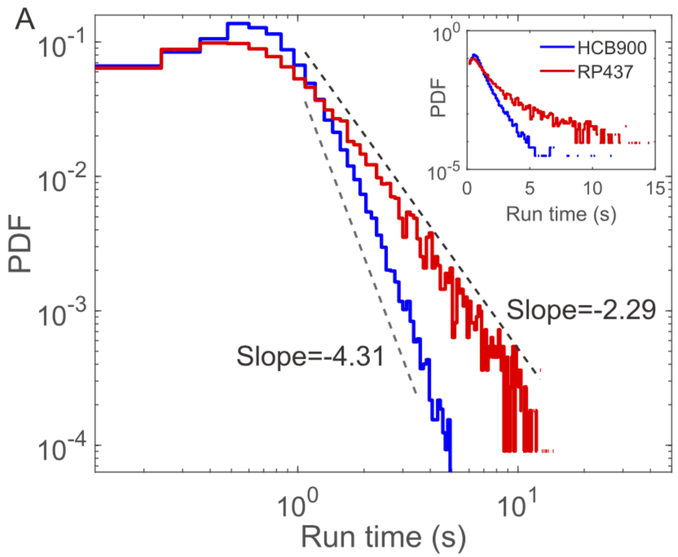


(Liu et al. 2021)

Do *e coli* use Lévy motion to explore?





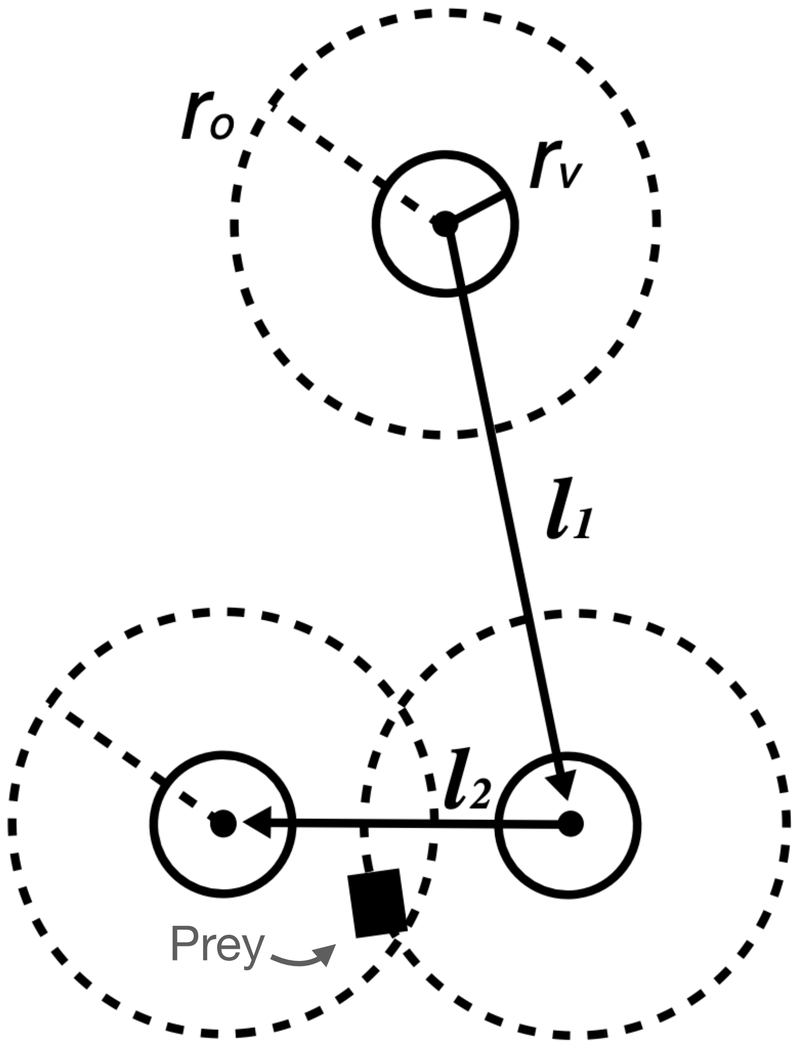


Compared to mutants (HCB900) who lack a critical part of the chemotaxis pathway, wild type *e coli* exhibit super diffusivity in their movements consistent with a Lévy walk process.

(Huo et al. 2021)

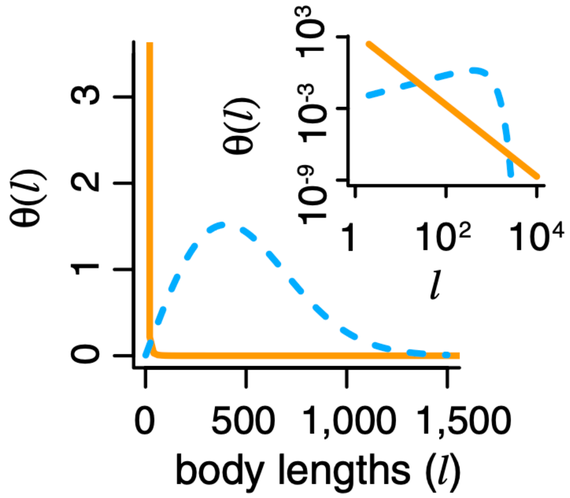
The value of simple sensing

Bacteria as predators



Two types of senses

- Visual
- Visual-olfactory

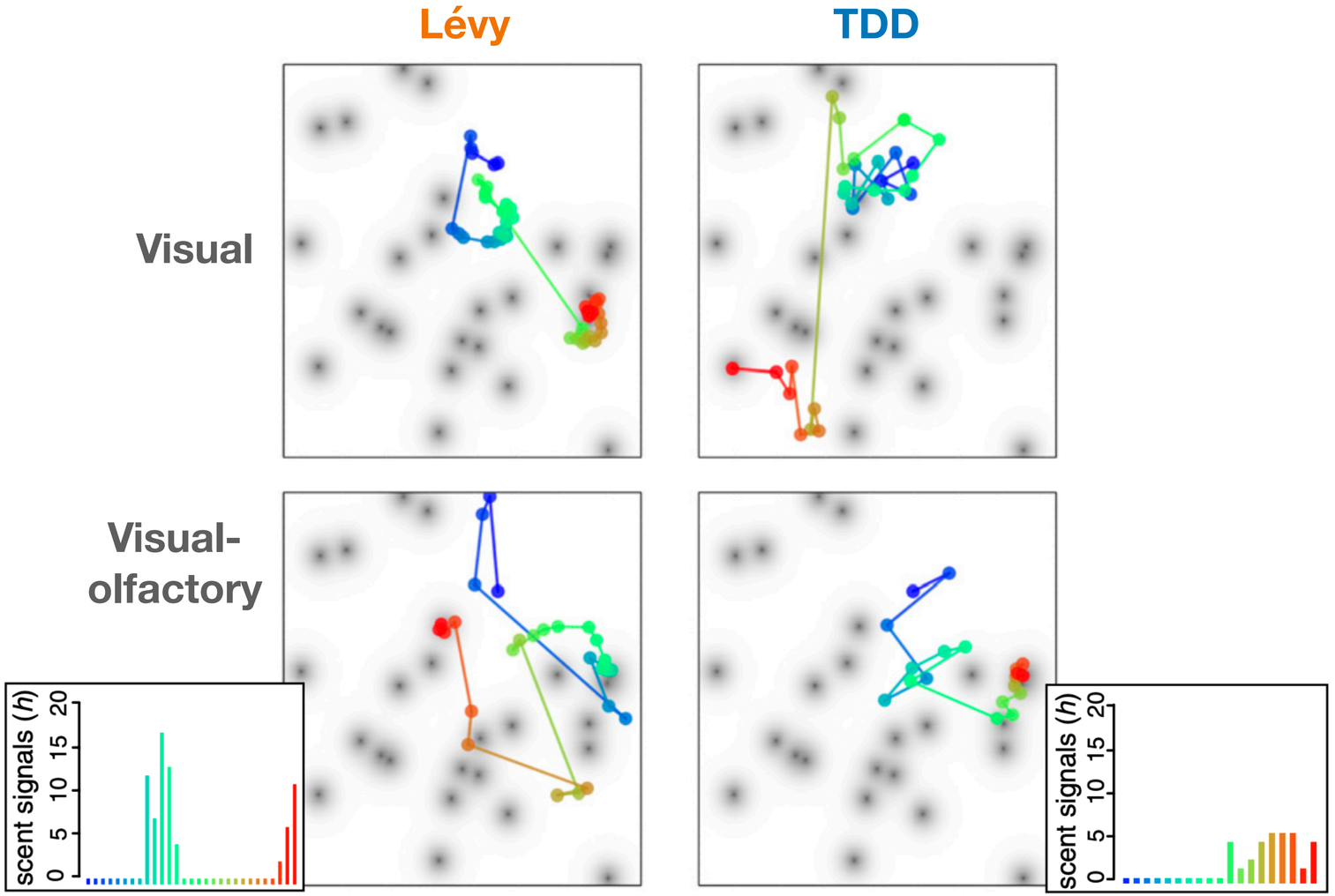


Two types of search

- Lévy: $\theta(l) = (\alpha - 1) l_m^{\alpha-1} l^{\alpha-1}$
- True distance distribution (TDD): $\theta_T(l) = 2\eta\pi l e^{-\eta\pi 2}$

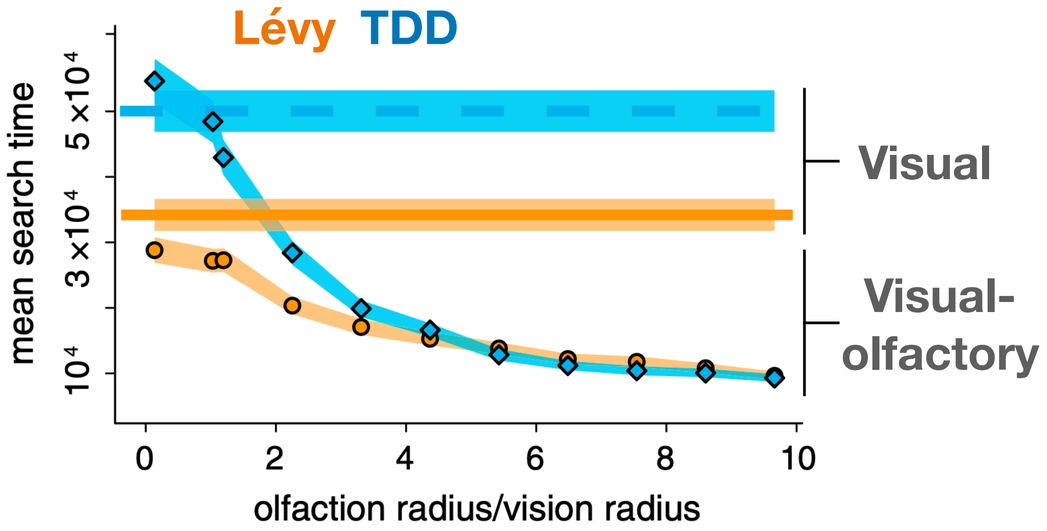
(Hein & McKinley, 2012)

Example search patterns

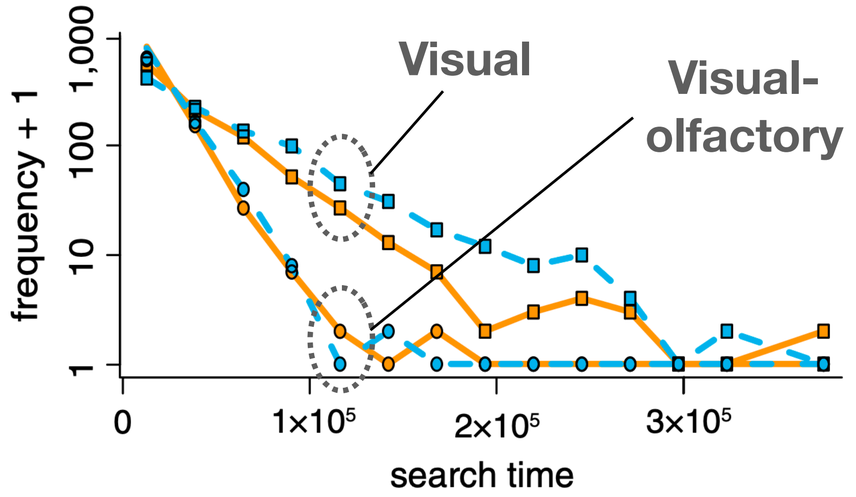


(Hein & McKinley, 2012)

Example search patterns



Lévy search is more efficient than TDD



Increasing sensory channels boosts search efficiency

(Hein & McKinley, 2012)

Take home message

- Organisms without brains can effectively explore.
- They use Lévy flight processes to increase efficiency of random exploration (*e. coli*).
- Adding sensory modalities improves local efficiency of random search strategies.

Lab time!

https://coaxlab.github.io/BIX-book/notebooks/lab2-explorelib.html