Bio-Inspired Flight Control — What we learn from bats and birds

John Baillieul
Intelligent Mechatronics Lab
Boston University
johnb@bu.edu

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Graphs and Frameworks are Tools for Patterns of Information Use

Definition 1: A *formation framework* $(S;E;q)$ consists of a *formation graph* $(S;E)$ and a function $q(\cdot)$ from the vertex set S into a squadron configuration space

$$\mathrm{SE}(m,\mathrm{R}) \times \cdots \times \mathrm{SE}(m,\mathrm{R}).$$

$$\left(\mathbf{r}_1, \mathbf{X}_1; \ldots; \mathbf{r}_n, \mathbf{X}_n\right)$$ = typical point.

position orientation

Definition 2: Motions which preserve all pairwise relative distances $\left\|\mathbf{r}_i - \mathbf{r}_j\right\|$ are called *rigid*.

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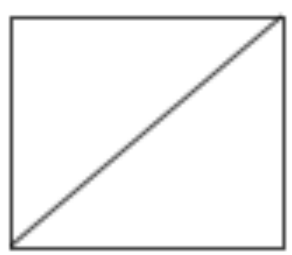
Rigid Formations---Creation and Motion Control Strategy

- Sensor data should be used in a maximally parsimonious fashion,
- There will always be a *leader-first-follower* pair.

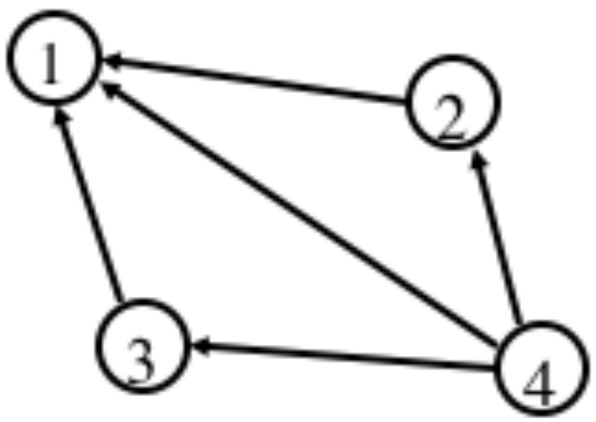
We say that a formation framework (S, E, q) is *isostatic* if the removal of any edge ε∈E results in a framework which is not rigid.



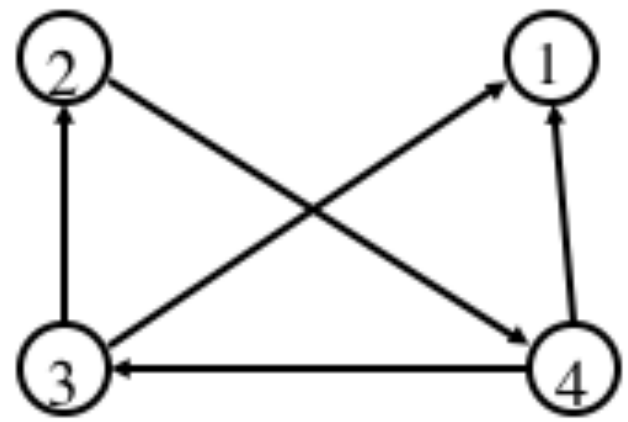
Yes

No

The Rigidity Theory of Directed Graphs Differs from the Undirected Case



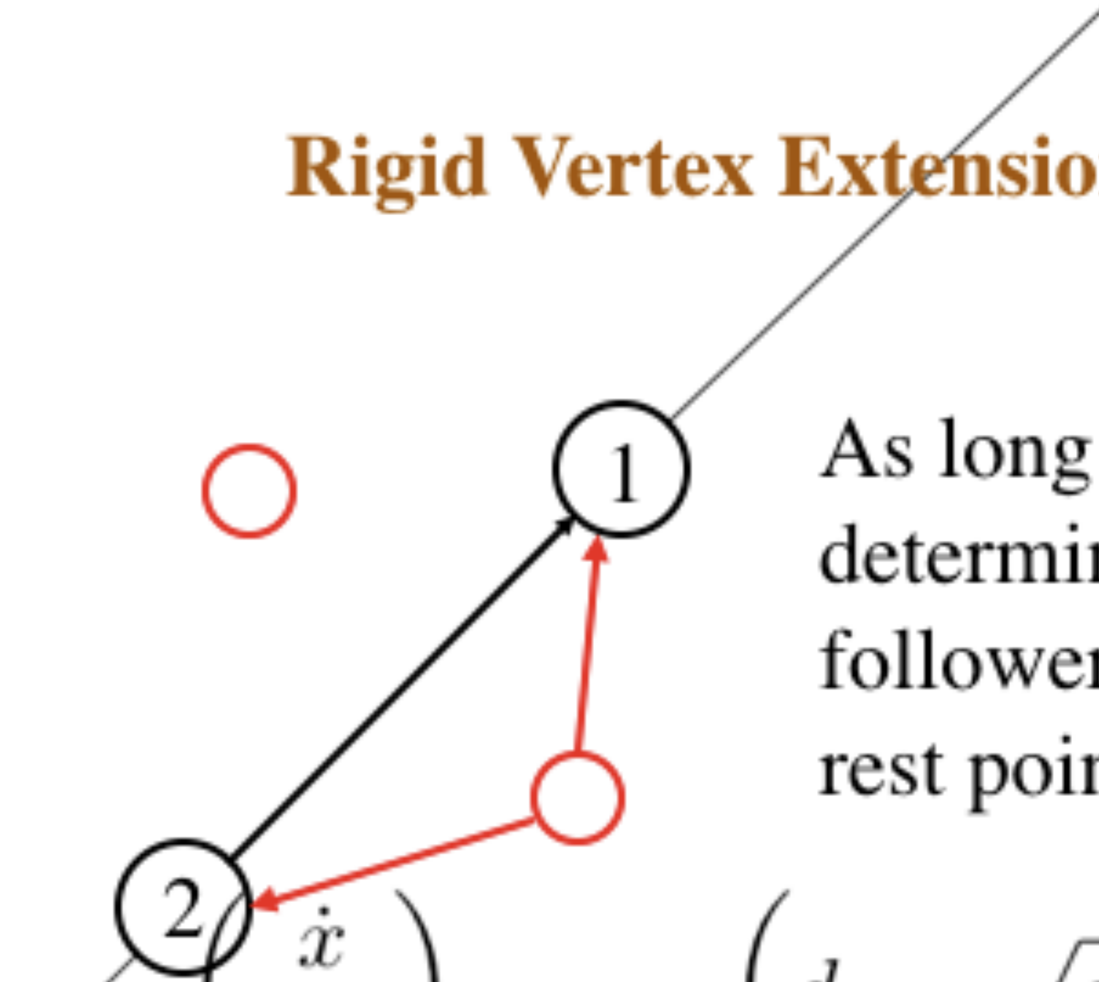
(a)



(b)

Both graphs are rigid (and isostatic by Laman's theorem) as undirected graphs, but as directed graphs they are not rigid.

Rigid Vertex Extension of a Formation Framework



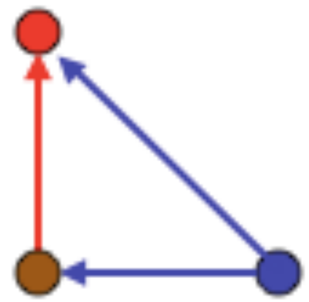
As long as the rest point is not on the line determined by the leader (1) and first follower (2), it is an asymptotically stable rest point for the motion:

$$
\begin{aligned}
\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} &= \left(d_1 - \sqrt{x - x_1)^2 + y - y_1)}\right)\begin{pmatrix} x - x_1 \\ y - y_1 \end{pmatrix} \\
&+ \left(d_2 - \sqrt{x - x_2)^2 + y - y_2)}\right)\begin{pmatrix} x - x_2 \\ y - y_2 \end{pmatrix}.
\end{aligned}
$$

This is a *semi-global* result.

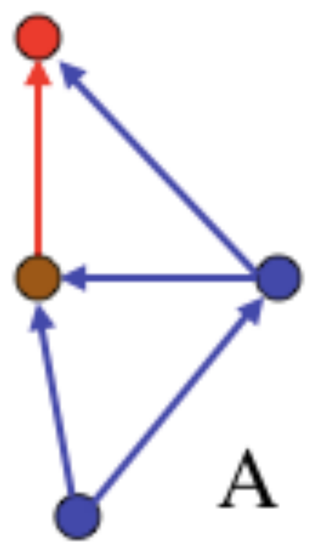
Leader - First-Follower - Subsequent Follower Formations

3

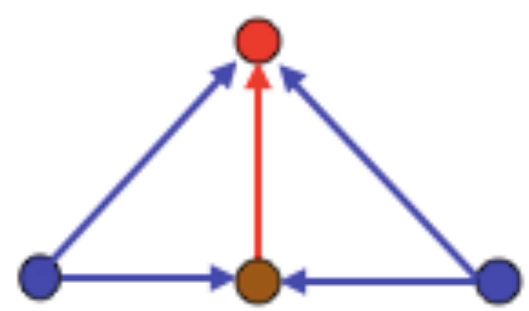


Modulo a left-right symmetry, this formation is unique on three vertices.

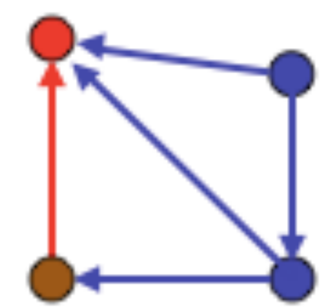
4



A



B



C

Formation B can be constructed in one step - once the leader and first-follower are in place. Followers must join in sequence for A and C.

The enumerative theory of logical isostatic directed graphs remains to be explored

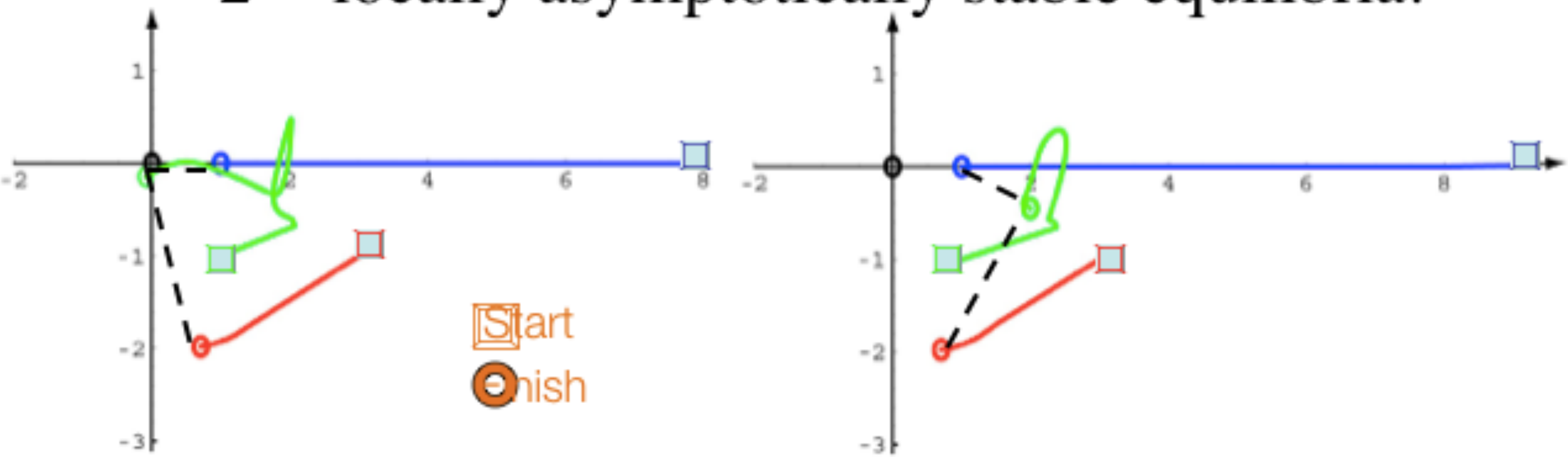
Number of Formation Types on n Vertices								
n	1	2	3	4	5	6	7	8
Formation Types	1	1	1	3	13	79	633	6430

Currently, closed form expressions for this enumeration do not exist.
Many stratification classes do have closed-form enumerations.
This is a new sequence, not previously in Sloan's sequence list.

"The Combinatorial Graph Theory of Structured Formations," In *Proceedings of the 46-th IEEE Conference on Decision and Control*, New Orleans, December 12-14, 2007.

Careful Planning of Group Motions Is Needed to Deal with Extraordinary Sensitivity to Initial Conditions

For each of the formation-types on n-nodes, there are 2^{n-2} locally asymptotically stable equilibria.



I.C.'s $(x_2(0),y_2(0))=(8,0)$, $(x_3(0),y_3(0))=(3,-1)$, $(x_3(0),y_3(0))=(1,-1)$.

F.C.'s $(x_2(\infty),y_2(\infty))=(1,0,)$, $(x_3(\infty),y_3(\infty))=(0.705, -1.97812)$, $(x_3(\infty),y_3(\infty))=(-0.0906396, -0.143197)$.

I.C.'s $(x_2(0),y_2(0))=(9,0)$, $(x_3(0),y_3(0))=(3,-1)$, $(x_3(0),y_3(0))=(1,-1)$.

F.C.'s $(x_2(\infty),y_2(\infty))=(1,0,)$, $(x_3(\infty),y_3(\infty))=(0.705, -1.97812)$, $(x_3(\infty),y_3(\infty))=(1.99511, -0.45236)$.

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Perception-Enabled Control - toward a bio-inspired understanding of machine autonomy

Talk Outline

1. What is perception-enabled control and why is it different?
2. Control in the natural world is perception enabled - how perceptions differ from one species to the next.
3. What are feature networks?
4. Vision, optical flow, and ***tau*** **and** ***loom.***
5. Other elements of animal perception.
6. The interplay among vision, bio-sonar, and spatial memory.
7. Perception is an emergent phenomenon.

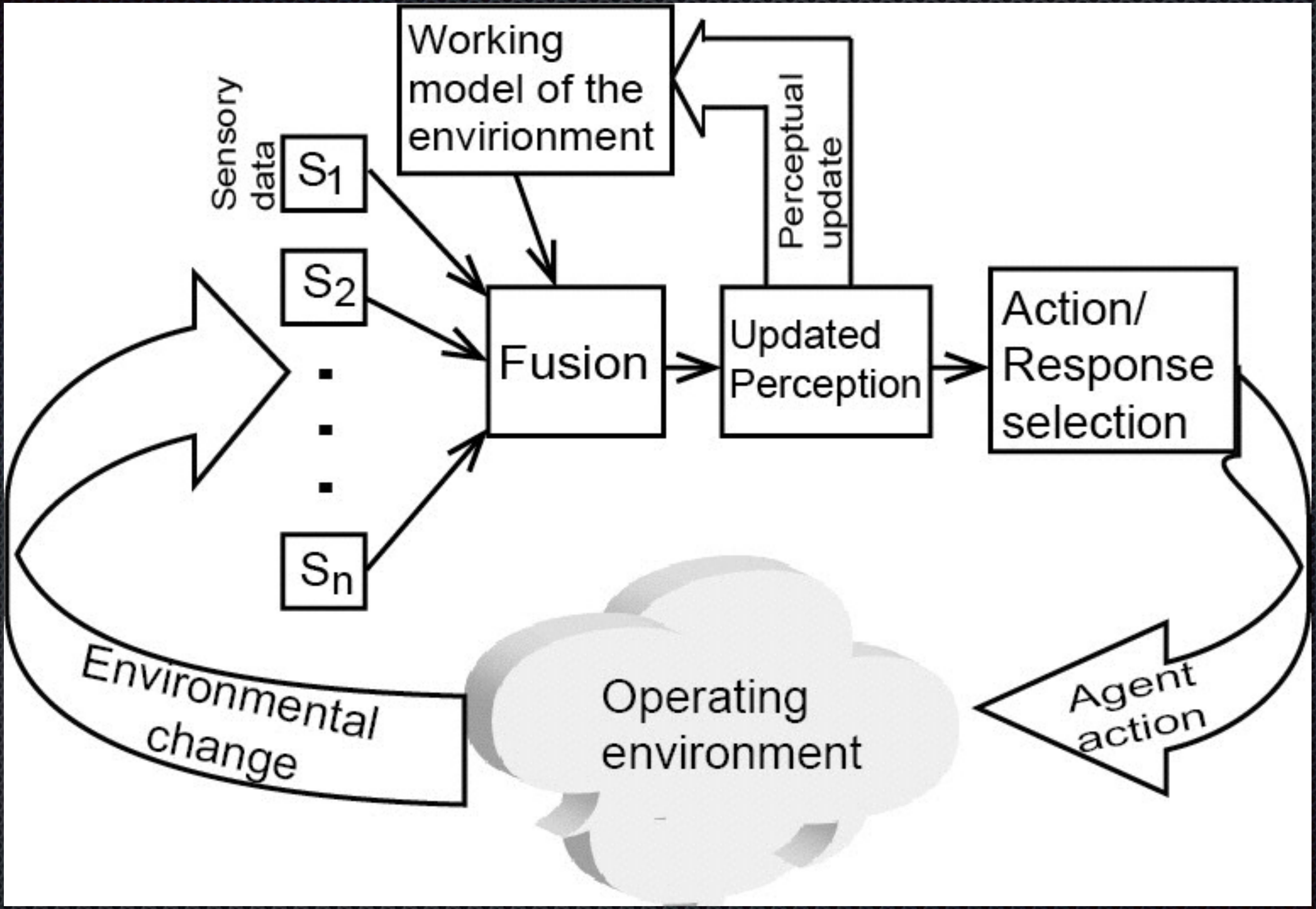
Perception-Enabled Control — Text for today's lecture

Perceptual Modalities Guiding Bat Flight in a Native Habitat

Zhaodan Kong, Nathan Fuller, Shuai Wang, Kayhan Özcimder, Erin Gillam, Diane Theriault, Margrit Betke & John Baillieul

http://www.nature.com/articles/srep27252

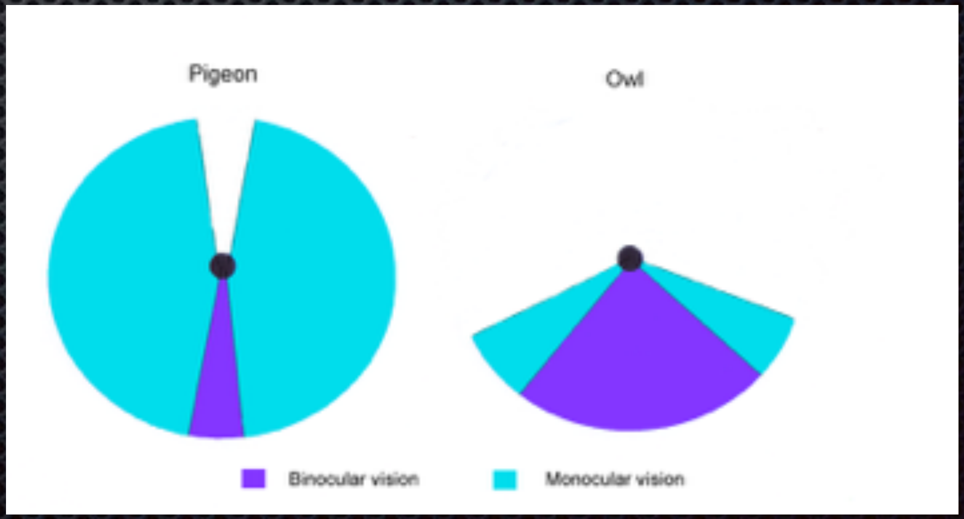
The perceptual basis of motion control



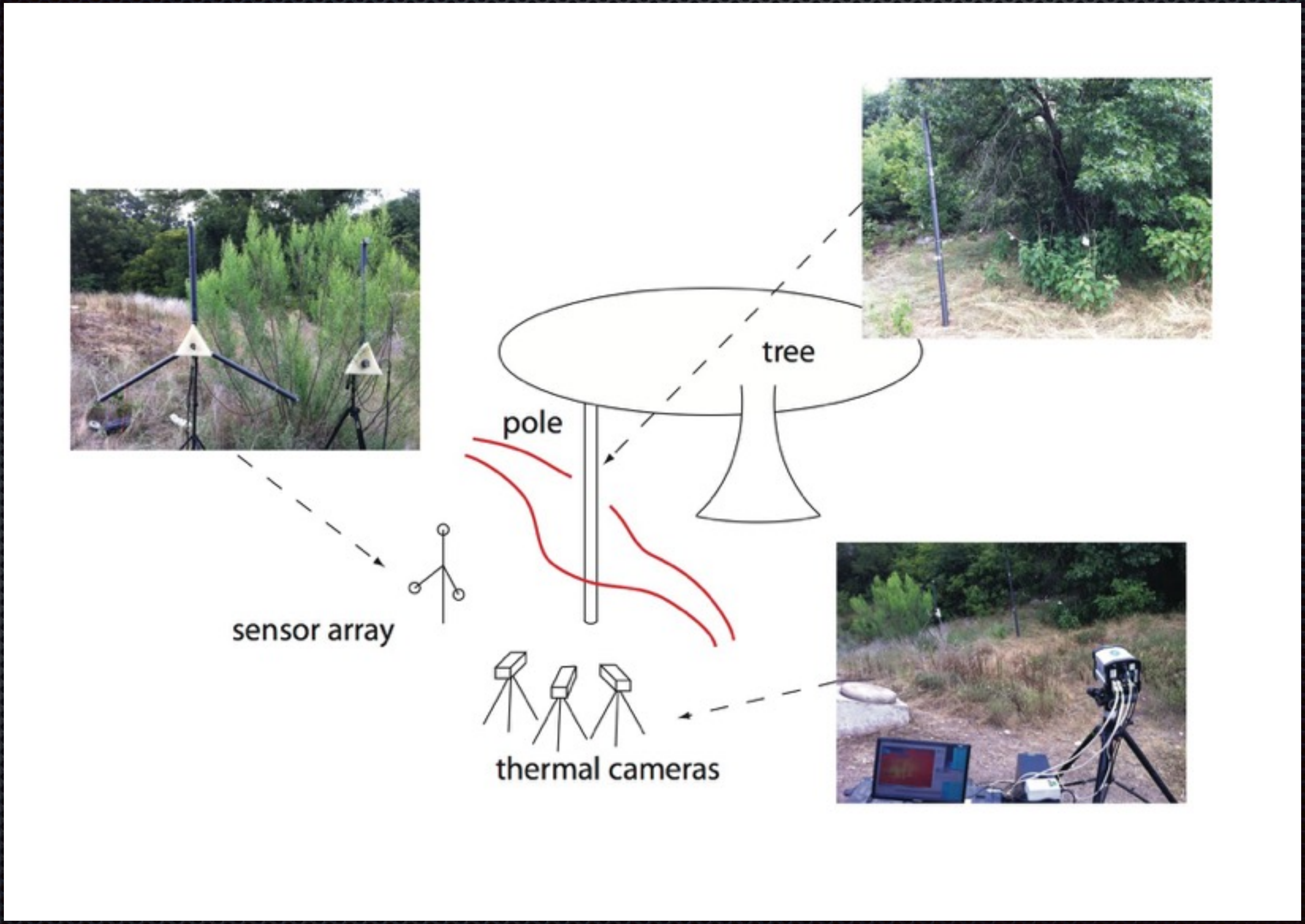
Sensory information

- Echolocation
- ~~Binocular vision~~
- Optical flow
- Dead reckoning (spatial memory)
- Reacting to conspecifics
- Response to ambient airflow
- Inertial sensing

Myotis velifer

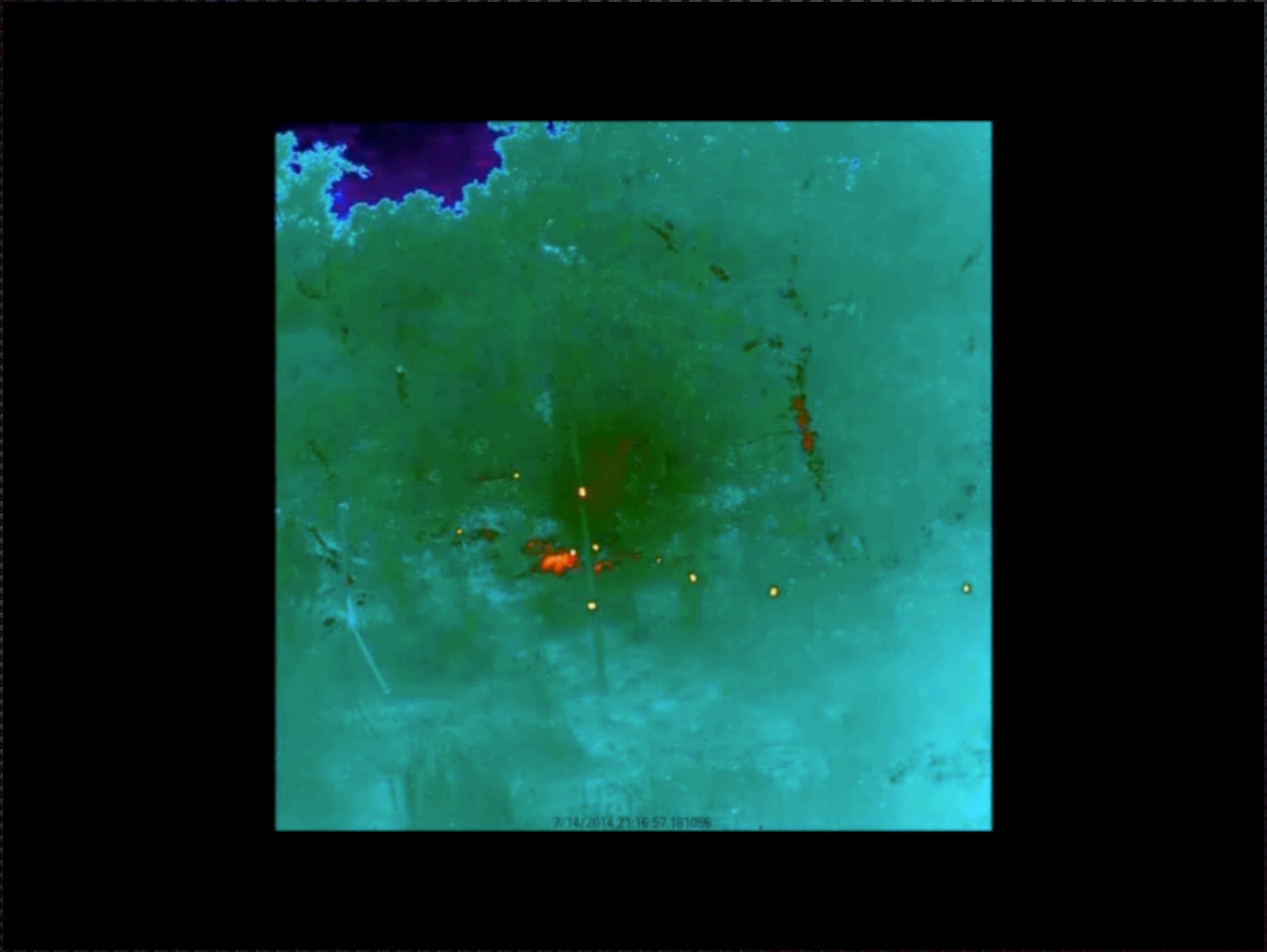


The feature networks of bats



Motion and position perceptual modalities

Why *M. velifer*?

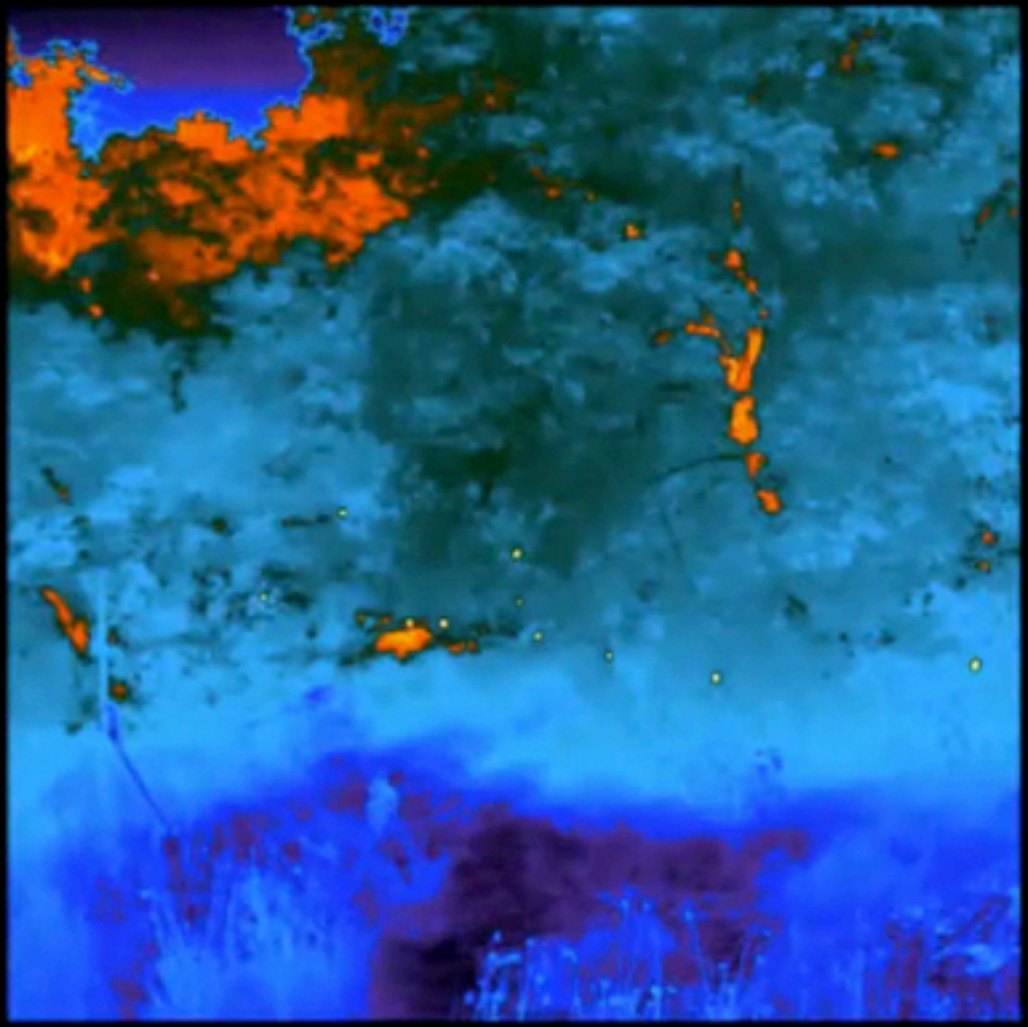


Our experiment: *M. velifer* in their natural habitat were challenged with a novel obstacle.

Over seven days in the summer of 2013, observations of the emergence of *M. velifer* were made.

Day 1: Baseline observations were made—no unexpected obstacles.
Day 2: A PVC pole, 30 meters in height placed in the flight path.
Day 2-6: PVC pole in place.
Day 7: PVC pole removed - returning the flight corridor to its original state.

Why *M. velifer*?



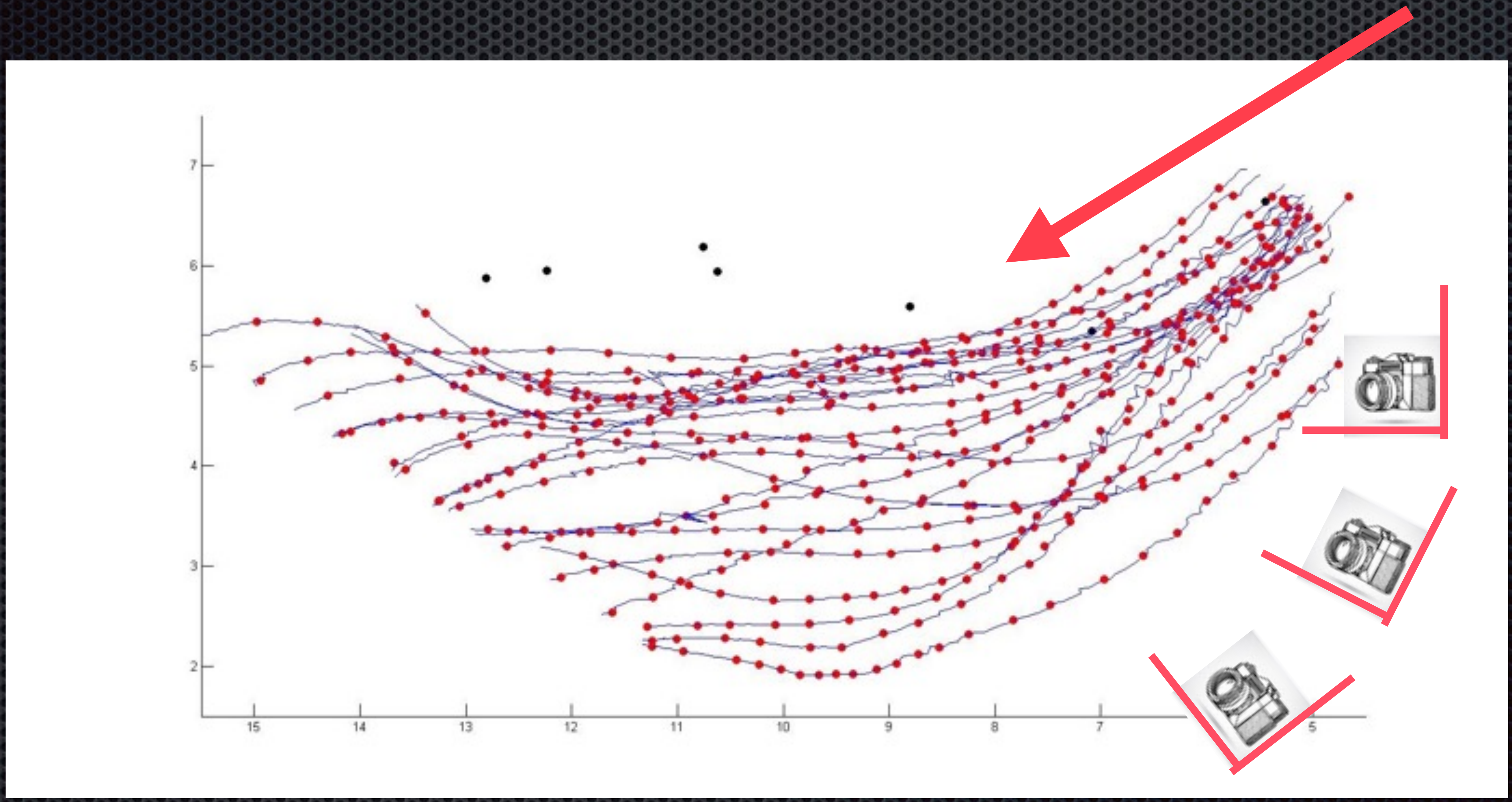
What we learn from bat pairs

M. velifer emerging from cave in small groups allow leader-follower pairs to be isolated in the FOV.

- From 10,000 reconstructed bat trajectories 282 leader-follower pairs were identified.
- Data on how leader and follower reactions to an obstacle were recorded.
- By analyzing call signaling and changes in heading, evidence of followers using visual feedback was obtained.

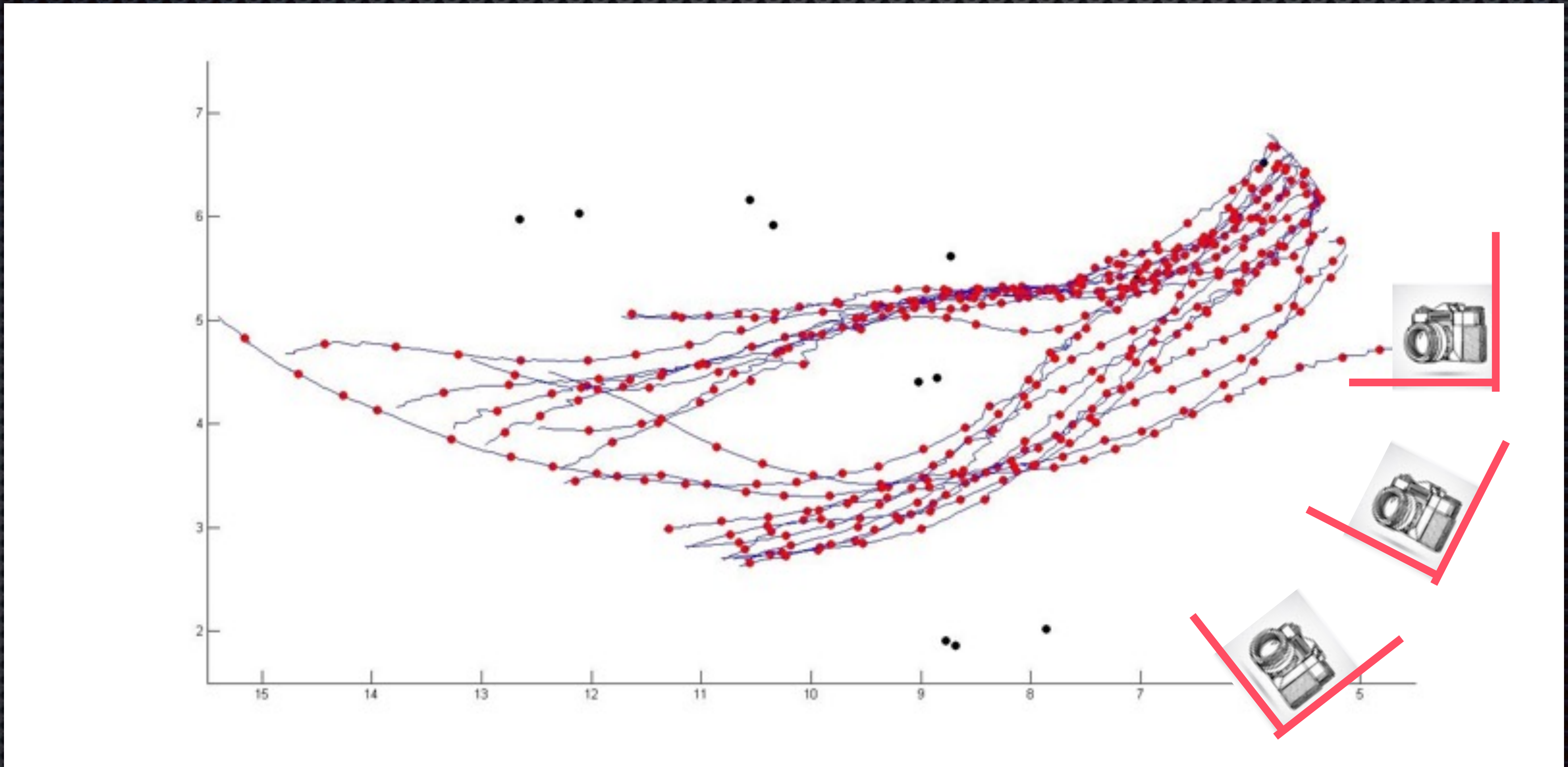
Why *M. velifer*?

Day 1



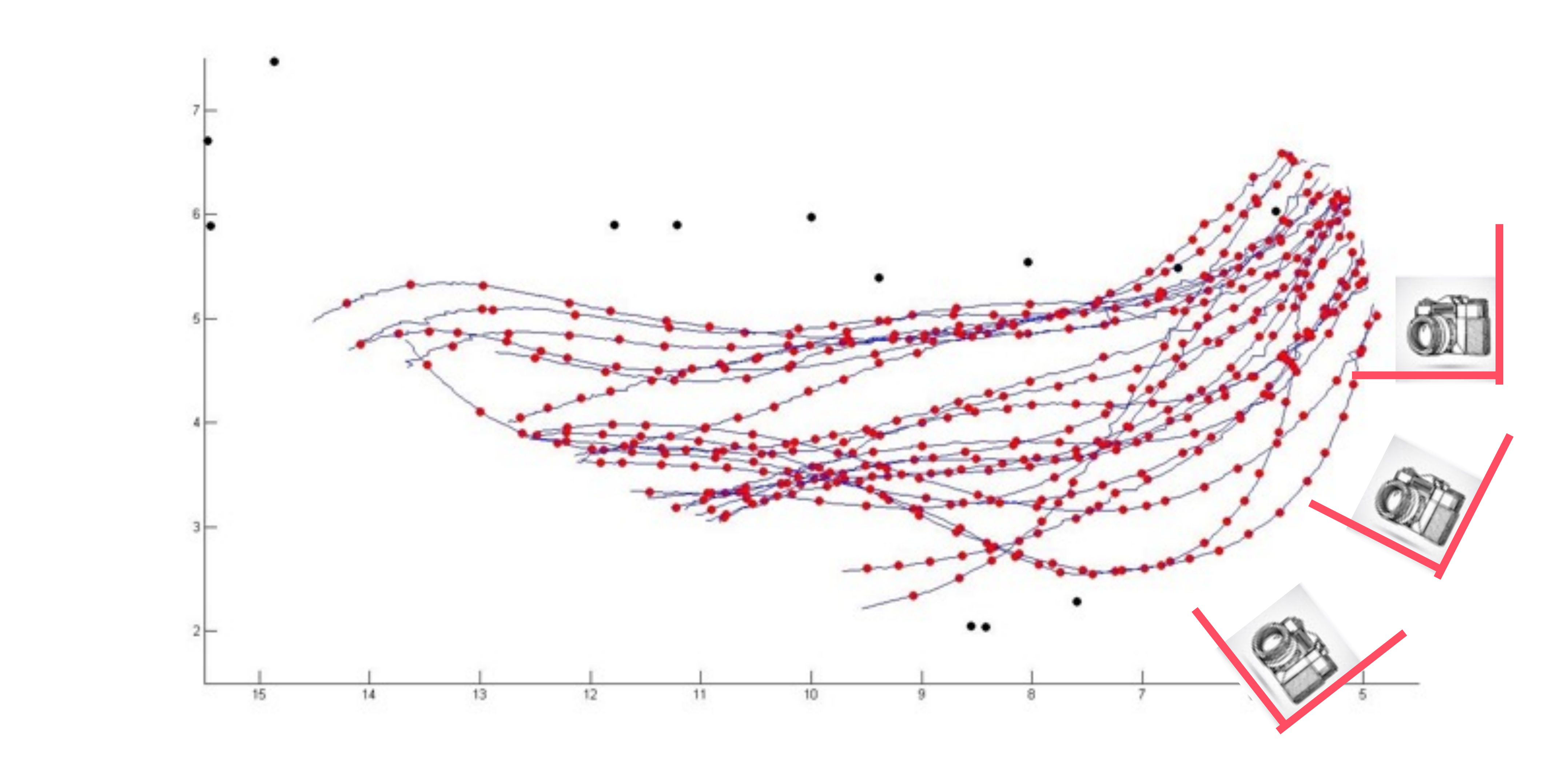
Why *M. velifer*?

Day 2



Why *M. velifer*?

Day 7



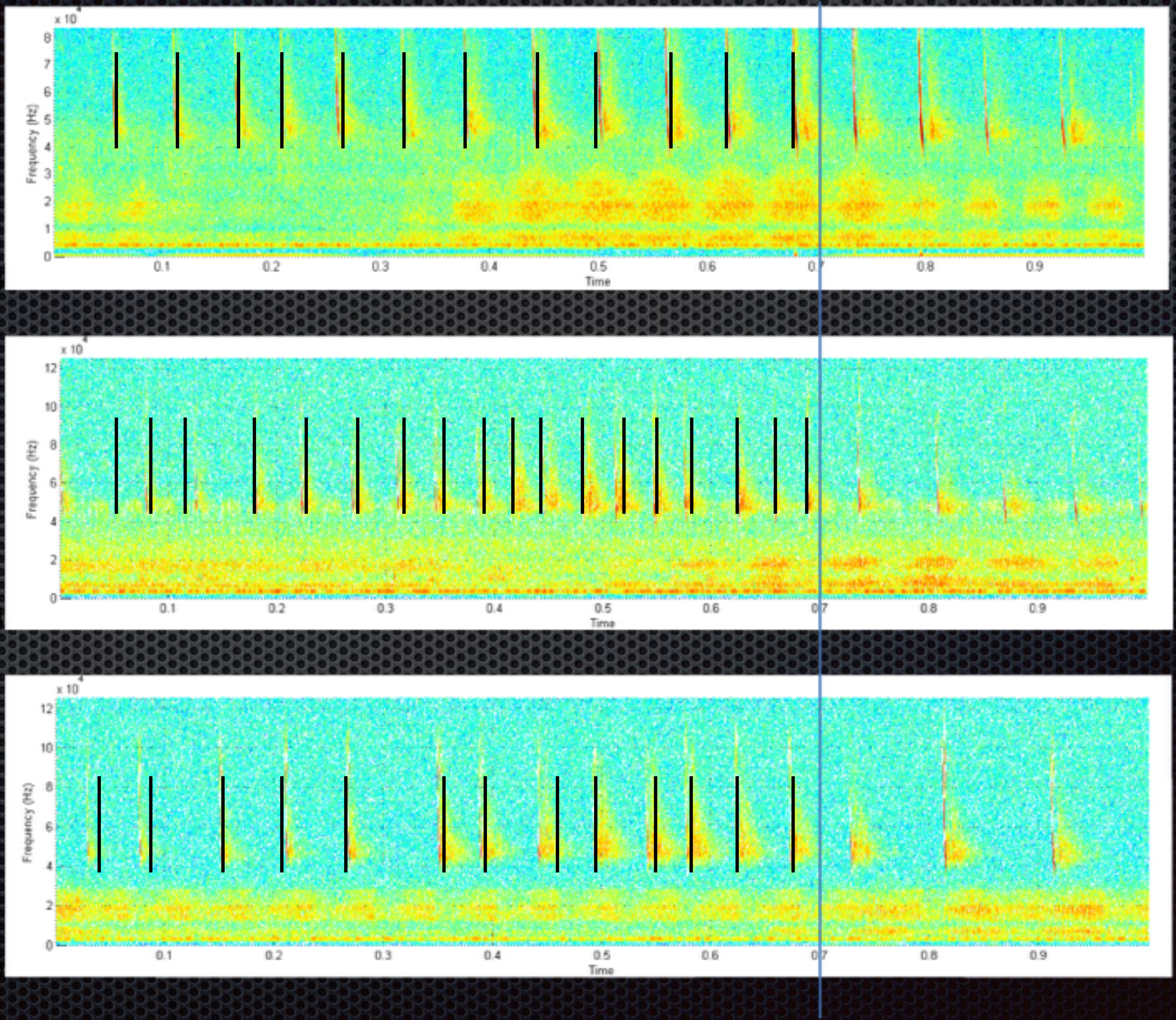
How the call rates change:

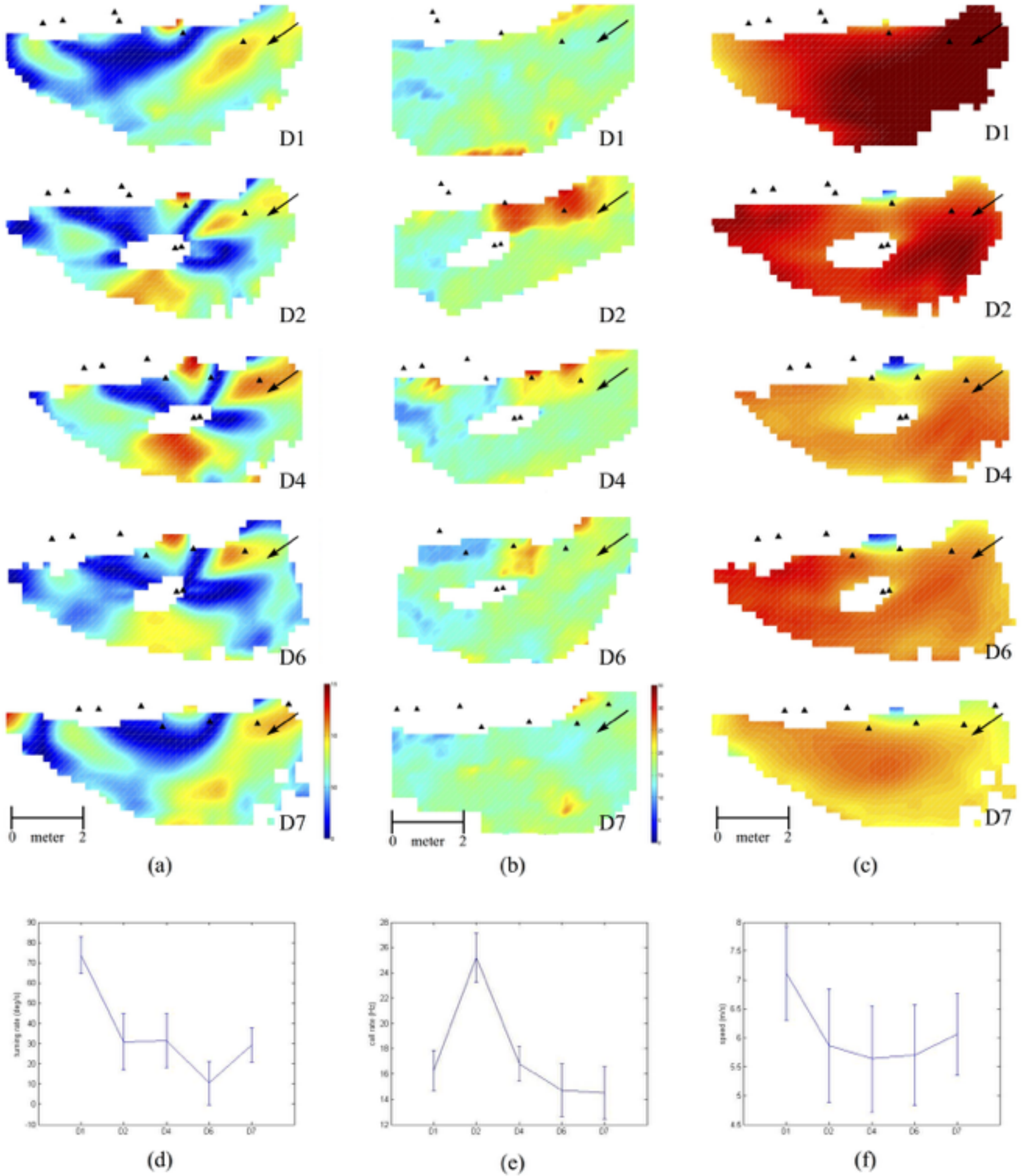
Day 1

(no pole)

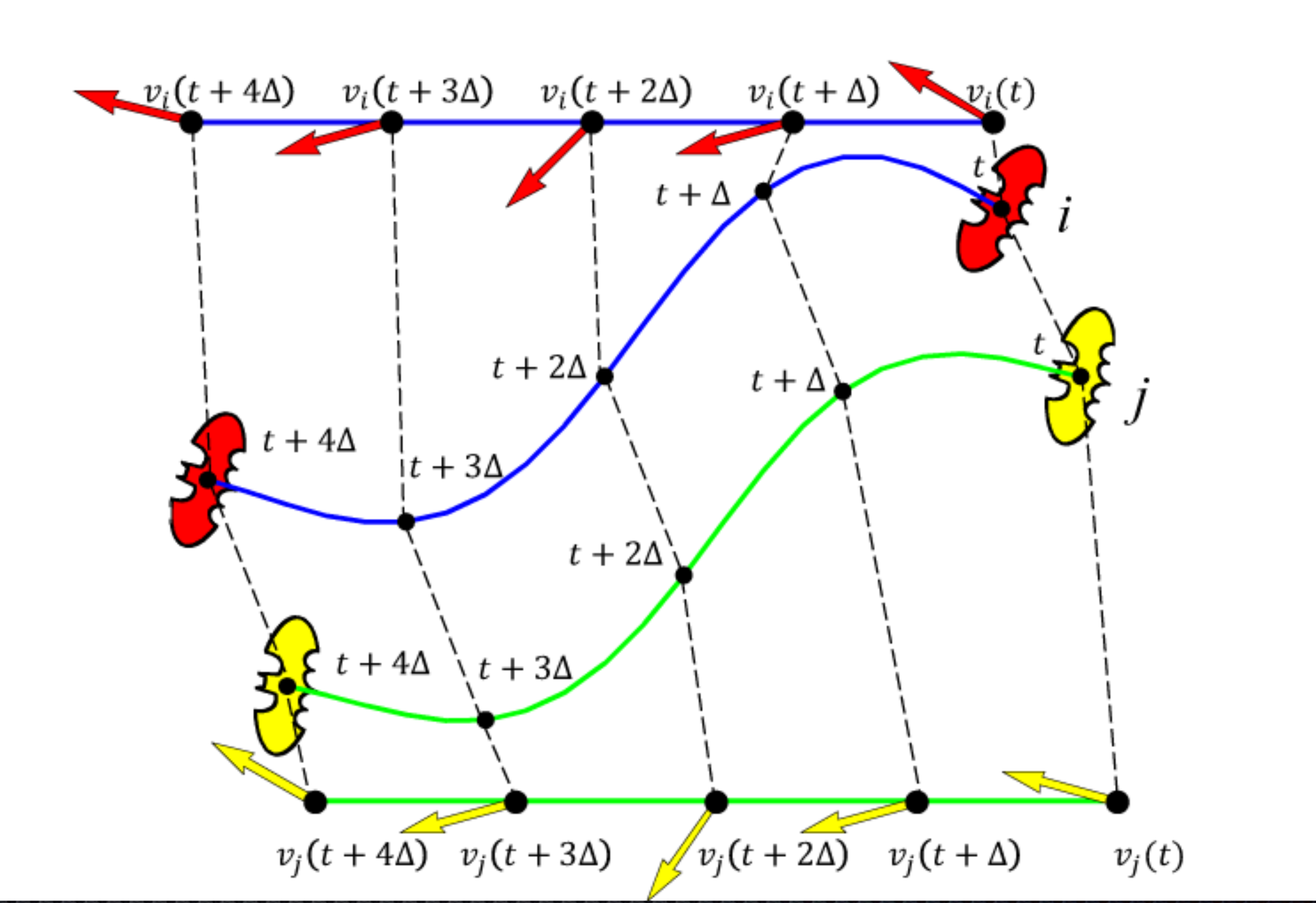
Day 2

Day 4




D1
D2
D4
D6
D7
0 meter 2
(a)
(b)
(c)
D1
D2
D4
D6
D7
(d)
(e)
(f)

What we learn from bat pairs



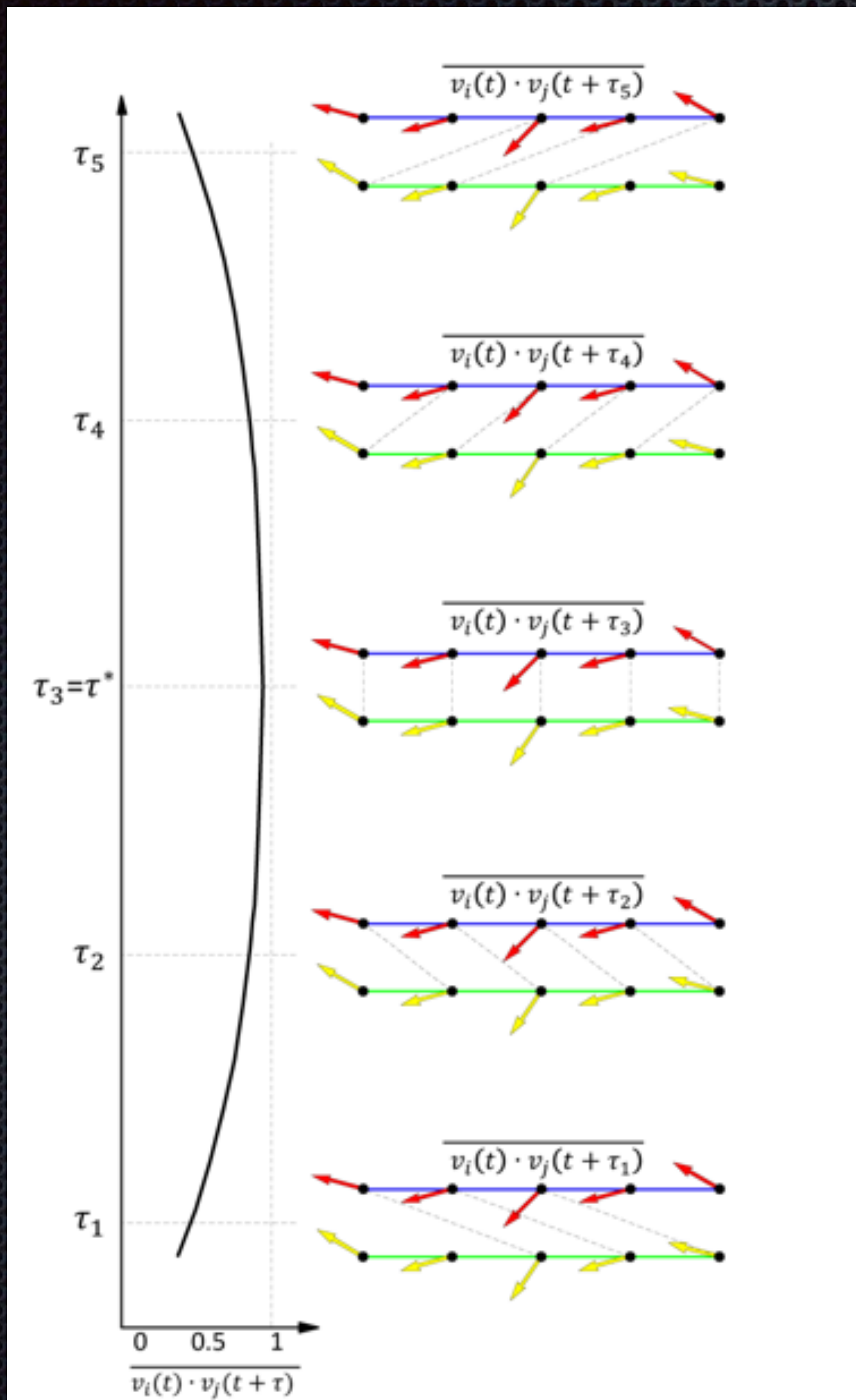
What we learn from bat pairs

Among approx. 10,000 recon-structed bat trajectories we identified 282 leader-follower pairs.

Two bats constitute a leader-follower pair if:

- Both trajectories lie in the field-of-view of all cameras for longer than one second,
- The time difference between when the leader and follower entered the field of view is less than half a second,
- The spatial distance between the leader and follower was <1 meter when the follower entered the FOV, and
- There was at least 3 meters separation between the leader-follower wait and the next closest bat.

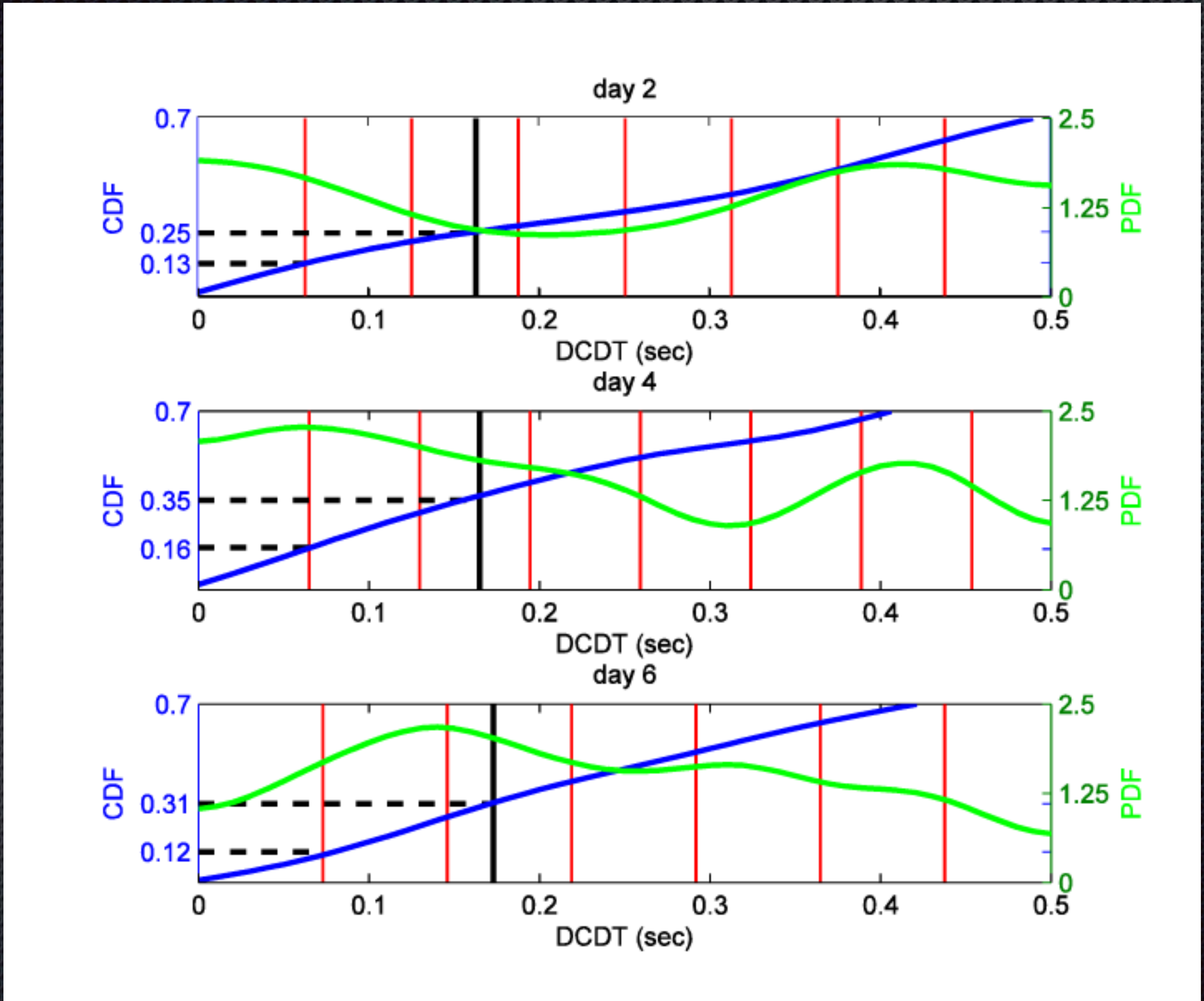
Directional correlation delay time



$$C_{ij}(\tau) = \overline{\vec{v_i}(t) \cdot \vec{v_j}(t+\tau)}$$

$$\tau^* = \underset{\tau}{\operatorname{argmax}} \; C_{ij}(\tau)$$

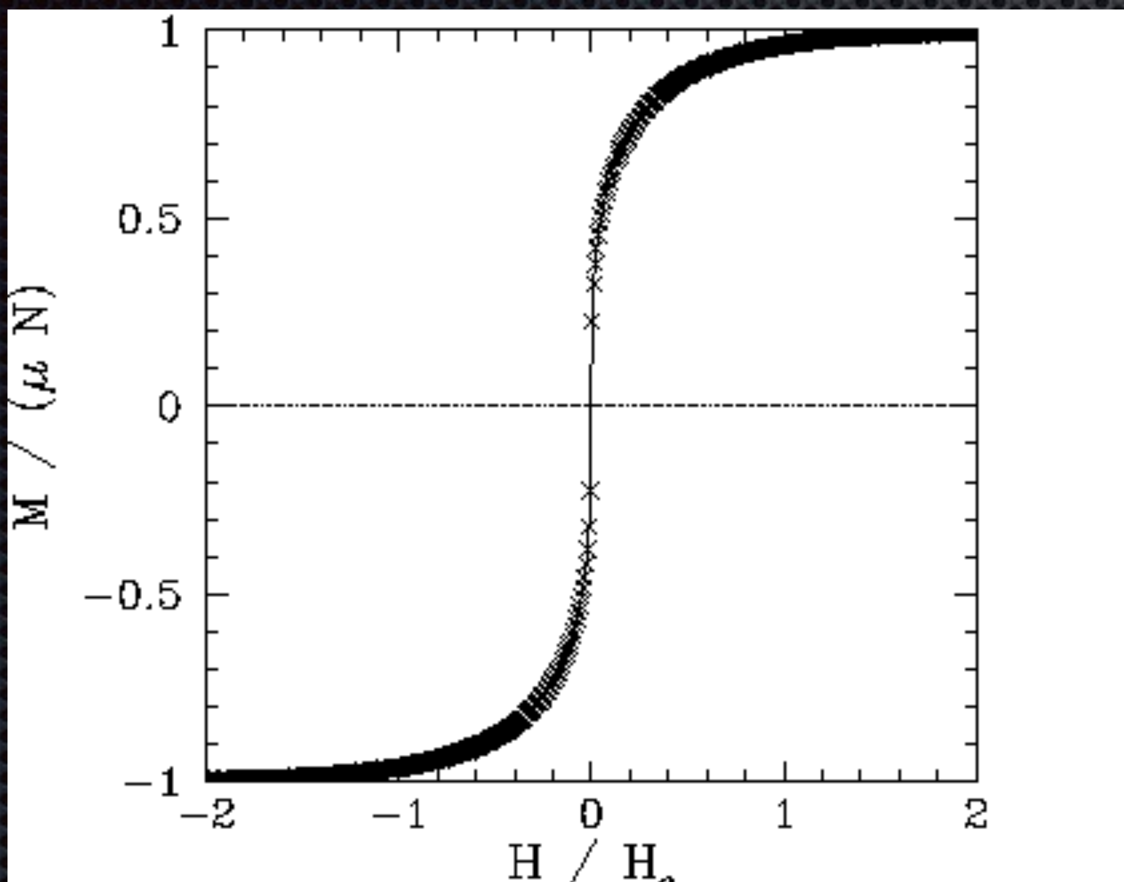
Evidence for the role of vision

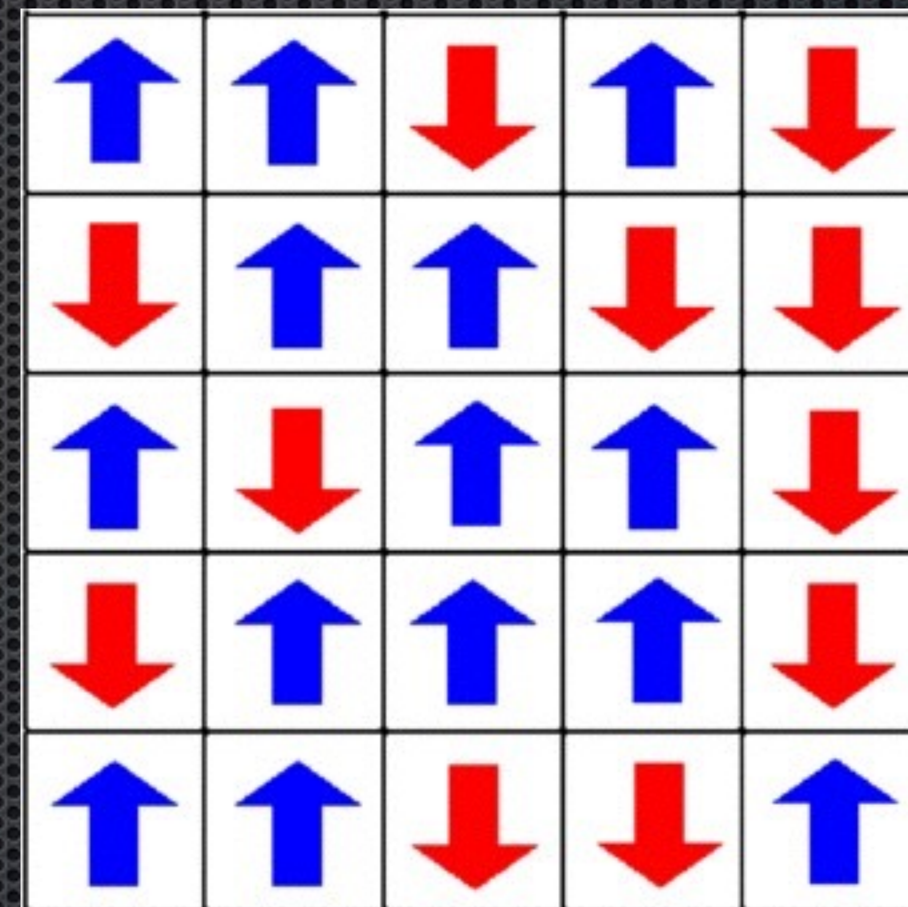


Conclusions

- Some evidence that vision is an important for bat navigation.
- Strong evidence that spatial memory plays a role.
- In the field experiment, spatial memory develops over the course of several days — consistent with observations in Jim Simmons’ laboratory experiments.

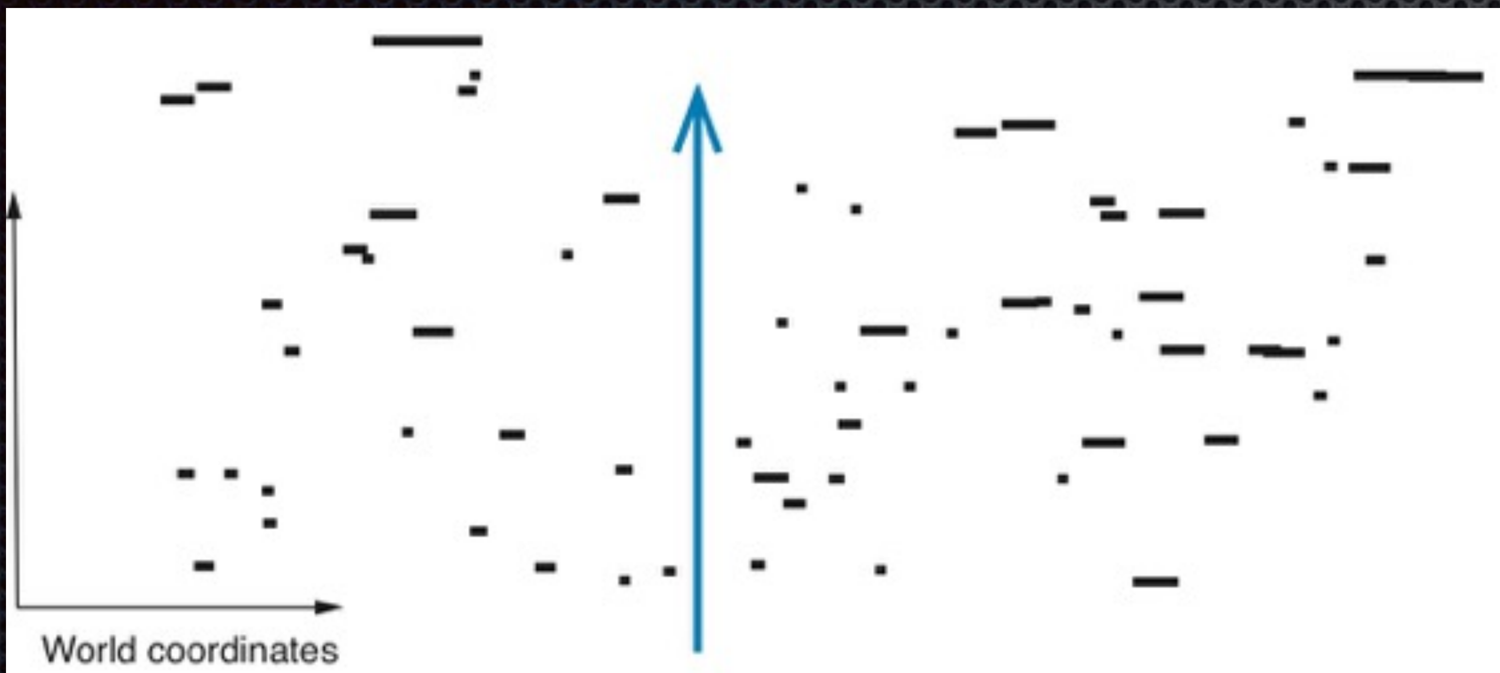
A *critical phenomenon* is a distinguished operating state that appears suddenly as a parameter is varied.





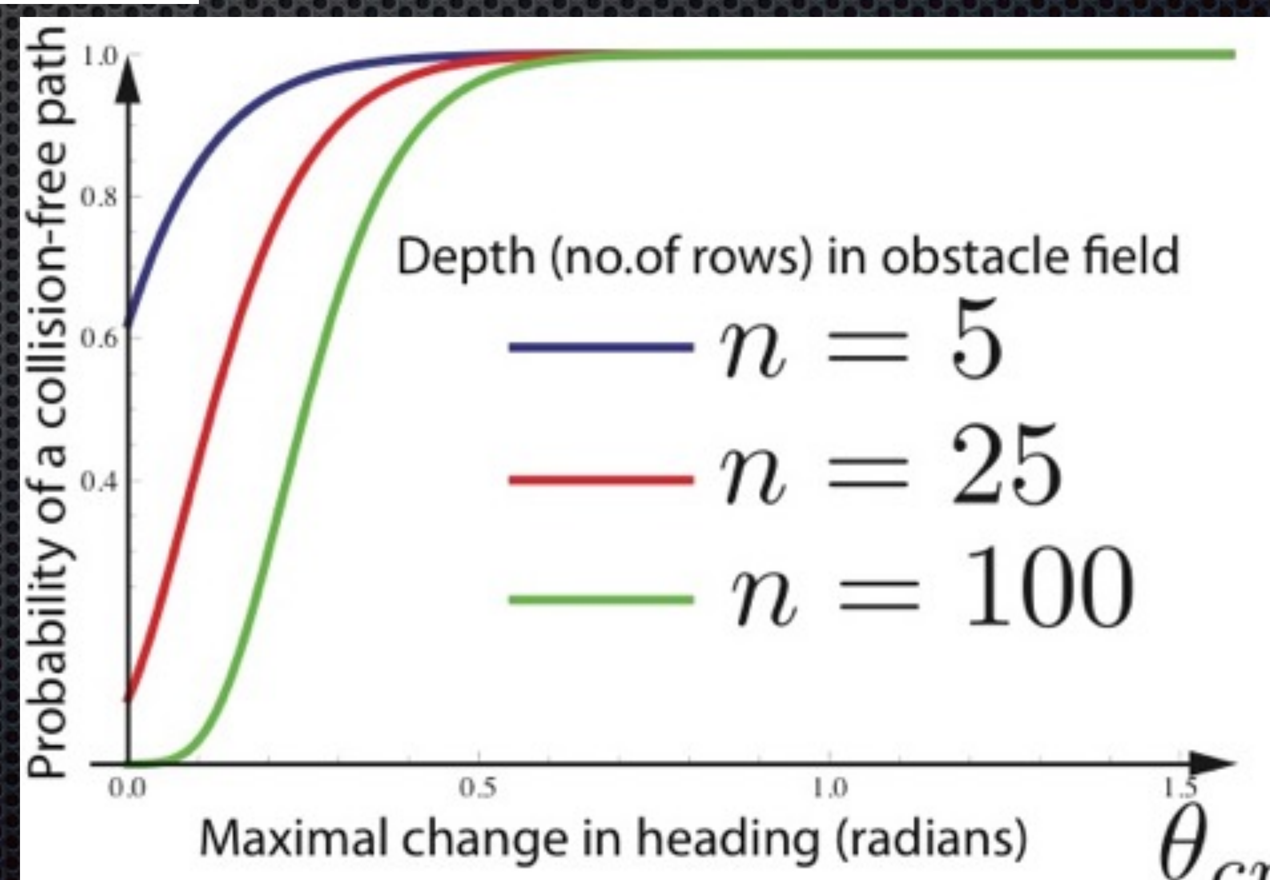
In a network of atoms, magnetization is a critical phenomenon that occurs abruptly as either temperature or ambient magnetic field strength increase.

Controlled motion through a simulated obstacle field



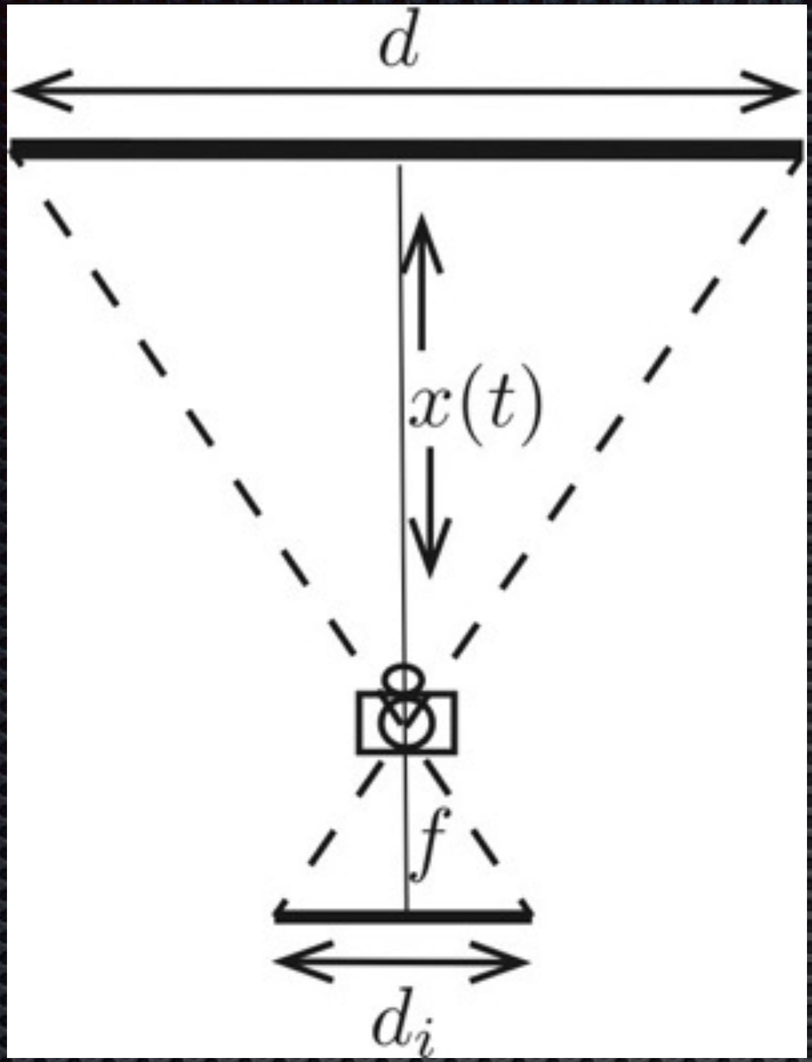
The obstacle widths follow and exponential distribution, as do the inter-obstacle spaces.

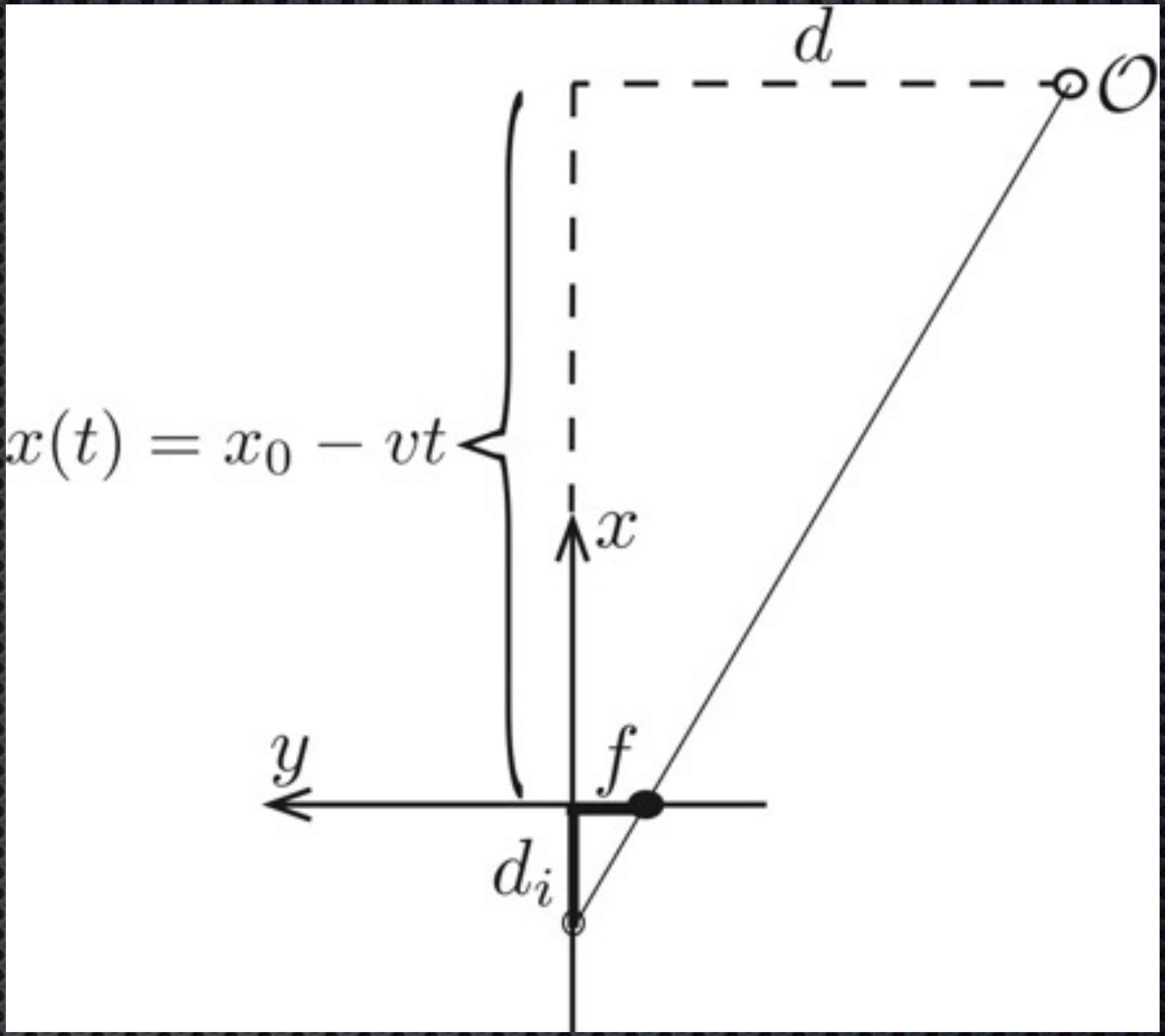
With the obstacle field as realized above, the probabilities of collision-free transit are



See also Frazzoli and Karaman.

Navigating based on visual cues —τ





$$\tau = \frac{d_i}{\dot{d}_i}$$ = time-to-transit

Outdoor optical flow

Visual cues for navigation

τ is a purely geometric quantity that is directly sensed by the visual cortex.

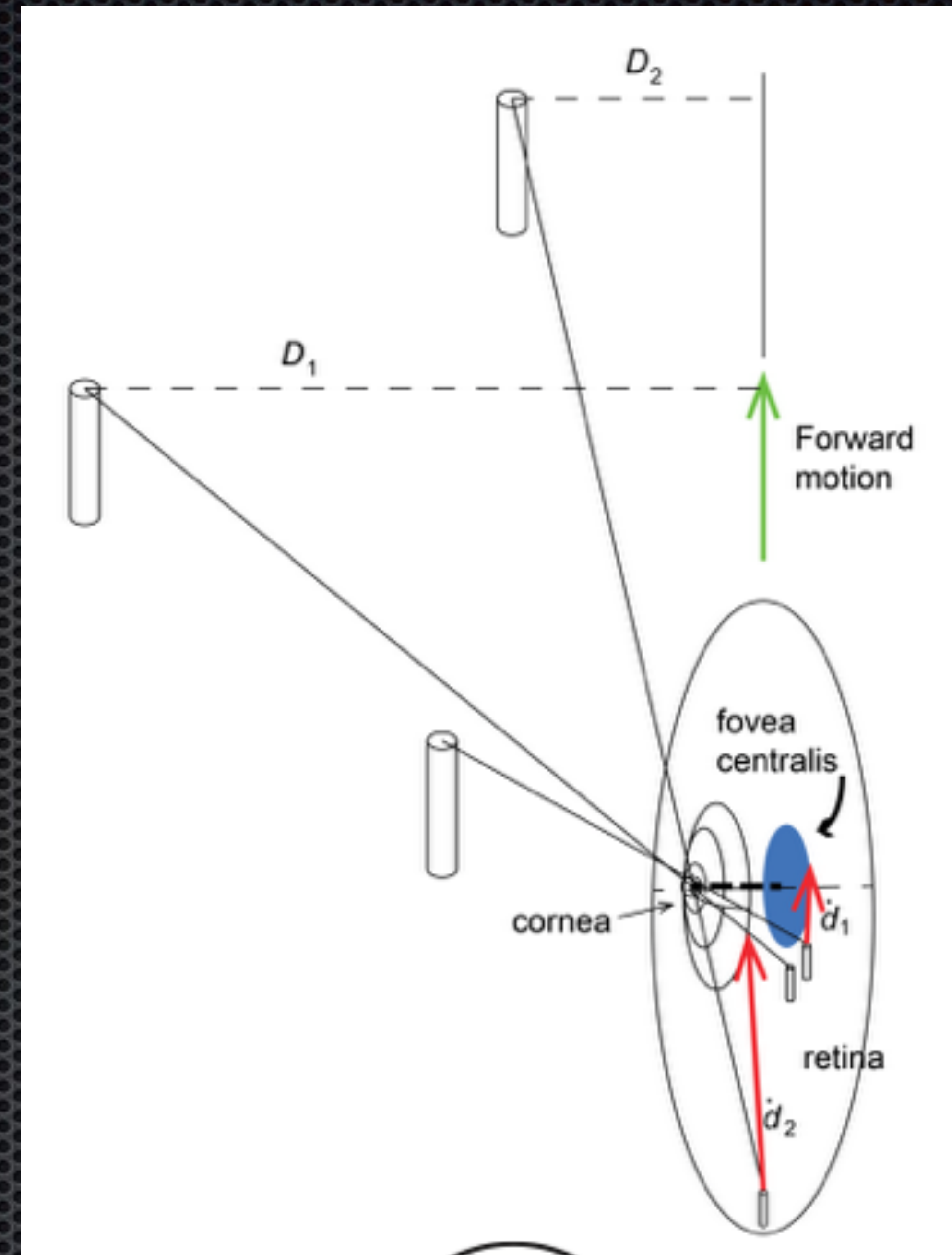
$$\tau = \frac{\cos\theta\,(x_w - x) + \sin\theta\,(y_w - y)}{v}.$$

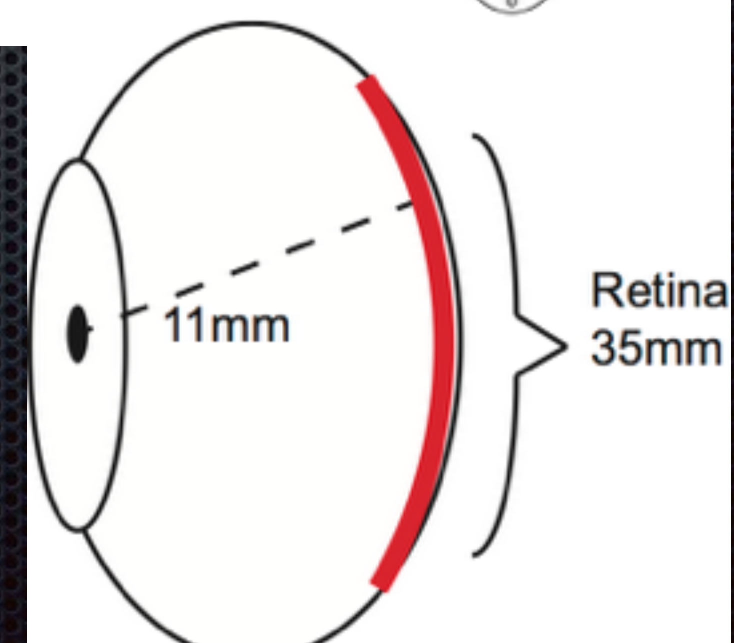
$$\tau = \frac{d_i}{\dot{d}_i}$$

τ_i and d_i together give enhanced situational pereption.

Thoughts on feature saliency

- Optical flow algorithms depend key point associations between video frames.
- Key point associations between frames becomes difficult if the key point image moves a large amount between frames.
- Key point images associated to nearby environmental features have high retinal velocity.





Thoughts on feature saliency

The velocity of image points $\dot{d}_i$ on the retina is inversely proportional to how close a straight line trajectory will pass the feature.

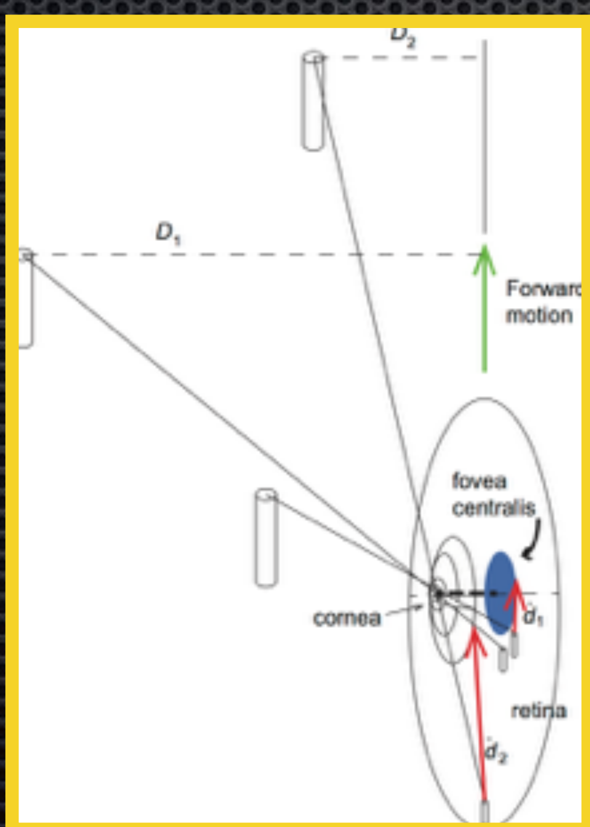
Simple geometry:

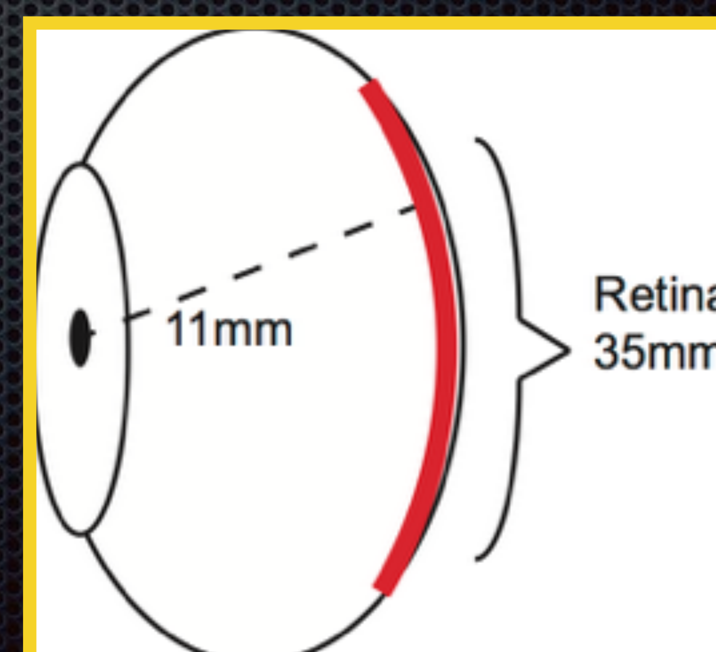
$$\frac{f}{\dot{d}} \sim \frac{D}{v}$$

For *M. velifer*:

$v = 10\,m/s$, $f = 11\,mm$ (in appropriate scale), and we assume $\dot{d} = 35mm/s$.

$\Rightarrow D \sim 3\,m$





Motion primitives based on τ and d

- Fly between features
- Fly in alignment with a row of features
- Circle features

Motion primitives based on τ and d

- Fly between features
- Fly in alignment with a row of features
- Circle features

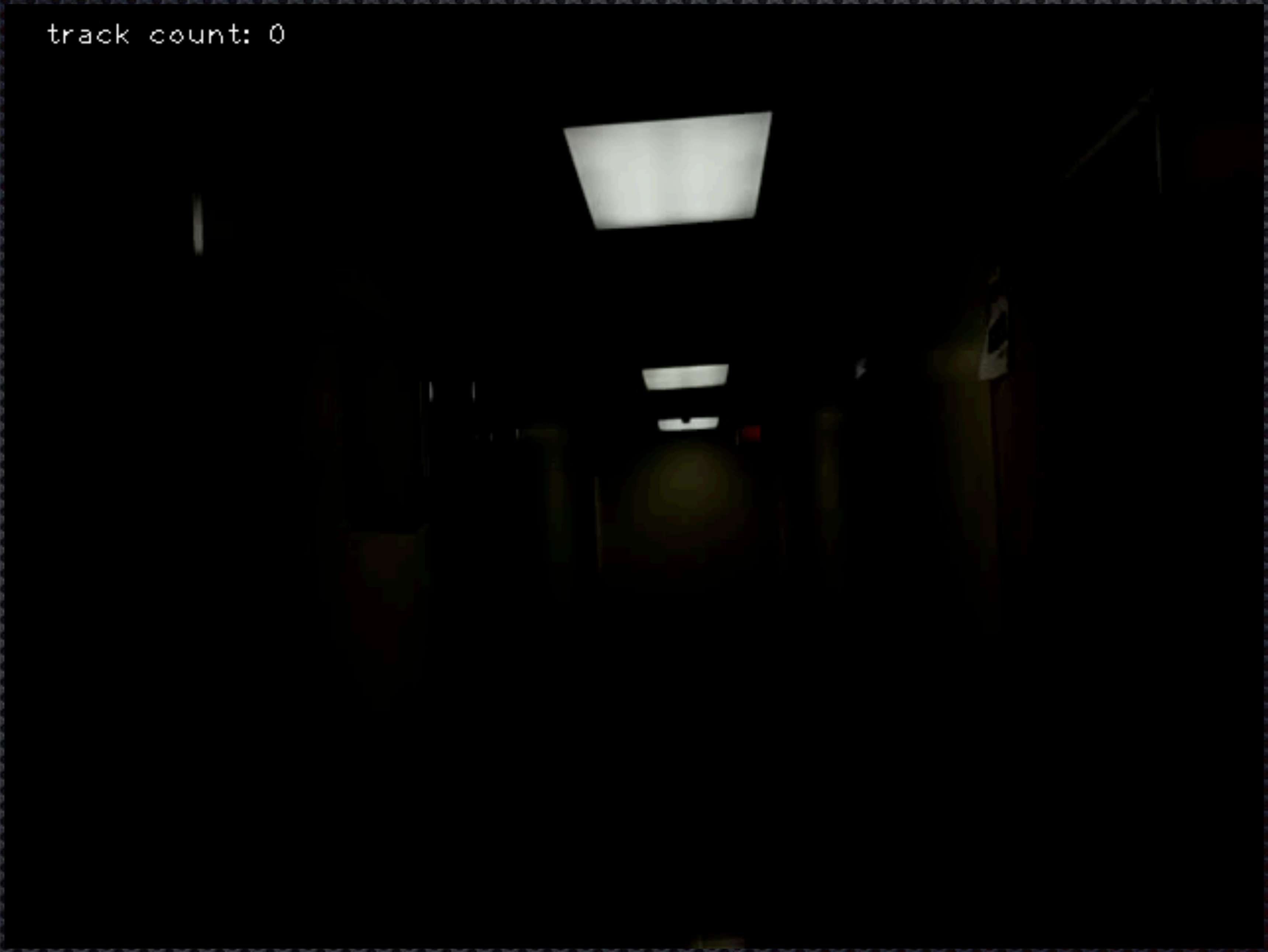
But, at high speed, features are ephemeral. . .

Motion primitives based on τ and d

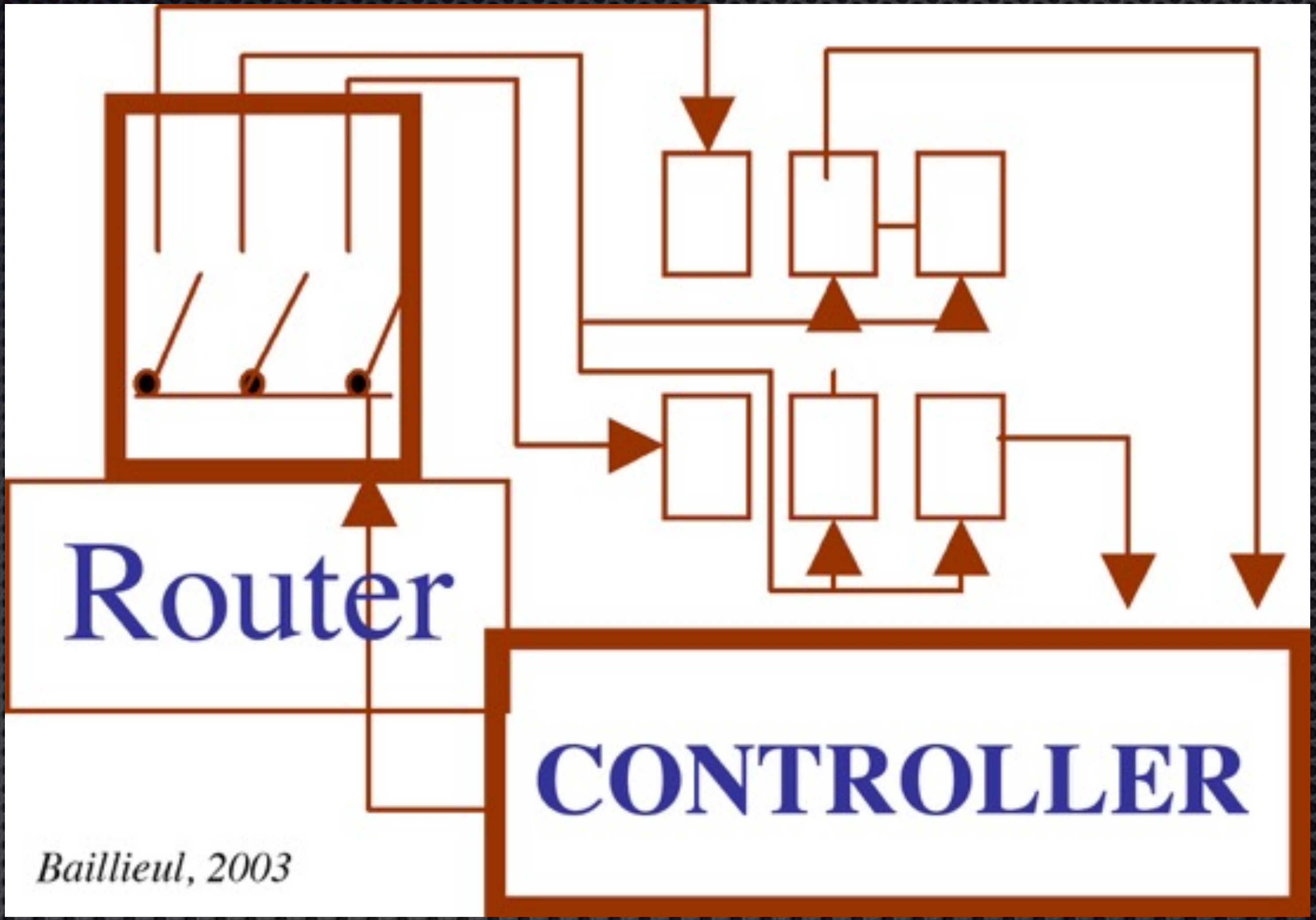
- Fly between features
- Fly in alignment with a row of features
- Circle features

Experiments with vision-based navigation

Translating Optical Flow into a Steering Signal



Networked control with channel intermittency:



Contributions to this problem:
Zhang & Hristu, Automatica, 2006, Yu and Andersson, CDC, 2013, JB and Kong, CDC, 2014 & arXiv.org

Networked control with *random* channel intermittency:

Lemma: Let $\mathbf{X} = \{x_1, \ldots, x_n\} \subset \mathbb{R}^n$ be a set of n linearly independent vectors. Let $\{\gamma(j)\}_{j=0}^{k-1}$ be a random sequence of integers drawn form the uniform distribution on the set $\{1, 2, \ldots, n\}$. The probability that the corresponding sequence $\{x_{\gamma(0)}, x_{\gamma(1)}, \ldots, x_{\gamma(k-1)}\}$ spans $\mathbb{R}^n$ is

$$p(n, k) = \frac{n! S(k,n)}{n^k},$$

where $S(k, n)$ is the Stirling number of the second kind denoting the number of ways to partition a set of k objects into n nonempty subsets.

Networked control with channel intermittency:

Proposition: Consider the system

$$\dot{x} = Ax + Bu$$

under the assumption that (A, B) is a controllable pair and B is an $n \times m$ matrix with $M > 1$. Let $\gamma(0), \ldots, \gamma(k_f - 1)$ be a random sequence drawn sequentially with equal probability and replacement from the index set $\{1, \ldots, m\}$. If $k_f \geq n$, the probability $p(m, k_f)$ that the corresponding random vector sequence

$$b_{\gamma(k_f-1)}, Ab_{\gamma(k_f-1)}, \ldots, A^{k_f-1}b_{\gamma(0)}$$

spans $\mathbb{R}^n$ satisfies the following inequality

$$0 < p(m, k) \leq \frac{m!\, S(k, m)}{m^k}, \tag{1}$$

where $S(k, m)$ is the Stirling number of the second kind.

Networked control with channel intermittency:

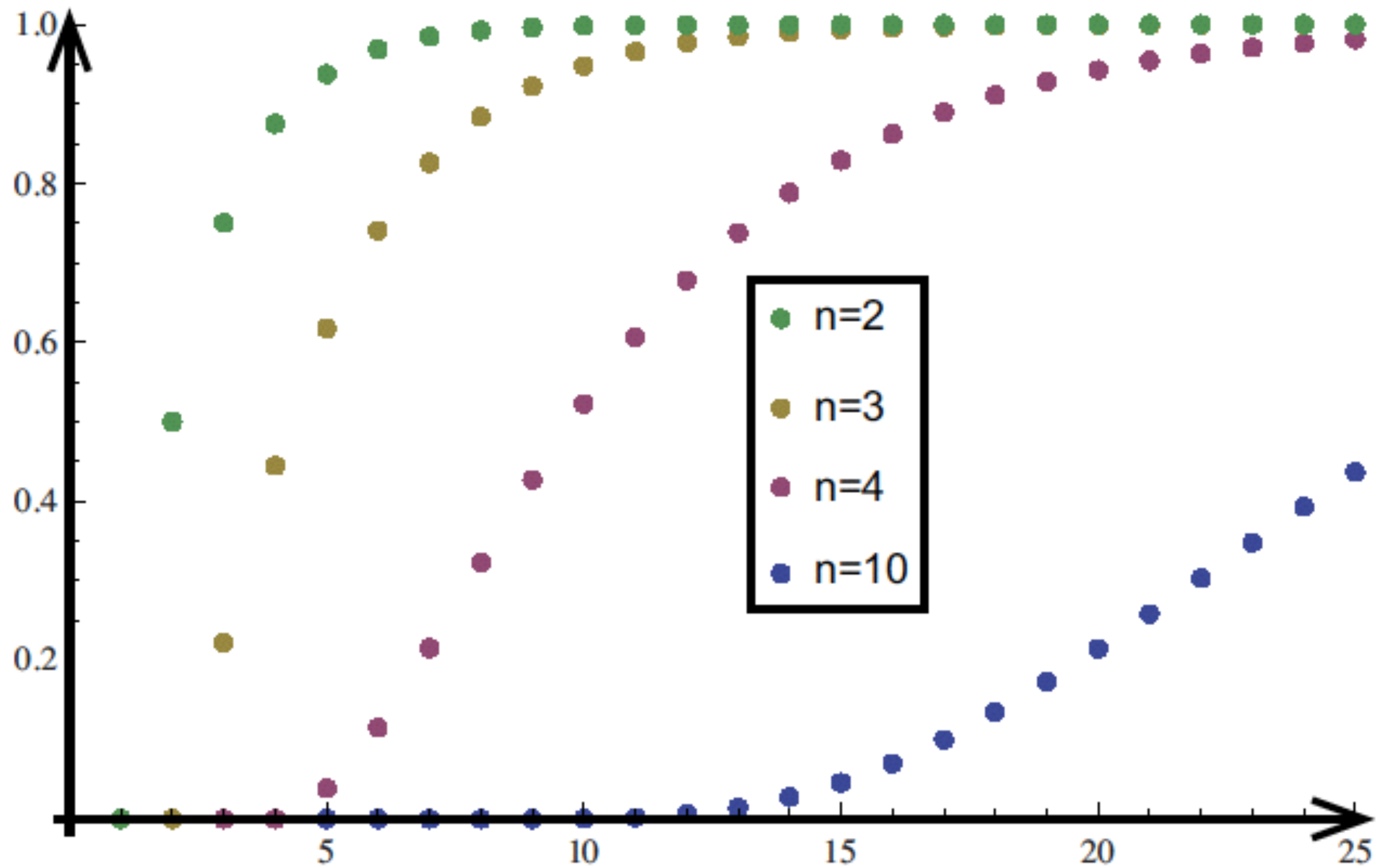


FIG. 2.1. *For a spanning set* $\mathbf{X}$ *of vectors in* $\mathbb{R}^n$ *for any* n*, the probability that a random sample of size* $k \geq n$ *will span approaches 1 as* k *becomes large. The rate of approach decreases for large* n*, as illustrated in the figure (for* $n = 2, 3, 4, 10$*).*

Conclusions:

- Animals are in general social — they react to each other as they carry out life's activities.
- Animals typically rely on spatial and other situational memories.
- Perception is a complex combination of cognition and sensing, and while each stream of sensory information plays an important role in bat navigation, it is the emergent effects of combining modalities that enables bats to fly through complex spaces.