Searching In Random Environments

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Searching

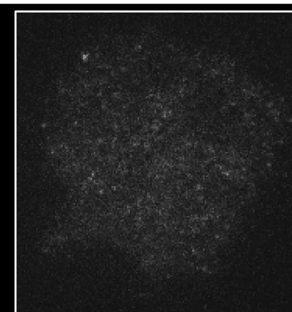
- Scale: nm, μm , mm , m , 10^{th}m, km.
- Cue (if any) propagation: Diffusion, ballistic, turbulence.
- Statistics of the environment: homogeneous, heterogeneous, disappearing probability.
- Searcher motion dynamics: velocity, run-tumble, crawl-headcast, fly-walk etc.
- Computation capacities of the searcher: Biochemistry, few neurons, numerous neurons.
- Representation of the environment: Space perception, statistics of environment, other searchers.

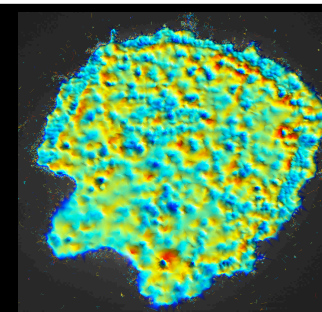
Outline

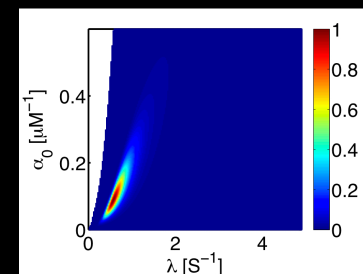
- Biomolecules Random Walks

Large knowledge, Models
Strategies and Bayesian Inference

- Bacteria (*E. coli*), *C. elegans*, Neutrophils





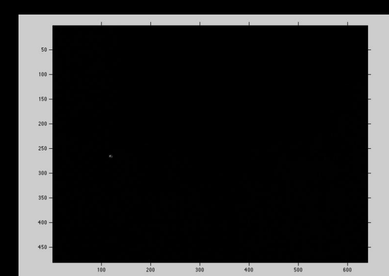


- Larva

- Robots

Heterogeneity, Intermittency, turbulence
Less knowledge (growing)

- Insects



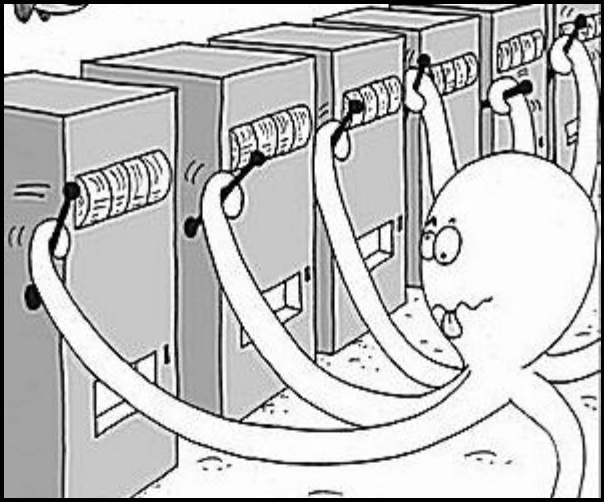
M. El-Beheiry *et al*, *Nature Methods* ***12****, 594-595 (2015)*
JBM et al, PNAS 109, No 5, p1802-1807,(2012)
M. Sarris *et al*, Current Biology, 22, p2375-2382, (2012)
E. Korobkova *et al*, Nature 428:574–578. (2004)
H. Park *et al*, *Nature 468(7325): 819-23, (2010).*
L. Luo et al, Neuron 82:1115-1128 (2014)

Exploration/Exploitation

- Searching is an information game
- Source sends noisy message that the searcher attempts to decode
- for all searchers there is a balance in decision making
  - **Explore** the environment to acquire more information
  - **Exploit** accumulated information to make decision

2-Armed Bandit: explore-exploit Games

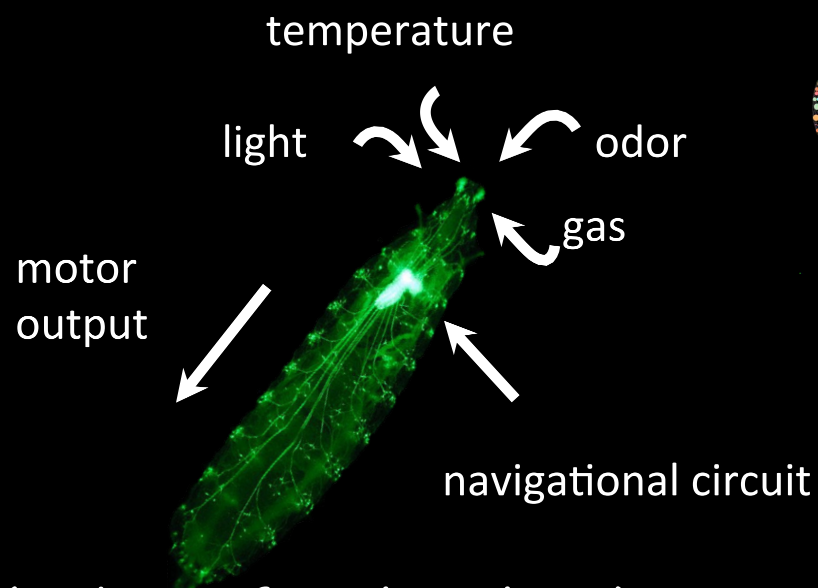
- Multi-Armed Bandit Game
  - N "Bandit" machines with unknown paying probabilities, p_i
  - Operator sequentially plays bandit to find the best one
  - Goal: efficient strategies to have the smallest regret

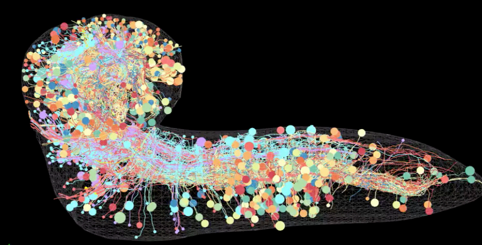


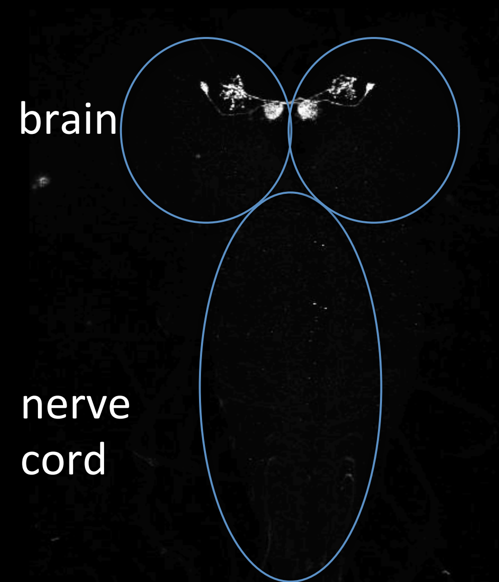
- Explore/Exploit
- Playing the same machine increase information on the machine
- Playing another machine : it might a better one
- Hard decision Making: Pain/Threat (Low level) ppk

J.C. Gitiins, J. Roy. Stat. Society Series B, 148-177, (1979)
T. Ohyama *et al*, *Nature* ***520****, 633–639 (2015)*

Drosophila Larval







- 3 instar (3 days after hatching)
- 2-5mm
- Start development on their food
- No Food: immediately start to search
- 10000 neurons
- Genetic targeting of individual neurons
- Optogenetic Stimulation of identified neuron/s with chrimson

Albert Cardona

Stephan Saalfeld

Marta Zlatic

James Truman

T. Ohyama *et al*, *Nature* ***520****, 633–639 (2015)*

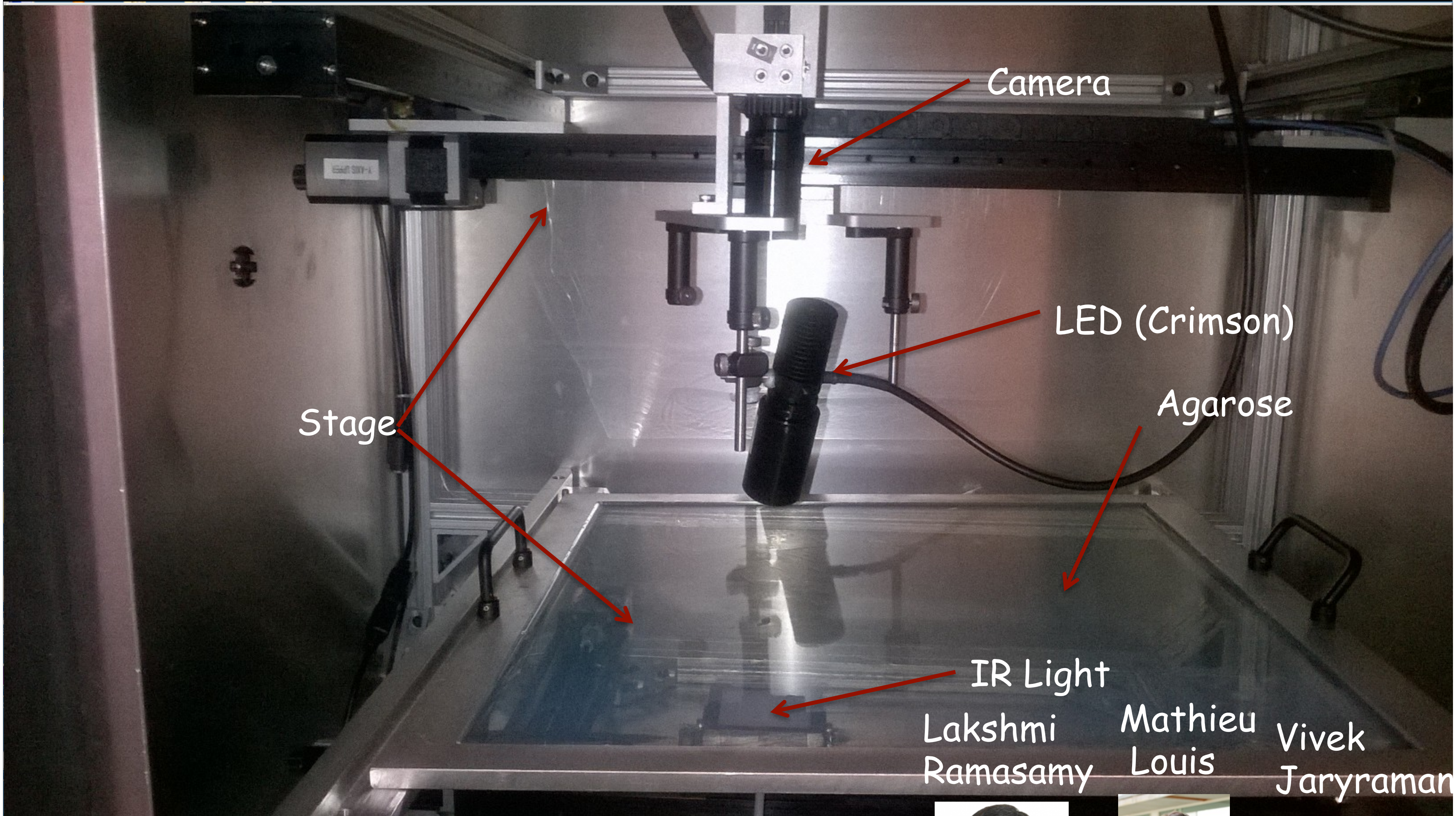
B.D. Pfeiffer *et al,* PNAS vol. 105 no. 28, p 9715–9720 (2008)

Playing the Bandit Game

- We need a close-loop system:
  - Assessing behaviour **live**
  - Stimuli depending on behaviour
- Increasing attempt to quantify Behaviour from video
- Large number of features extracted + Data Tagging
- JAABA based on GentleBoost
- The larva is complex
  - Large variance in images.
  - Deformable object, multiscale dynamics.
- Limited number of features
- Features are accessible up until time t
- Image analysis with OpenCV
- 15ms data acquisition and basic processing
- 5ms features + classification

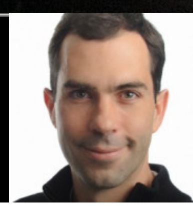
M. Kabra et al, Nature Methods 10, 64-67, (2013)
F. De Chaumont et al ,*Nature Methods* **9**, 410–417 (2012)
G.J. Stephens *et al*, Plos Comp Biol, 4(4): e1000028 (2008)
G.J. Stephens *et al*, *PNAS (USA)* **108,** 7286-7289 (2011).

Setup



- C++, Qt and OpenCV

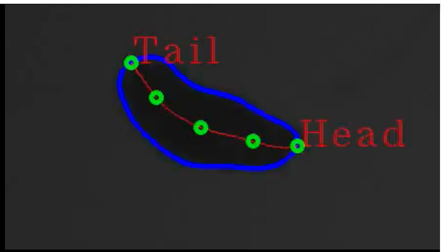
A. Schulze *et al,* eLife 2015;4:e06694



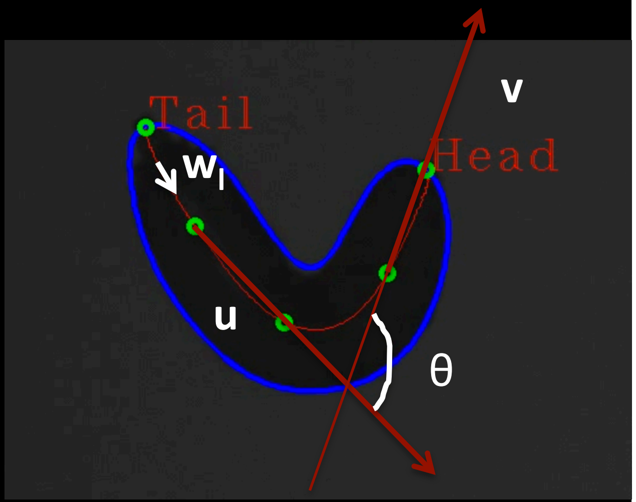
Eric
Trautman

ID&F ID&F

Features



- Angle $\theta = a\cos(\vec{u}.\vec{v})$
- Nematic spline $S = \frac{1}{N-1}\left(3\sum_{i=1}^{N-1}\vec{u}.\vec{w}_i - \frac{1}{2}\right)$
- Reduced eigenvalues $\tilde{\lambda} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} = \sqrt{1 - \frac{4\left(\langle x^2\rangle\langle y^2\rangle - \langle xy\rangle^2\right)}{\left(\langle x^2\rangle + \langle y^2\rangle\right)^2}}$
- Agitation velocity $\langle\|\vec{V}\|\rangle = \frac{1}{3}\left(\|\vec{V}_{neck}\| + \|\vec{V}_{top\_neck}\| + \|\vec{V}_{down\_neck}\|\right)$
- Asymmetry factor $As = \vec{u}.\vec{v}$
- Damped distance $d = \sum_{i=0}^{t}\gamma^i d_{t-i} \qquad d_{t-i} = \|\vec{r}_{neck}^{\,t-i} - \vec{r}_{neck}^{\,t-i-1}\|$
- Negative velocity $\vec{V}_{neg} = \vec{V}_{neck}.\vec{u}$
- Squared Smoothed delayed derivatives

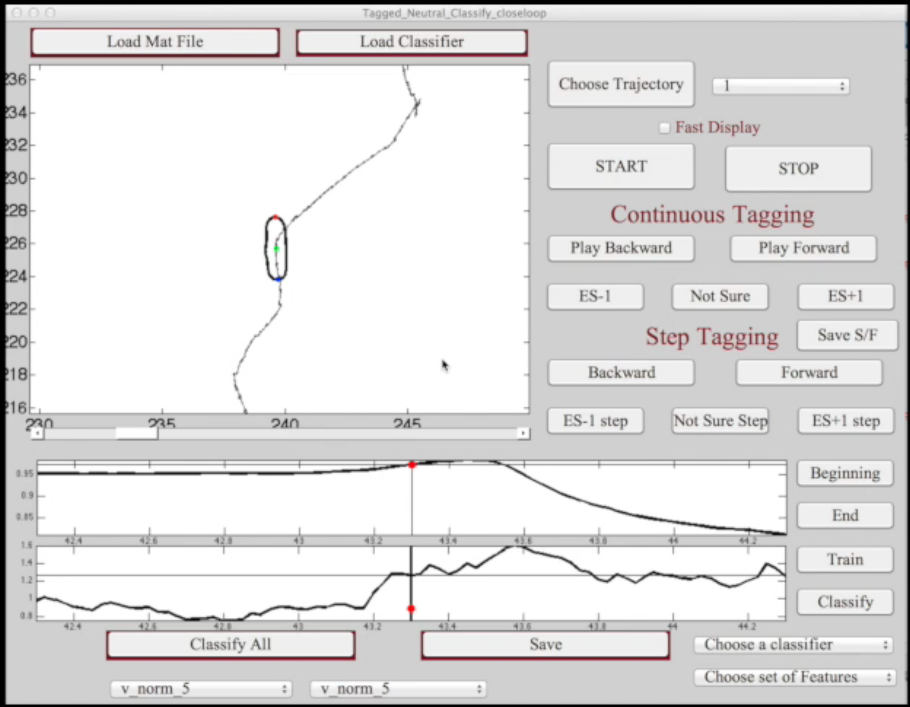


$$F'(t) = \left\|\int_{-\infty}^{t} K(t-s)F(s)\,ds\right\|^2$$

$$K(t) = e^{-\lambda t}(1 - \lambda t)$$

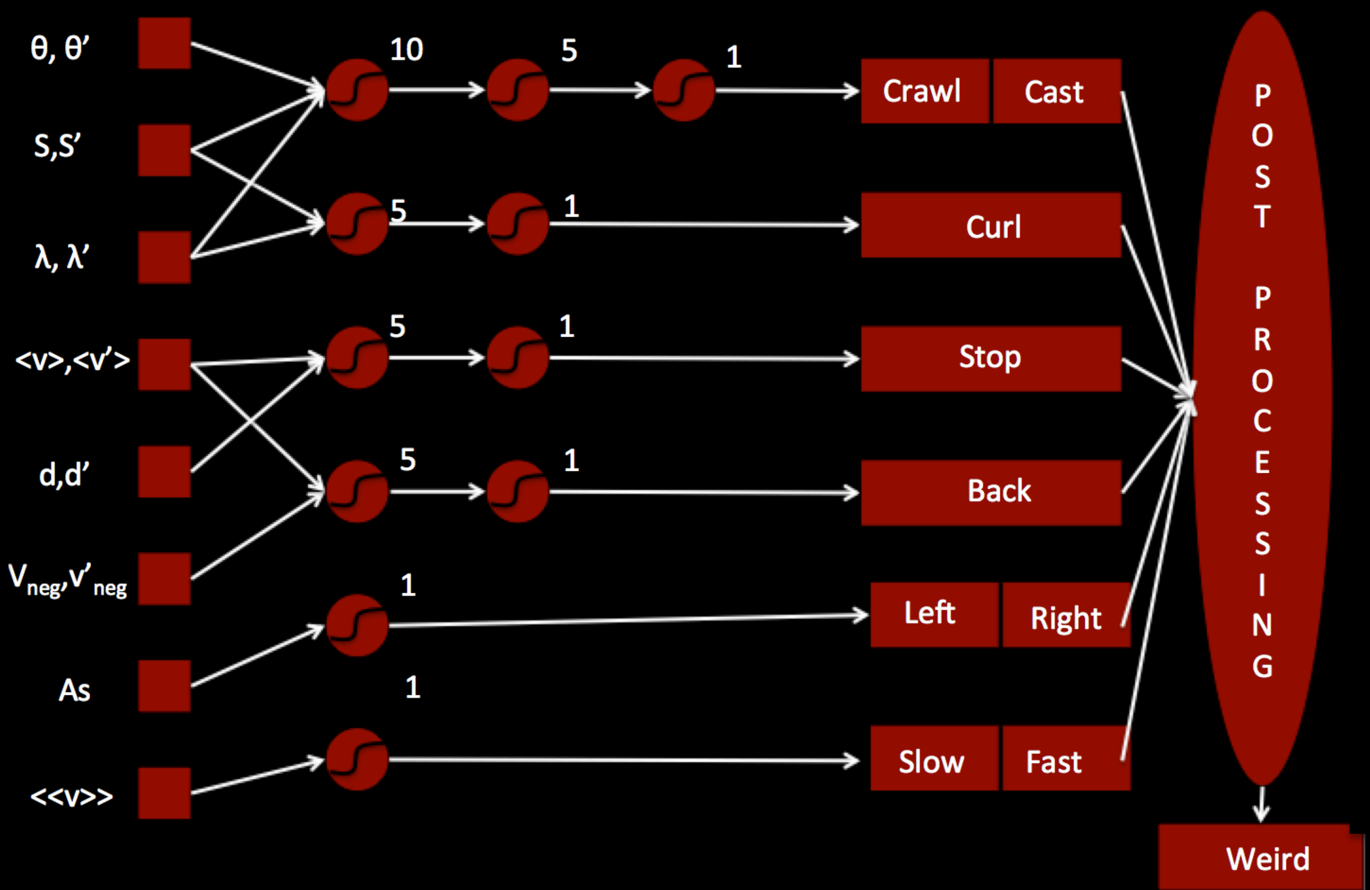
Custom tagging sofware

- Matlab Gui
- Replay experimental data
- Evaluate features at all time
- Trajectory + specific points
- {+1;0;-1} tagging
- Issue with Ground-Truth-ing
  – No easy agreement on some behaviour
  – Tagging extreme state
  – 2-3 larvae tagging
- Save features + states

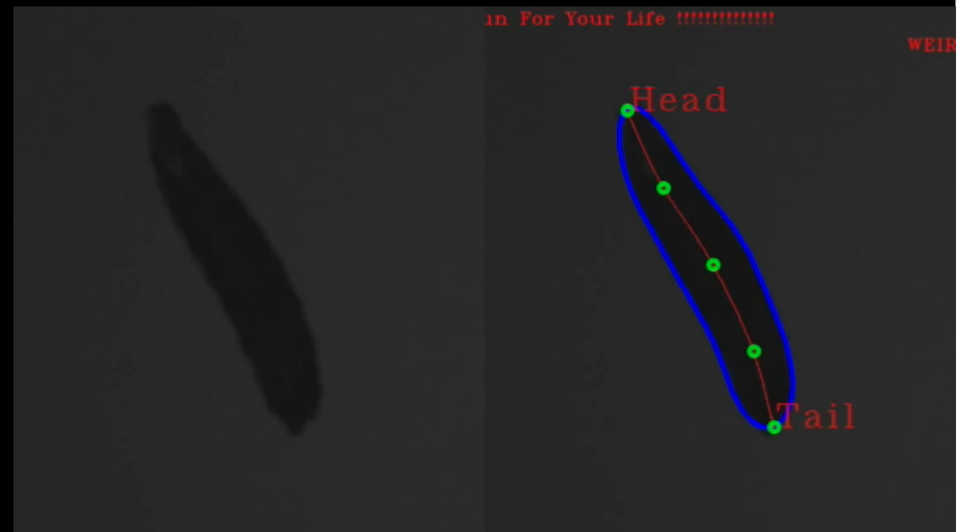


Classifying

- Simple Neural Network
- Pre-structure architecture
- Small data set
- New Version: Random Forest



Live Behaviour

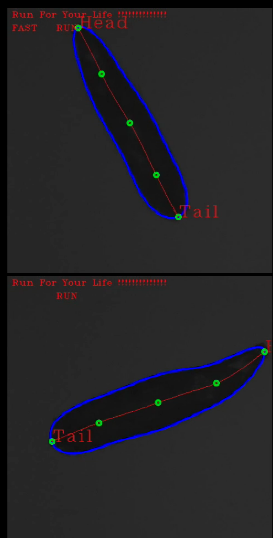


- 40-50 Hz recording
- Live behaviour assessment
- No fast oscillations between Behaviour
- 2 larvae tagging

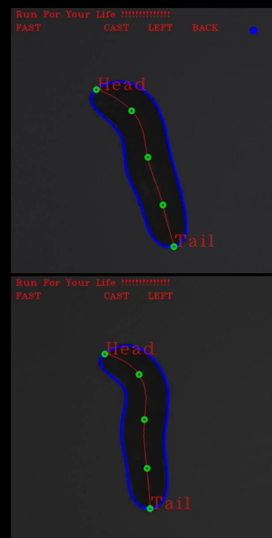
- Save videos
- Save features + contour in text files
- 5min-5hours recording

Behaviour

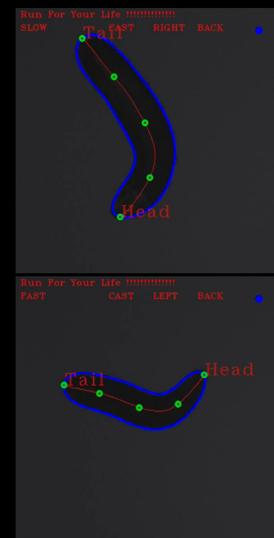
Crawl



Cast

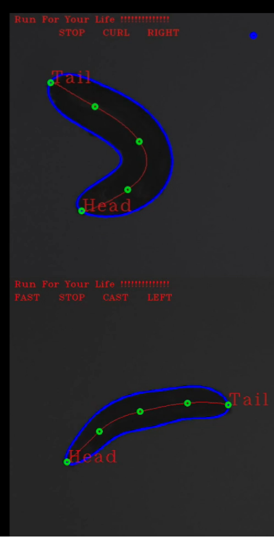


Back

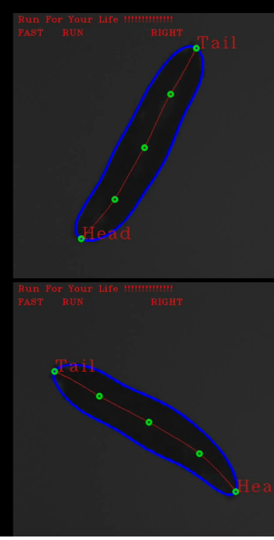


Curl

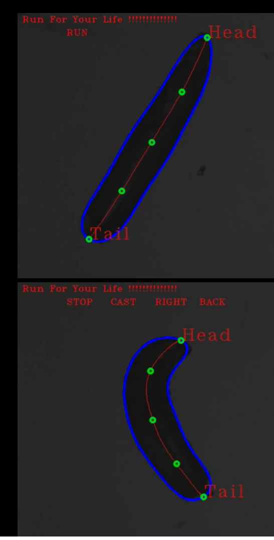
Stop



Roll



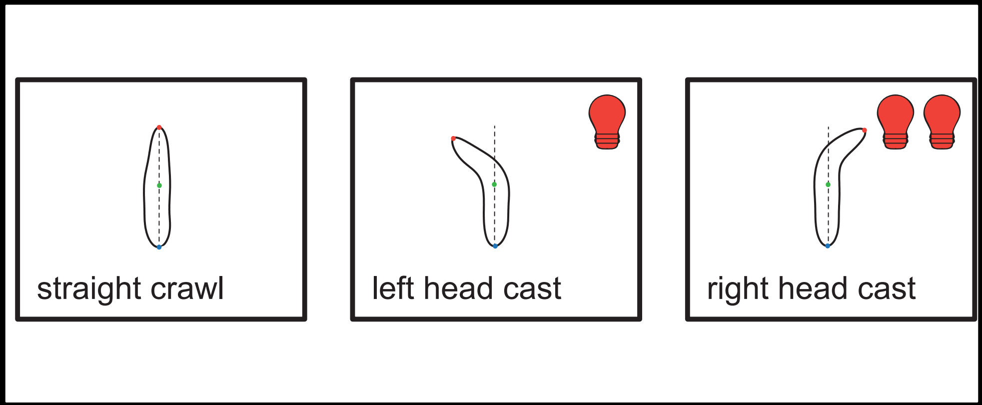
Escape



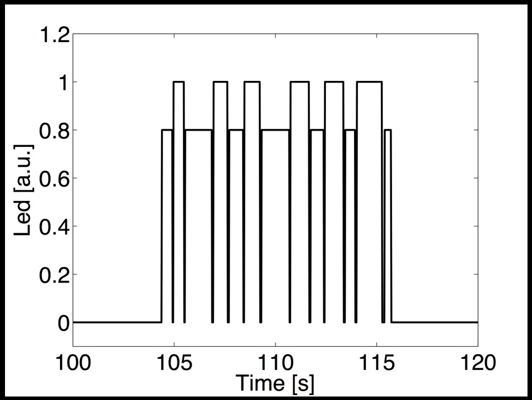
Larva Playing The Bandit Game

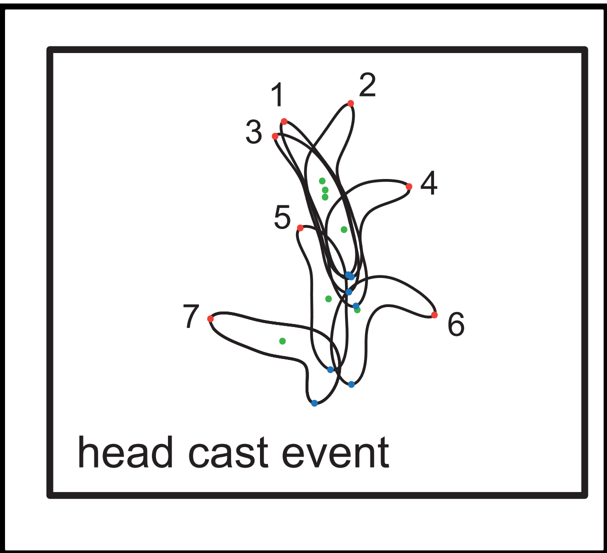
- 2-Armed Bandit
- The Game starts when the larva starts Head-Casting
- Each Side Is associated to a stimulus
- The Game is finished when the Larva choses a side and crawl

- 2 Games
- Game 1: S_0=0, S_1=50%-S_2=100%
- Game 2: S_0=100, S_1=25%-S_2=75%



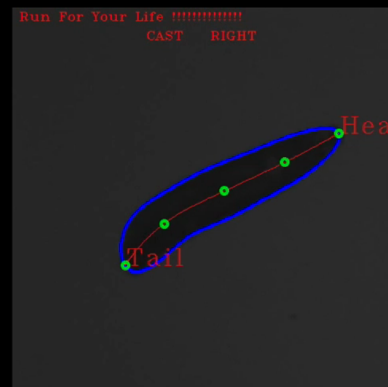
Example Stimuli Game 1



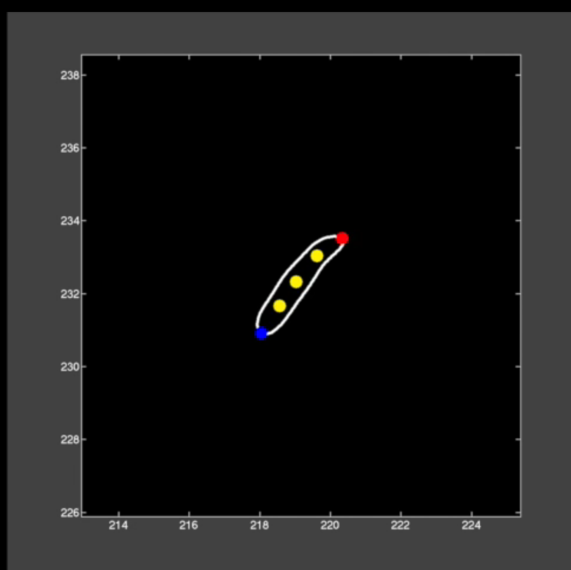


Larva Playing the Game

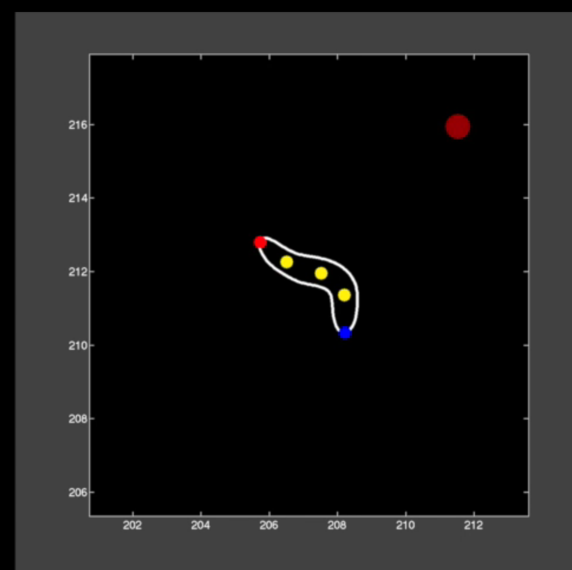
HeadCast



Game 1



Game 2

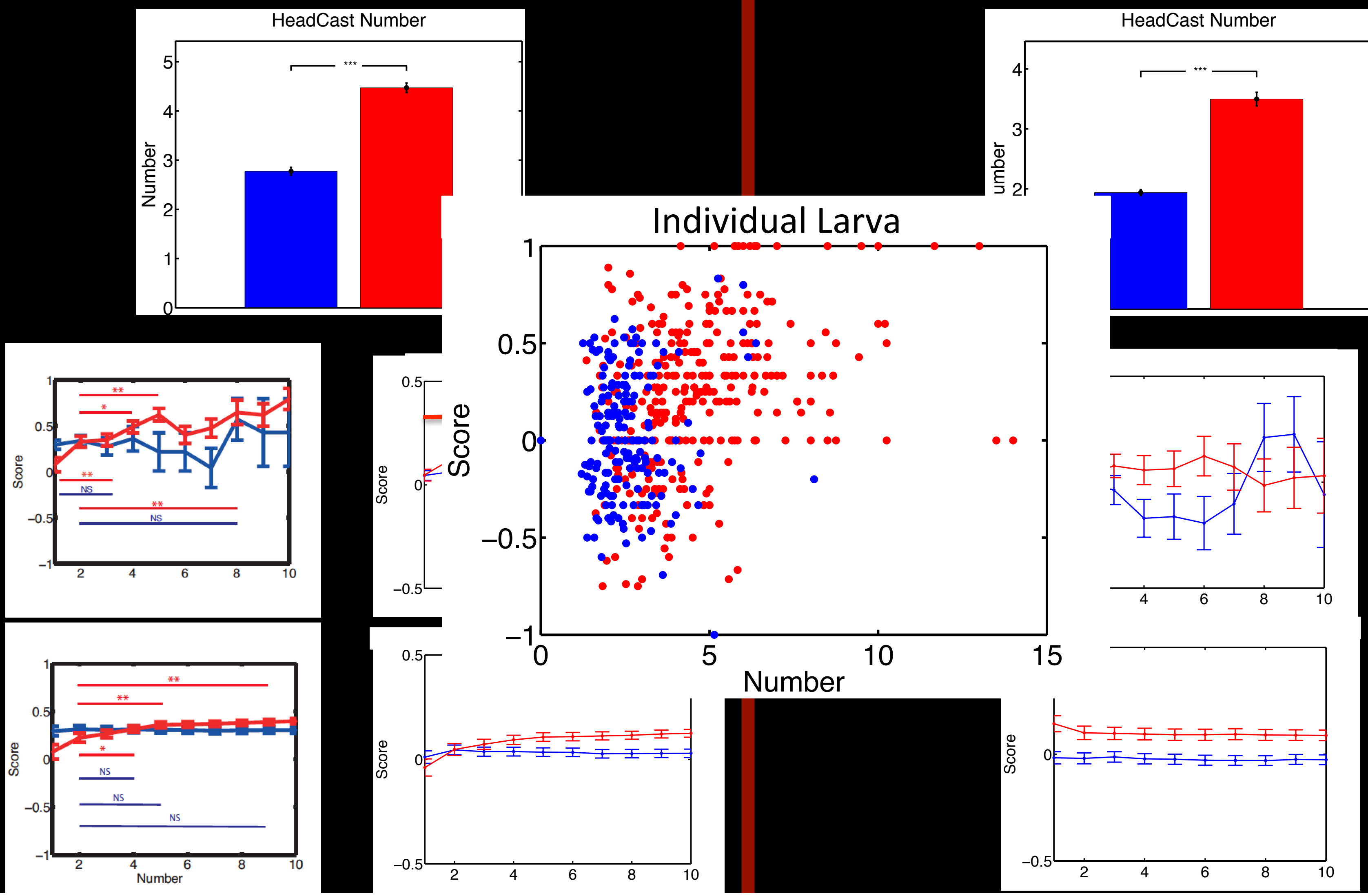


Exploring to make good decision vs ε-greedy

Game 1
(5500 games)

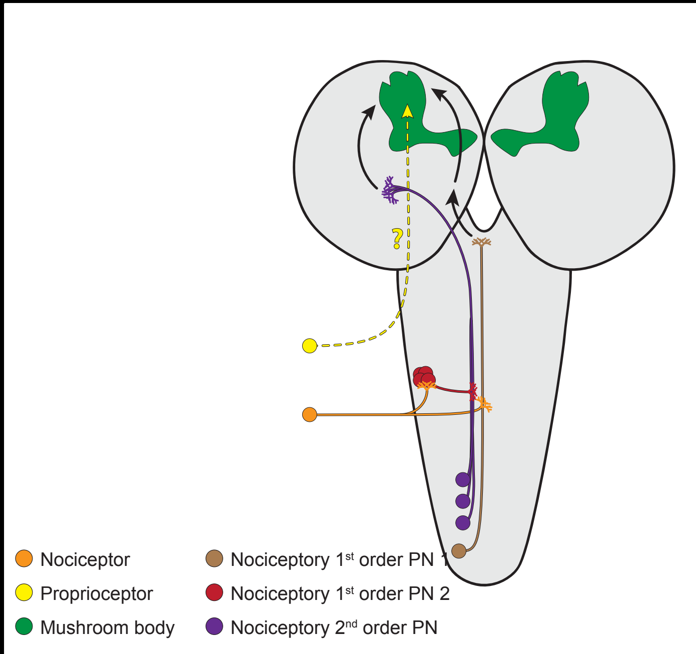
ppk
attp2

Game 2
(3000 games)



Larva playing the Bandit Game

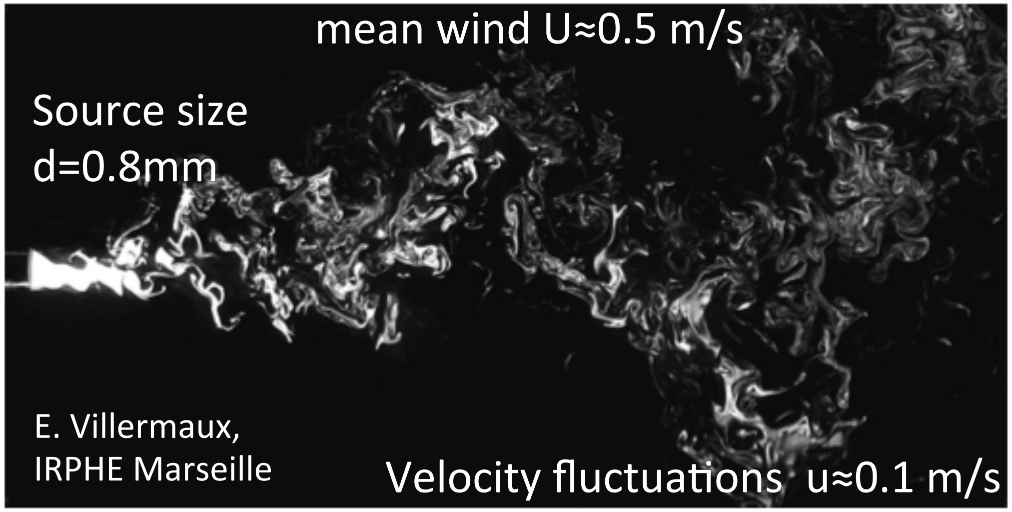
- The Bandit Game as a probe of exploration/ exploitation dynamics
- Larva modulates the number of HeadCasts
- Explorers outperforms exploiters
- Strategy Switch between games
- Neural substrate for the strategy



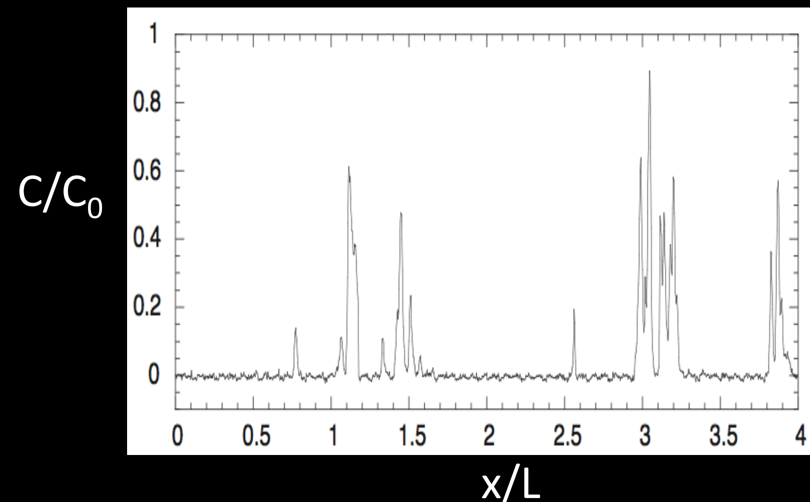
- Strategies depend on the nature of the stimuli: Nociceptive, Olfactory, Thermal.

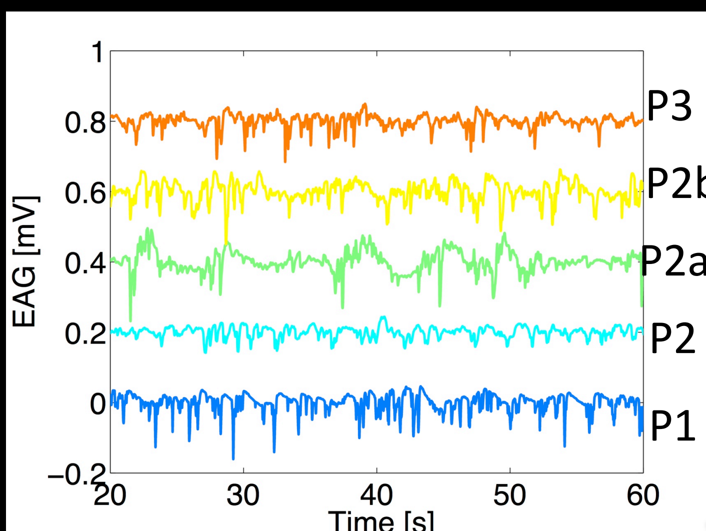
L. Hernandez-Nunez *et al*, eLife 2015;4:e06225 (2015)
R. Gepner *et al* , *eLife.06229 (2015)*
M. Klein, PNAS 112(2):E220-229 (2015)
E.A. Kane, PNAS;110:E3868-77 (2013)

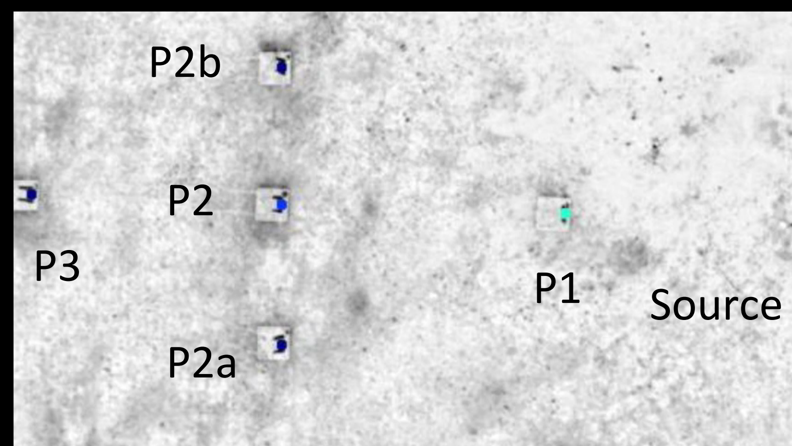
Turbulence



turbulent velocity correlation length L=8 cm







G. Falkovich *et al*, Rev. Mod. Phys. 73:913-975 (2001)

A. Celani *et al,* Phys. Rev. X 4, 041015 (2014)

Consequences

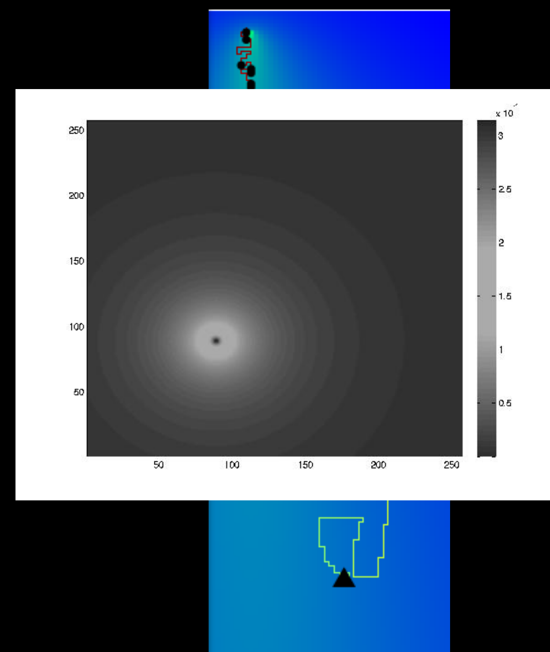
- No Global Gradients
- Intermittent Signal
- Local Gradients don't point towards the source
- Local detections give very limited information on the source (Position, Emission Rate, Multiple Sources)
- Information Theory

R.S. Sutton & A.G. Barto, MIT Press, Cambridge (1998)
R.E. Bellman, Princeton University Press (1957)
K.L. Leyton-Brown & Y. Shoham, Syn. Lect. Art. Int. Mach. Learn. (2008)
D. Mackay, Cambridge Univ Press (2003)

Deciphering the Noisy Message sent by the source

- Detections (and no detections) are messages sent by the source
- $R(r \mid r_0)$ hit rate at the position r when the source is at r_0
- After H detections

$$P_t(r_0) = \frac{e^{-\int_0^t R(r(s)\mid r_0)ds} \prod_{h=1}^{H} R(r(t_h)\mid r_0)}{\int dz\, e^{-\int_0^t R(r(s)\mid z)ds} \prod_{h=1}^{H} R(r(t_h)\mid z)}$$



- Maximizing Likelihood : Lost Searchers
- Information Based Decisions: Infotaxis

$$\langle \Delta S \rangle (r \rightarrow r_j) = P_t(r_j)[0 - S] + (1 - P_t(r_j))[\rho_0 \Delta S_0 + \rho_1 \Delta S_1 + \ldots]$$

M. Vergassola *et al,* Nature 445(7126):406–409
JBM *et al,* J. Phys. A.: Math. Theor., 42, 434009, (2009)
C. Barberia *et al*, Europhys Lett 94(2):20005.
T.M. Cover & J.A. Thomas, Wiley & Sons, (2006)
N. Tishby *et al* , The 37th an.l Allerton Conf. on Com., Cont., and Comput. pp. 368–377 (1999)

Insect Space Perception

- Probability Map building requires space perception and odometry error corrections.
- How to integrate external cues?
- Definition of cognitive maps and space perception?
- Various Orientation/navigation Strategies depending on insects
- Integrating space perception in search strategies

R. Wehner, Birkhauser, Basel (1987)
P.K. Visscher *et al*, Ecology 63:1790-1801 (1982)
A.T. Bennet, J. Exp. Biol. 199, p219-224 (1996)
M. Colett *et al*, Nature 394:269:272 (1998)
J. Jefferey, Oxford Univ Press (2003)
M. Mizumani *et al,* J. Comp. Neurol. 402, 501-537, (1998)
R. Wehner *et al,* Annu. Rev. Neurosci. (1990)
T.A. Ofstad *et al,* Nature 474(7350):204:207

J. Murlis *et al*, Annu Rev Entomol 37:505–532 (1992)
A. Mafra-Neto *et al* Nature 369:142–144 (1994)
J.S. Kennedy *et al,* Physiol Entomol 27:58–66 (1983)
N.J. Vickers *et al*, Nature 410(6827):466–470 (2001)
N.J. Vickers *et al*, Biol Bull 198(2):203–212 (2000)
M.A. Willis *et al*, Exp Biol 214, 4121–4132 (2011)
F. Van Breugel, Cur. Biol , 25, 2123–2129 (2015)

Free Energy Based Search Strategy

- Limited Space Perception

$$P_t^M\left(\vec{r}_0 \middle| \Theta_t\right) = \frac{e^{-\frac{\|\vec{r}_0-\vec{r}_G\|^2}{\lambda_G^2}}\left(1-\frac{1}{N_M}\sum_{j=N_t-N_M+1}^{N_t} e^{-\frac{\|\vec{r}_0-\vec{r}_j\|^2}{\lambda_u^2}}\right)}{Z_t}$$

Detections term — No Detections term

$$\vec{r}_G = \sum_{i=1}^{G}\gamma^{G-i}\vec{r}(t_i) \Big/ \sum_{i=1}^{G}\gamma^{G-i}$$

- Decision process

$$F_t(\Theta_t) = W_t(\Theta_t) + TS_t(\Theta_t) = \iint_A d\vec{r}_0 P_t^M(\vec{r}_0|\Theta_t) - T\iint d\vec{r}_0 P_t^M(\vec{r}_0|\Theta_t)\log P_t^M(\vec{r}_0|\Theta_t)$$

Work — Entropy — Max Likelihood — Exploration/exploitation

$$\Delta F_t(\vec{r}_t \to \vec{r}_{t+dt}|\Theta_t) = P_t^M(\vec{r}_{t+dt})\left[1-F_t\right] + \left(1-P_t^M(\vec{r}_{t+dt})\right)\sum_{i=0}^{1}\rho_i(\vec{r}_{t+dt})\Delta F_t^i$$

Discovery — Nothing

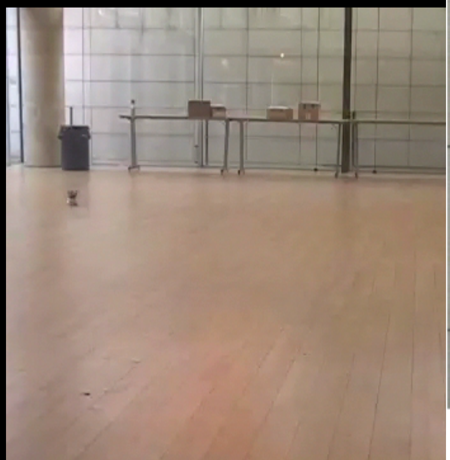
- Tradeoff between exploration and exploitation : Control with T

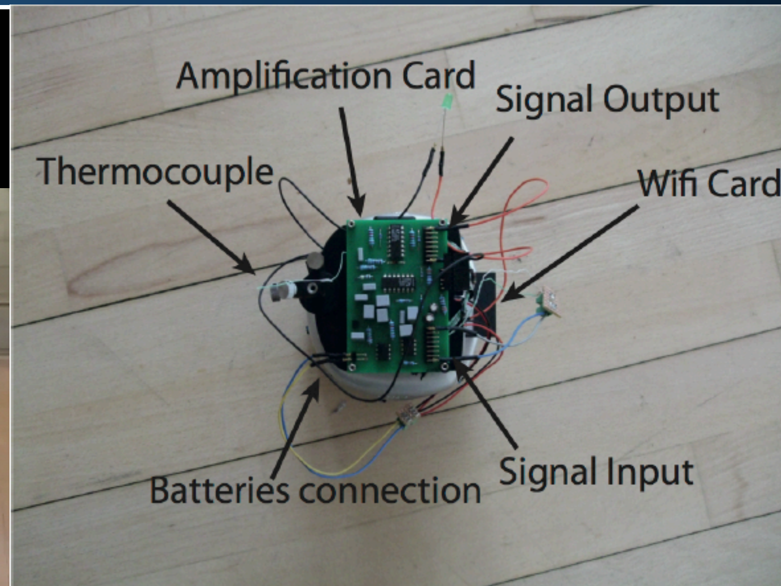
JBM, PNAS, vol. 110, No. 28 p.11261-11266 (2013)

K. Friston, Entropy 14, p2100-2121, (2012)

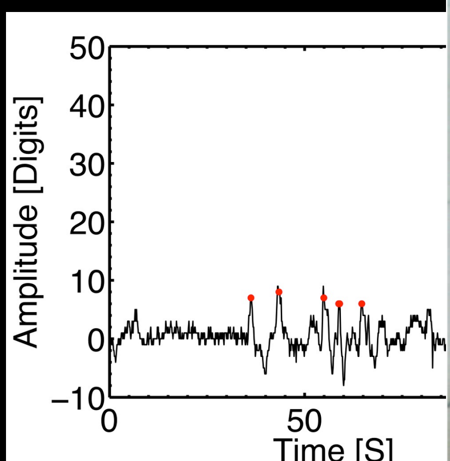
Experimental Searches

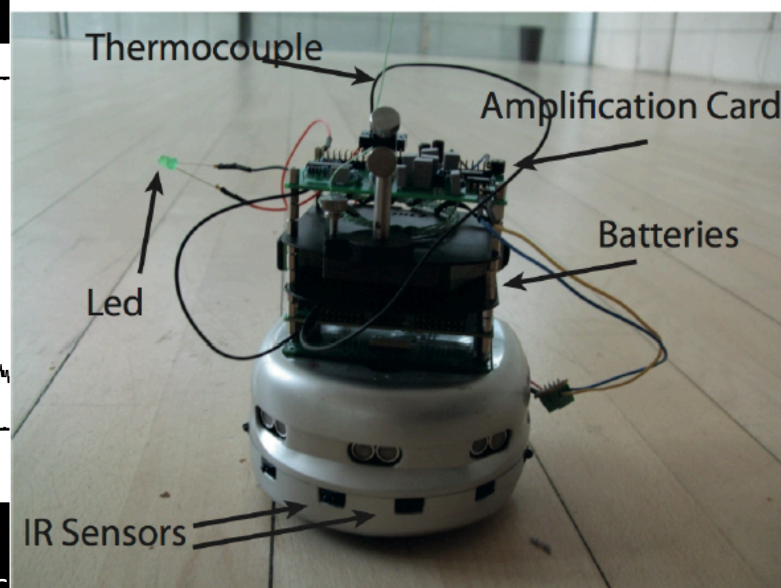
Windless

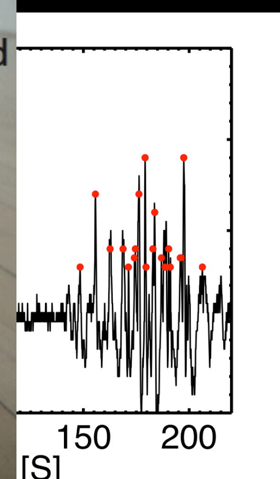




nformation







JBM, PNAS, vol. 110, No. 28 p.1126

d PCT/EP2014/055097

Swarm of Robots

$$\Delta F_t^s(\vec{r}_t^s \rightarrow \vec{r}_{t+dt}^s|\Theta_t) = P_t^M(\vec{r}_{t+dt}^s|\Theta_t)\;[1 - F_t] + (1 - P_t^M(\vec{r}_{t+dt}^s|\Theta_t))[\rho_0 \Delta F_t^{s,0} + \rho_1 \Delta F_t^{s,1}]$$

$$\Theta_t = \{\Theta_t^1, \Theta_t^2, \ldots, \Theta_t^s, \ldots\}$$

S. Zhang *et al*, *Front. Robot. AI* 2:12. (2015)

Searching in the Turbulent Realm

- Space Perception not required
- Error accumulation
- Short memory
- Greedy Decision
- Sharing incomplete and noisy Information

Rhyncophorus Ferrugineus (Rhynco)

- Advantage
  - Complex Behaviour
  - Large and small scale searches
  - Flying ($5 m.s^{-1}$) Walking ($1\text{-}5 cm.s^{-1}$) search strategies
  - No predators (in some ways)
  - Eat Palm Trees (No more Palm Trees)

- Disadvantage
  - Very Limited knowledge
  - Realistic environments (light, sky, landscape)
  - Small pieces of knowledge on neuro-biology
  - No Dictionary of Behaviour

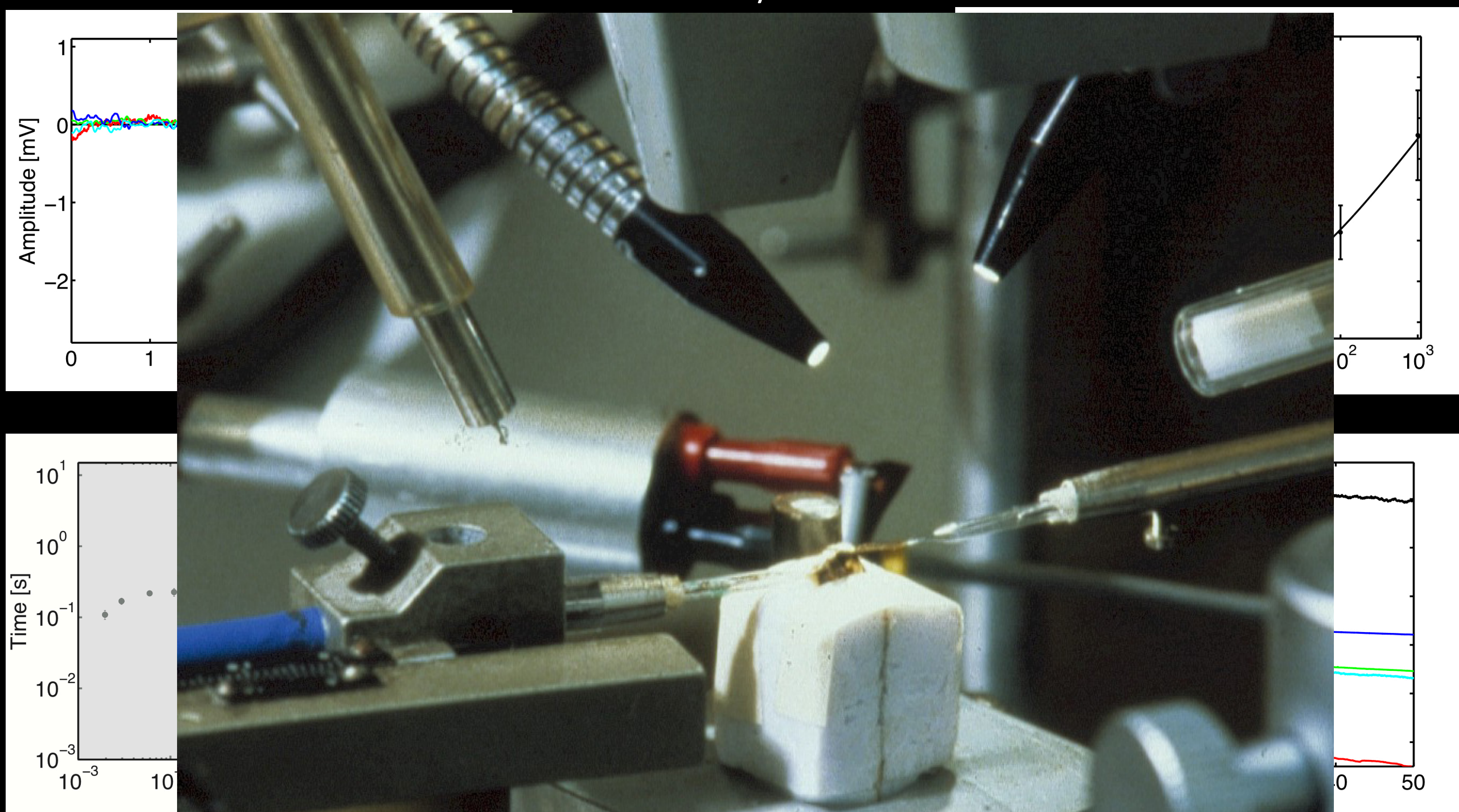
Experimental Searches

- Infer detections from behaviour is too difficult
- 2 Elements
  - Insect trajectories
  - Olfactory signal along the decision path

Antenna as "Sensors"

- Insects' Antenna highly efficient detectors
- Simple ElectroAntennoGram measures

cis-7-dodecenyl acetate



K.-E Kaissling *et al*, Naturwissenschaften 55:395, (1968).
Vivkers

G. Falkovich *et al*, Rev. Mod. Phys. 73:913-975 (2001)

Exploiting Turbulence properties and Antenna Selectivity

- Few Scaling and order of magnitudes

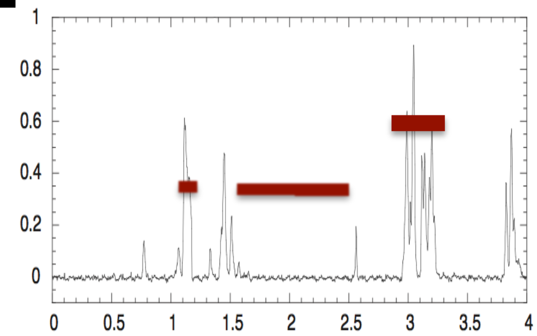
$$p(t) \propto \frac{1}{\tau}\left(\frac{\tau}{t}\right)^{\frac{3}{2}} f(\tau)$$ Whiffs/Blank duration

Whiff Clumps

$$\kappa \propto 10^{-7} - 10^{-8} m^2 . s^{-1}$$

$$Pe = \frac{UL}{\kappa}$$

$$N(T_w) \propto \sqrt{T_w / \tau}$$



- Turbulence maintains blends in the plumes

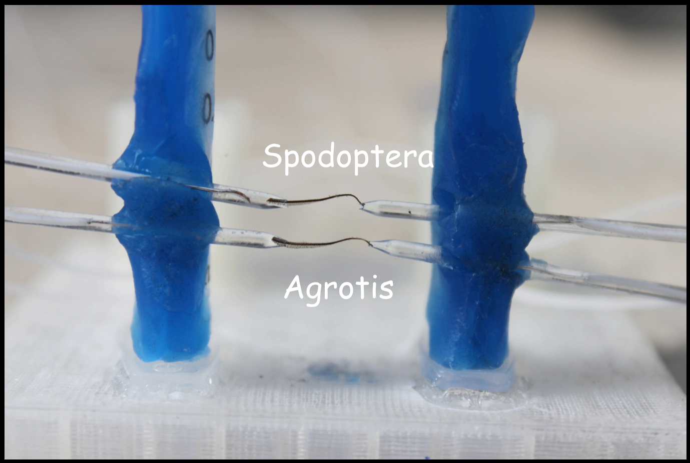
- Pheromones are specific to insect species

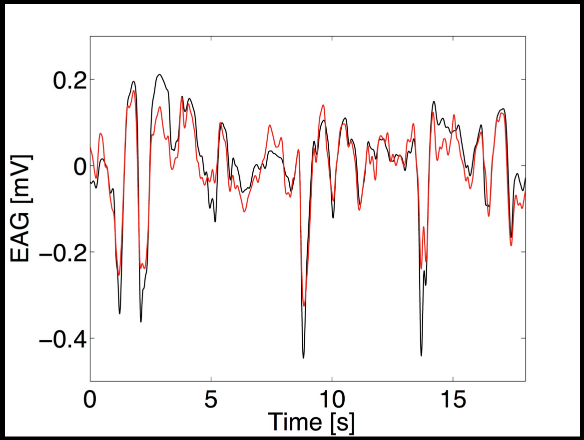
- Add Pheromone detected by another antenna to the odor mix.

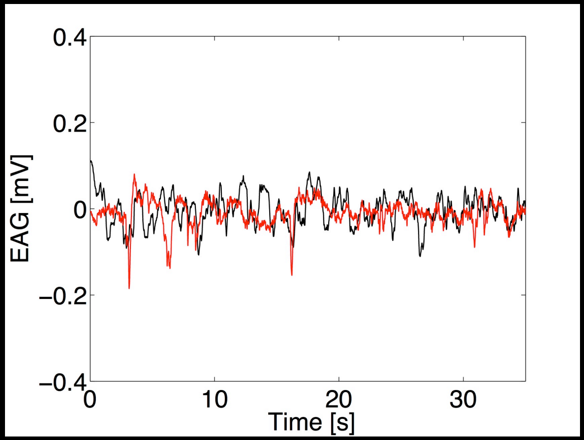
M. Kree *et al*, Phys. Fluids 25:091103 (2013)
G. Falkovich *et al*, Rev. Mod. Phys. 73:913-975 (2001)
A. Celani *et al*, Phys. Rev. X 4, 041015 (2014)

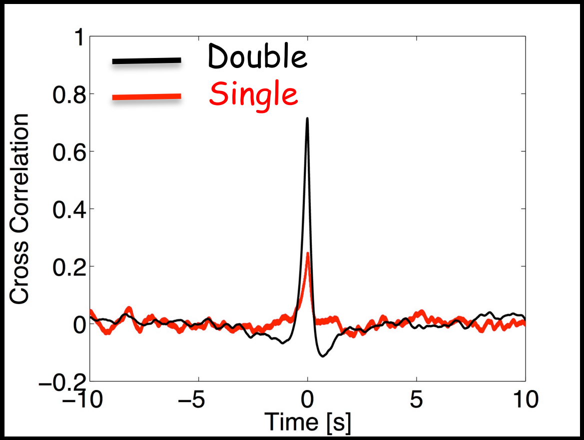
Mixture Plume Detection

- PID not sensitive enough
- Measure with double EAGs:
  - One Agrotis (Black)
  - One Spodoptera (Red)





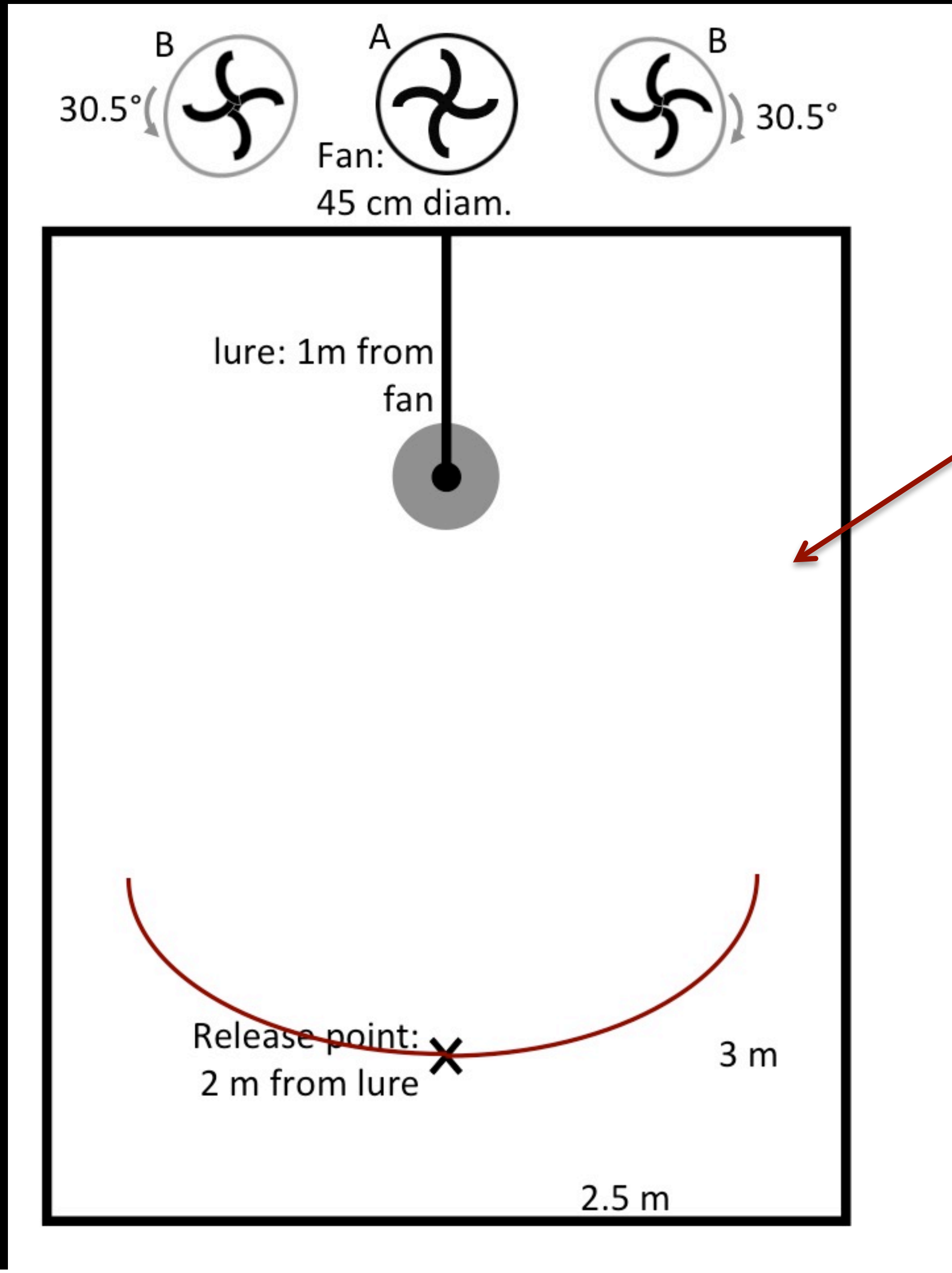




Setup

Quantitative elements

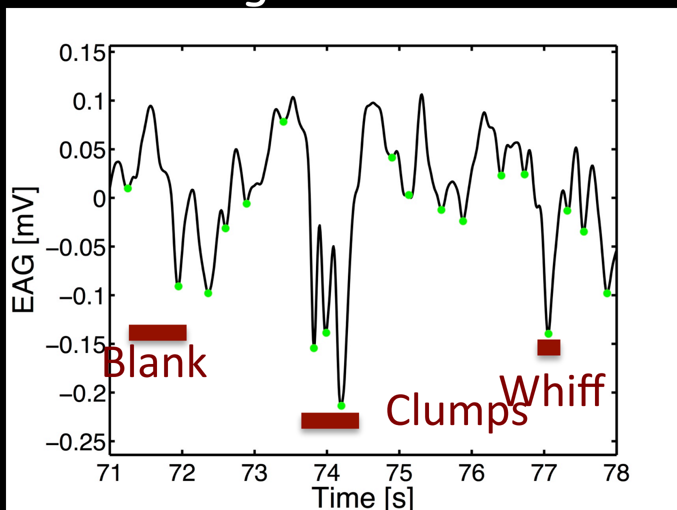
- U = 0.3- 2m.s
- $\delta v/U \approx 0.05\text{-}0.3$
- Re ≈ 10^3-10^4
- Pe ≈ 10^6
- (*Z*)-7-dodecenyl acetate (Agrotis Pheromon)
  1-10µg in 10µl Hexane
  EAG(10m) ≈ 300µV
- 4-méthyl-5-nonanol (ferrugineol)
  1µg in 10µl Hexane



Faraday Cage

Trajectory and Pheromone Detection

- Complex temporal dynamics
- Multi-scale peaks, Multi-duration peaks and peaks in peaks
- Peak detection using Random Forest
- Ground-Truthing on double EAG experiments (Manual correction)
- Out of Bag Error = 5.10^{-3}



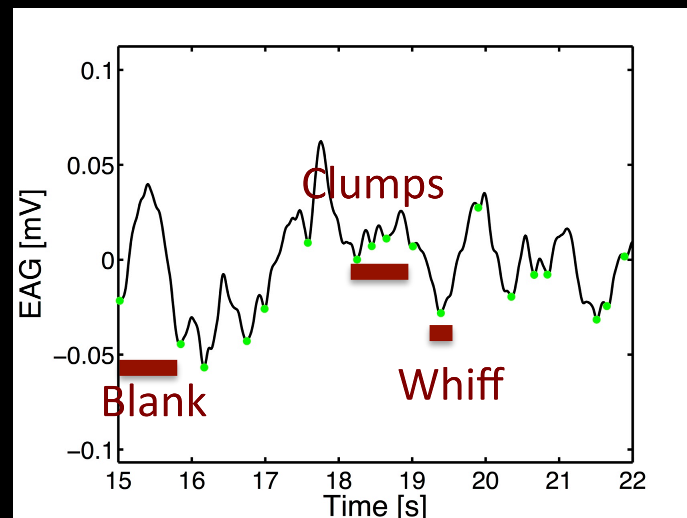
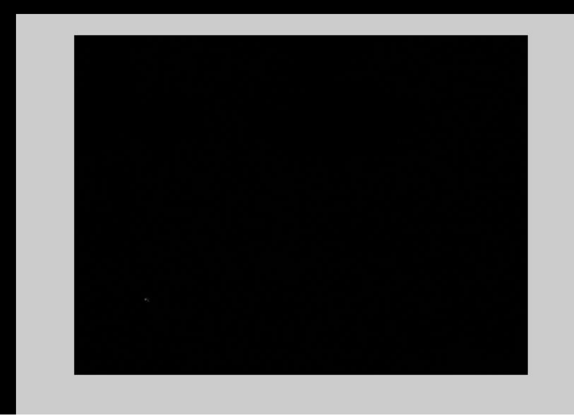
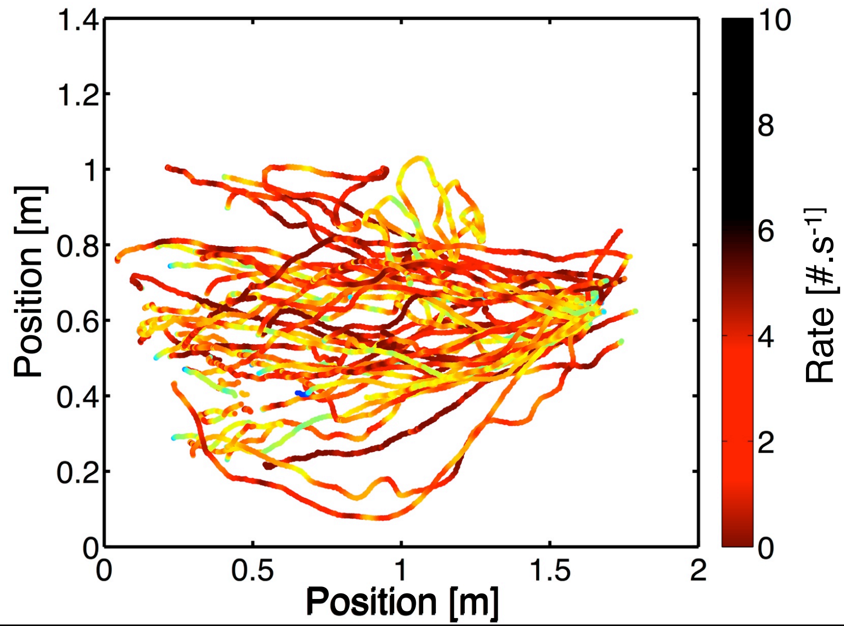
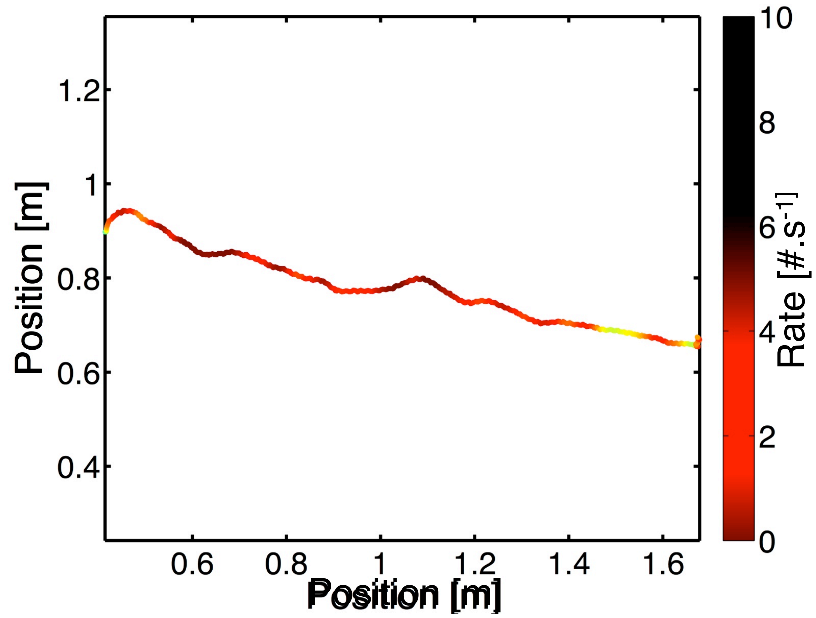


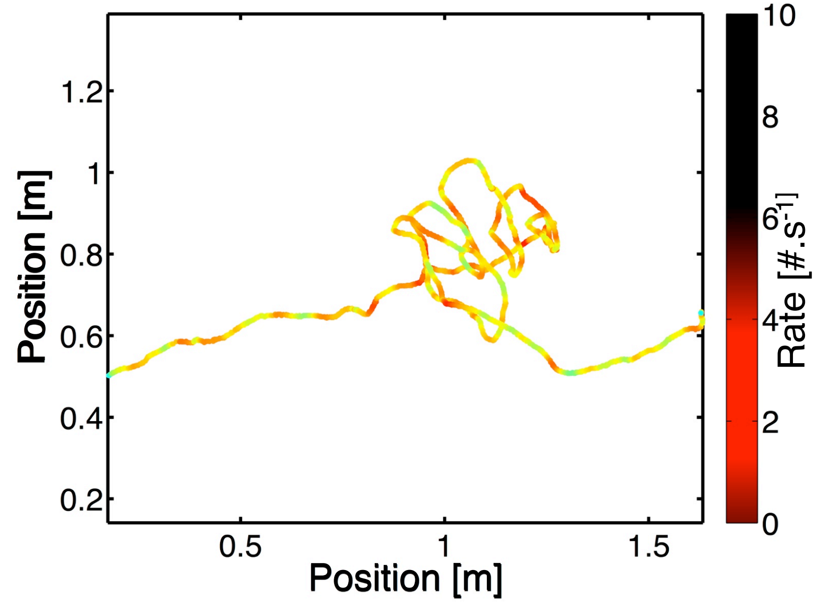
Image Analysis Using Robust PCA



Trajectory/Detections



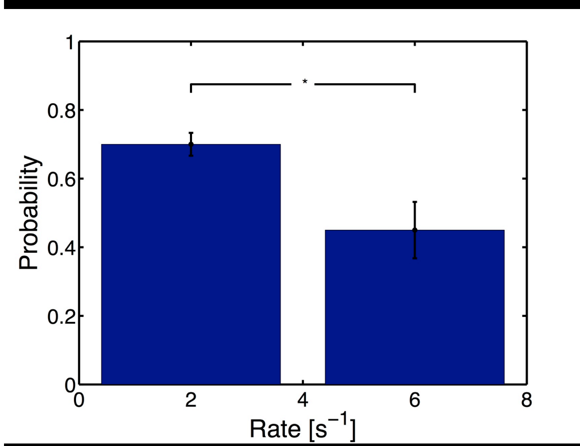


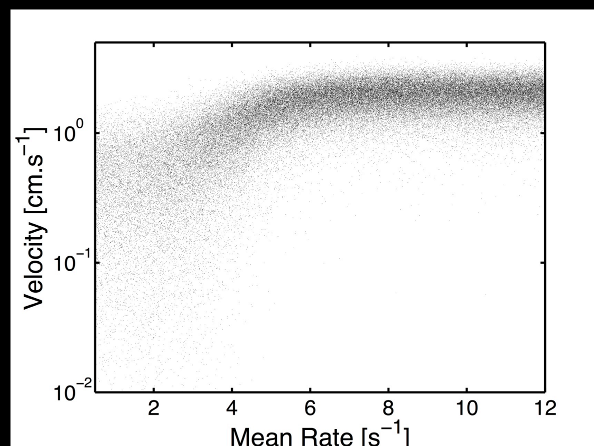


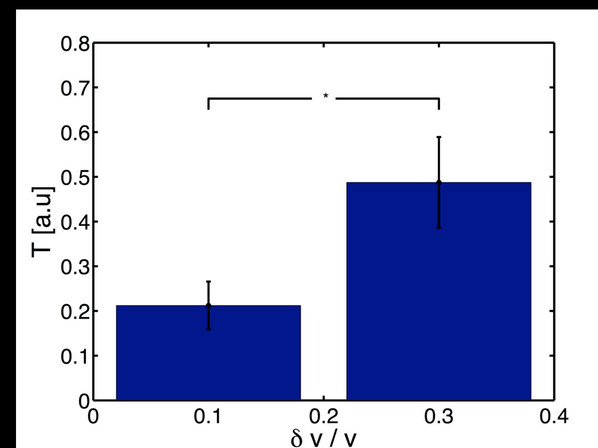
N.J. Vickers *et al, Nature* **2001**, 410, 466-470.

The surprising, **disappointing** and inefficient strategy of the Rhynco: Key elements

- Correlated Two Mode Poisson motion: Run-Stop ($0.08s^{-1}$, $0.1s^{-1}$)
- Decorrelation of characteristic scales
  - $\tau_{turbulence}$~100 ms-1s
  - τ_{rhynco}~ 10s

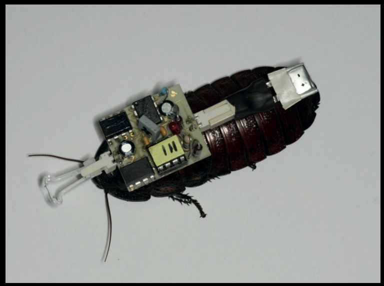




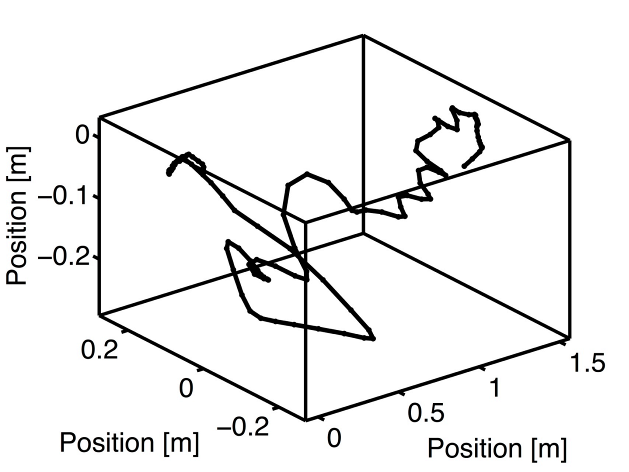


- Velocity-Rate correlation: non-adapted chemotaxis (Bacteria) $v_{chemotaxis}$~$0.7\pm0.2 cm.s^{-1}$
- Stop-Rate correlation: Exploiting rather than exploring

Conclusion and Perspective



- Neural substrate to play the Bandit Game (Mushroom body?)
- Q-Learning for olfactory search
- Disentangling cue statistics and other cues
  - Pheromone detection statistics and wind dynamics
  - The Bandit Game for thermal (chiral thermal Gradient)
- Agrotis *Ipsilon* turbulent searches
  - Challenge: adding the extra antenna setup without modifying flight pattern
  - Clear Patterns during flight



M. Renou, INRA Versailles

Embedded olfactory circuits : Patent EP-B140164

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