How do ants navigate in natural environments?

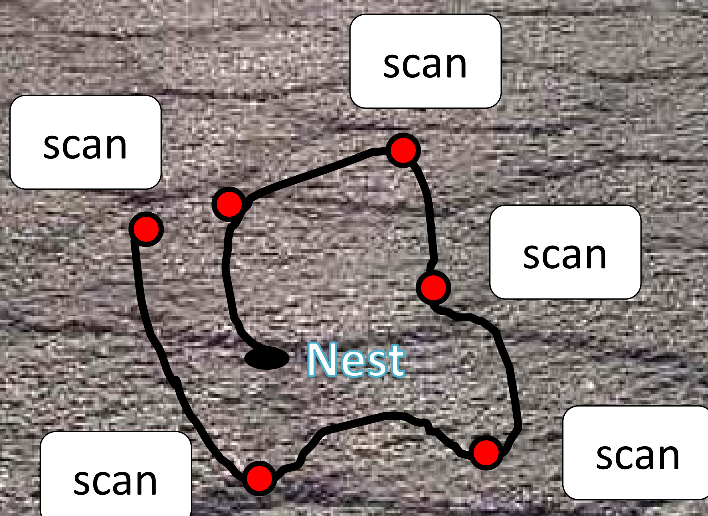
Université Paul Sabatier TOULOUSE III

CNRS

Antoine Wystrach


Nest entrance

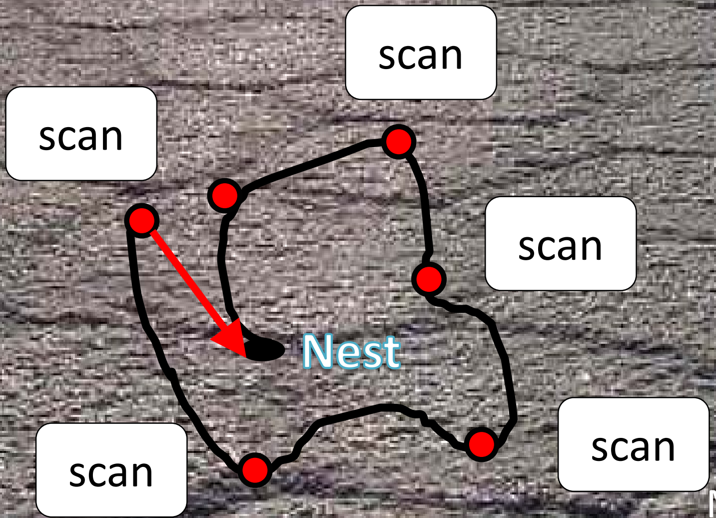
Learning walks



Mueller and Wehner 2010 Curr biol

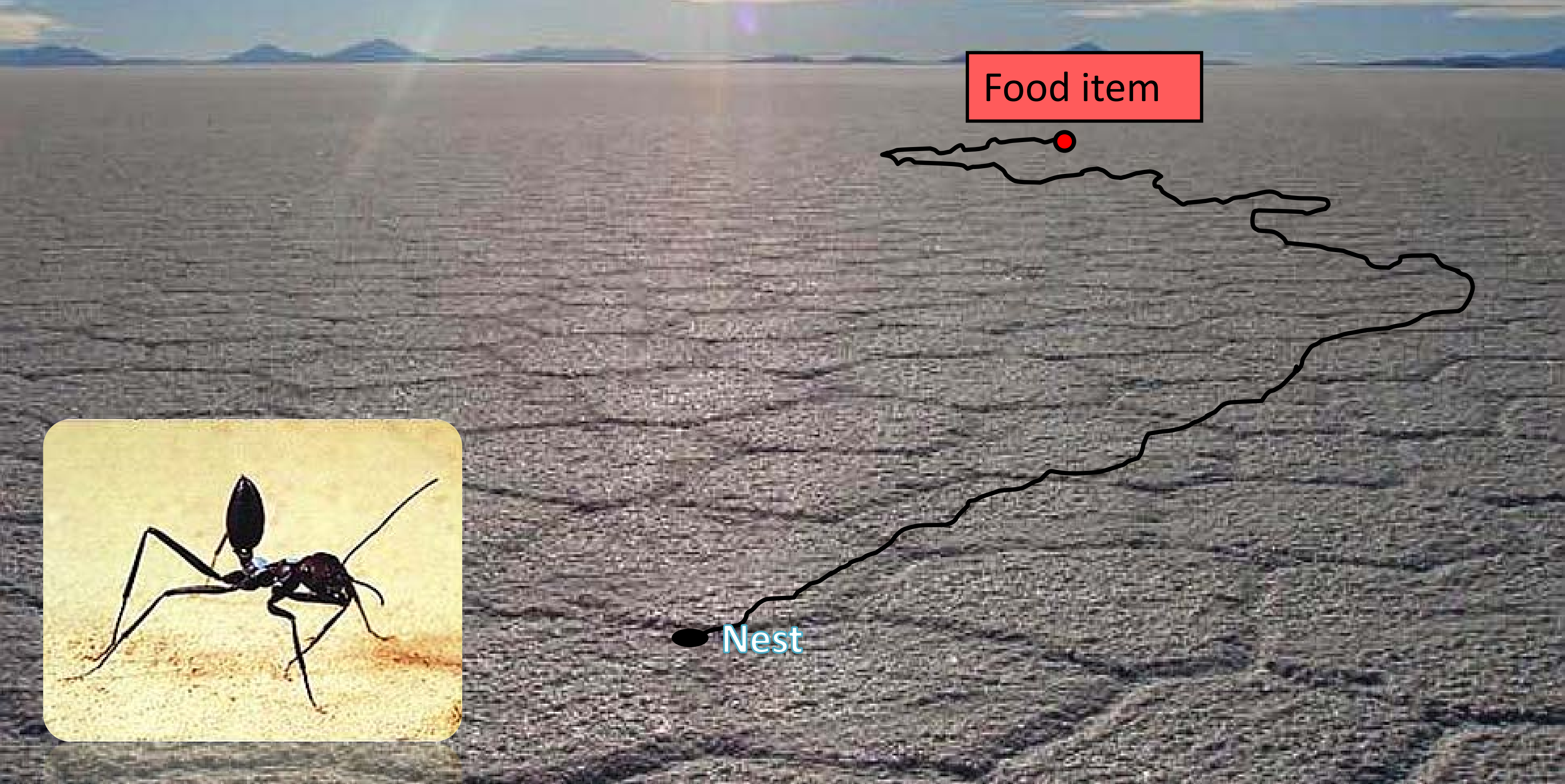
Path Integration

Fleishmann et al., 2018 Curr biol

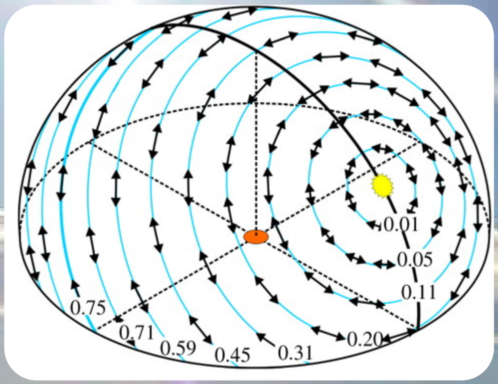


Mueller and Wehner 2010 Curr biol

Path Integration

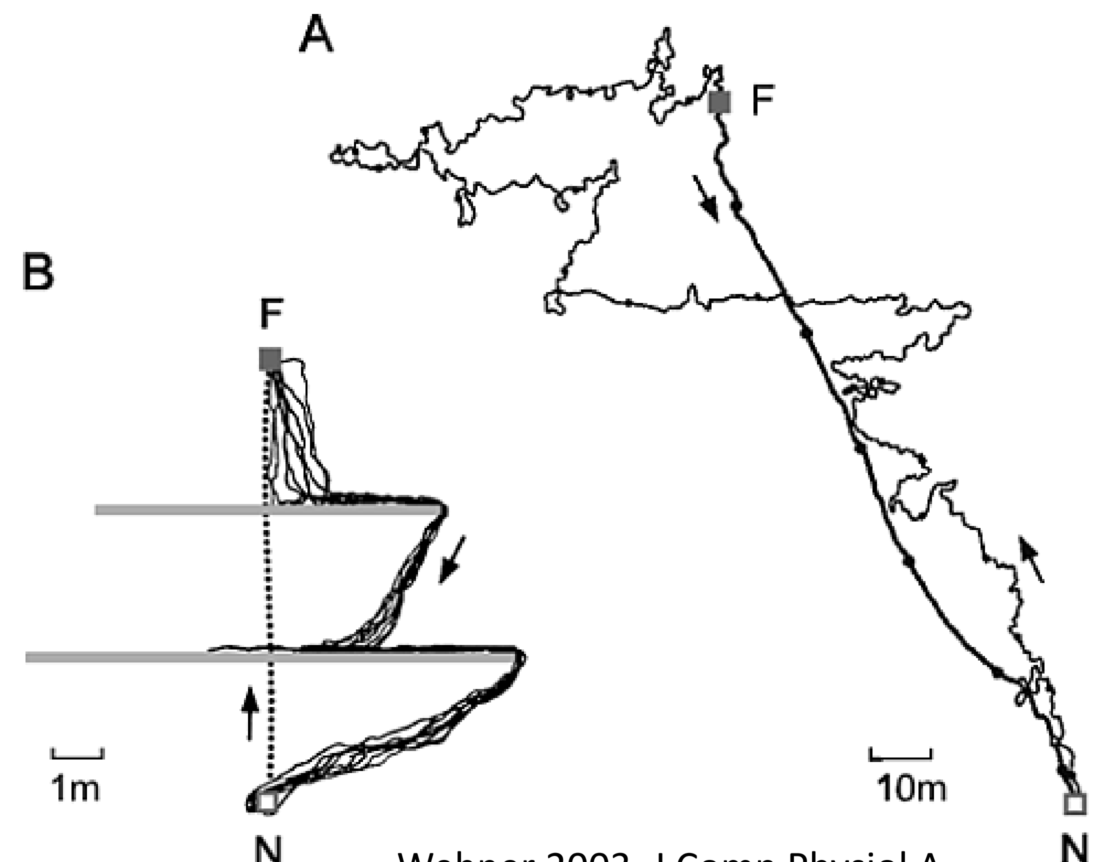


Path Integration



Ophion obscuratus.
Credit: Matthias Lenke/Flickr.co

Path Integration



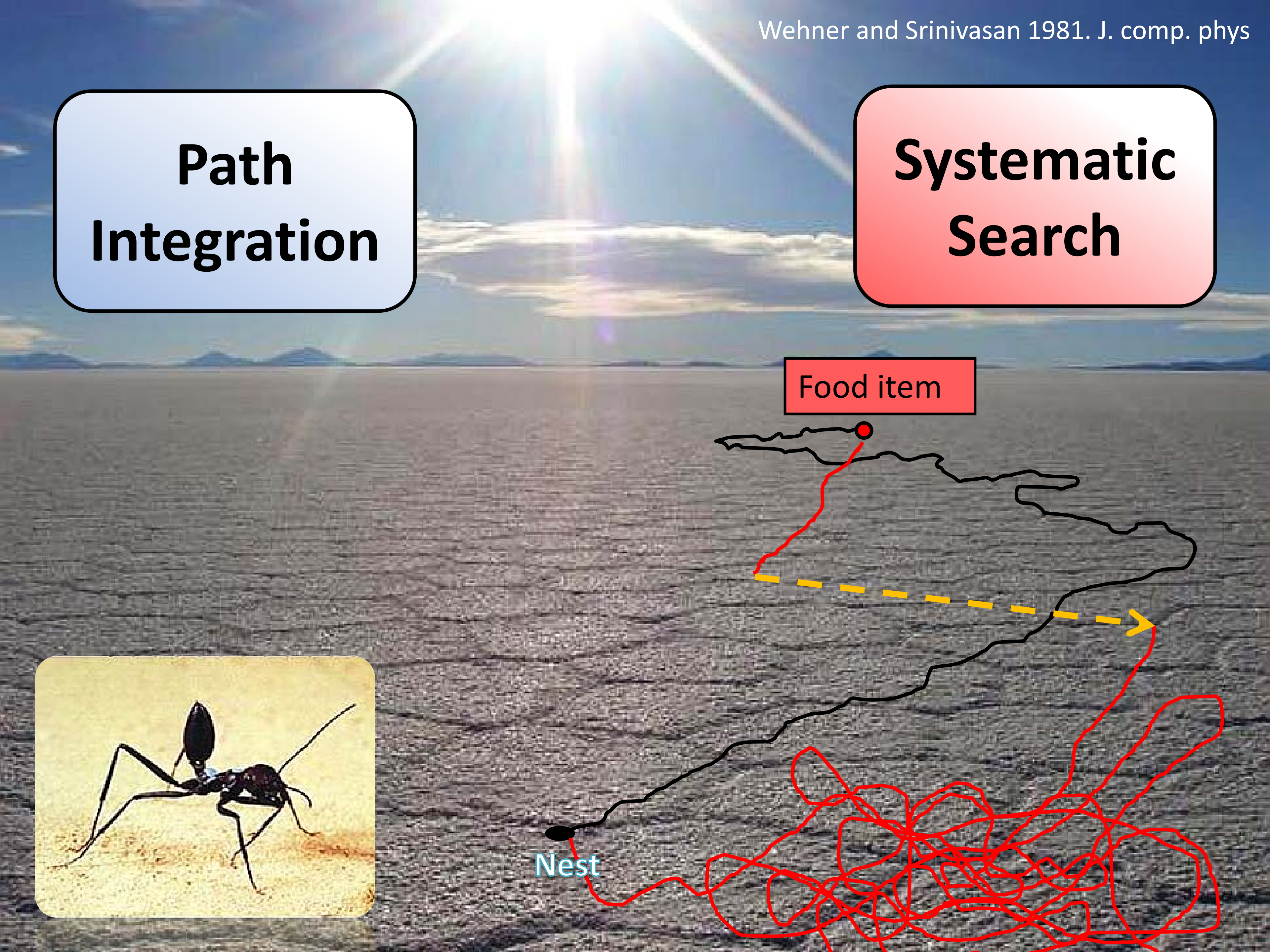
Wehner 2003. J Comp Physiol A

Path Integration

- Accumulate errors

Path Integration

- Accumulate errors
- Passive displacement

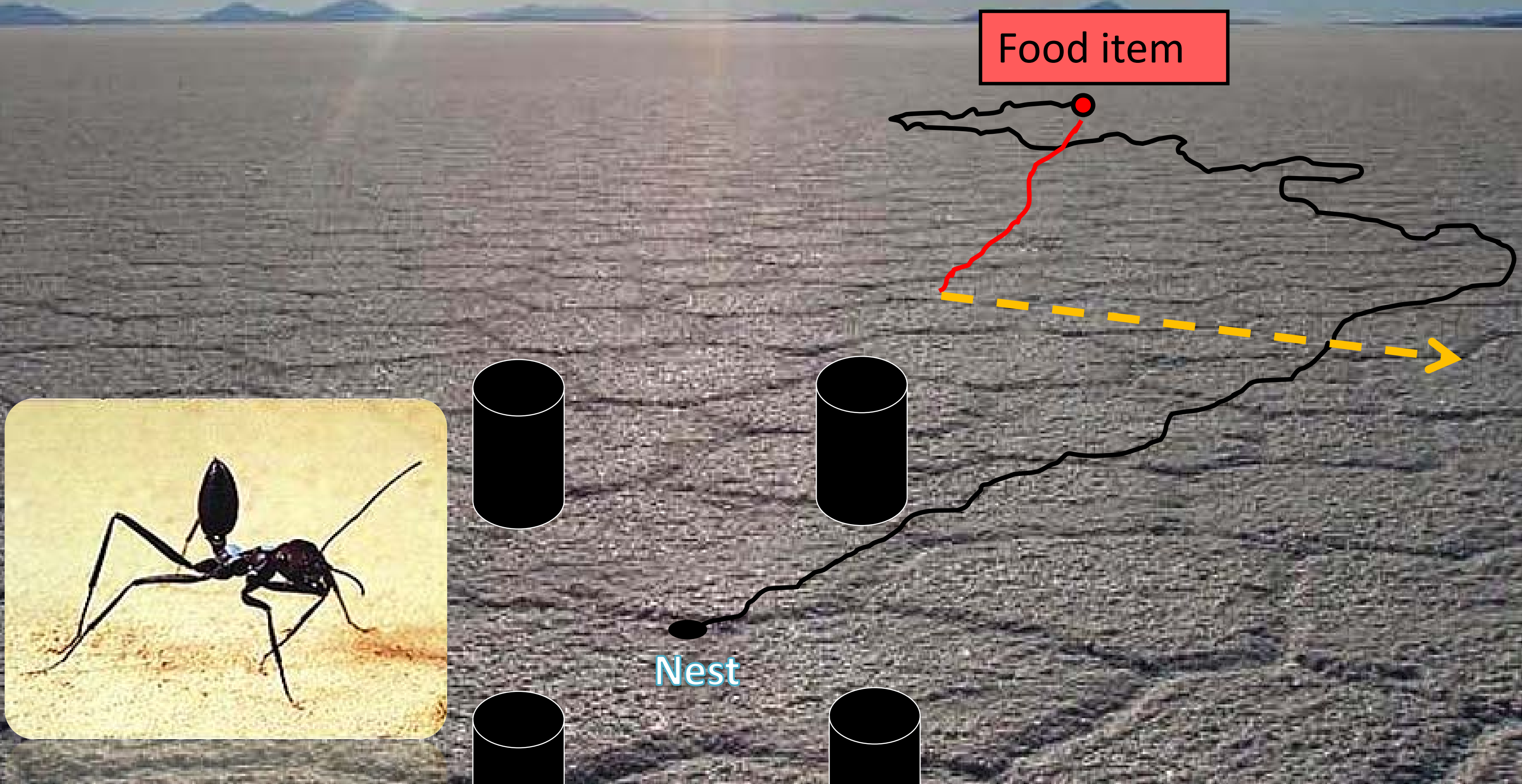

Wehner and Srinivasan 1981. J. comp. phys
Path Integration
Systematic Search
Food item
Nest

Wehner and Räber 1979. Experencia
Cartwright and Collett 1983. J. comp. phys

Path Integration

Visual scene navigation

Systematic Search

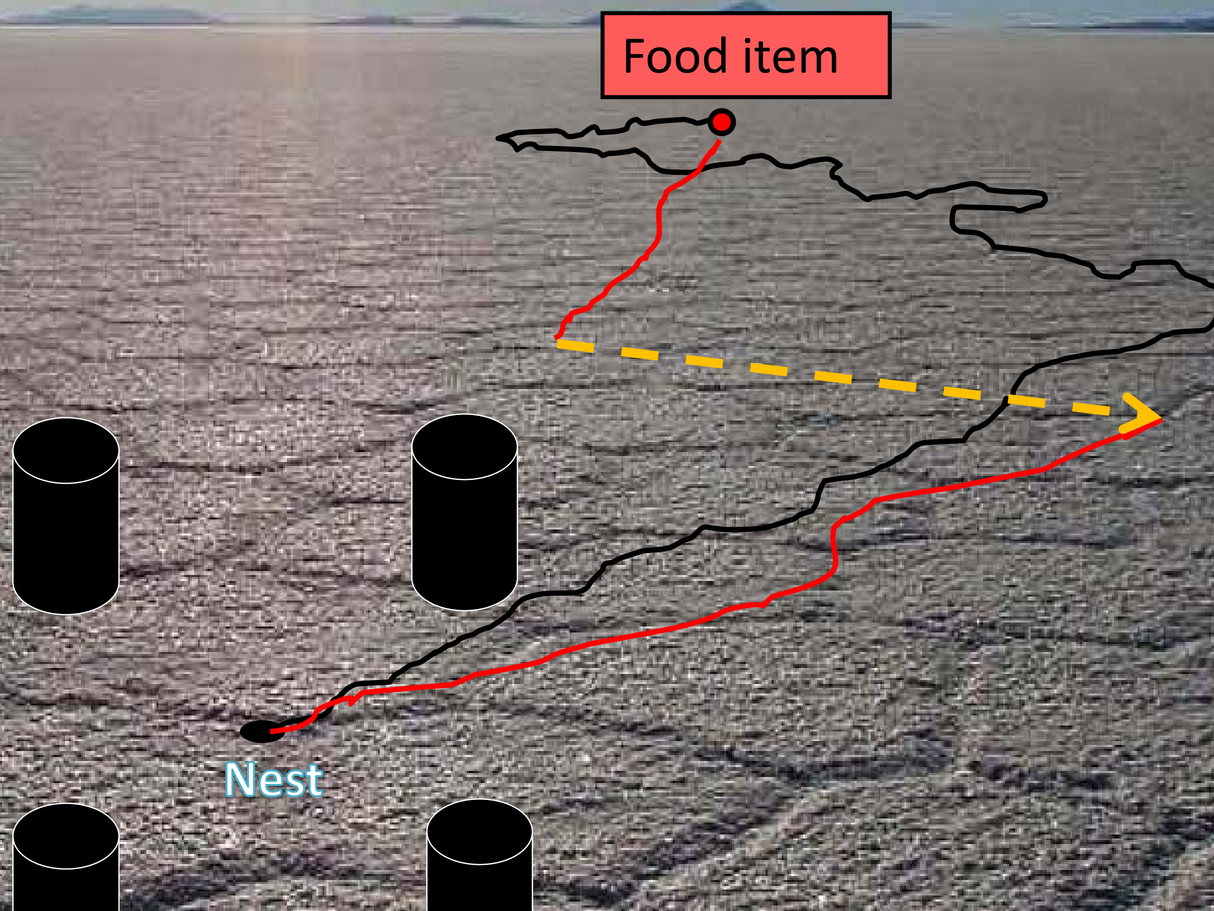


Wehner and Räber 1979. Experencia
Cartwright and Collett 1983. J. comp. phys

Path Integration

Visual scene navigation

Systematic Search



THE ANT NAVIGATIONAL TOOLKIT

Path Integration

Visual scene navigation

Systematic Search

Wehner 2008. Myrmec. news

THE ANT NAVIGATIONAL TOOLKIT

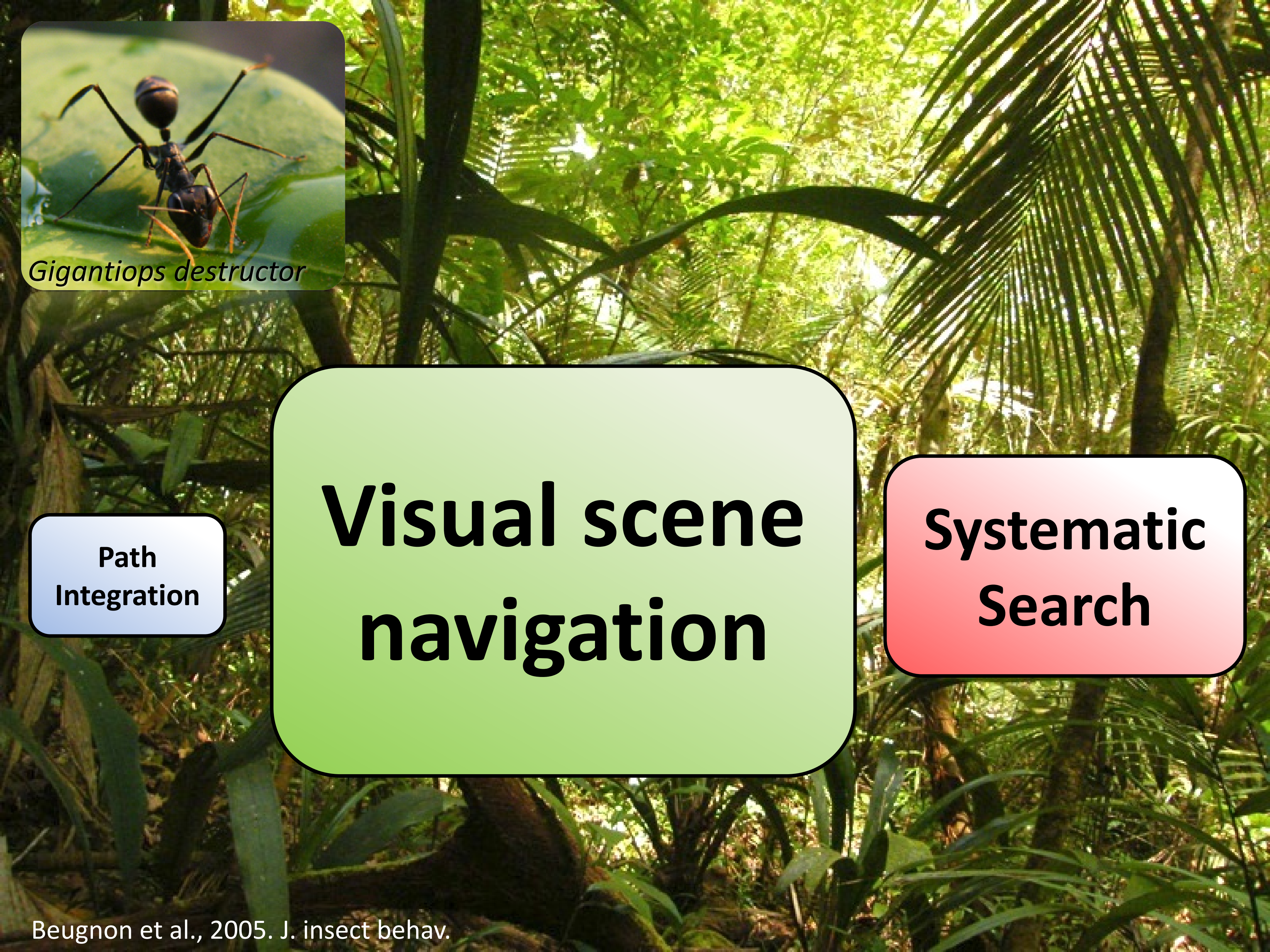
Path Integration

Visual scene navigation

Systematic Search

Wehner 2008. Myrmec. news

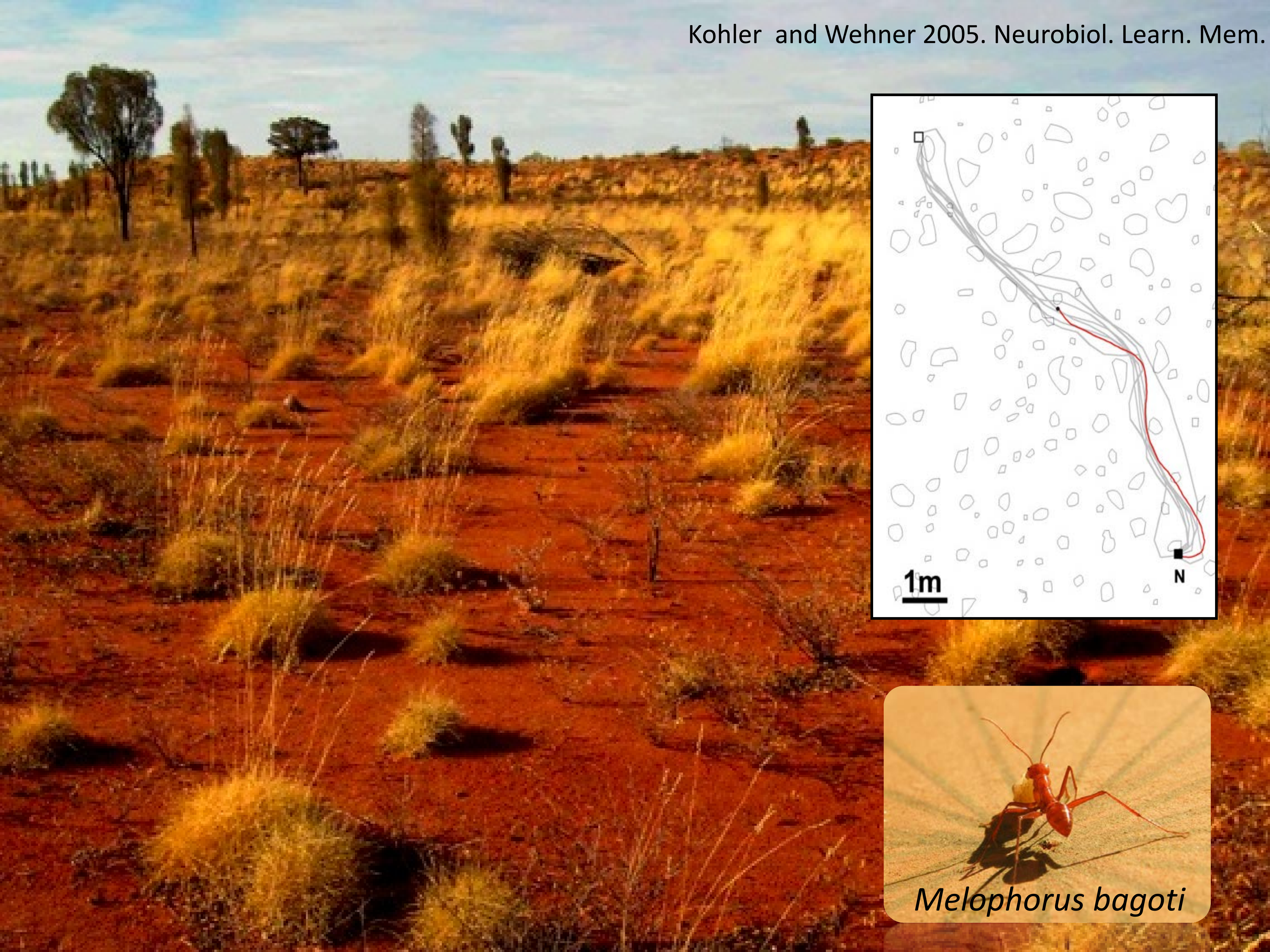

Gigantiops destructor


Gigantiops destructor
Path Integration
Visual scene navigation
Systematic Search
Beugnon et al., 2005. J. insect behav.


Gigantiops destructor


Gigantiops destructor

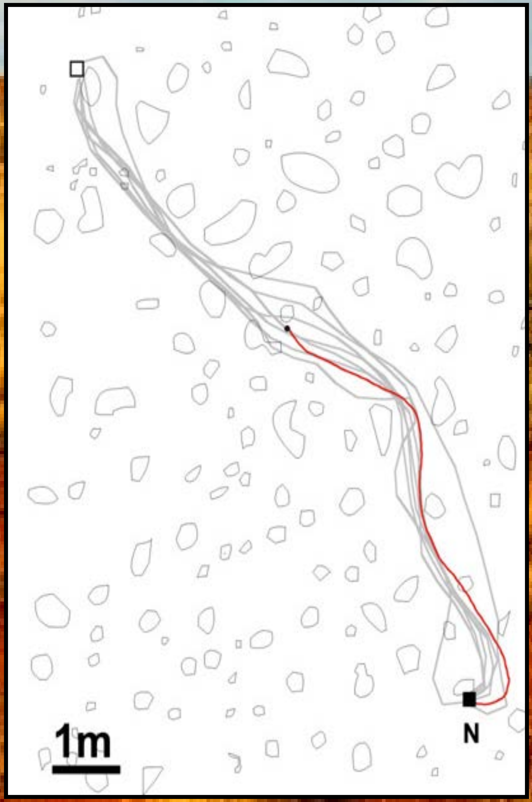
Kohler and Wehner 2005. Neurobiol. Learn. Mem.



Melophorus bagoti

Route following

Kohler and Wehner 2005. Neurobiol. Learn. Mem.



Melophorus bagoti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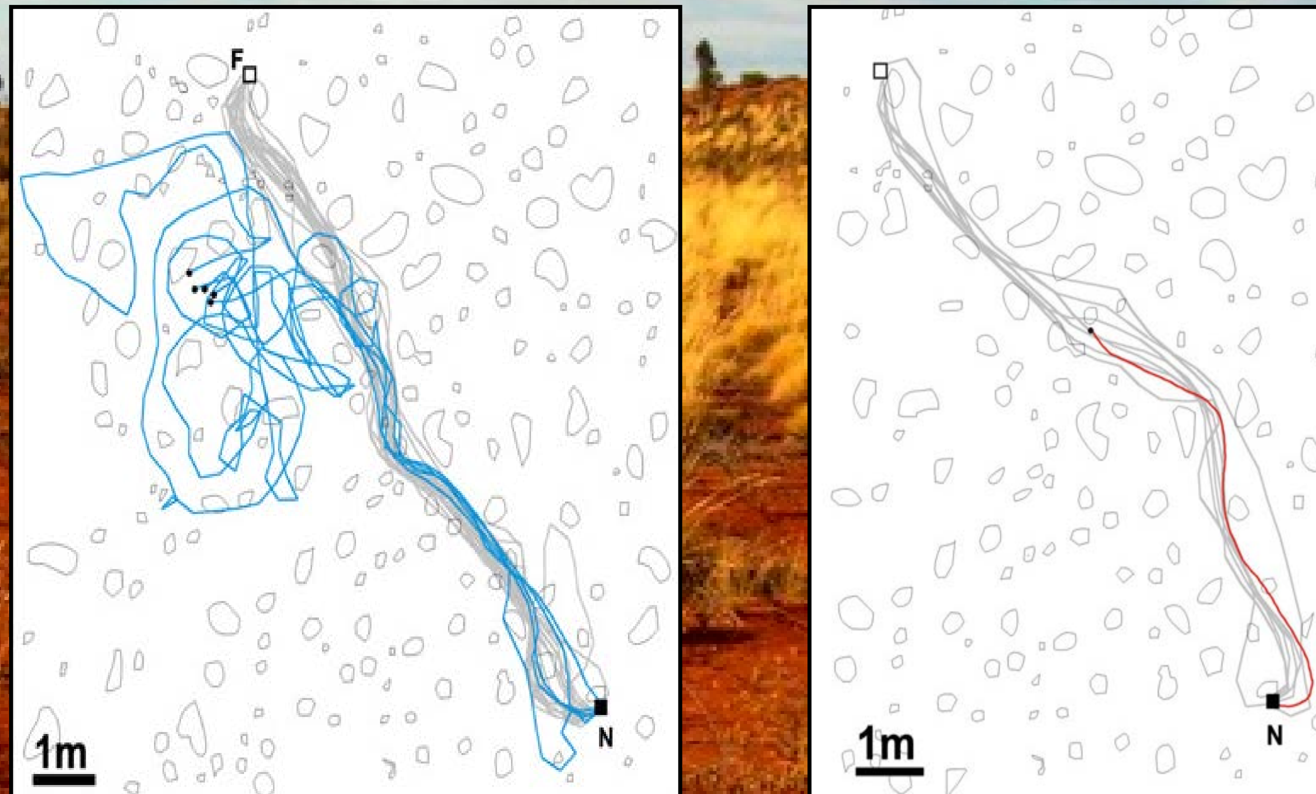


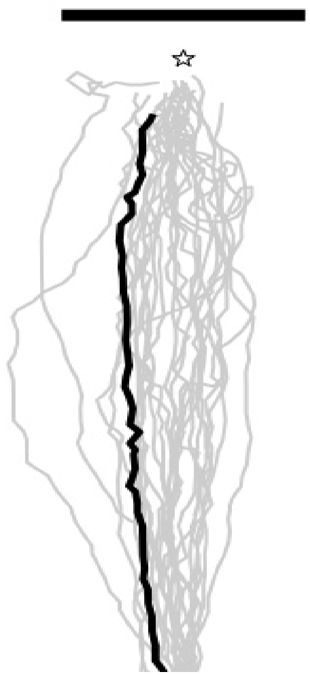
Melophorus bagoti


Landmarks ?
Melophorus bagoti

Wystrach et al. 2011. JCPA

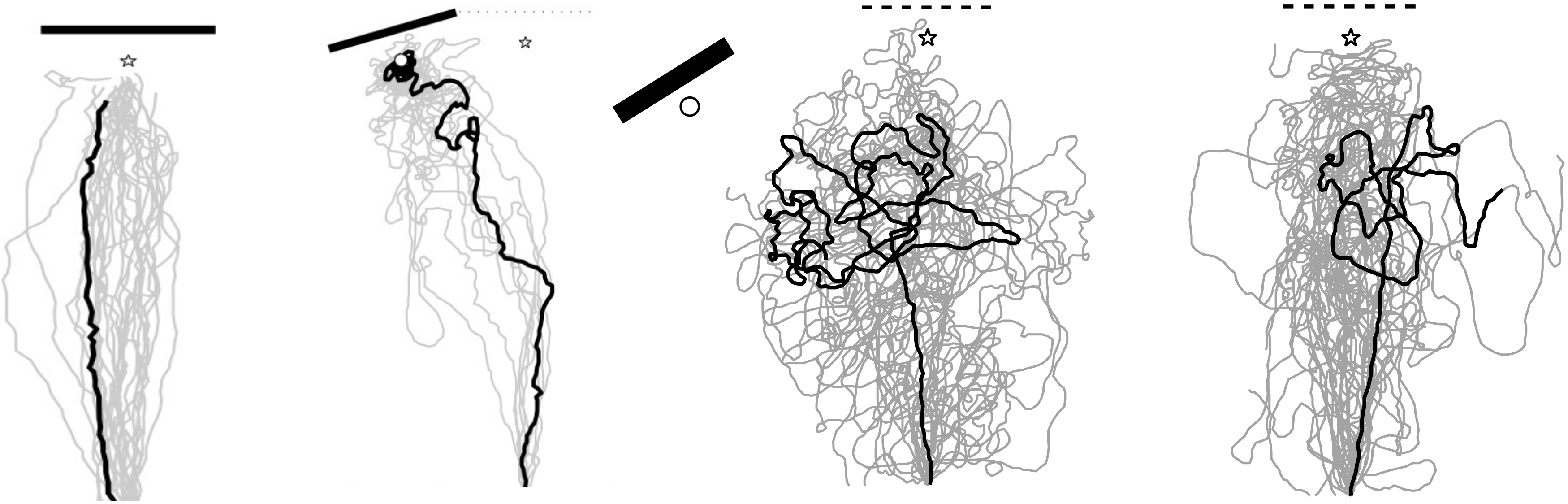

Nest
Melophorus bagoti
Wystrach et al. 2011. JCPA

Landmarks or panorama ?



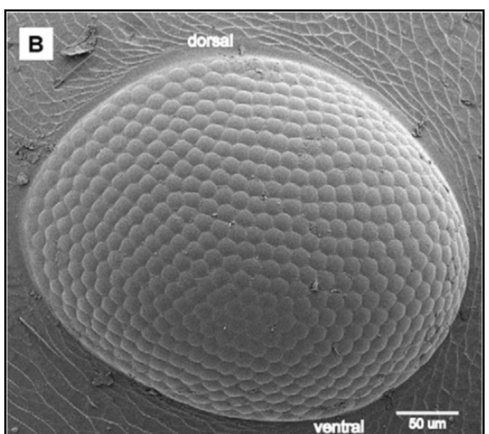
Wystrach et al., 2011. Front. In Zool.

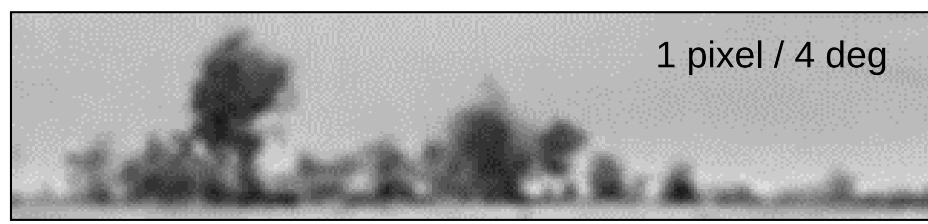
Ant paths



Quantifying visual Information

Ant eye



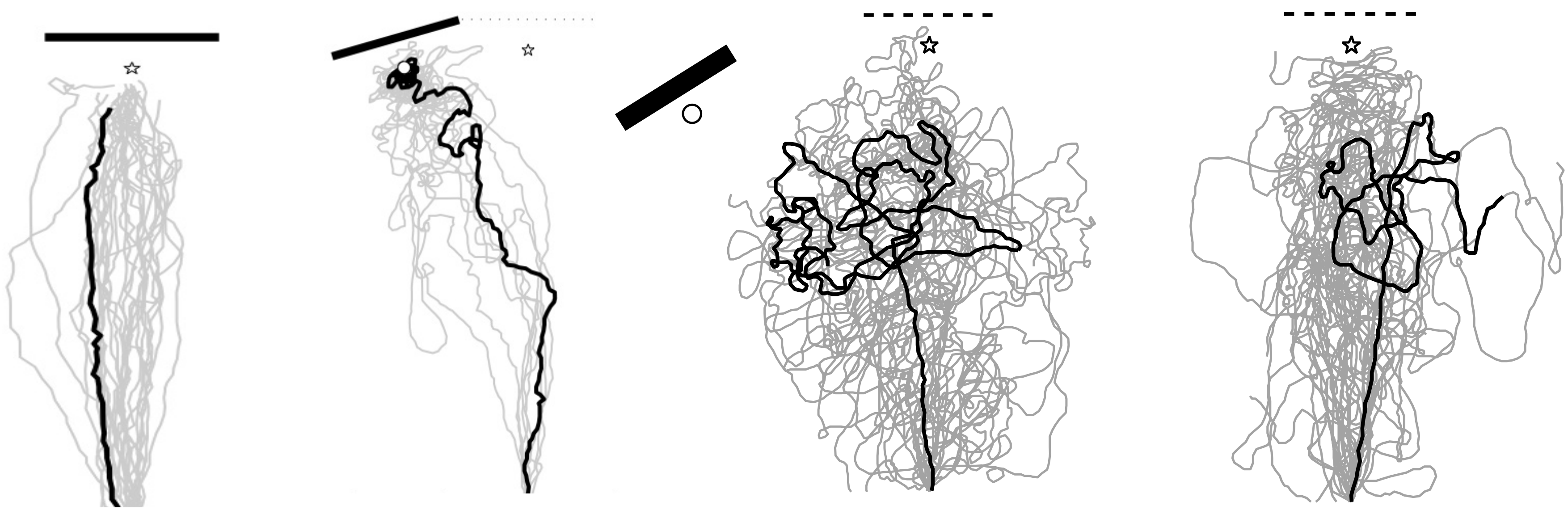


Wystrach et al., 2011. Front. In Zool.

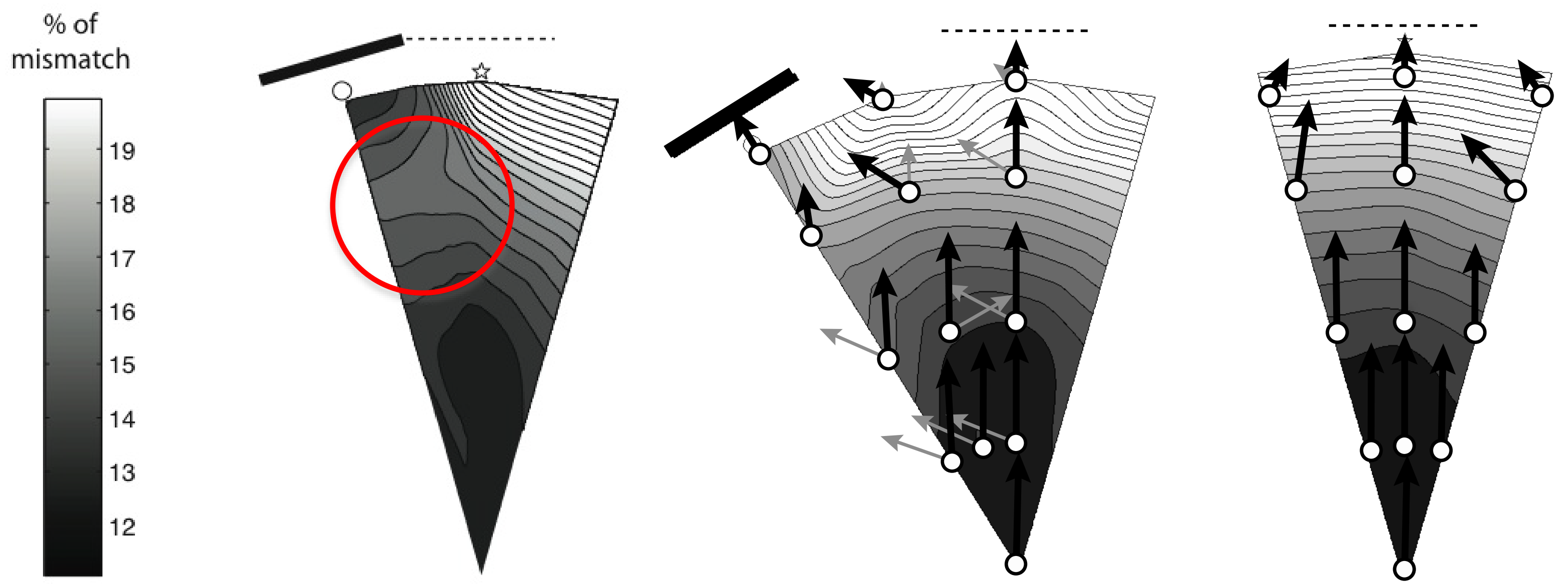
Human resolution

Ant resolution

Ant paths

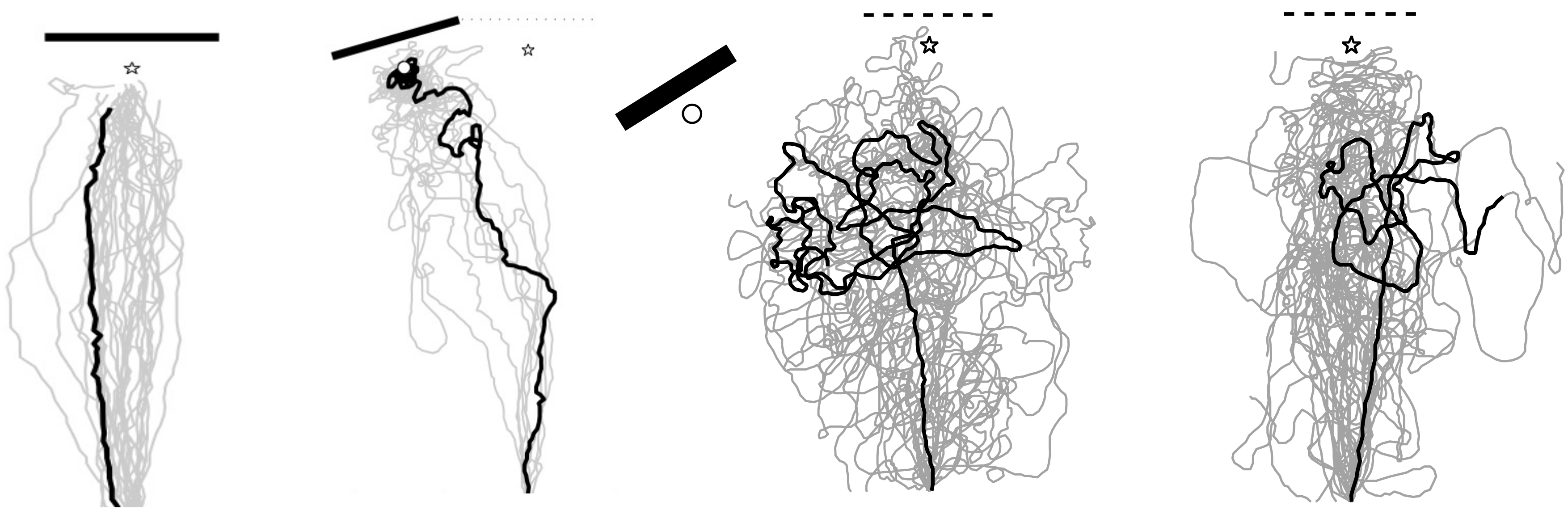


Picture based Hypotheses predictions



Wystrach et al., 2011. Front. In Zool.

Ant paths



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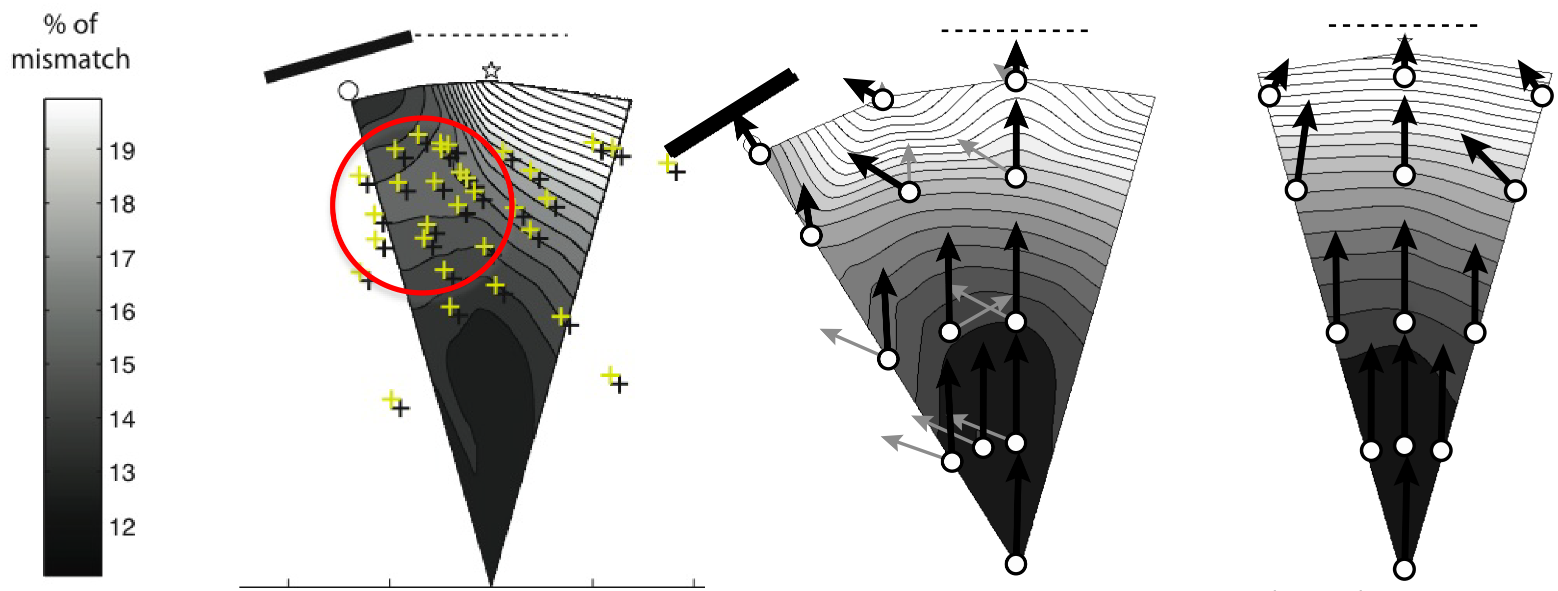
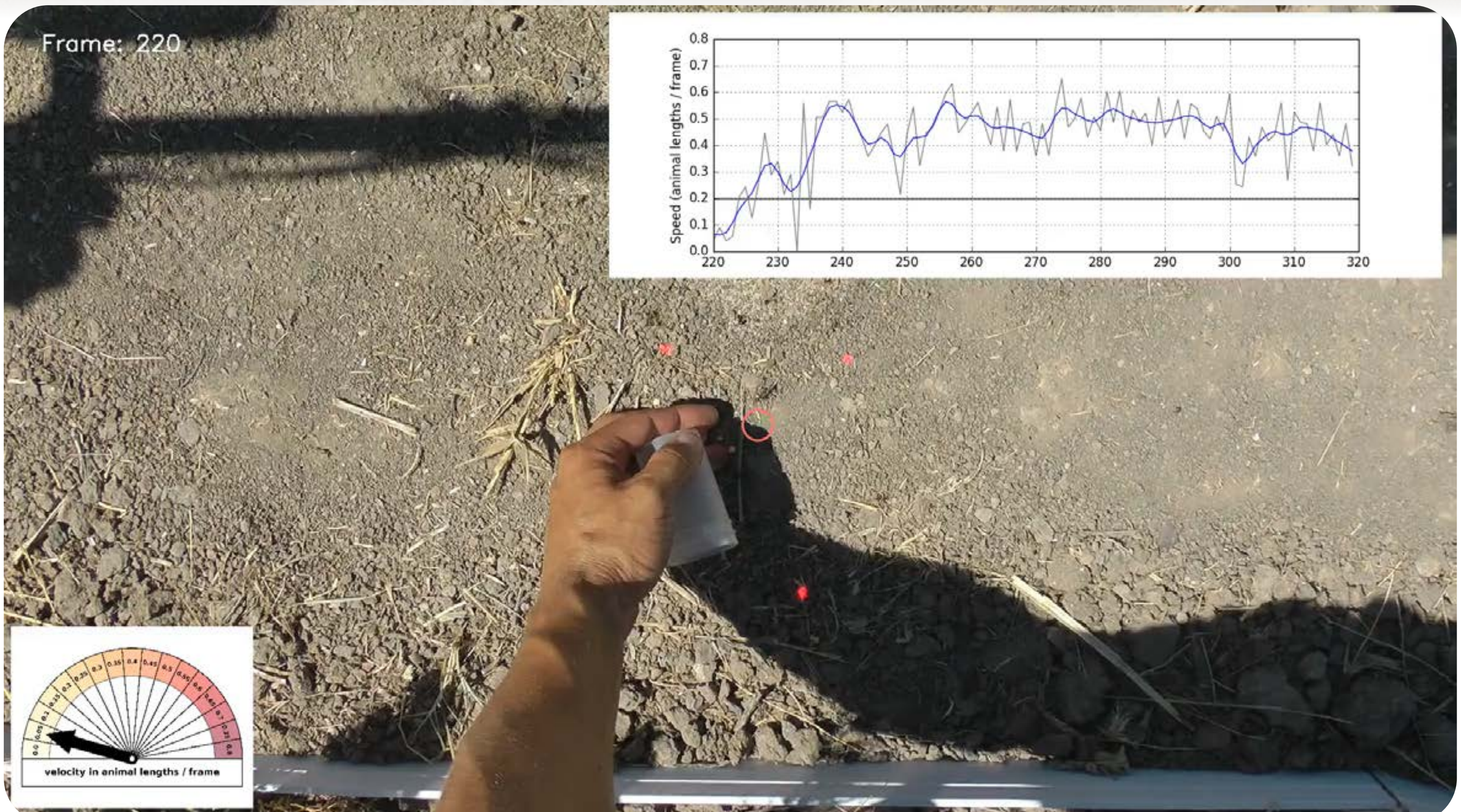


Wystrach et al., 2011. Front. In Zool.


Cataglyphis velox

Ant tracking in the field

HABITRACKS



Risse et al., (submited to *Nature Methods*)

Accurate tracking in the field

Ant tracking in the field

HABITRACKS

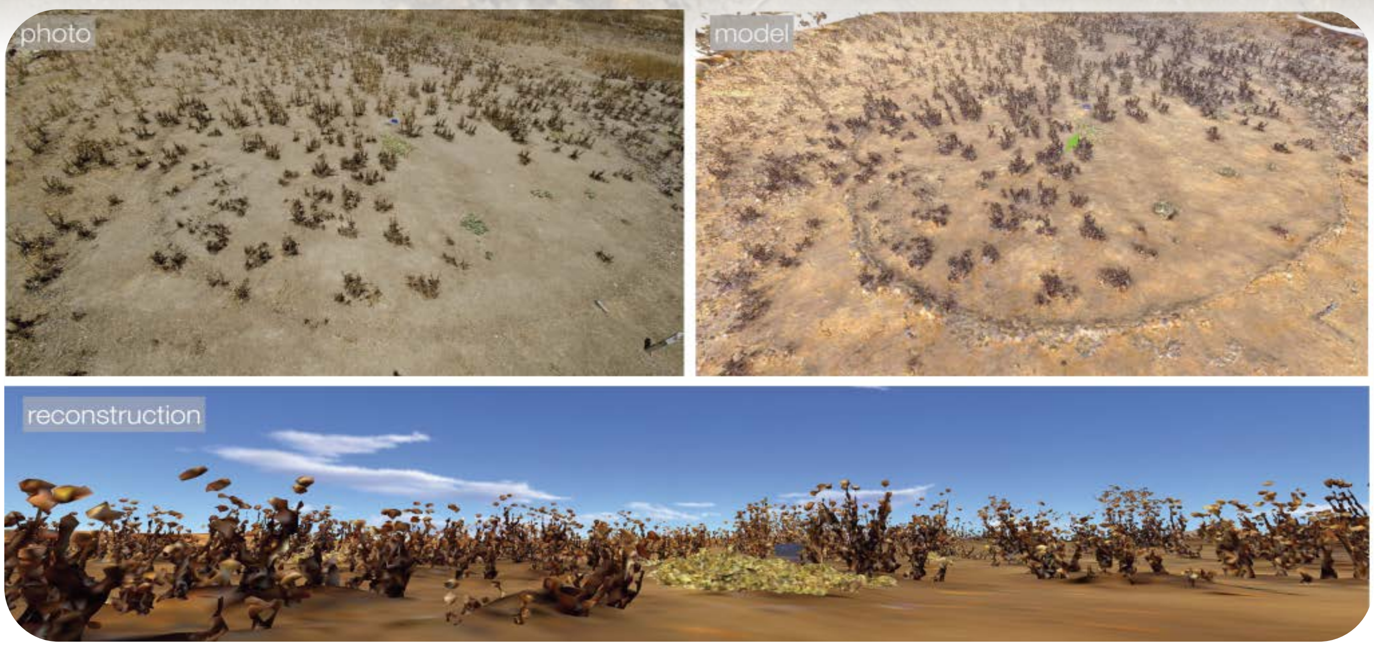
Risse et al., (submited to *Nature Methods*)

Accurate tracking in the field

Ant tracking in the field

HABITRACKS

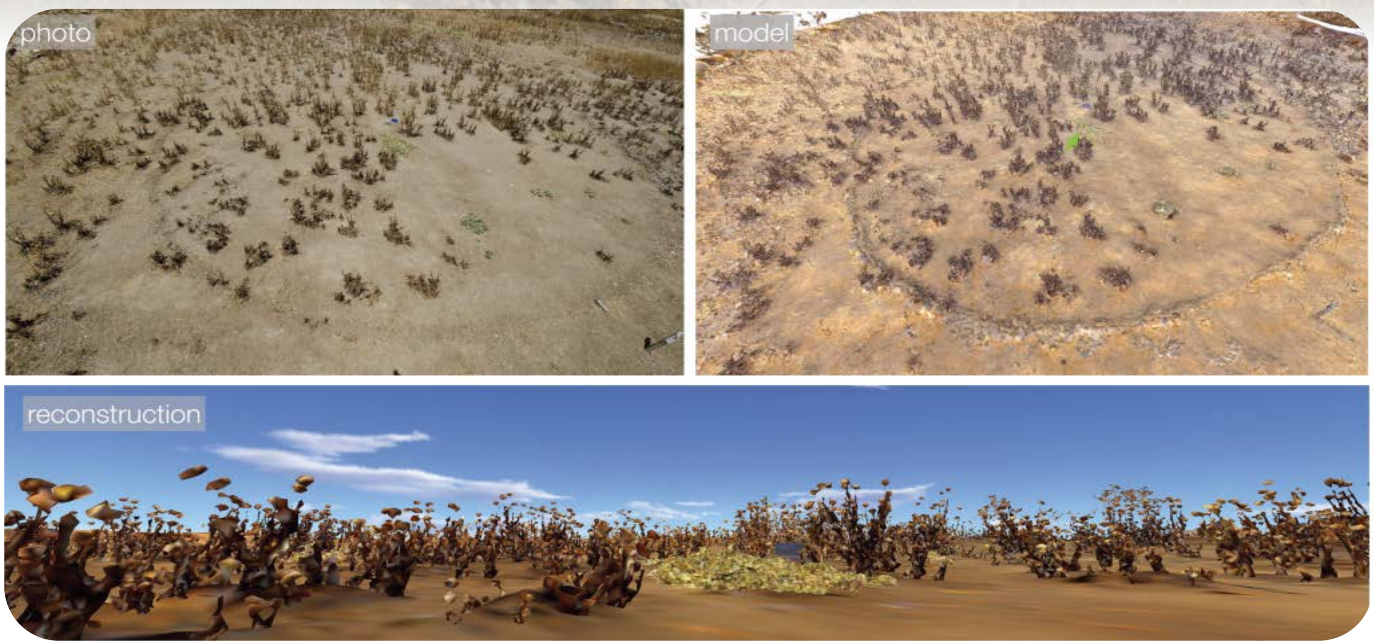
HABITAT-3D



Accurate reconstruction of natural habitats

Ant tracking in the field

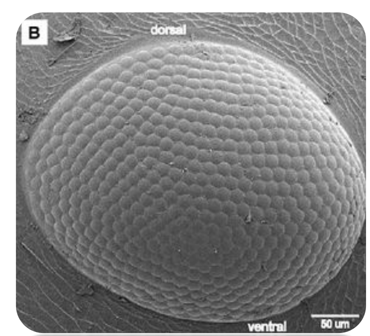
HABITRACKS



Reconstruction of ants’ visuo-motor experience

HABITAT-3D

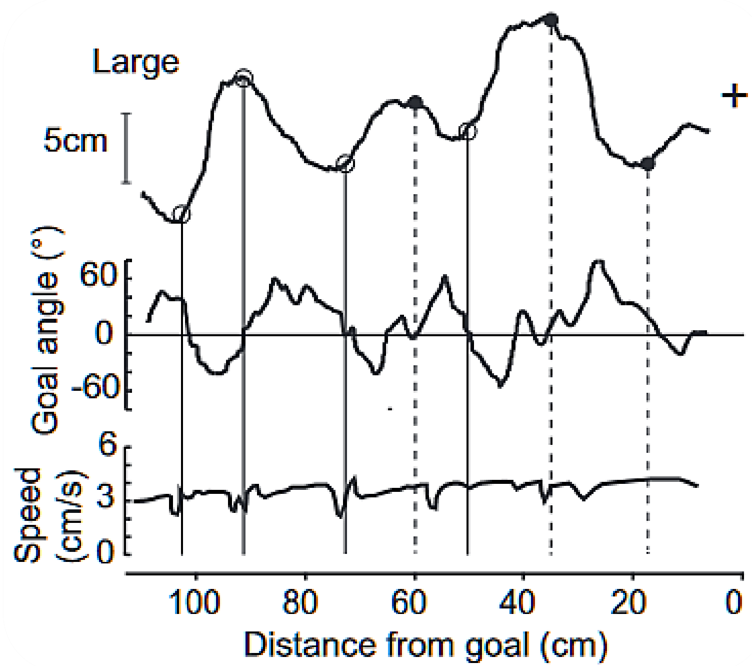
ANT EYE MODEL



Show the movie

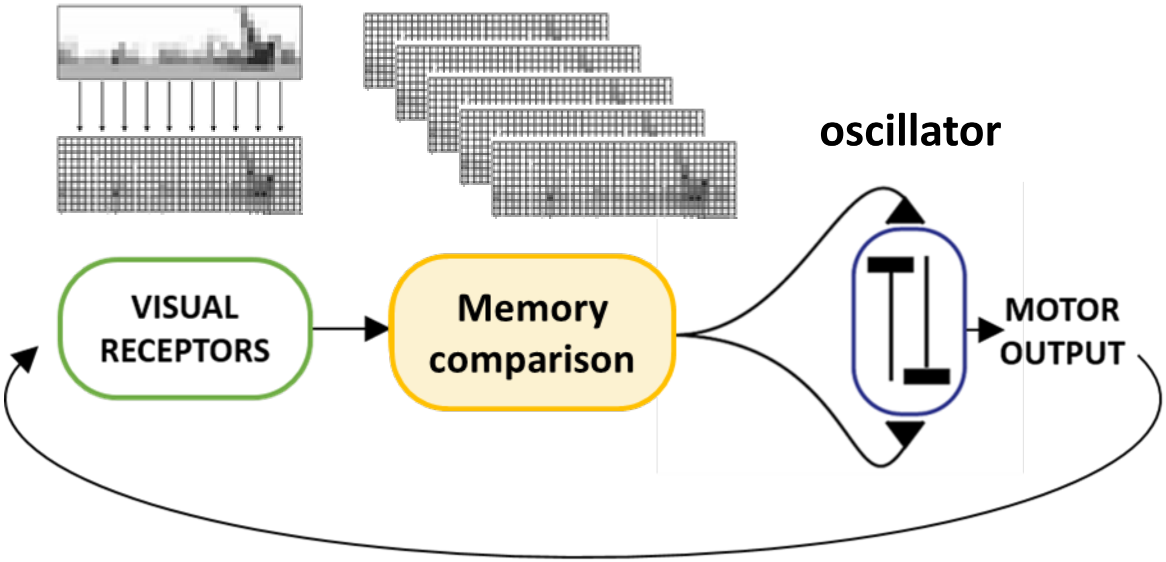
Motor pattern observation

Ants' paths are oscillating



Lent et al., 2013 *Proc. Roy. Soc. B*

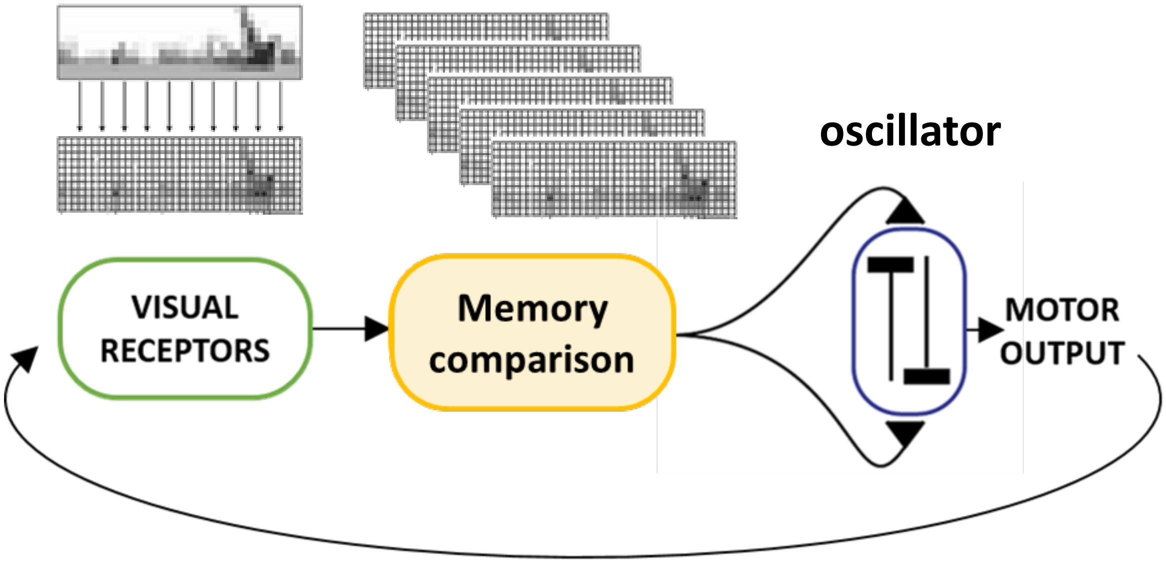
A simple oscillator model



View familiarity modulate the oscillator

Kodzhabashev et al., 2015 *Biomim. Syst.*

A simple oscillator model



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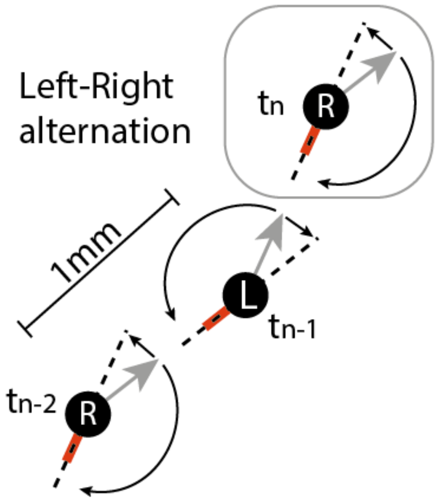
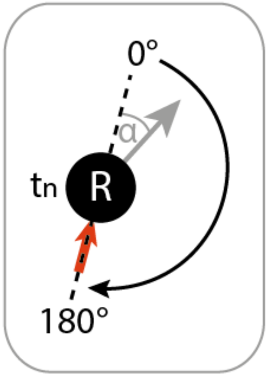


$\alpha_{n+1} = g \times \text{Unfamiliarity}$

$0° < \alpha < 180°$

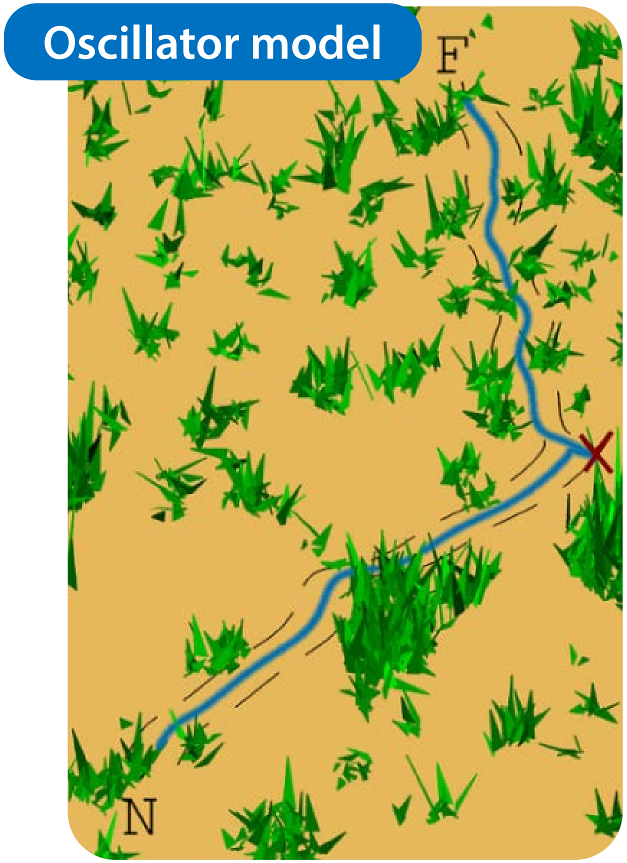


Kodzhabashev et al., 2015 *Biomim. Syst.*

A simple oscillator model

Tested on 15 ants' route

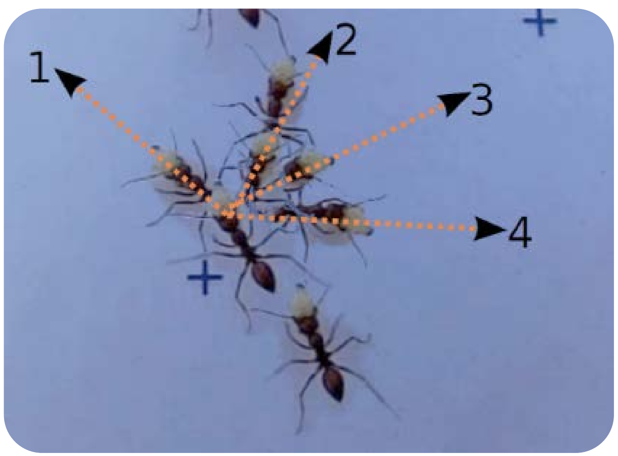
Mean: 1 error/12.8m travelled

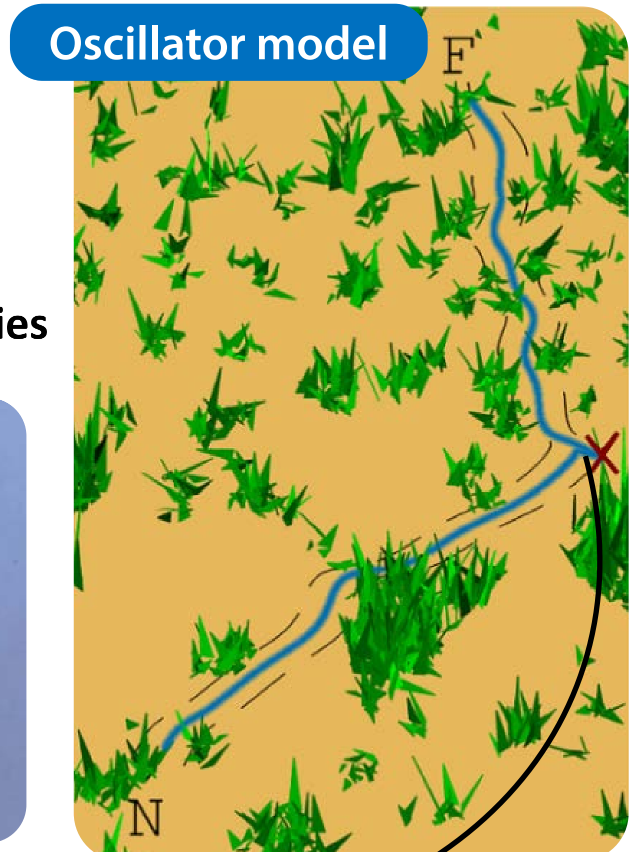


Kodzhabashev et al., 2015 *Biomim. Syst.*

A simple oscillator model

To explore emerging proprieties





When lost, scanning behaviour emerges!

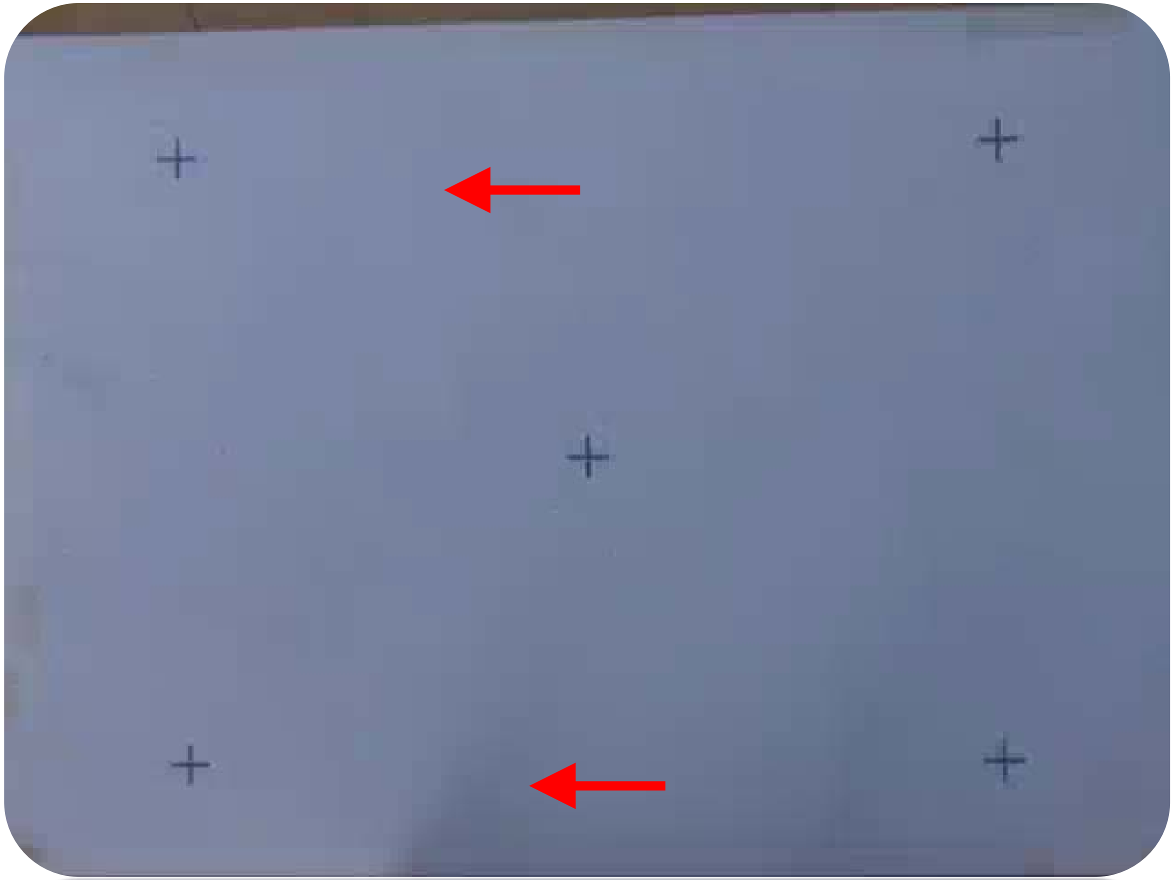
Kodzhabashev et al., 2015 *Biomim. Syst.*

Ants scan when lost

Real ant route

Wystrach et al., (2014)

Ants vs. Model prediction

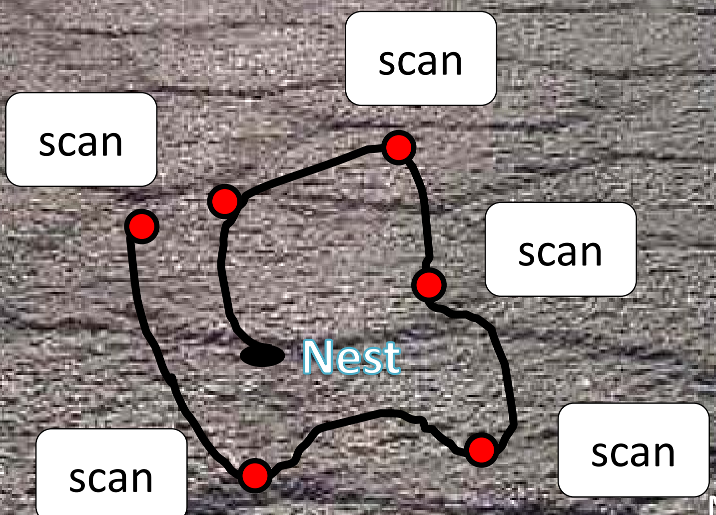


Wystrach et al., (2014)

Ants vs. Model prediction

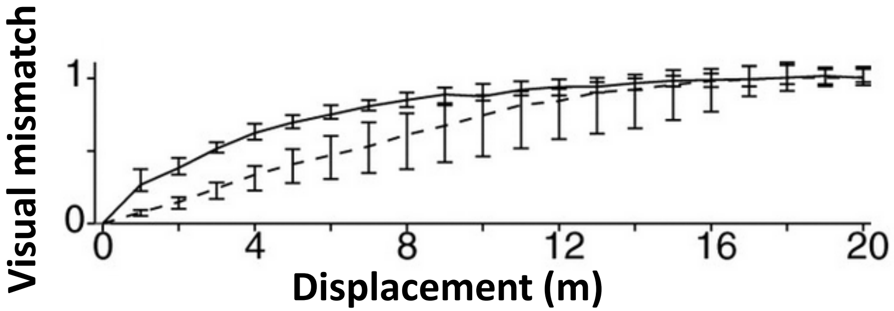
Learning walks

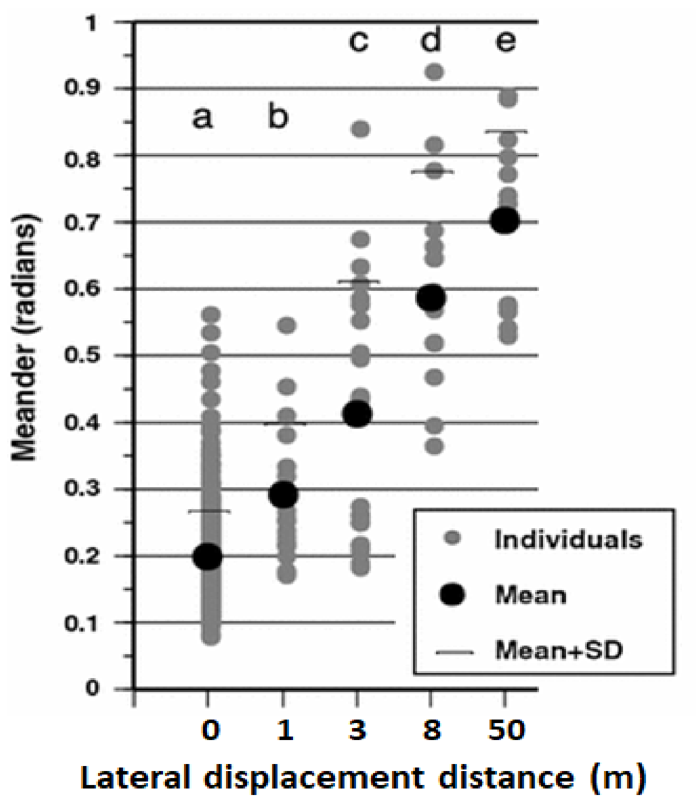
For a naïve ant, the world looks unfamiliar



Mueller and Wehner 2010 Curr biol

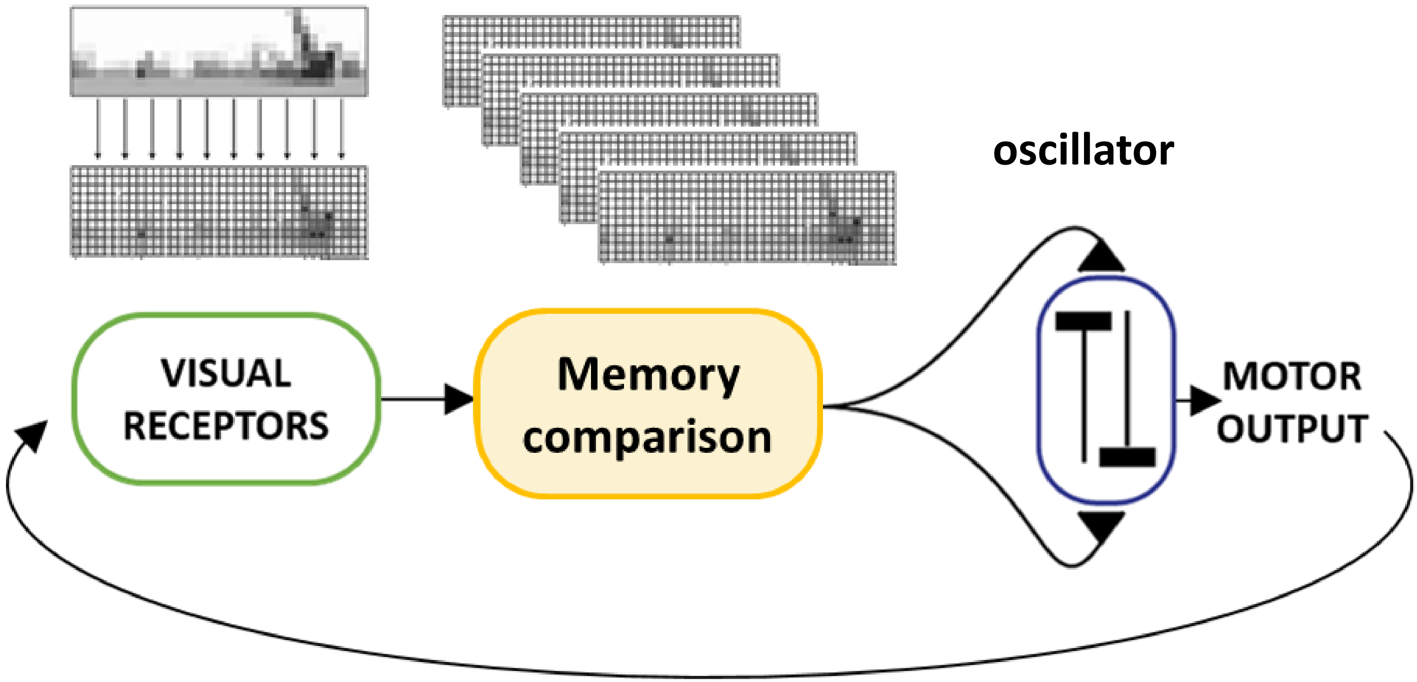
Ants vs. Model prediction





Wystrach et al. 2011. JCPA

Neural implementation ?



The connectome !!

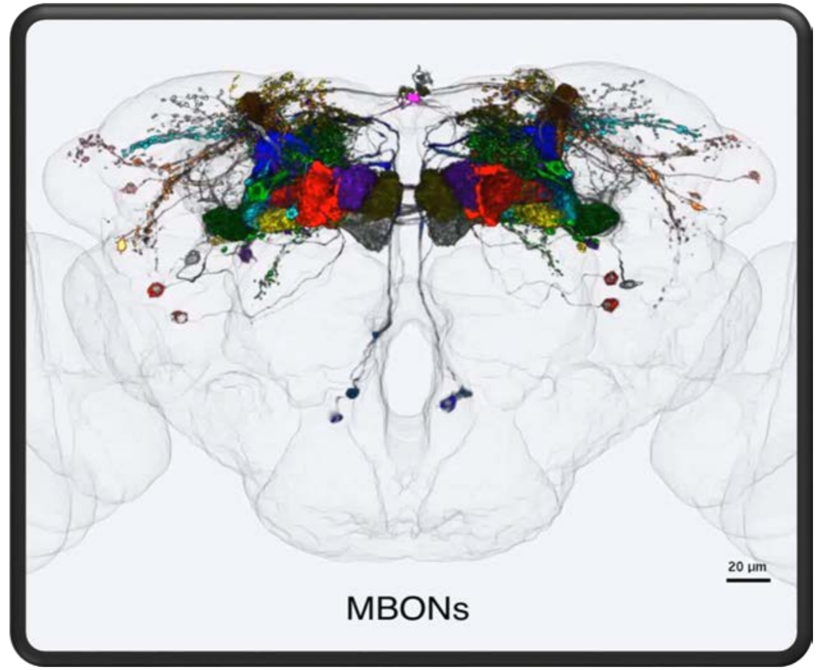
bioRxiv preprint first posted online May. 24, 2017; doi: http://dx.doi.org/10.1101/141762.

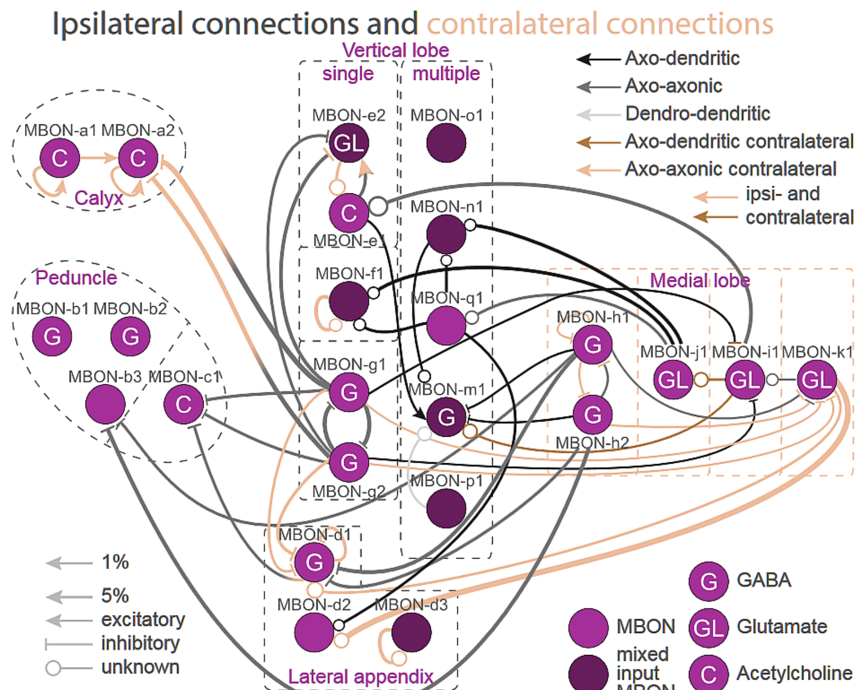
The complete connectome of a learning and memory center in an insect brain

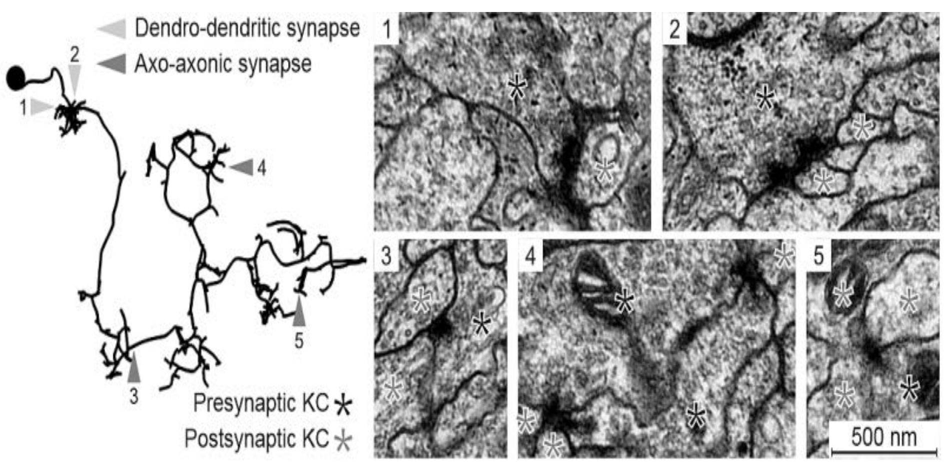
Katharina Eichler[1,2*], Feng Li[1*], Ashok Litwin-Kumar[3*], Youngser Park[4], Ingrid Andrade[1], Casey M. Schneider-Mizell[1], Timo Saumweber[5], Annina Huser[2], Claire Eschbach[1], Bertram Gerber[5,6,7], Richard D. Fetter[1], James W. Truman[1], Carey E. Priebe[4], L. F. Abbott[3,8,c], Andreas S. Thum[2,c], Marta Zlatic[1,9,c] & Albert Cardona[1,10,c]

Associating stimuli with positive or negative reinforcement is essential for survival, but a complete wiring diagram of a higher-order circuit supporting associative memory has not been previously available. We reconstructed one such circuit at synaptic resolution, the *Drosophila* larval mushroom body, and found that most Kenyon cells integrate random combinations of inputs but a subset receives stereotyped inputs from single projection neurons. This organization maximizes performance of a model output neuron on a stimulus discrimination task. We also report a novel canonical circuit in each mushroom body compartment with previously unidentified connections: reciprocal Kenyon cell to modulatory neuron connections, modulatory neuron to output neuron connections, and a surprisingly high number of recurrent connections between Kenyon cells. Stereotyped connections between output neurons could enhance the selection of learned responses. The complete circuit map of the mushroom body should guide future functional studies of this learning and memory center.

Massively parallel, higher-order neuronal circuits such as the cerebellum and insect mushroom body serve to form and retain associations between stimuli and reinforcement in vertebrates and higher invertebrates[1-6]. Although these systems provide a biological substrate for adaptive behavior, no complete synapse-resolution wiring diagram of their connectivity has been available and visual in adult[5,6,15] and larva (reported here for the first time). Previous analyses in adults[16,17] and larvae[14] suggest that the connectivity between olfactory PNs and KCs is random, but they do not eliminate the possibility of some degree of bilateral symmetry, which requires access to the full PN → KC wiring diagram in both hemispheres.

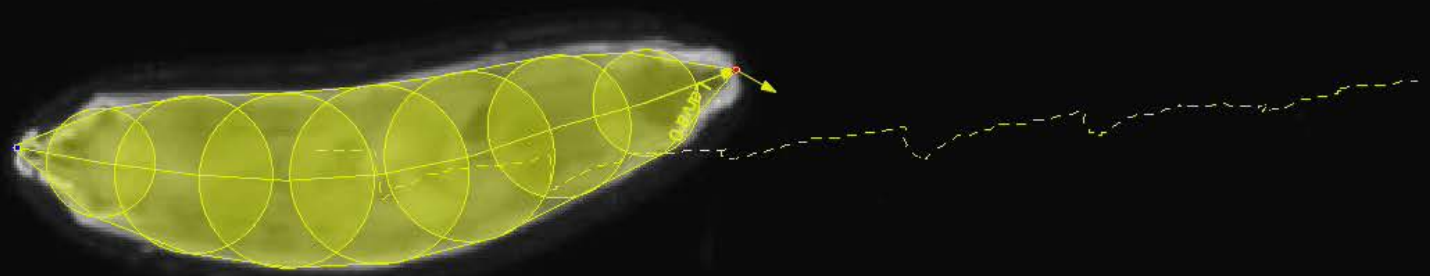






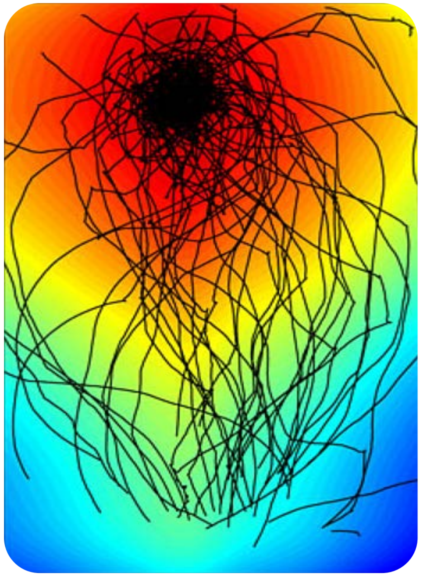
Eichler et al. "*Nature* 548.7666 (2017): 175.

Aso, Y (2014) *Elife*, *3*, e04577.

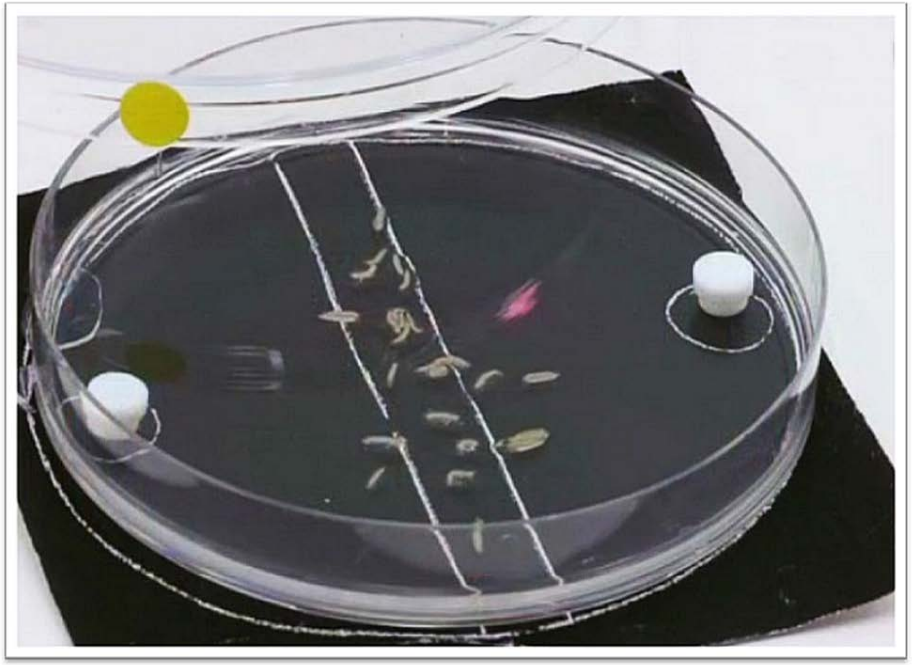


Risse et al., 2013 Plos One

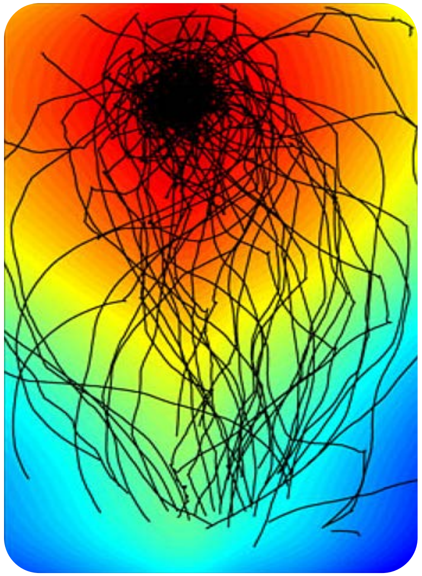
Chemotaxis in larva



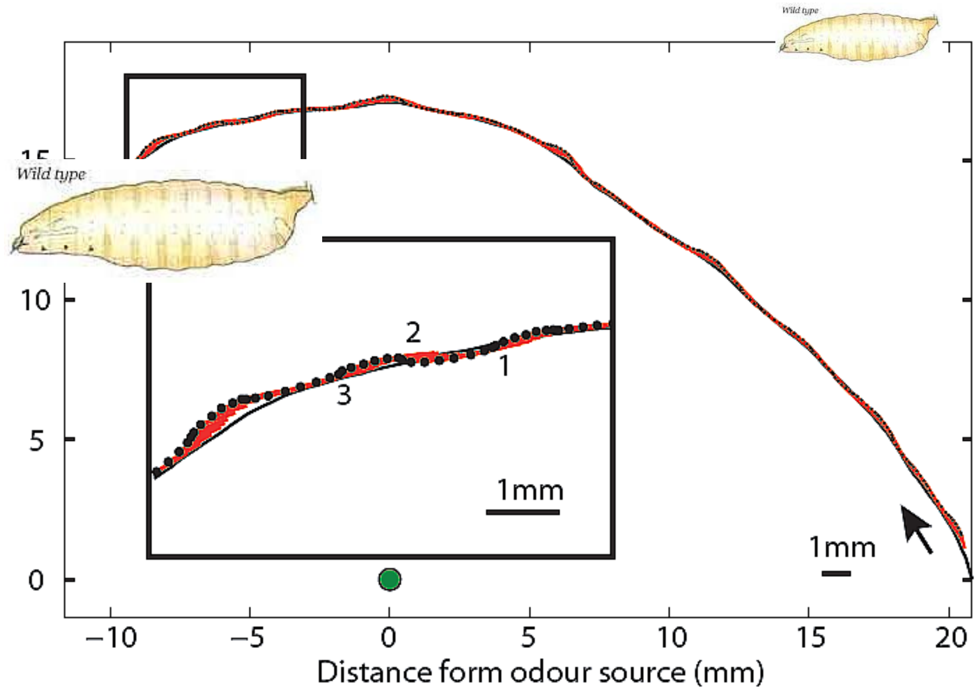
Gomez-Marin et al., 2011. Nat. com

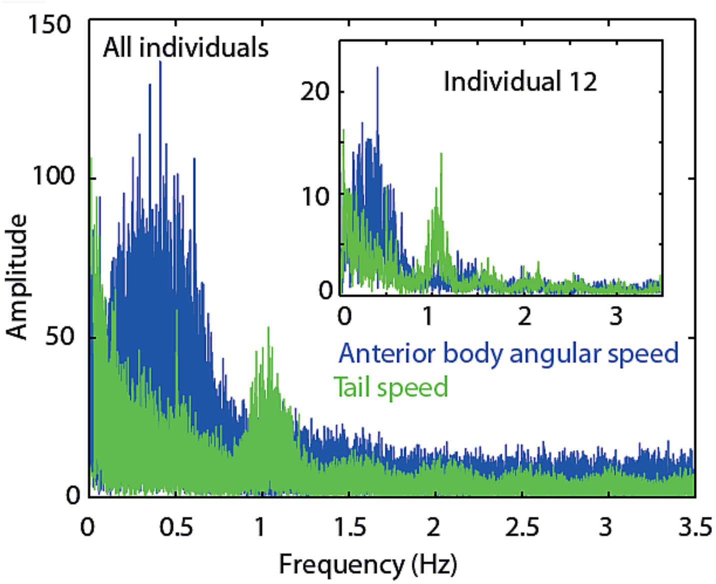


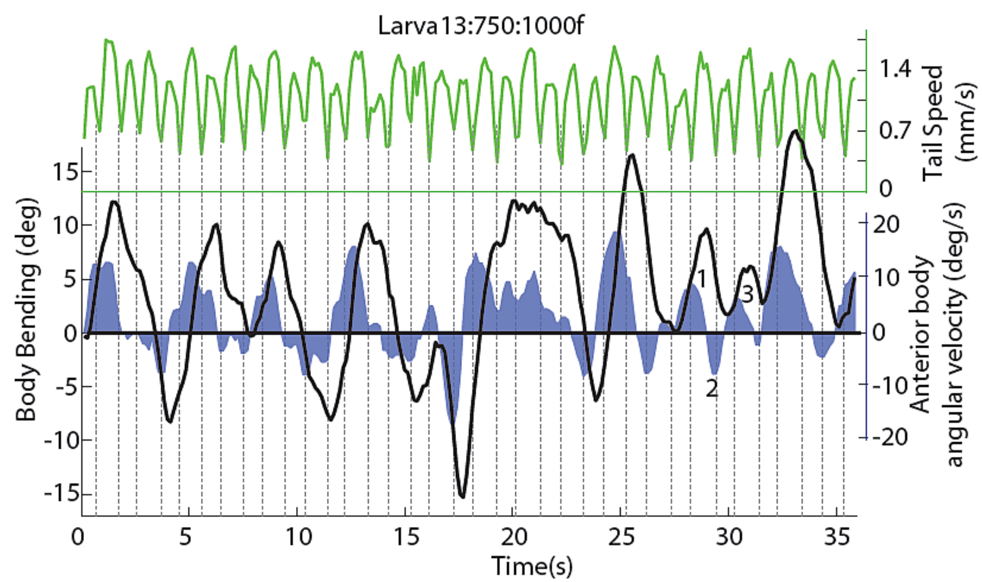
Chemotaxis in larva



Gomez-Marin et al., 2011. Nat. com

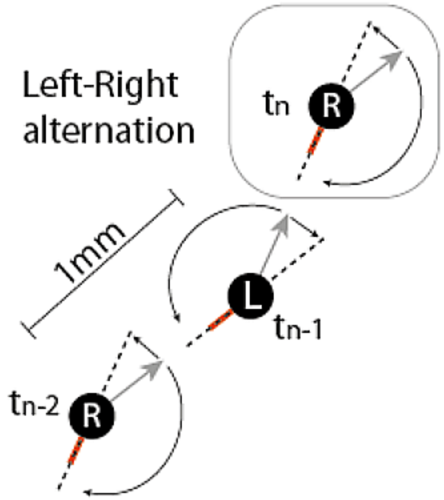


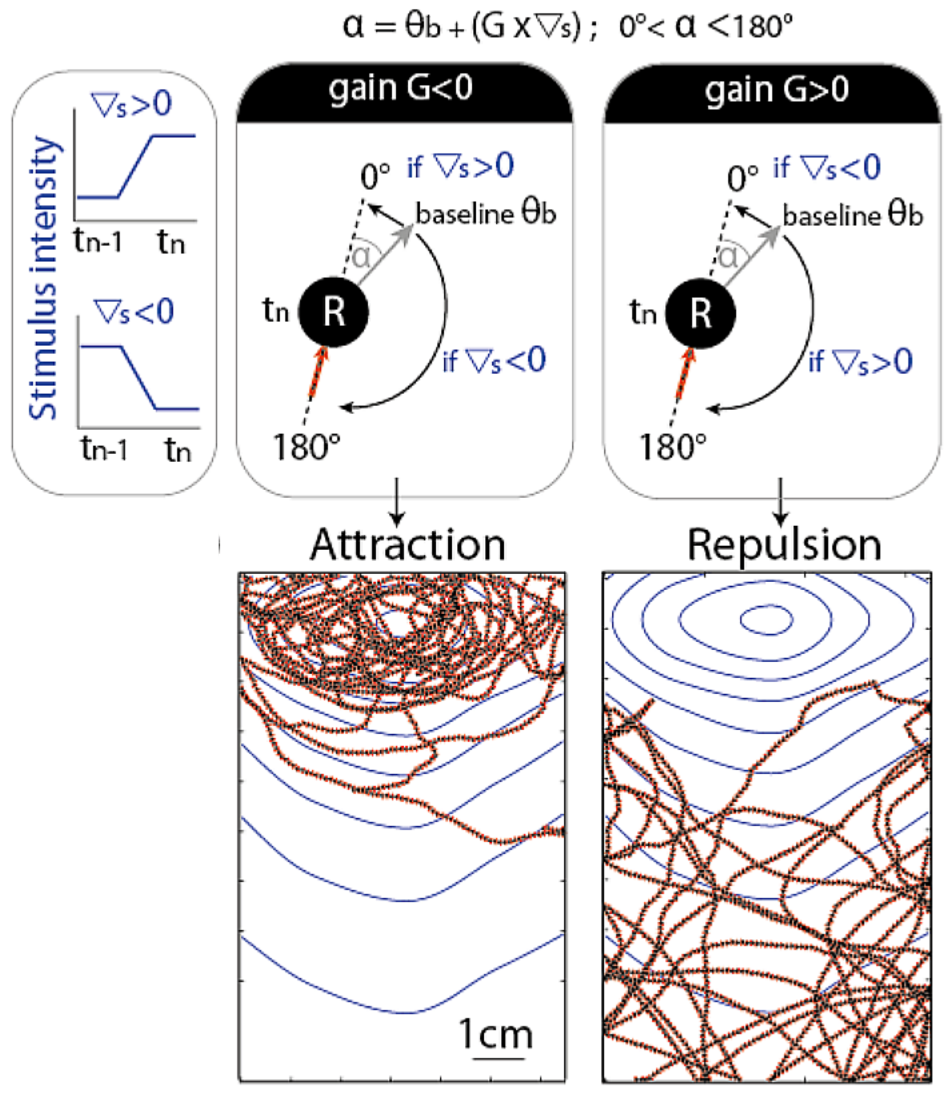


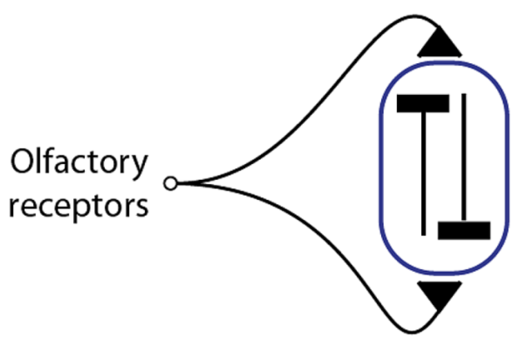


Wystrach et al., 2016 Elife

Simulation of larva chemotaxis







Wystrach et al., 2016 Elife

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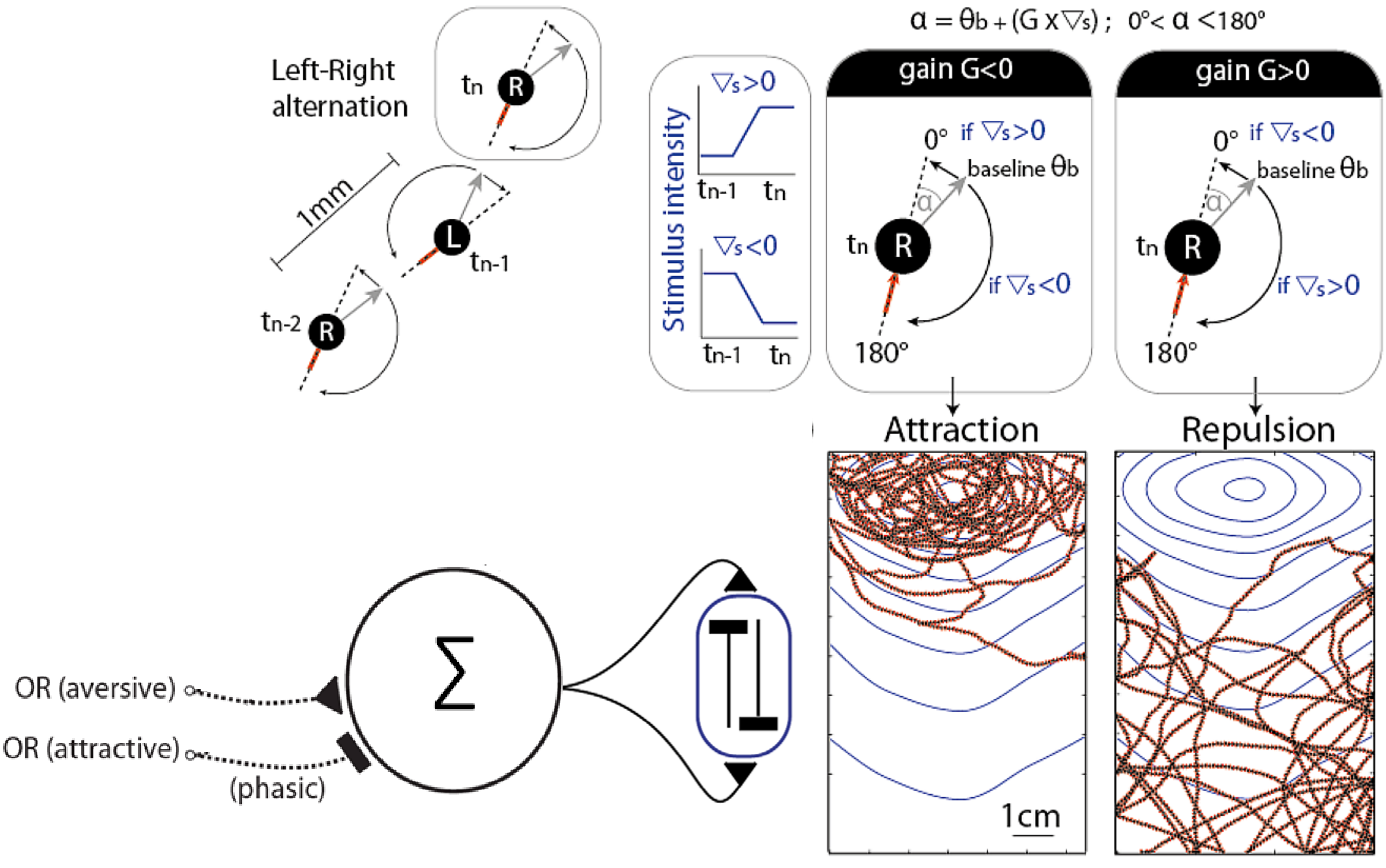
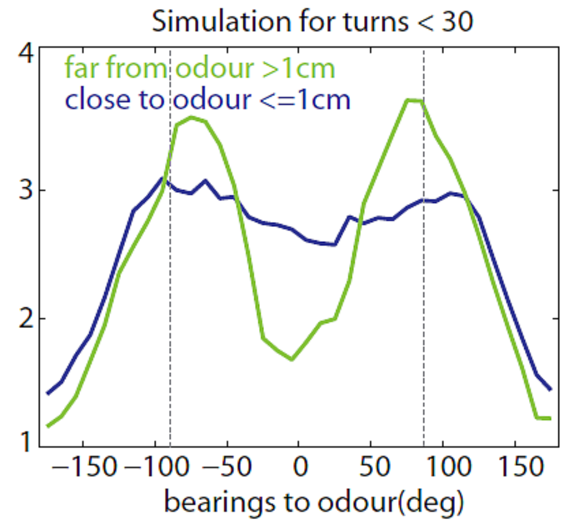
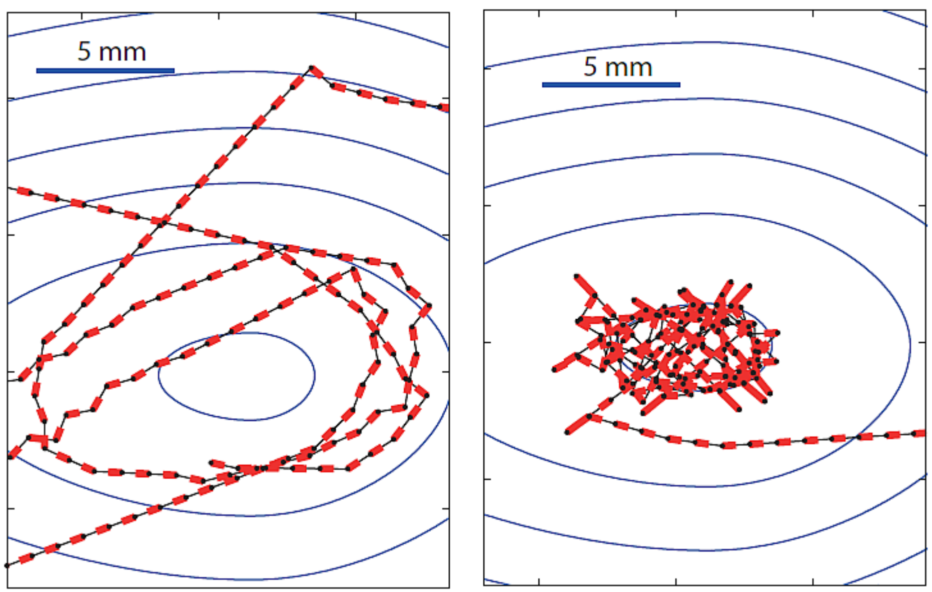


Wystrach et al., 2016 Elife

Larvae vs. Model predictions





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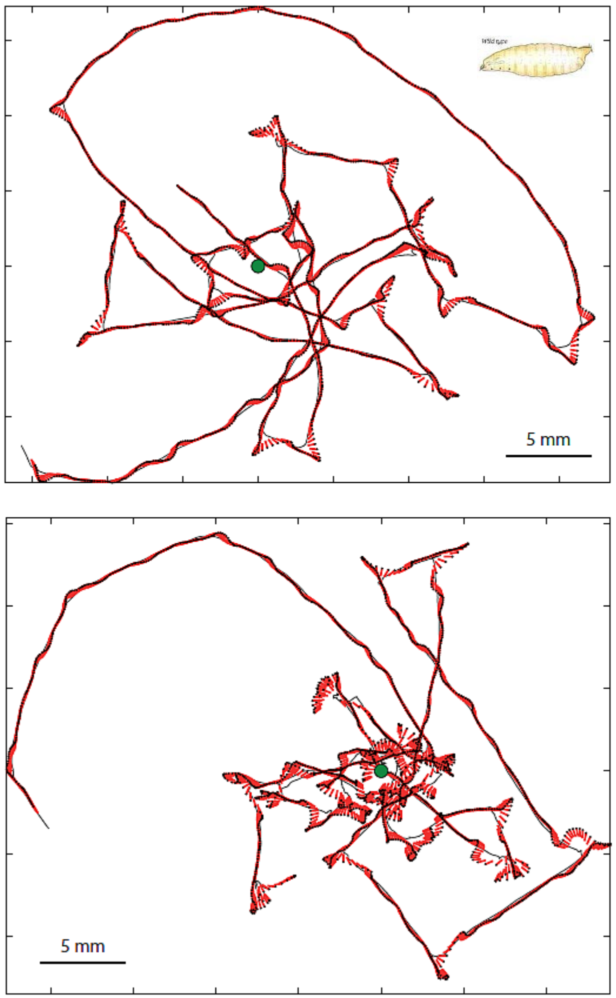
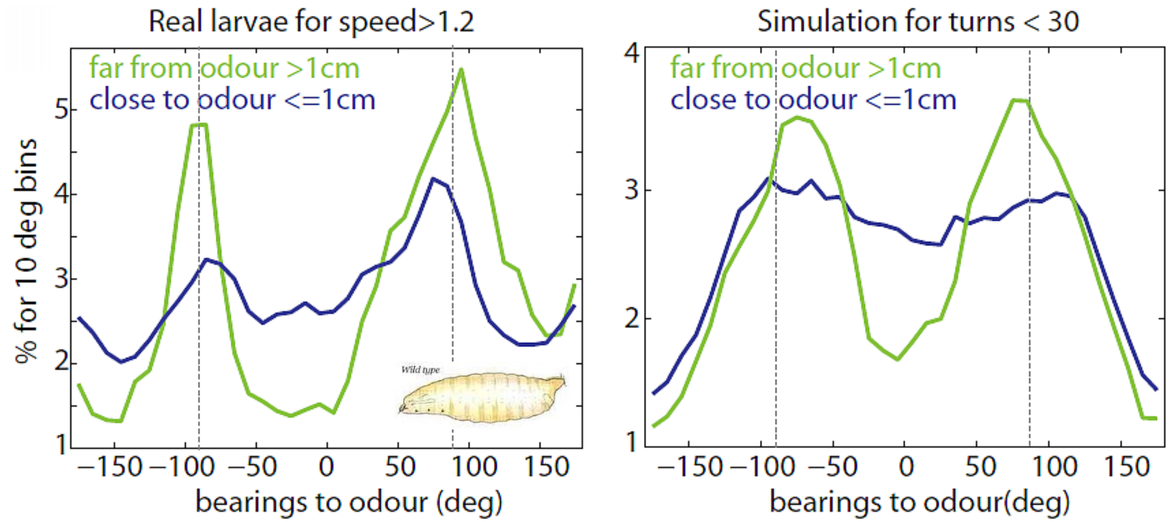
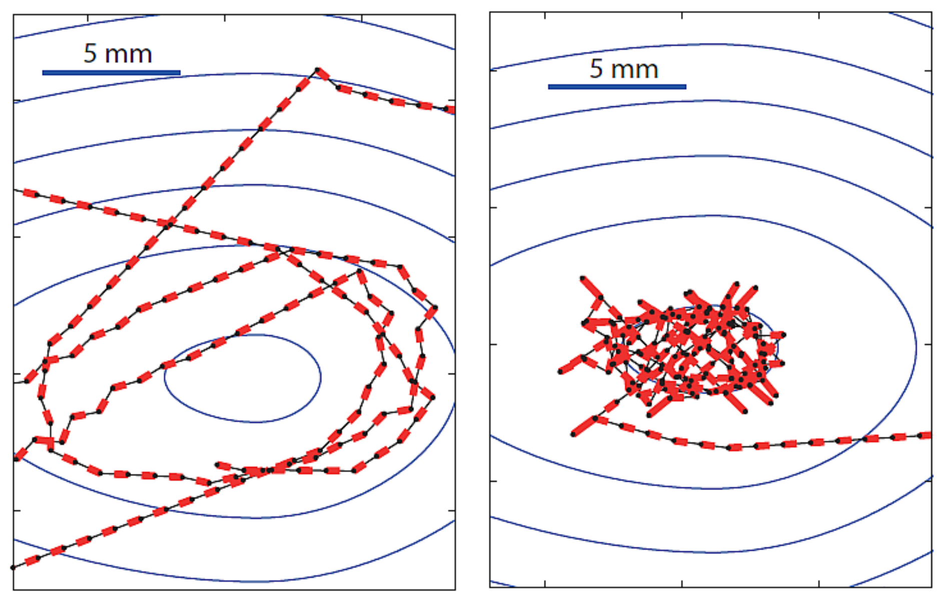
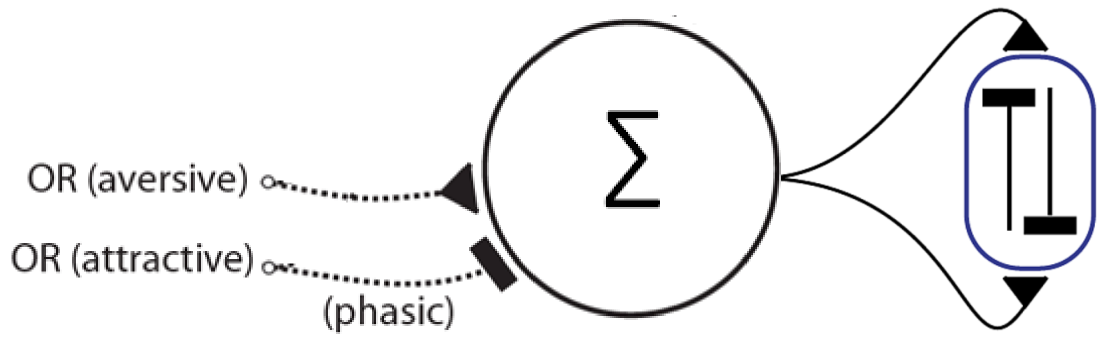


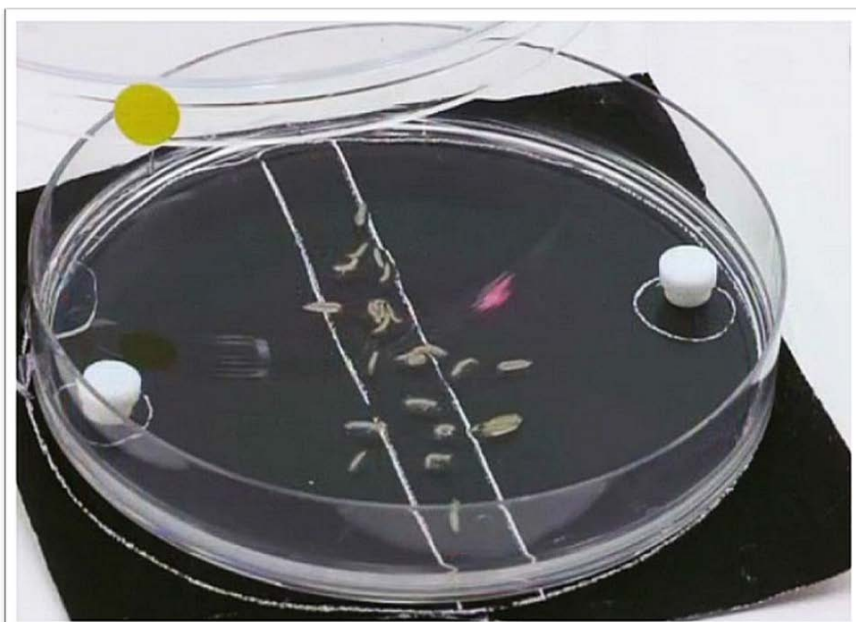


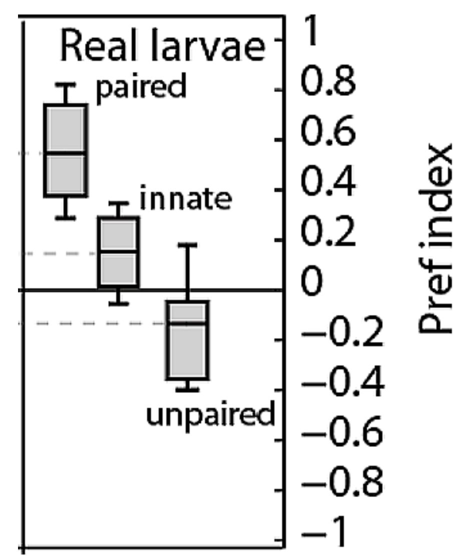


Wystrach et al., 2016 Elife

Learning assays

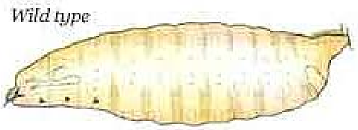


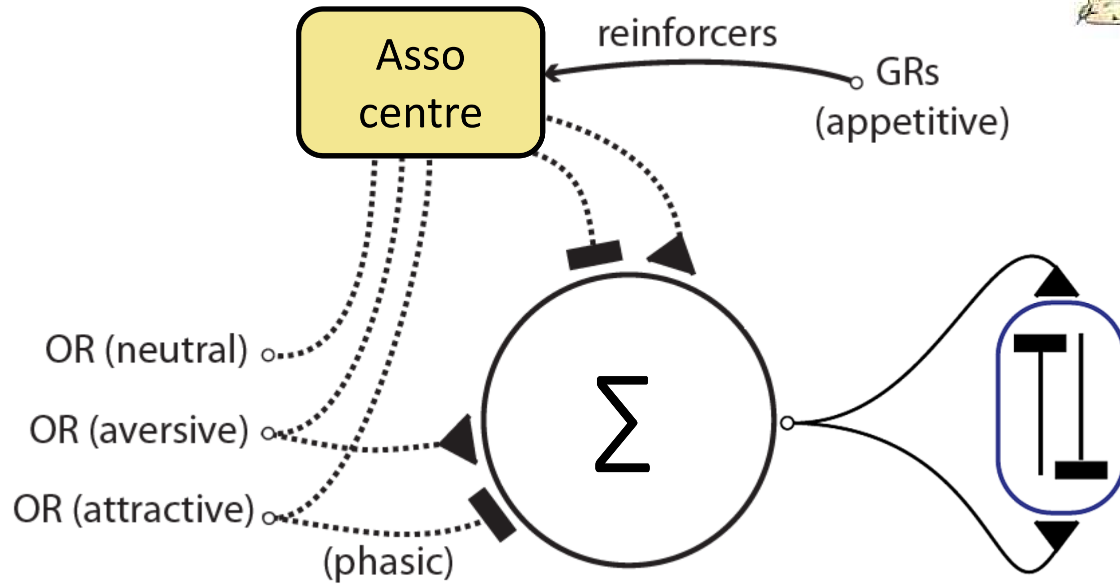


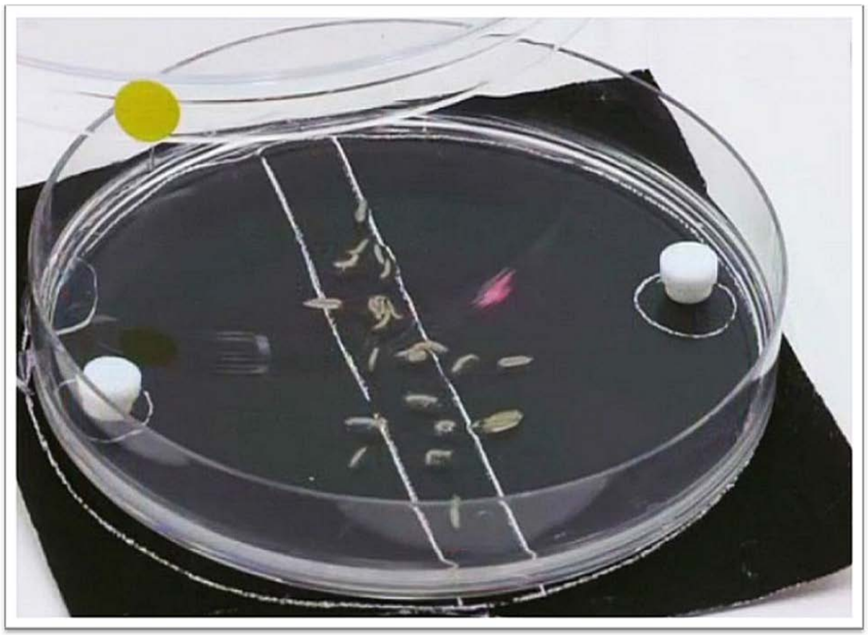


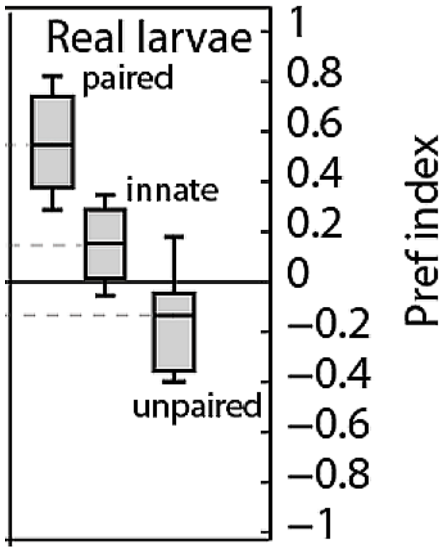
Schleyer et al., 2011 Learn. & Mem

Learning assays



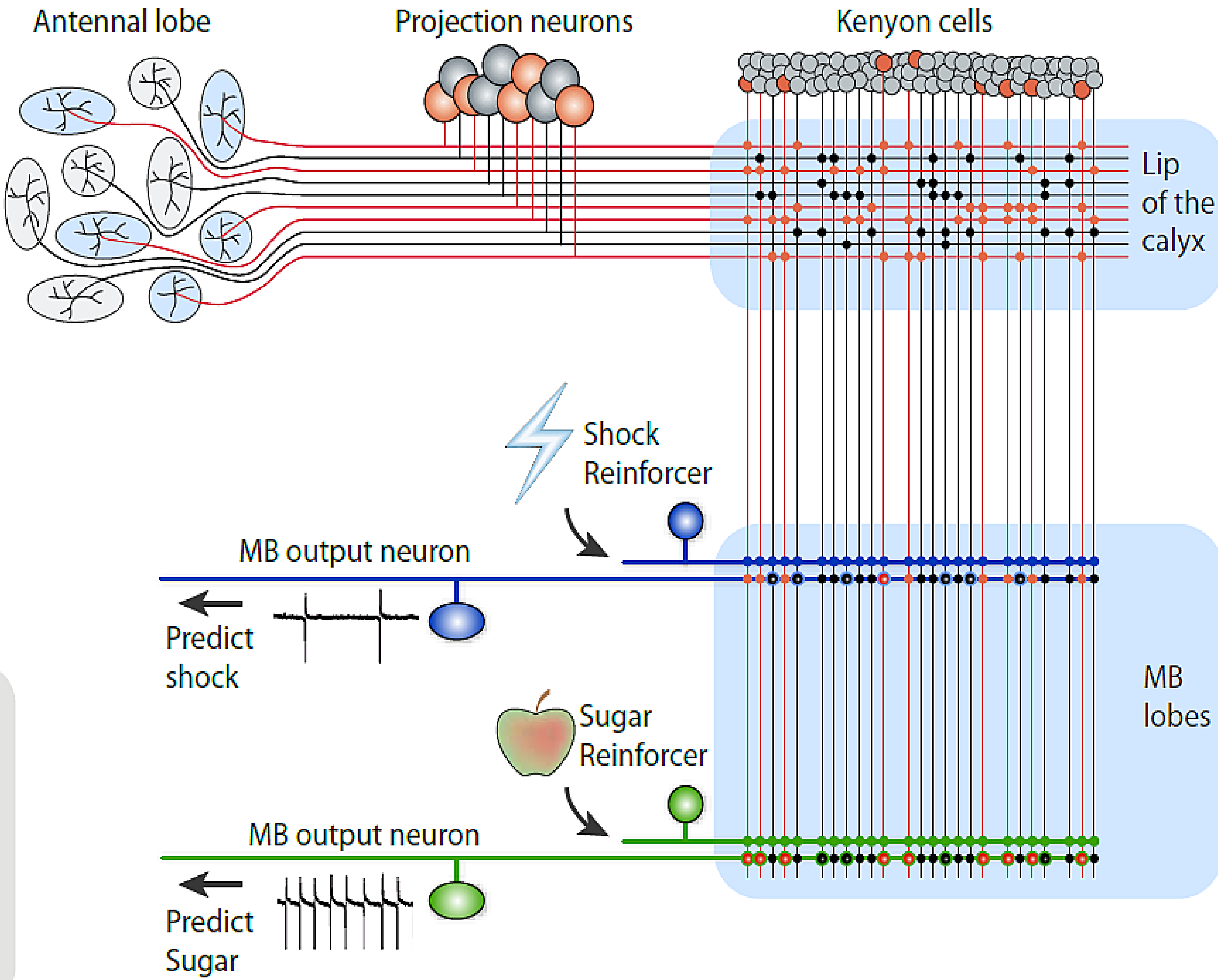


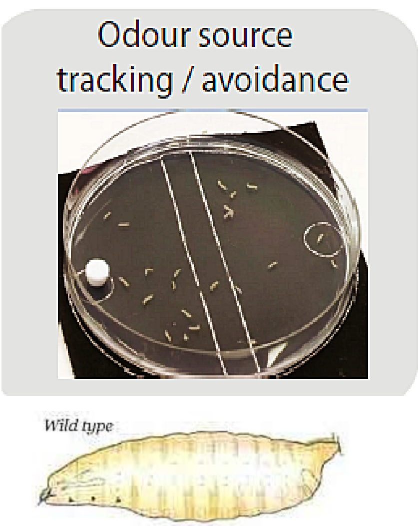




Schleyer et al., 2011 Learn. & Mem

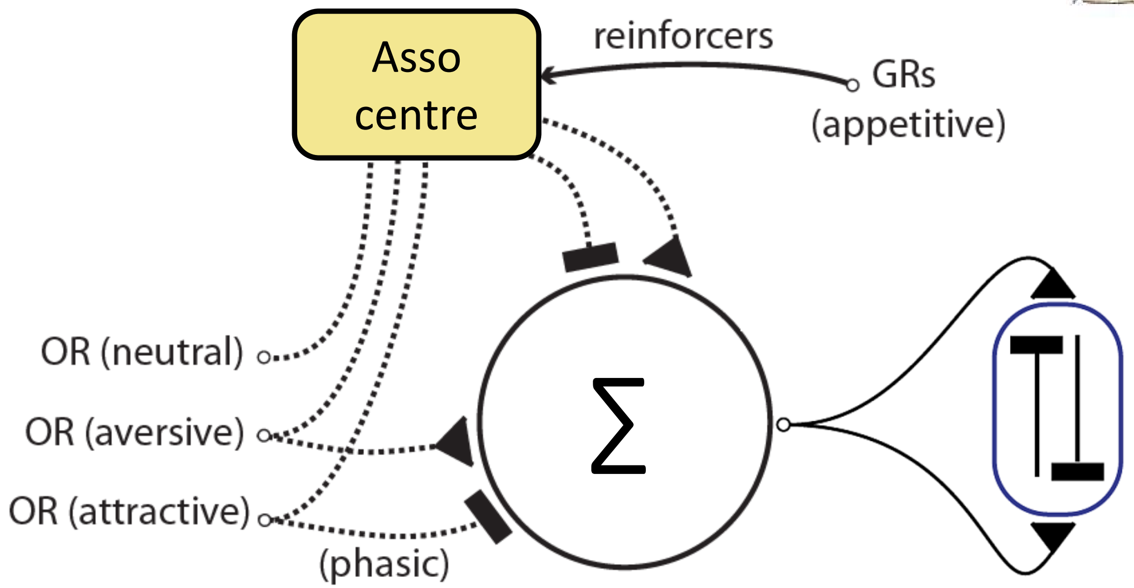
The Mushroom bodies: an associative centre

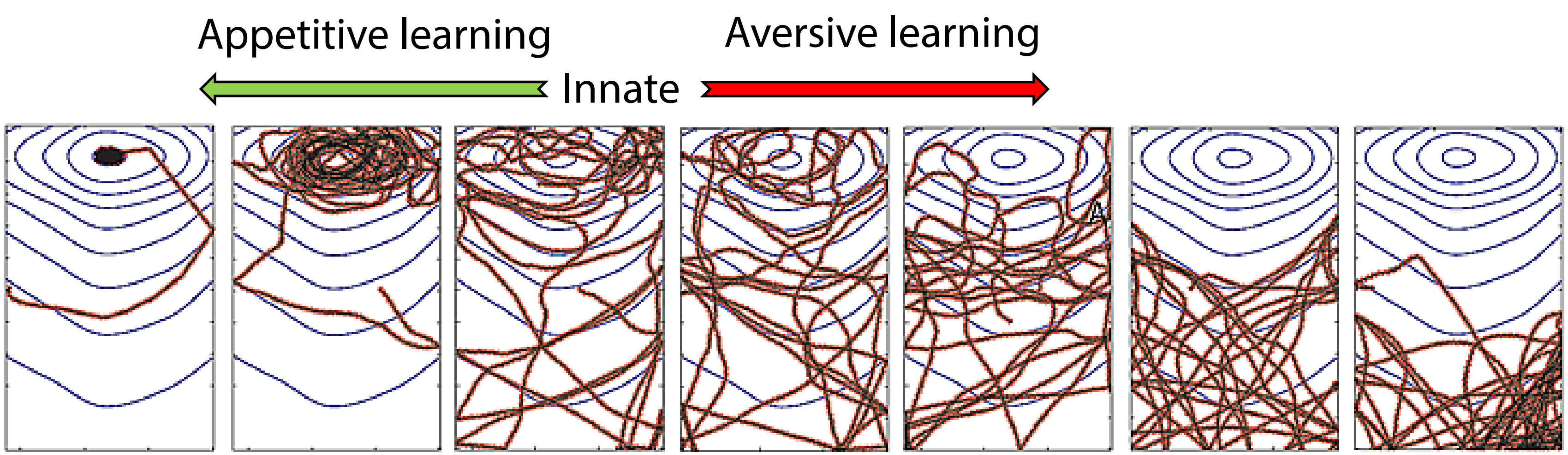




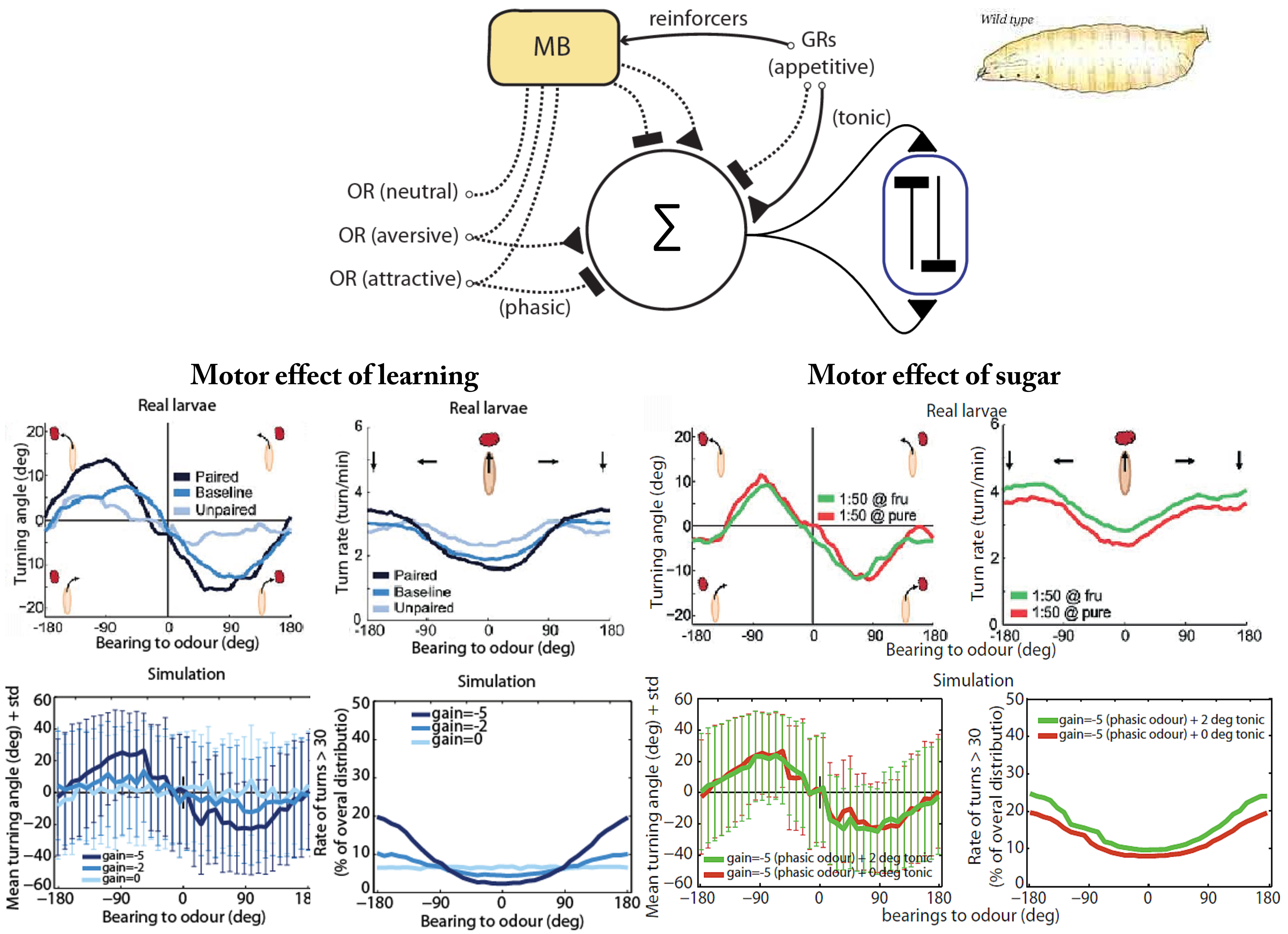
Heisenberg 2003 Nature Rev. Neurosc.
Aso et al., 2016 Elife

Simple summation of signals

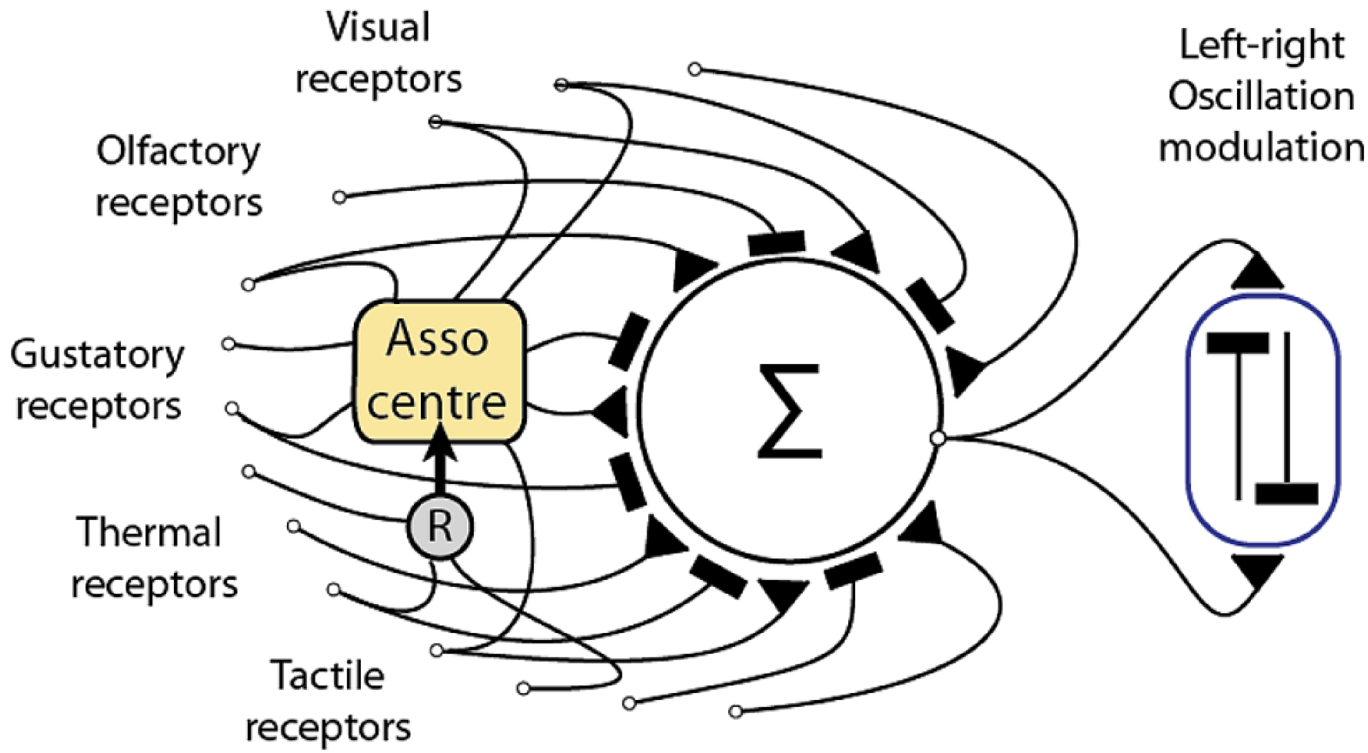




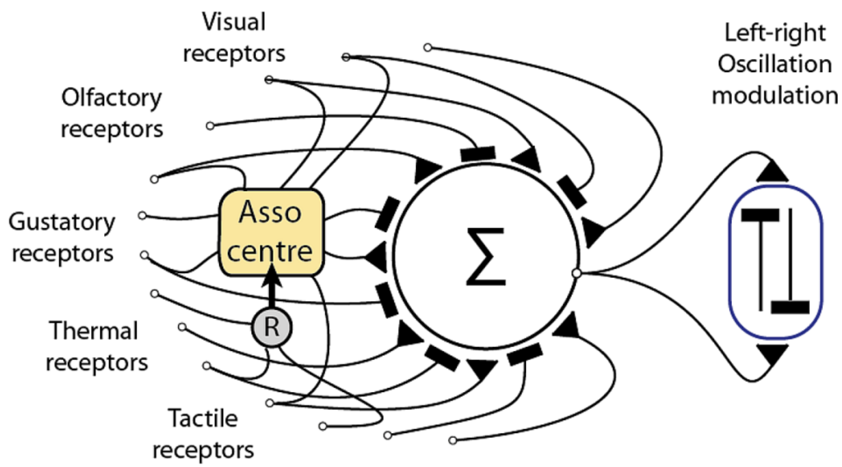
Wystrach et al., 2016 Elife

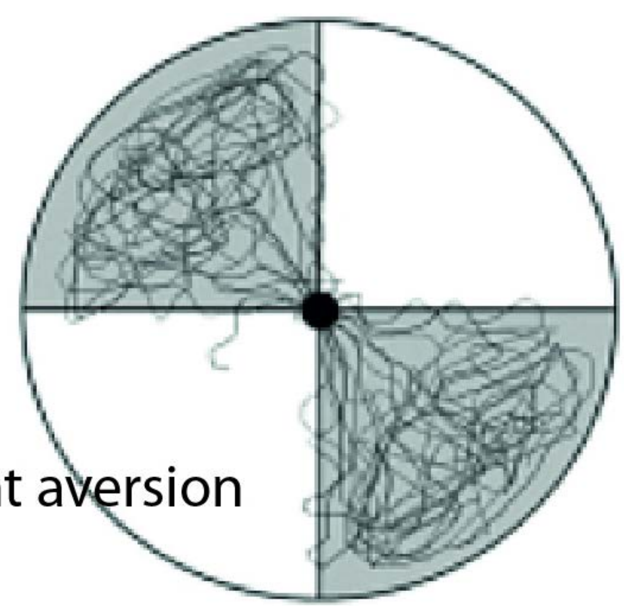

MB
reinforcers
GRs
(appetitive)
(tonic)
Wild type
OR (neutral)
OR (aversive)
OR (attractive)
(phasic)
Σ
Motor effect of learning
Motor effect of sugar
Real larvae
Turning angle (deg)
Paired
Baseline
Unpaired
Bearing to odour (deg)
Turn rate (turn/min)
1:50 @ fru
1:50 @ pure
Simulation
Mean turning angle (deg) + std
gain=-5
gain=-2
gain=0
Rate of turns > 30 (% of overal distributio)
gain=-5 (phasic odour) + 2 deg tonic
gain=-5 (phasic odour) + 0 deg tonic
bearings to odour (deg)

Across sensory modalities

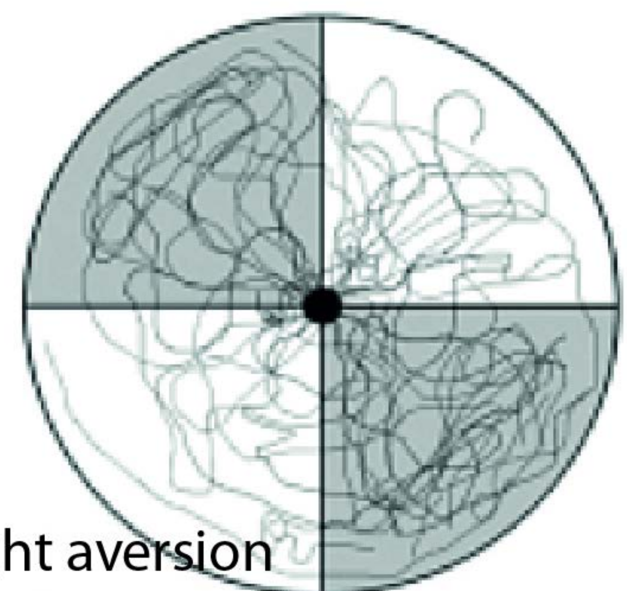


Across sensory modalities





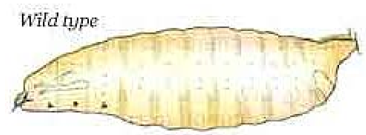
Light aversion

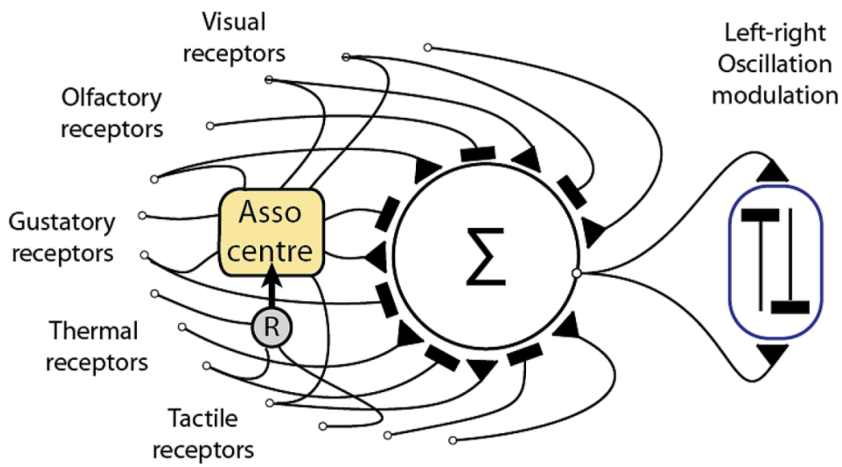


Light aversion
+ Odour attraction
(all Or83b optogenetics)

Bellman et al., 2010; Front. in Neurosci.

Across sensory modalities



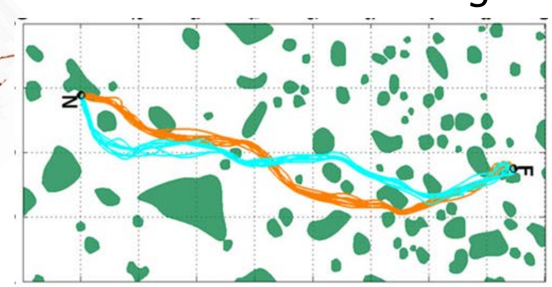


Flexibility for modulation/innovation.
Across species?

Plume Tracking

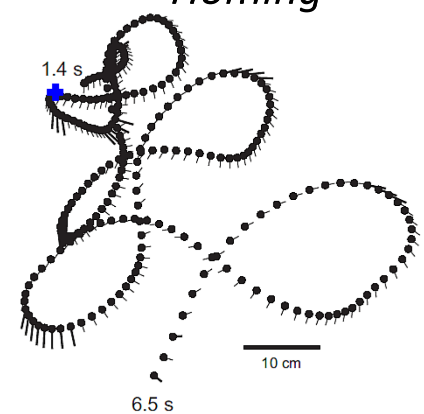
Pansopha, Ando and Kanzaki. 2014

Route Following

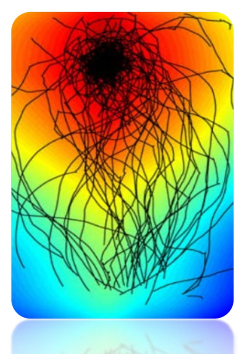


Mangan and Webb 2012

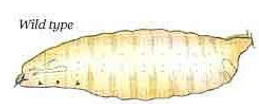
Homing



Philippides et al., 2013

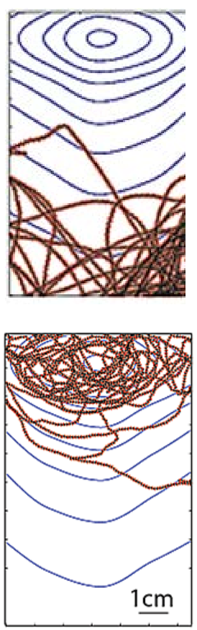


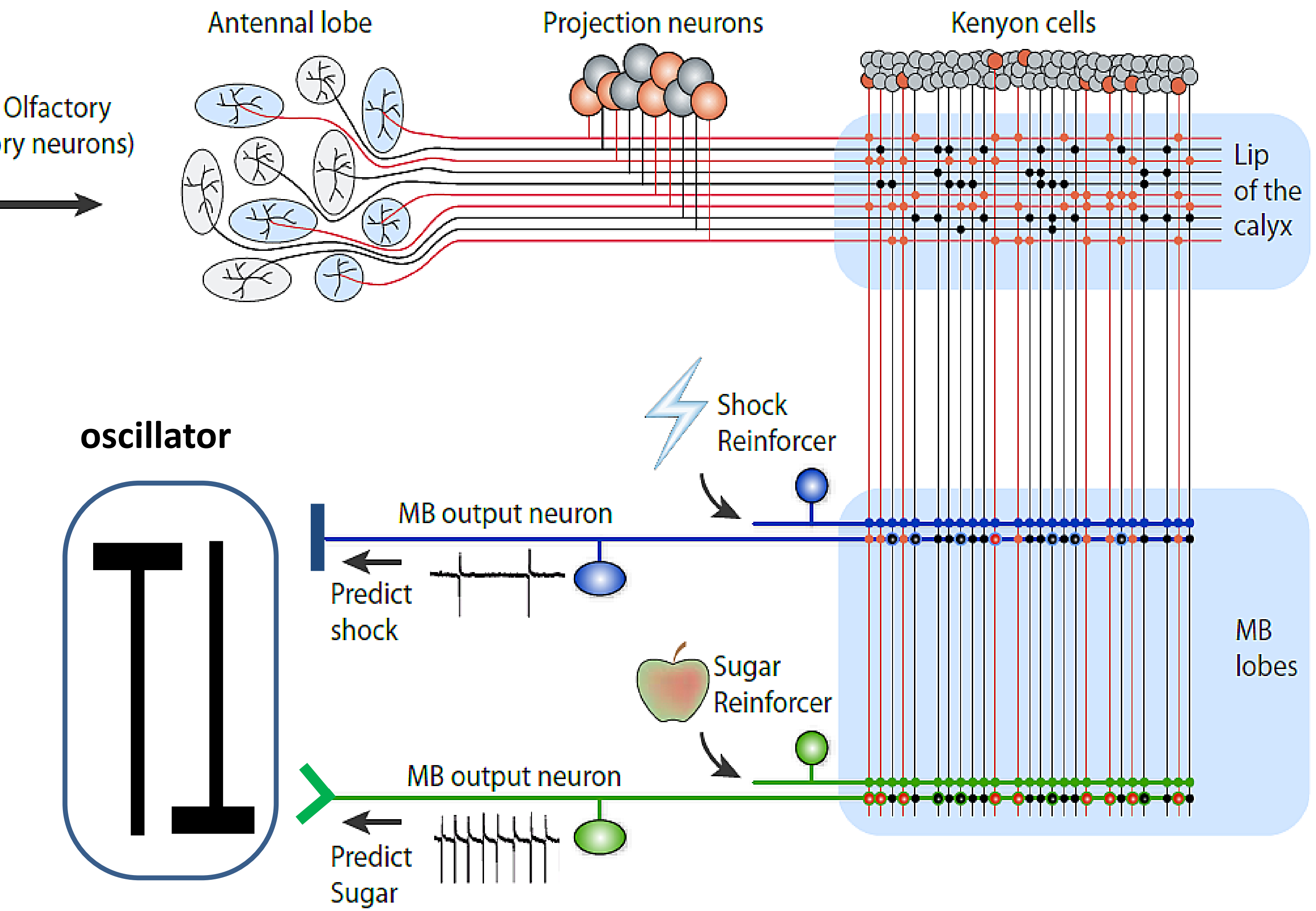
Taxis



Gomez-Marin et al., 2011

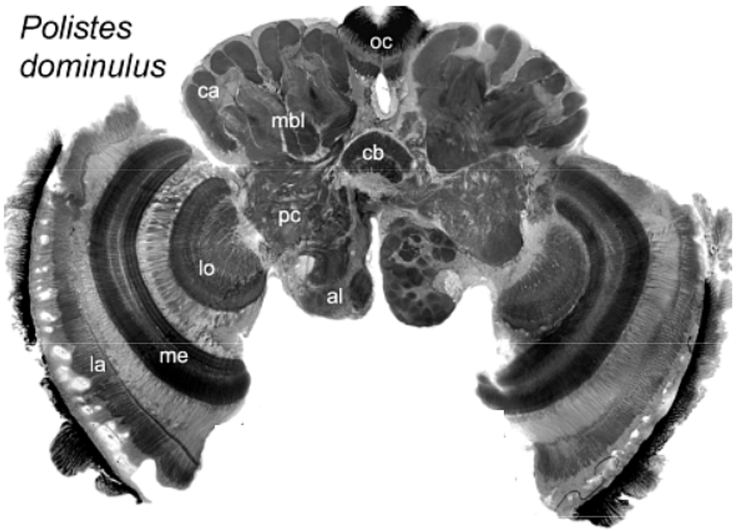
Olfactory input into the mushroom body

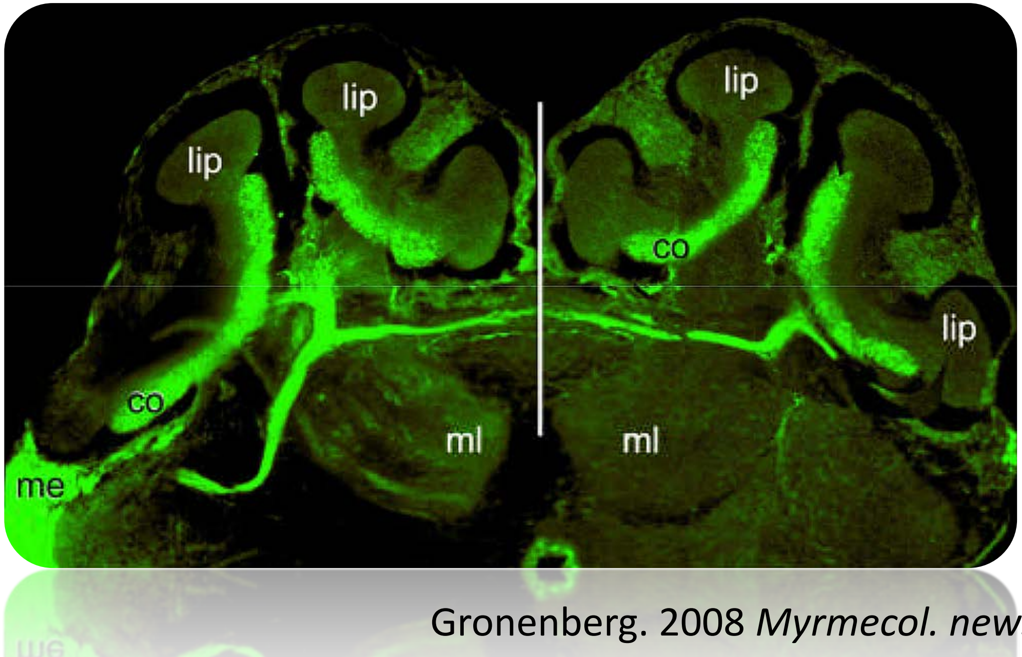




Heisenberg 2003 Nature Rev. Neurosc.

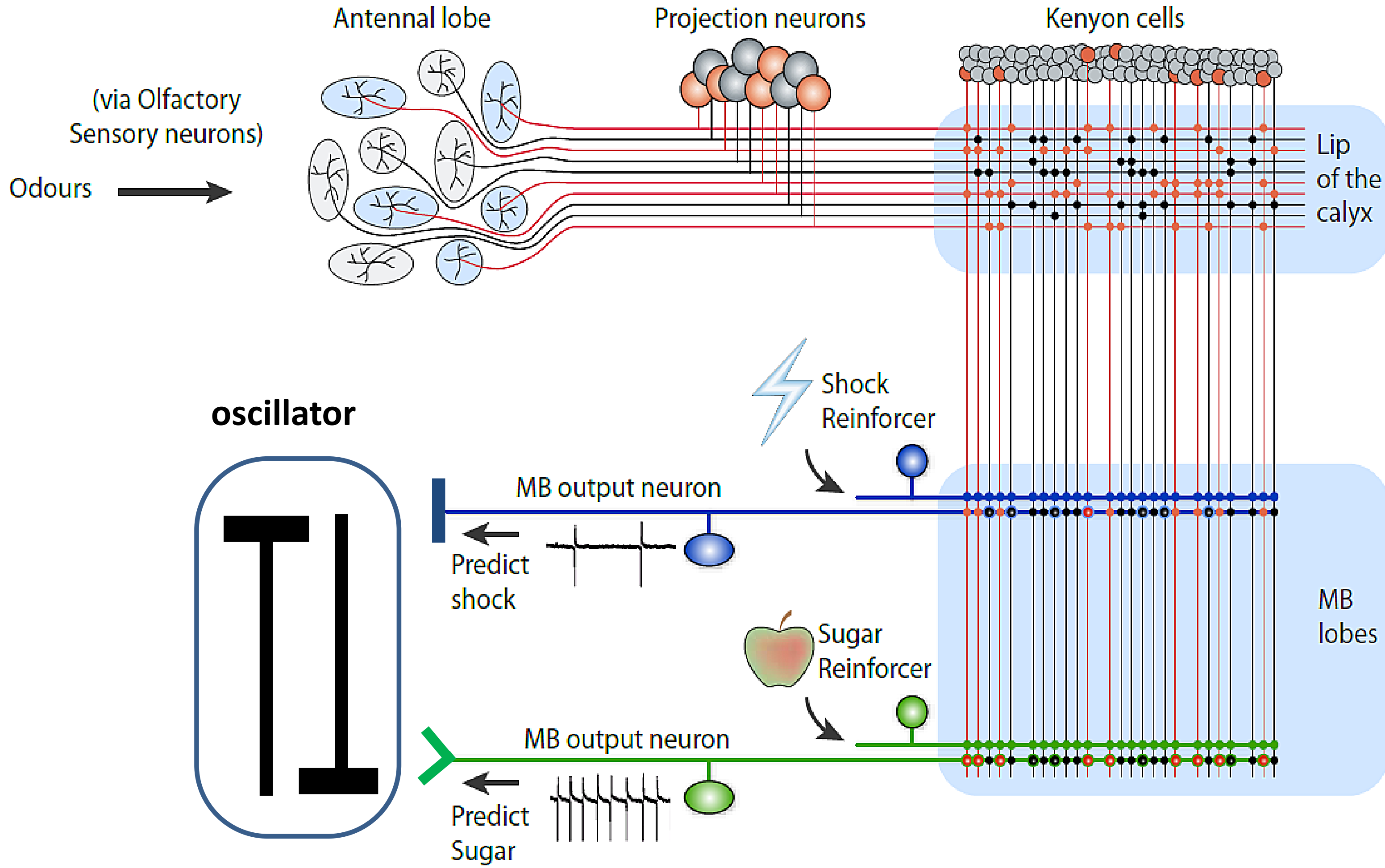
Visual input into the mushroom body





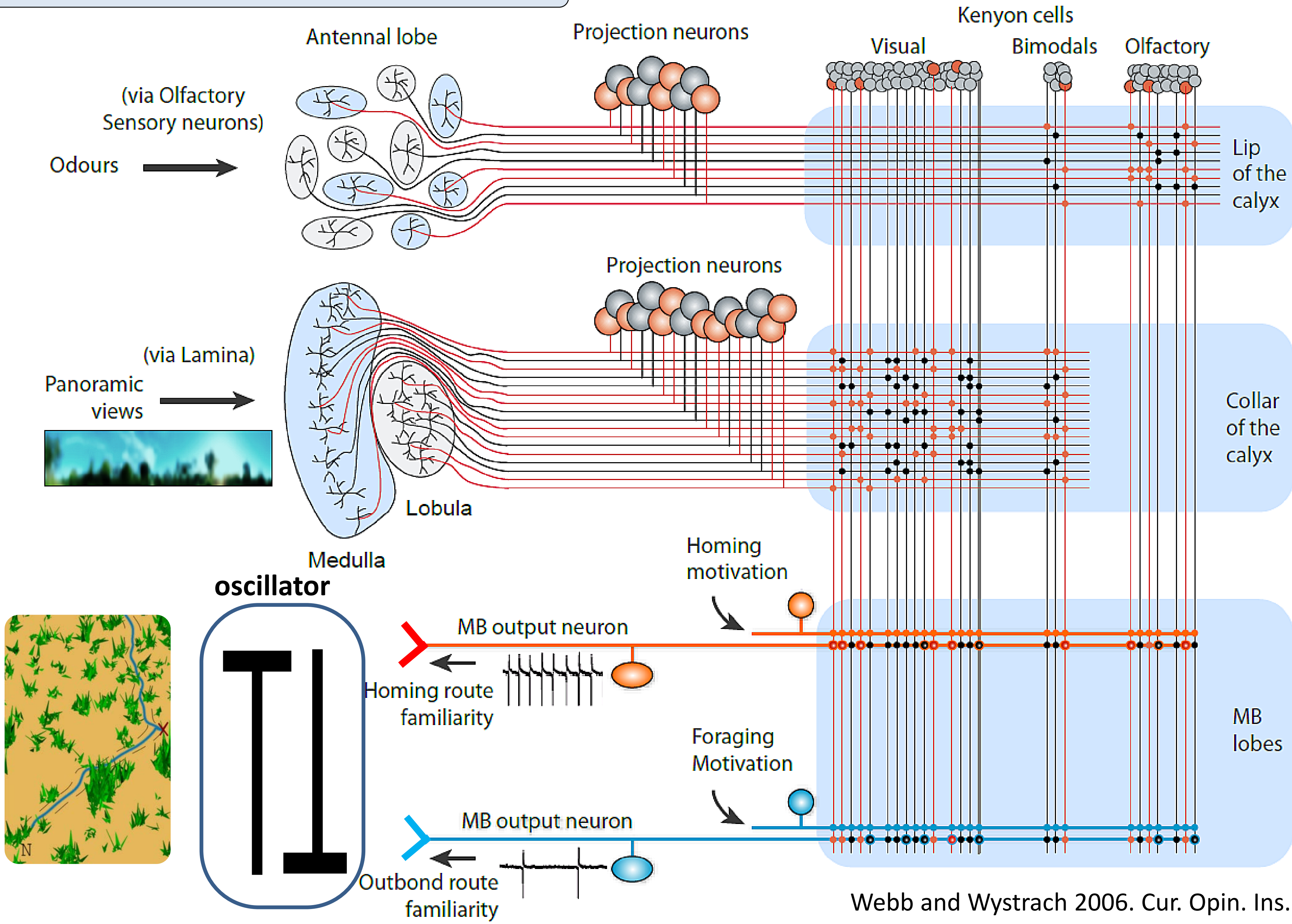
Gronenberg. 2008 *Myrmecol. news*

Olfactory input into the mushroom body



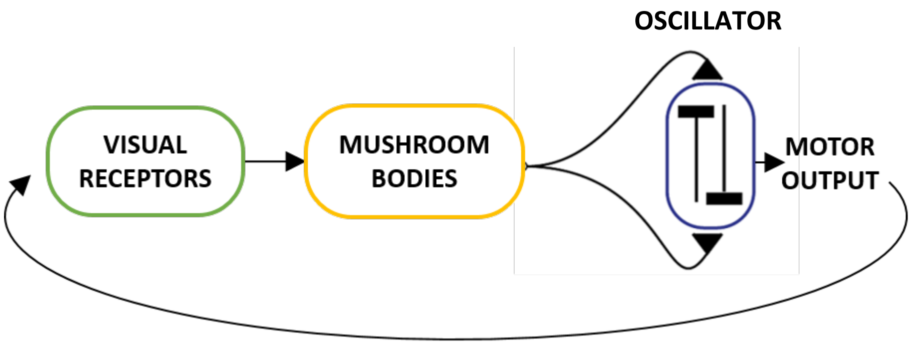
Heisenberg 2003 Nature Rev. Neurosc.

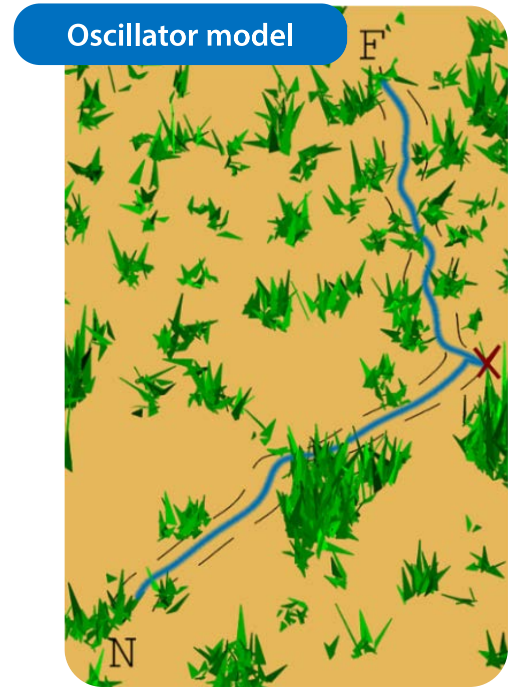
Visual input into the mushroom body

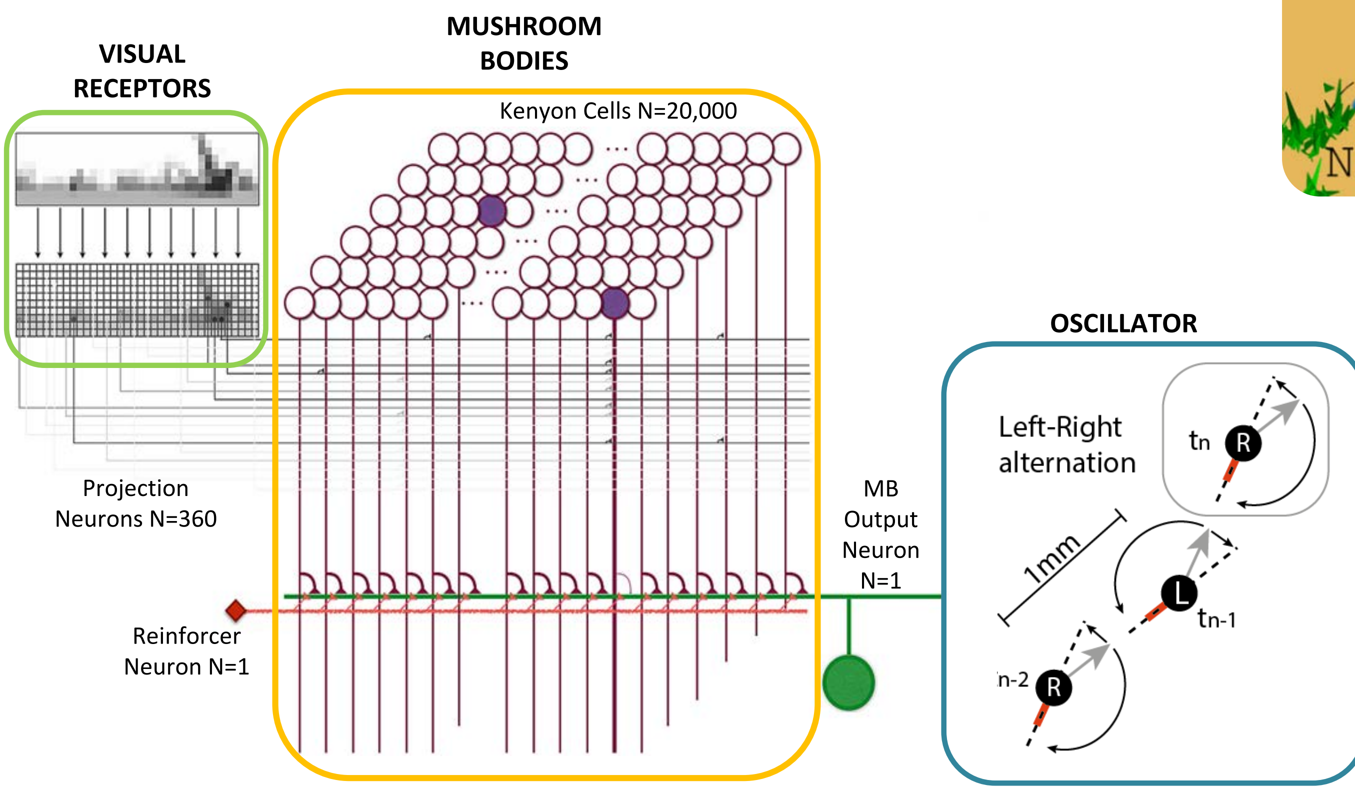


Webb and Wystrach 2006. Cur. Opin. Ins. Sci

Oscillatory model for route following

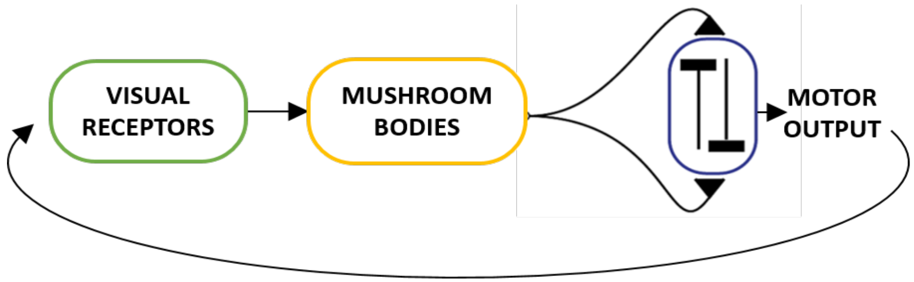




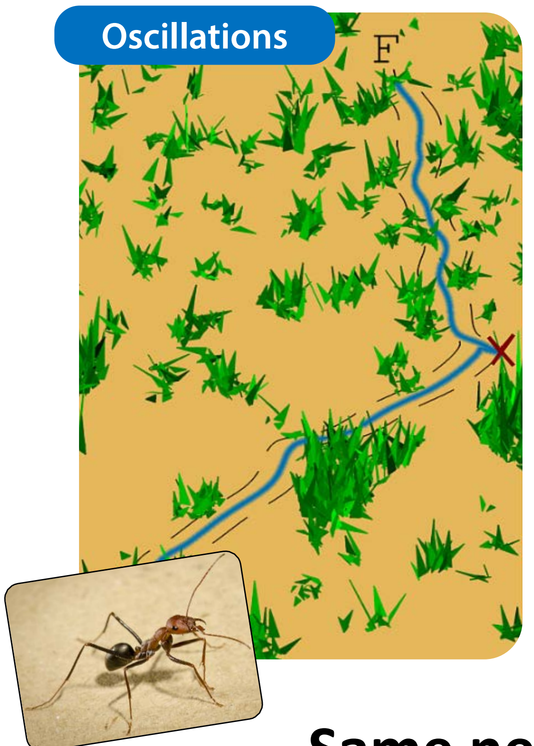


LeMoël and Wystrach in prep

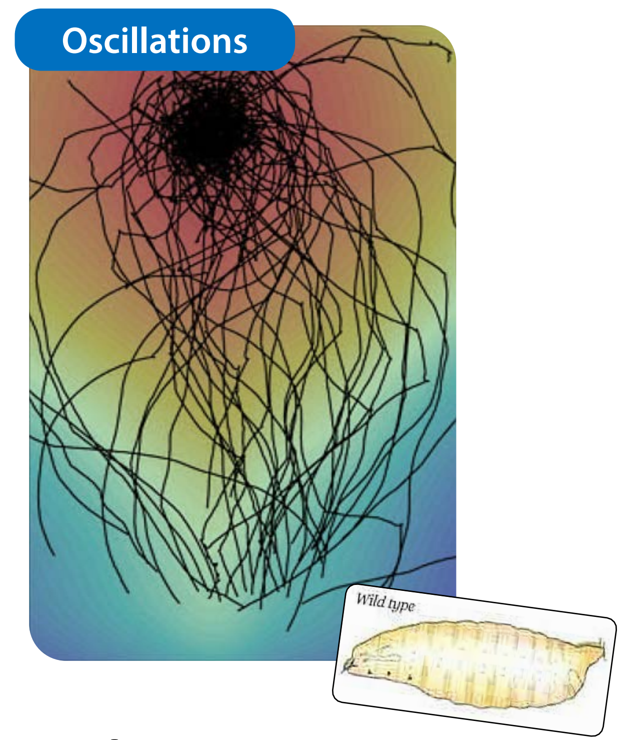
Emergence of new behaviours



Route following



Taxis

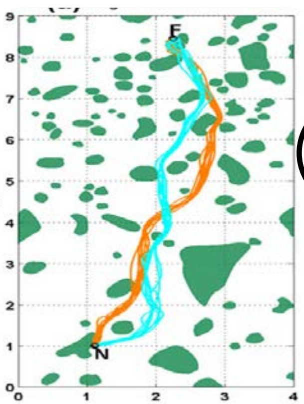


Same neural mechanisms
Different behaviours!

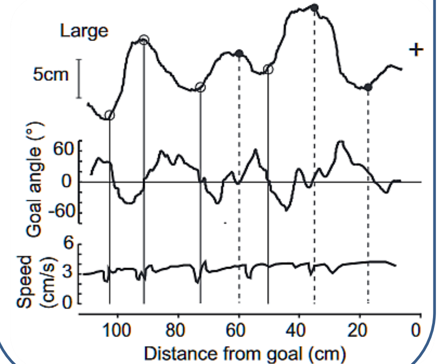
Three different angles

1. Observations of behaviours

Ecological task

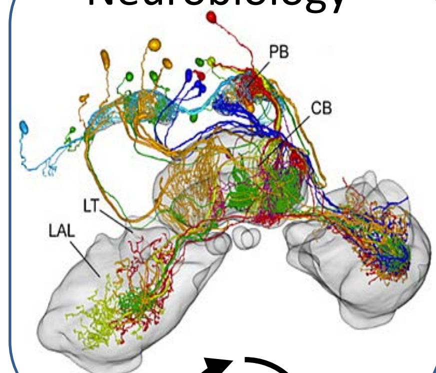


Fine motor pattern

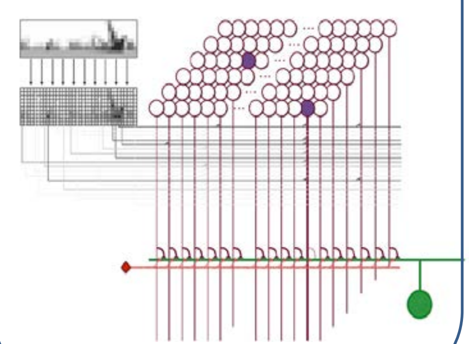


3. Neural implementation

Neurobiology

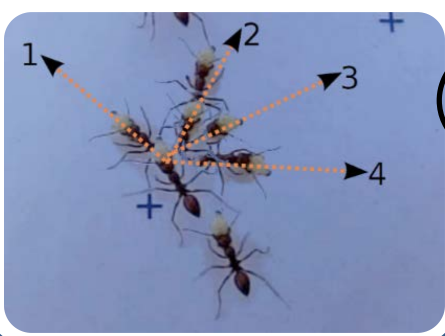


Neural models

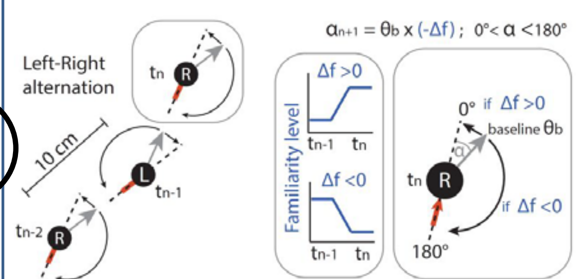


2. Cracking the algorithm

Behavioural experimentation

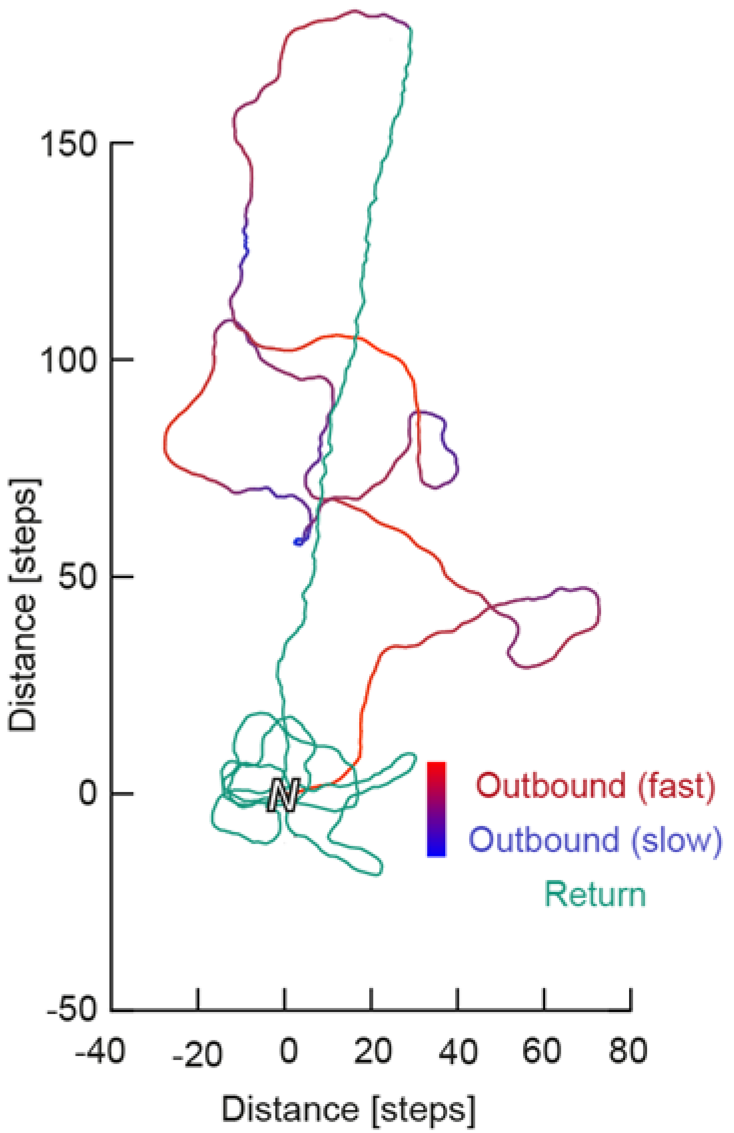


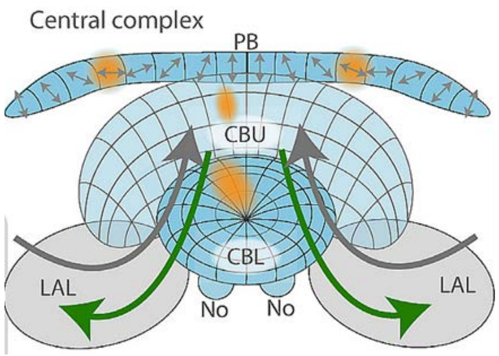
Hypothesised algorithm

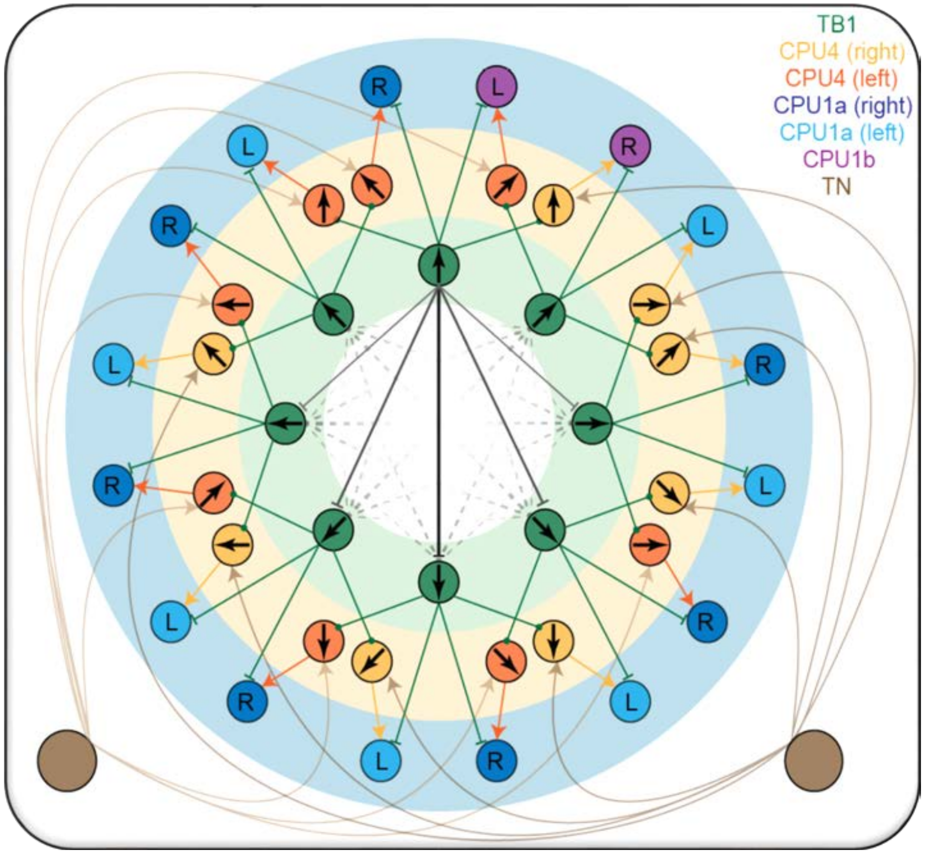


Unexpected prediction

Neural model of path integration







Stone et al., 2007 Current biology

The experimental approach is ahead…

Visual sequence learning
Chameron et al., 1998. PRSB

Directional cue integration
Wystrach et al., 2015, PRSB

Visuo – motor association
Beugnon et al., 2016, JCPA

Route optimisation and aversive memories
Wystrach et al., in prep

Homing from novel locations
Wystrach et al., 2012 JEB

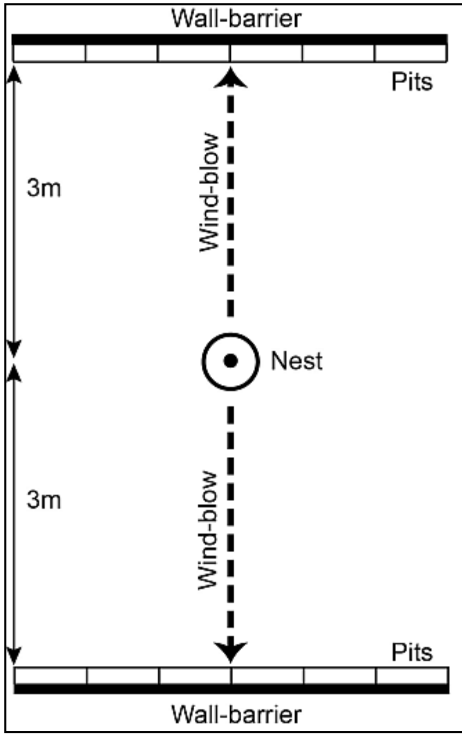
Encoding wind direction
Wystrach et al., 2012, Cur. Biol.

Navigation while walking backwards
Schwarz and Wystrach 2017, Cur. Biol.

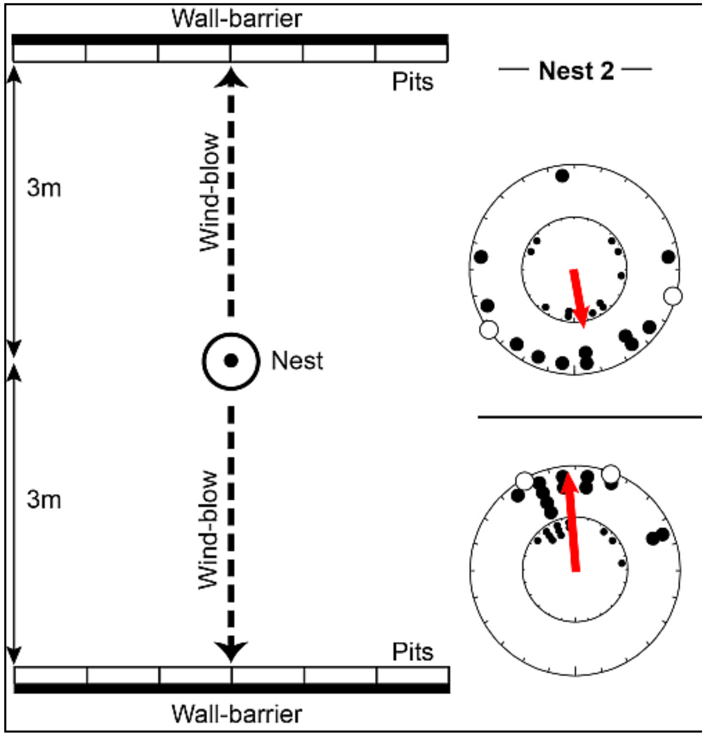
Blowing experiment

Wystrach and Schwarz 2013. Cur. biol.

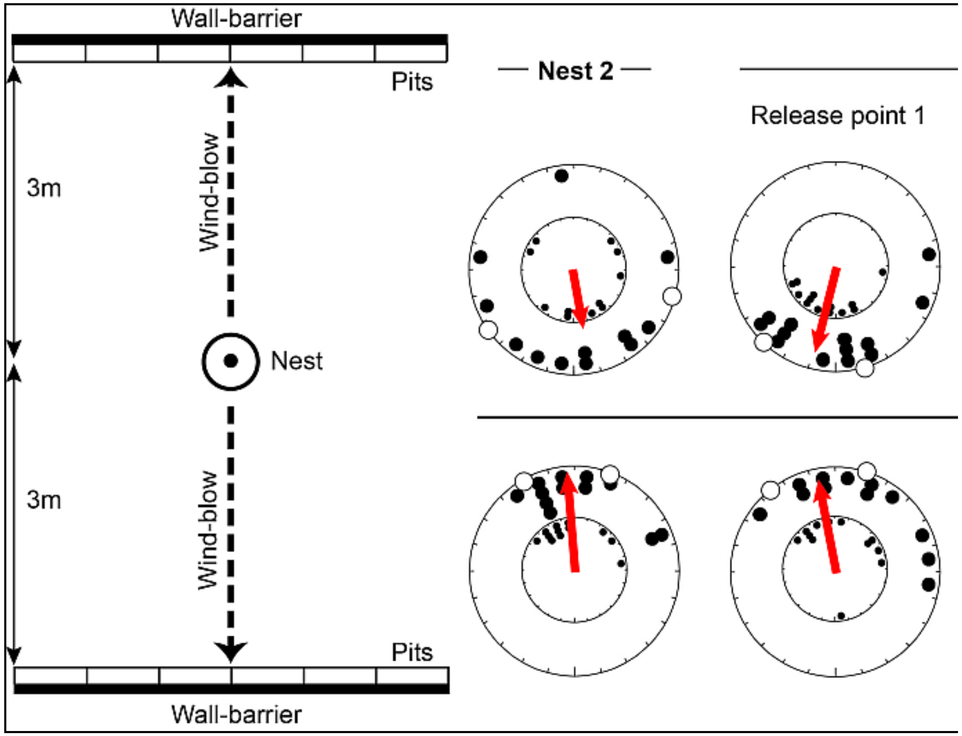
Wystrach and Schwarz 2013. Cur. biol.



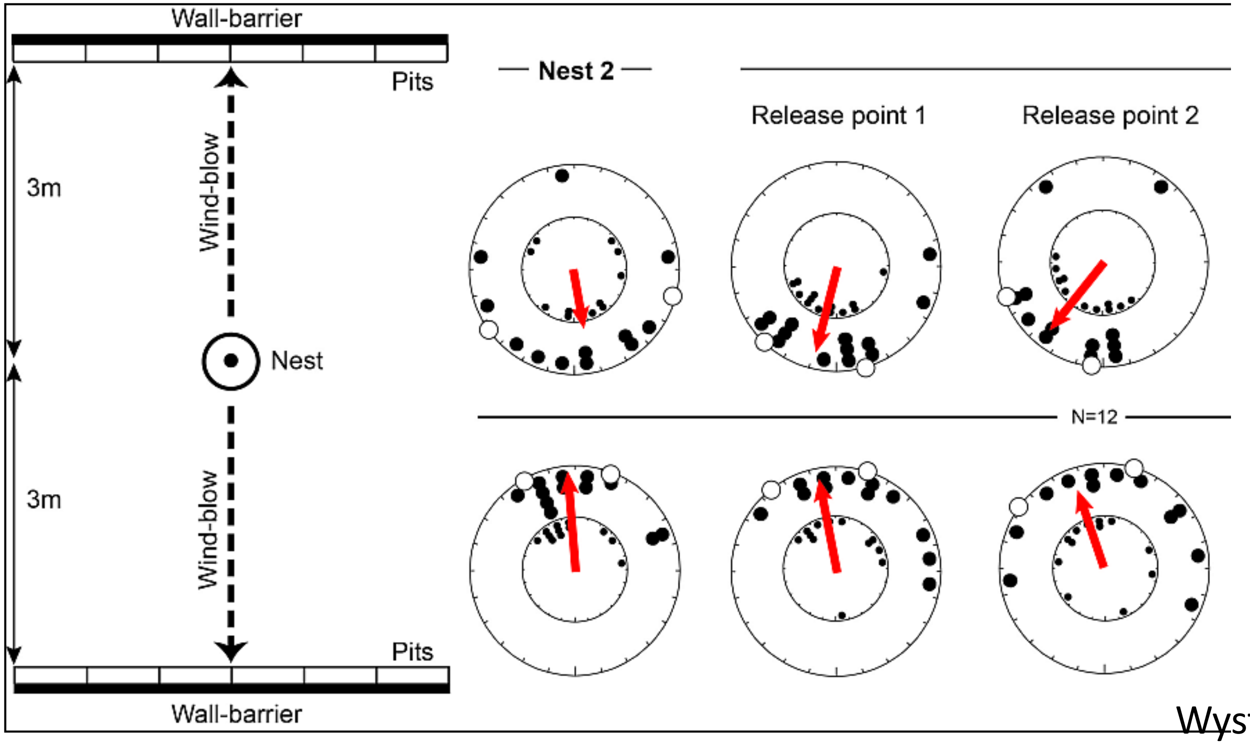
Wystrach and Schwarz 2013. Cur. biol.



Wystrach and Schwarz 2013. Cur. biol.



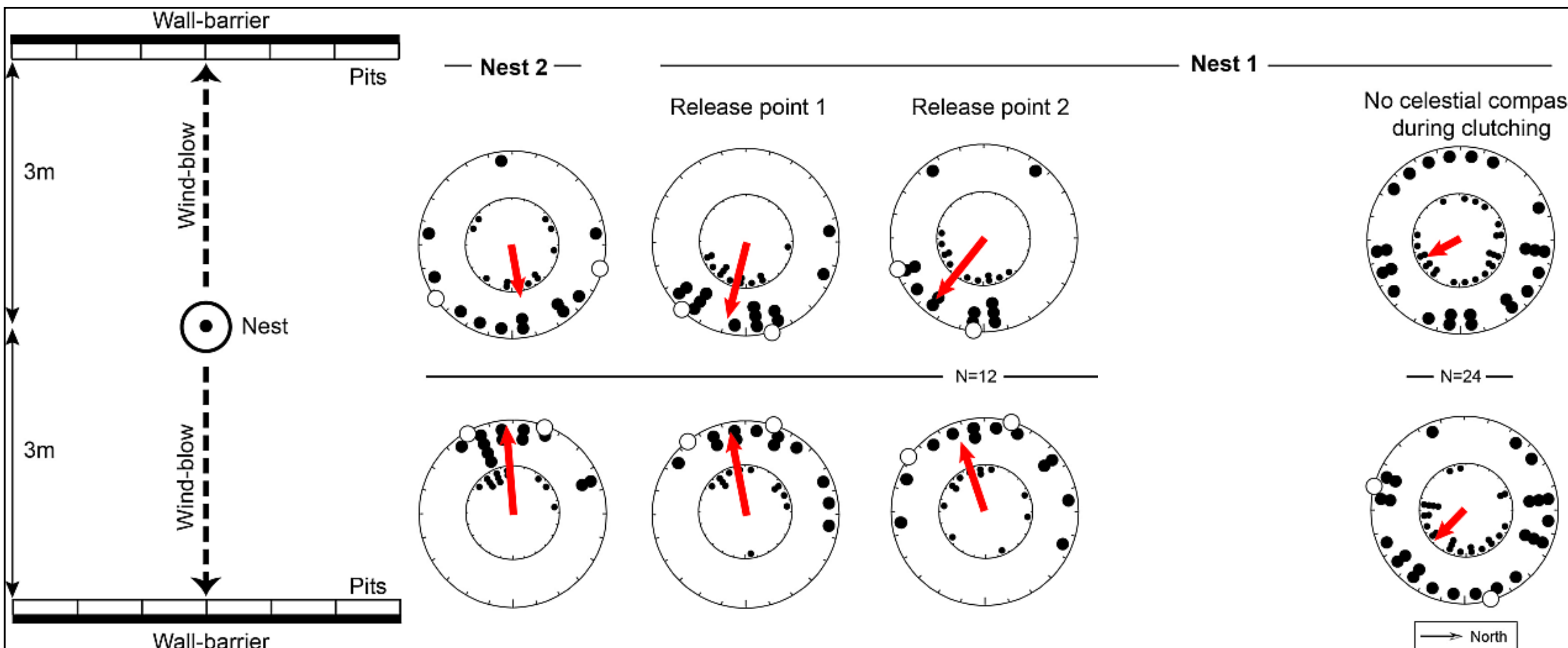
Wystrach and Schwarz 2013. Cur. biol.



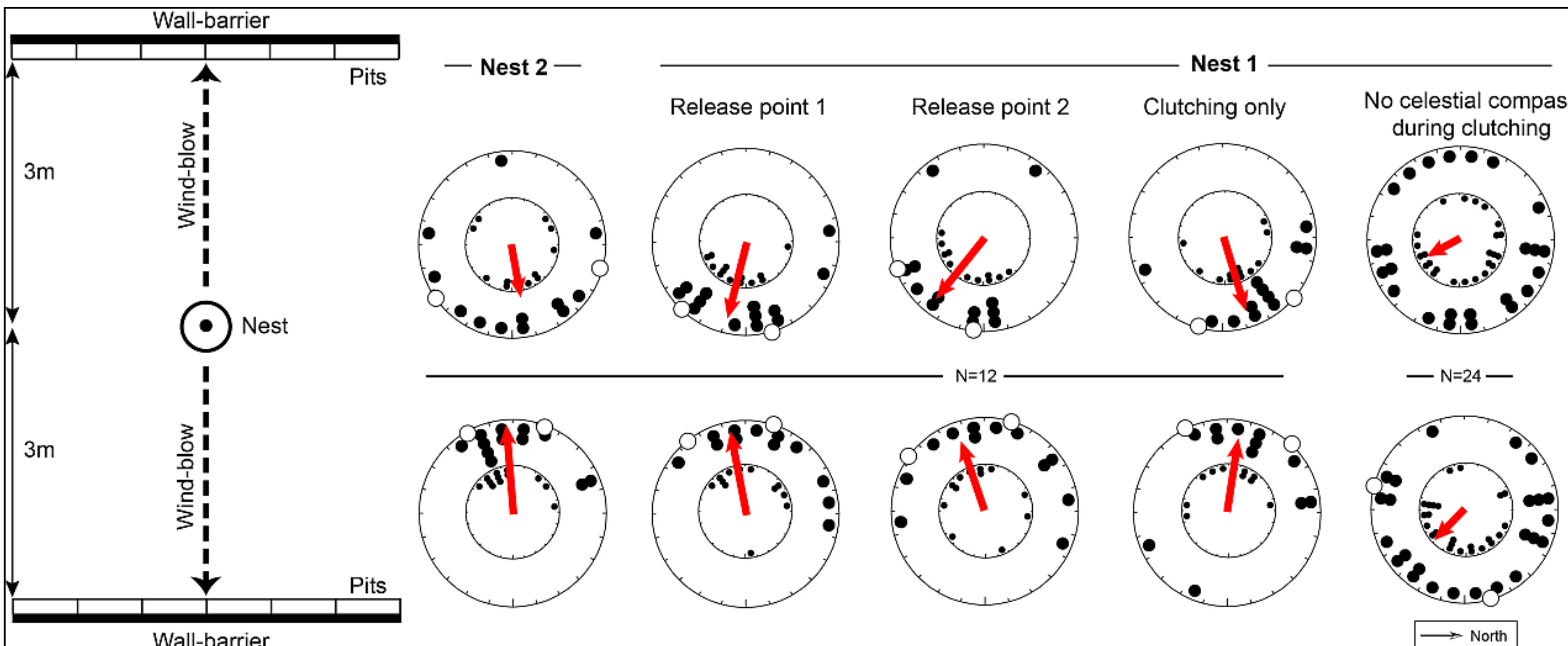
Wystrach and Schwarz 2013. Cur. biol.

Clutching !

Wystrach and Schwarz 2013. Cur. biol.



Wall-barrier
Pits
3m
Wind-blow
Nest
3m
Wind-blow
Pits
Wall-barrier
Nest 2
Nest 1
Release point 1
Release point 2
No celestial compass
during clutching
N=12
N=24
North

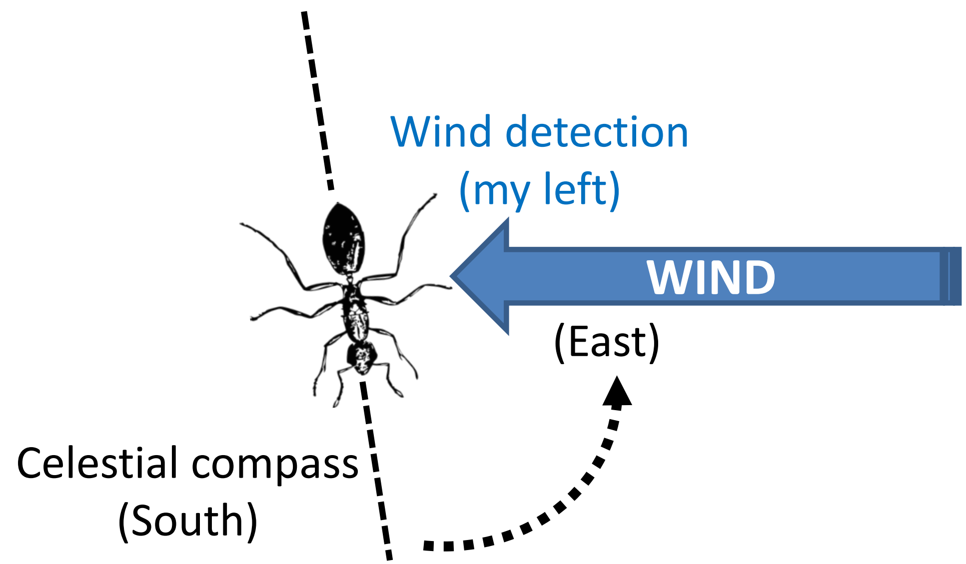


Wall-barrier
Pits
3m
Wind-blow
Nest
3m
Wind-blow
Pits
Wall-barrier
Nest 2
Nest 1
Release point 1
Release point 2
Clutching only
No celestial compass during clutching
N=12
N=24
North

Front

Back

Side

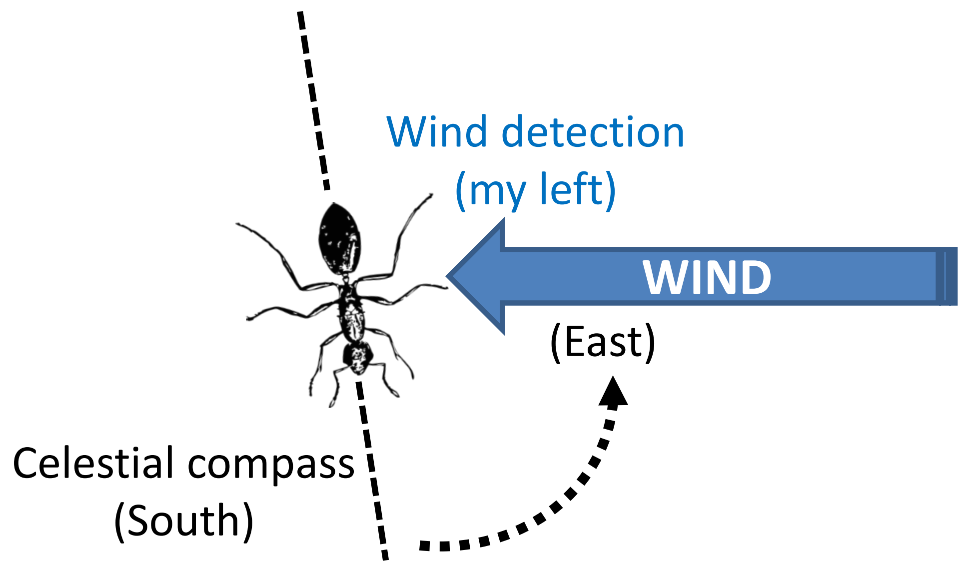


Wystrach and Schwarz 2013. Cur. biol.

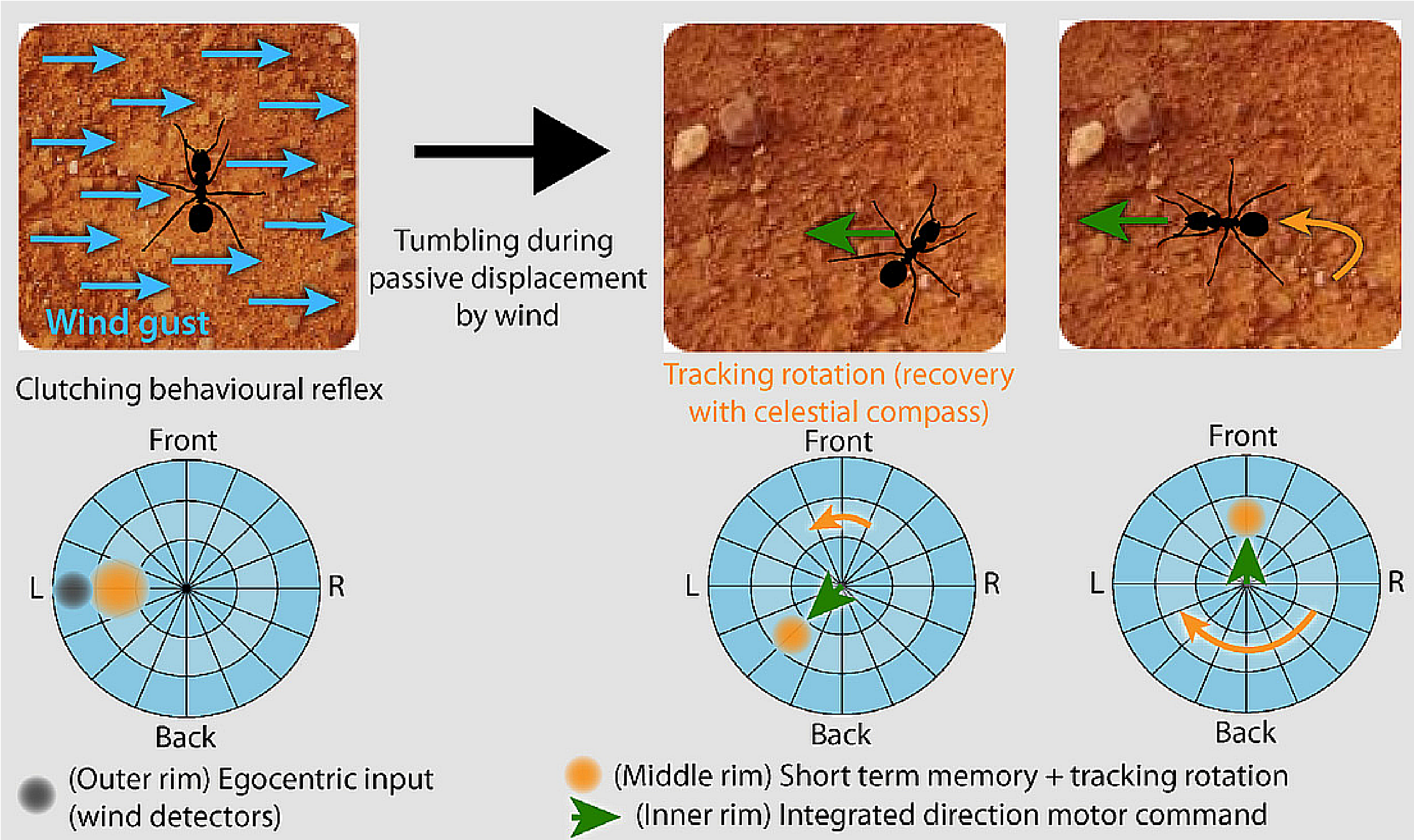
Front

Back

Side



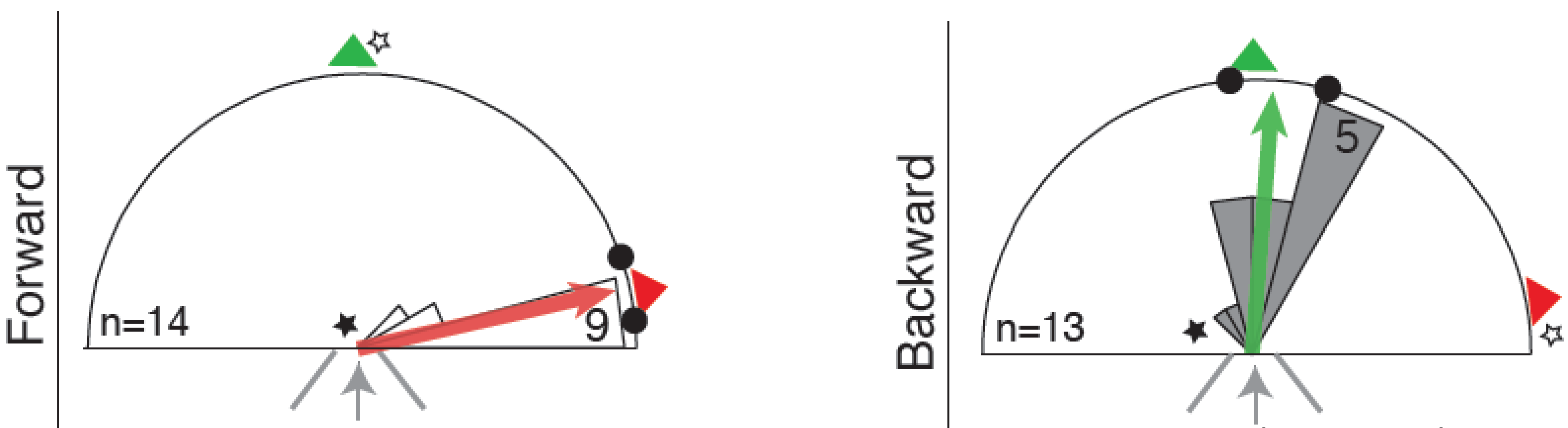
Wystrach and Schwarz 2013. Cur. biol.



Webb, B., & Wystrach, A. (2016). Neural mechanisms of insect navigation. *Current Opinion in Insect Science*, *15*, 27-39.

How can ants follow a route backward ?

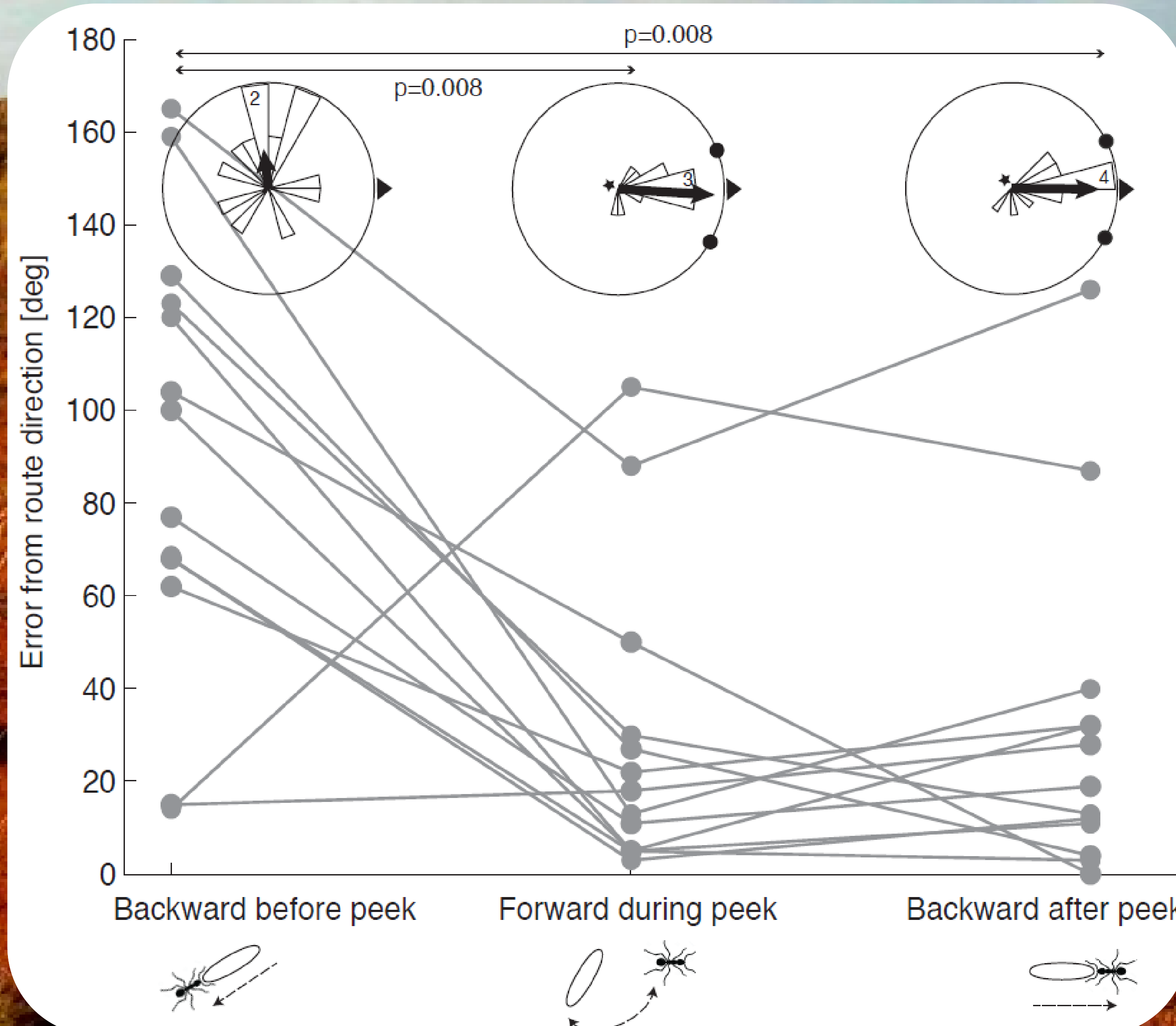
Schwarz et al. 2017. Cur. biol.



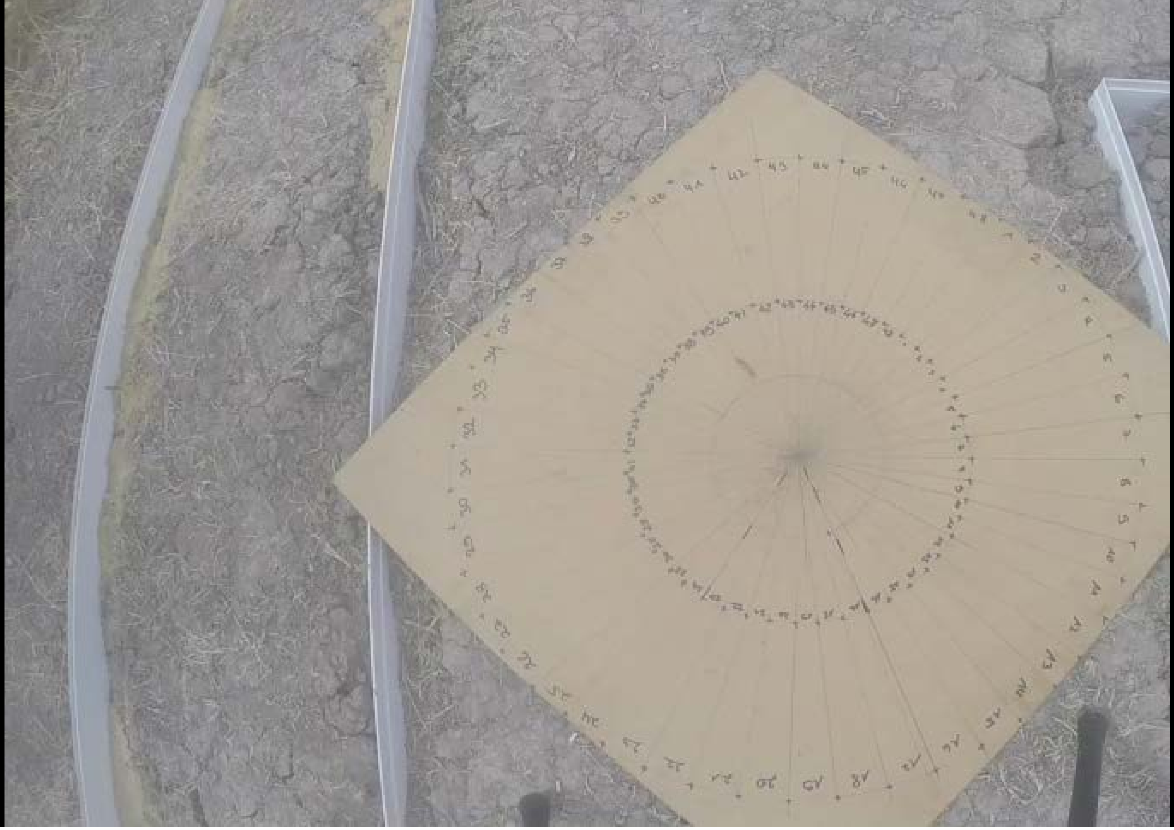
Schwarz et al. 2017. Cur. biol.

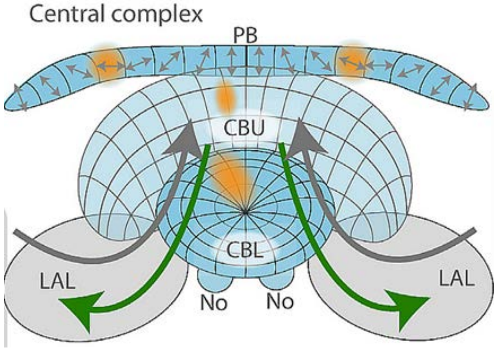
Schwarz et al. 2017. Cur. biol.

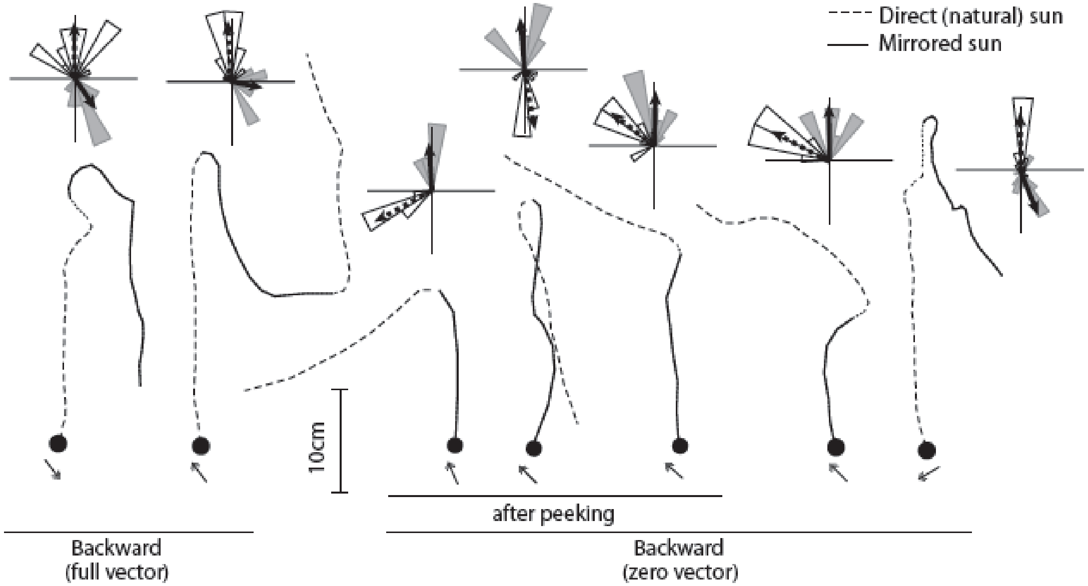
Peeking behaviour



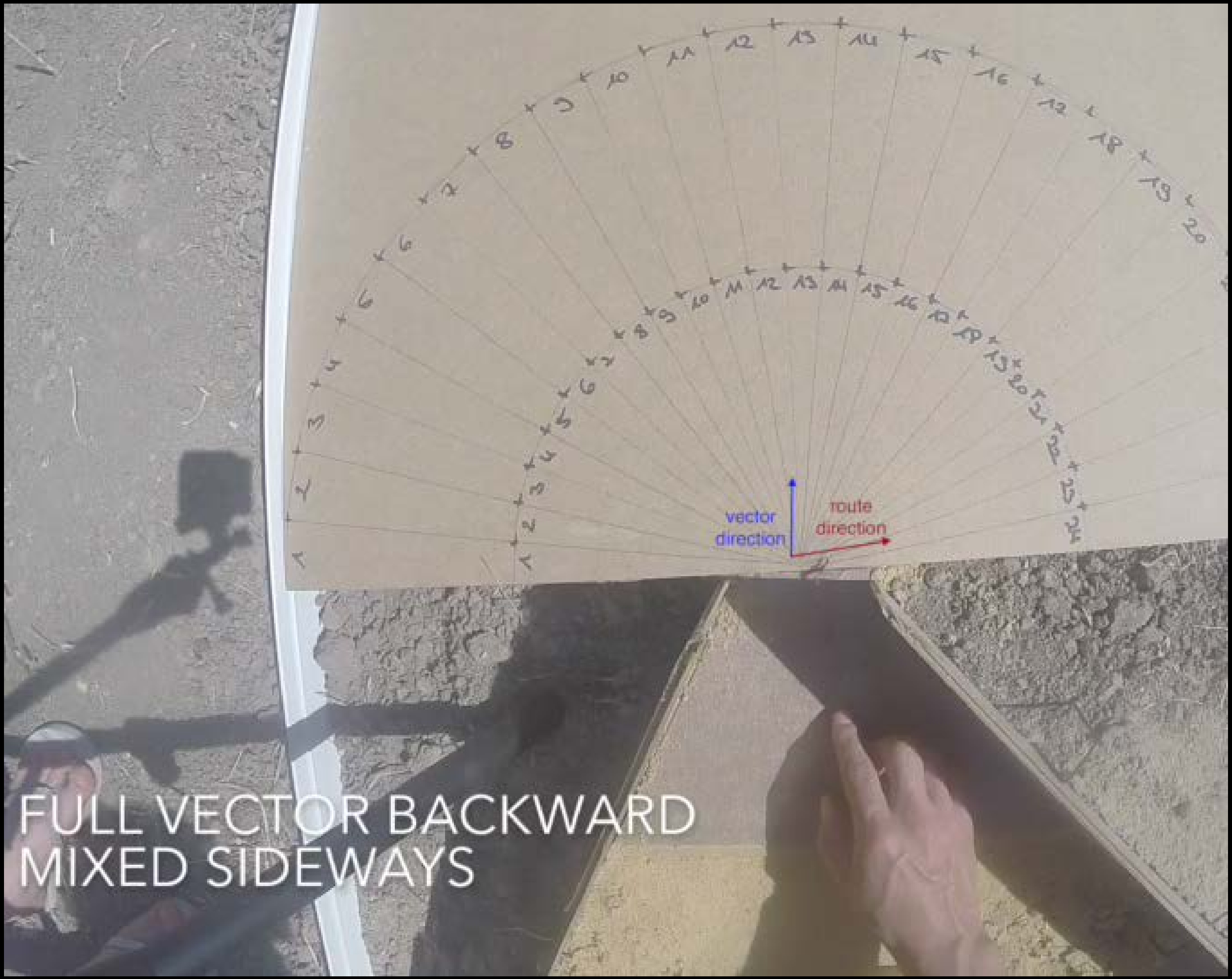
Schwarz et al. 2017. Cur. biol.





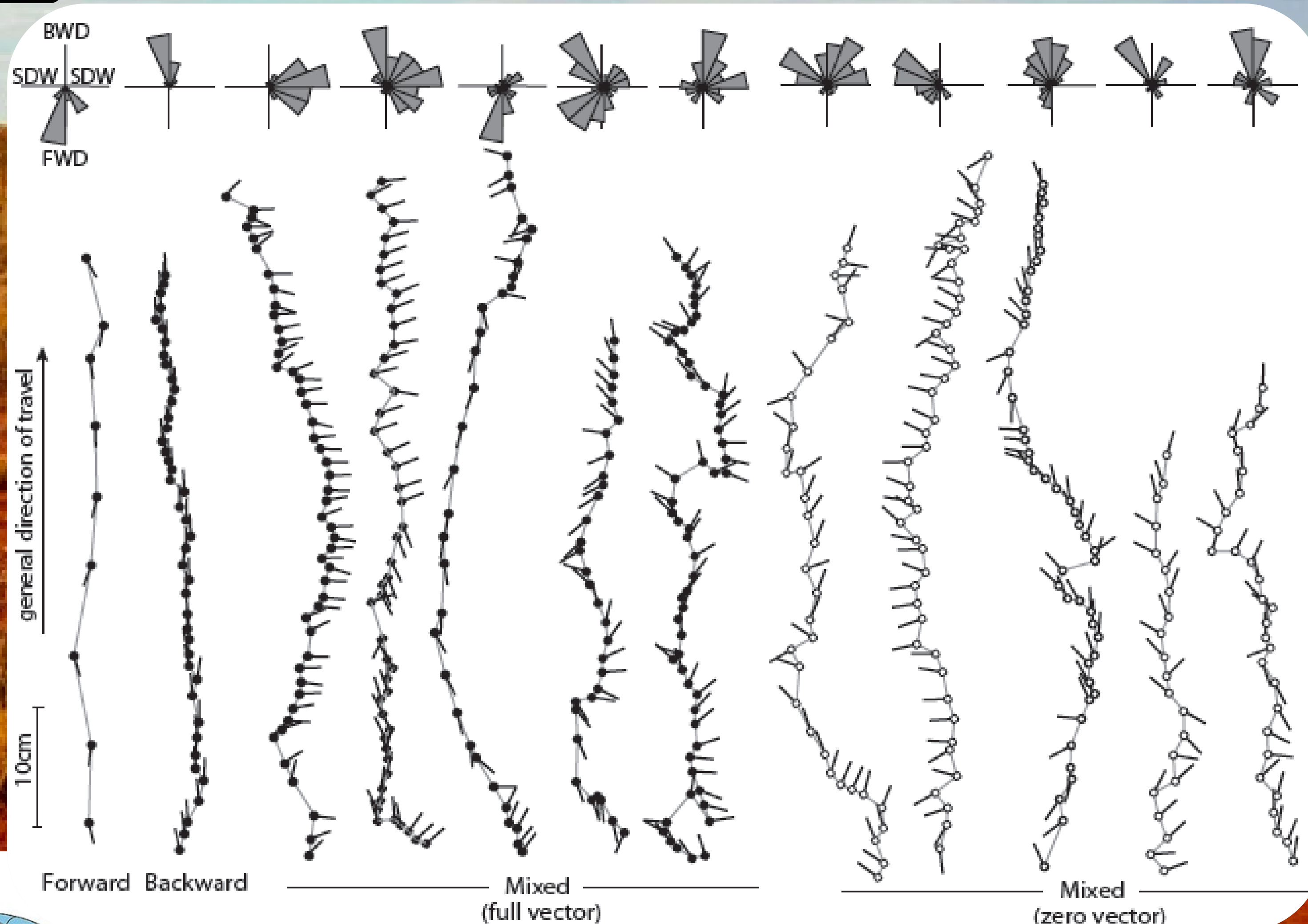


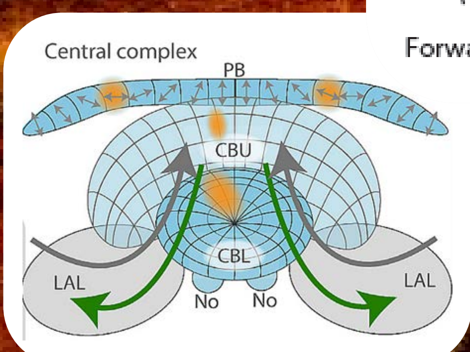
Schwarz et al. 2017. Cur. biol.



Schwarz et al. 2017. Cur. biol.

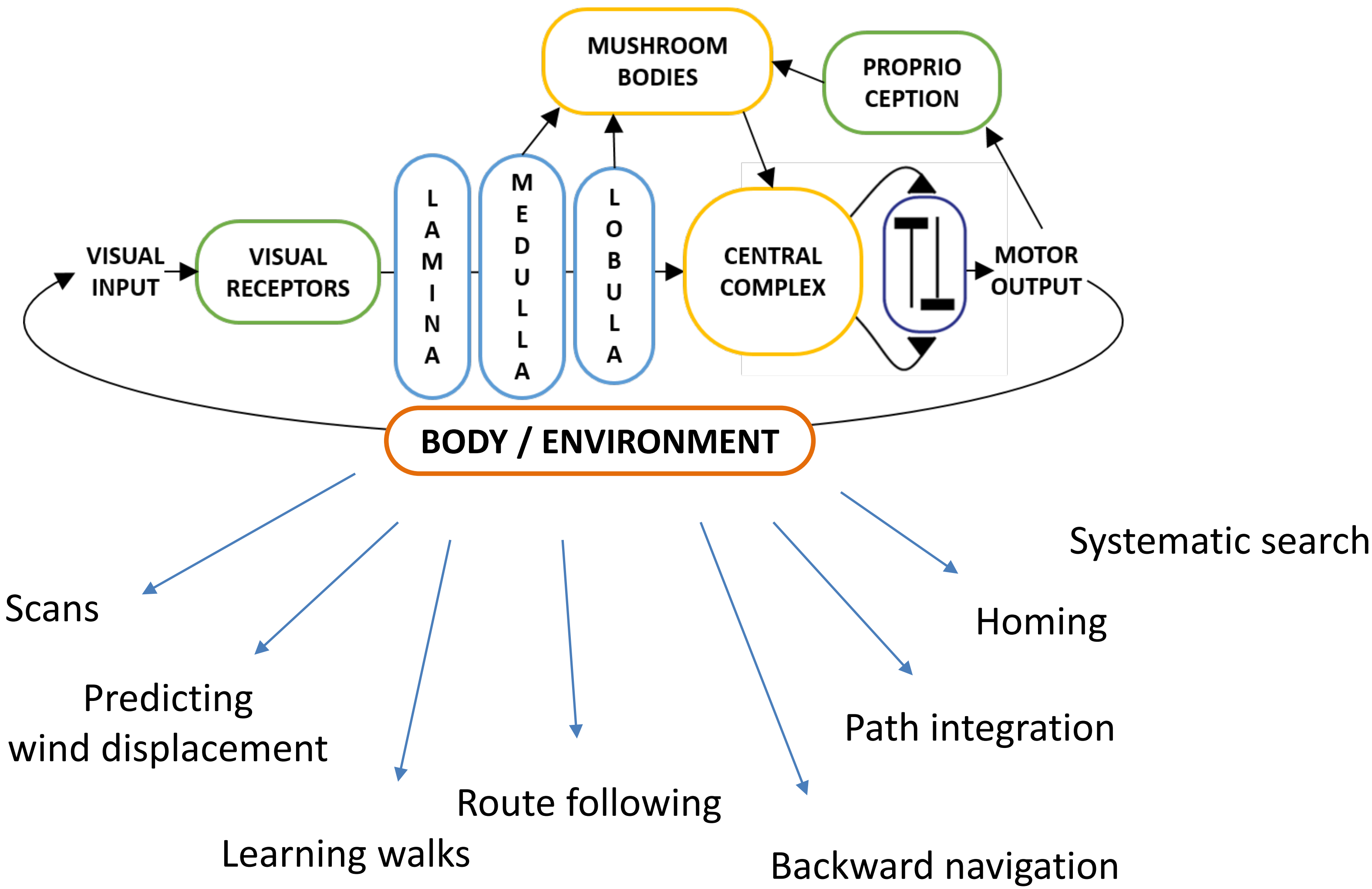
Holonomic control





Schwarz et al. 2017. Cur. biol.

Not a toolkit, but a distributed system



from which behaviours emerge

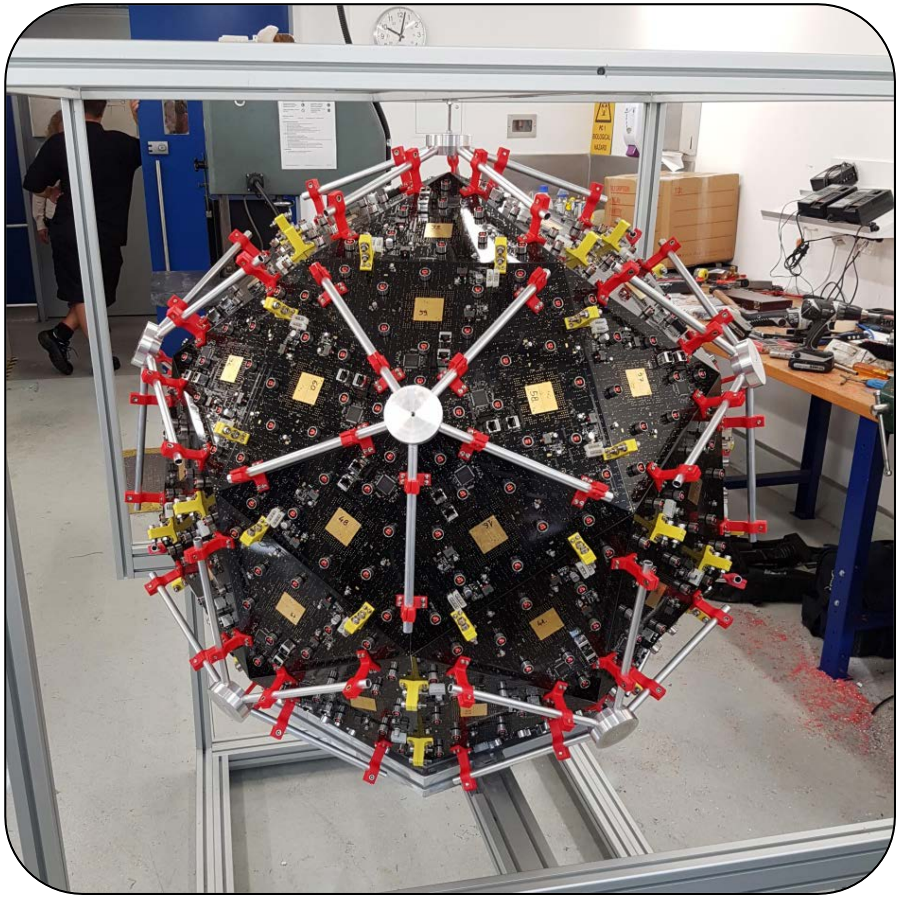
European
Research
Council

ANT TRACKBALL

Pilot trials in Macquarie University, with Dr. Narendra, 2017

European Research Council

ANT VISUAL DISPLAY ARENA

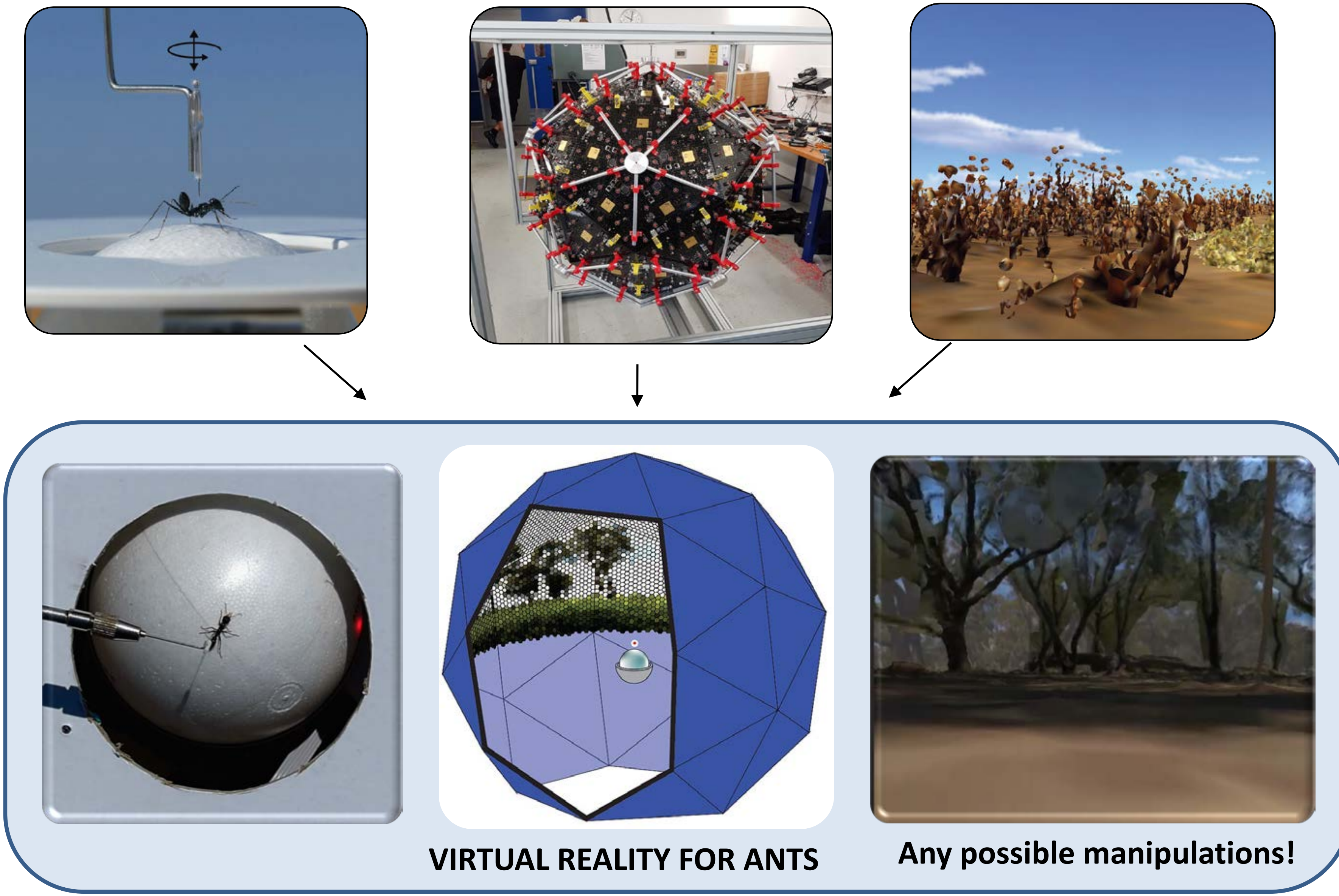


Outside view

Inside view

Courtesy Zoltan Kocsi

European Research Council



Thanks

Sebastian Schwarz

The CRCA

Benjamin Risse

Barbara Webb

Michael Mangan

Alek Khodshabashev

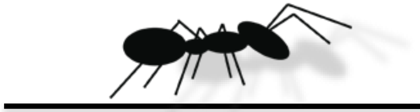
Paul Graham

The ants and larvae

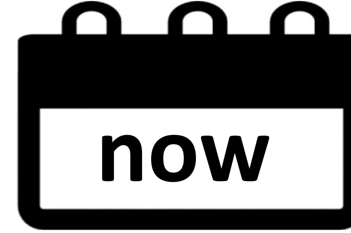
you

Andy Philippides

Konstantinos Lagogiannis



CRCA



Sebastian Schwarz

Alix Gabrielli

Mathieu Lihoreau

Audrey Dussutour

Florent Lemoel

Cristian Pasquaretta

Guillaume Isabelle

Martin Giurfa

Thanks !