EU HORIZON 2020 PROJECT STEP2DYNA

WORKSHOP

Cue Integration in Insect Navigation

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Wednesday, 16th Oct, 2018

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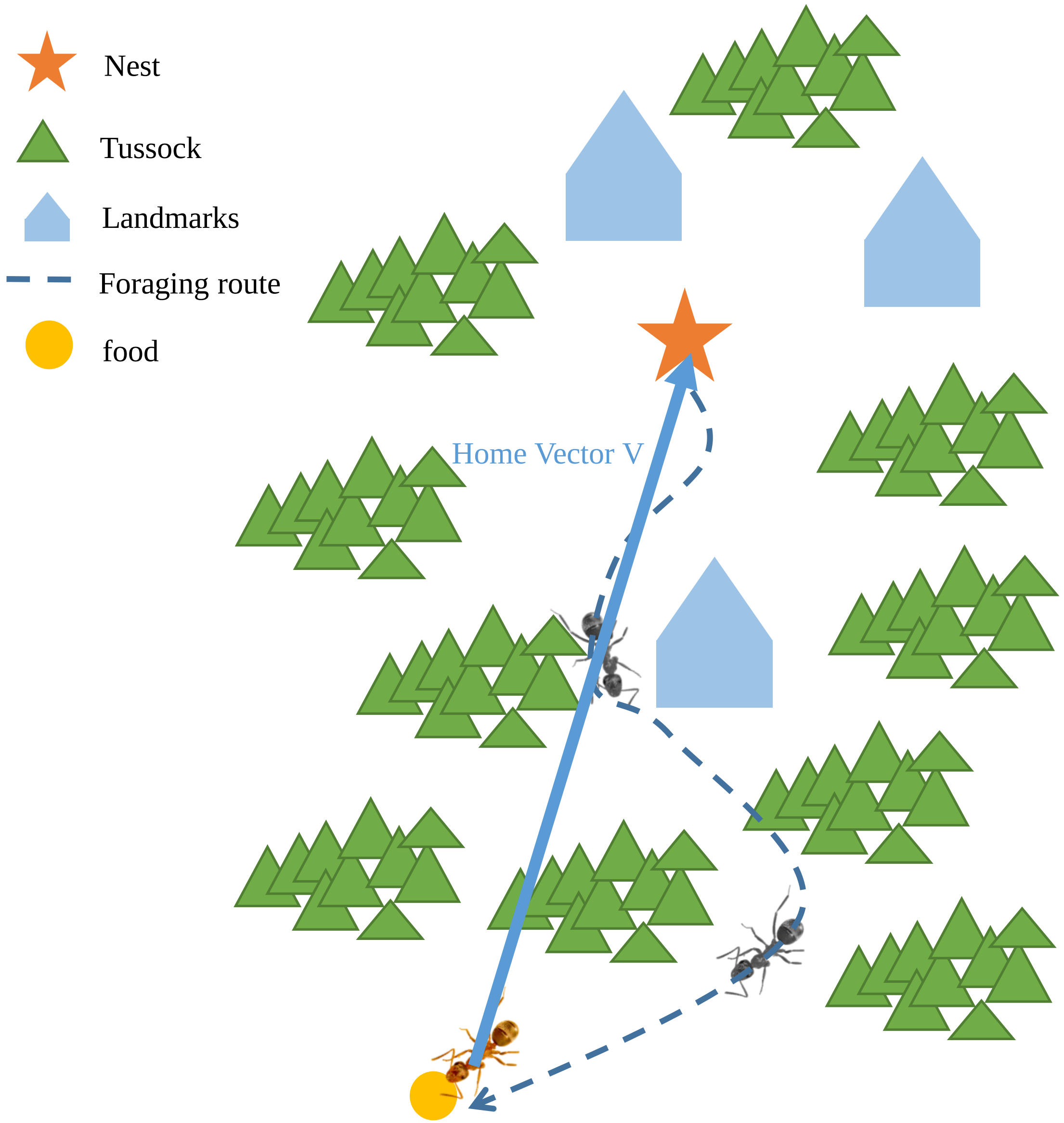
Insects are skillful navigators!

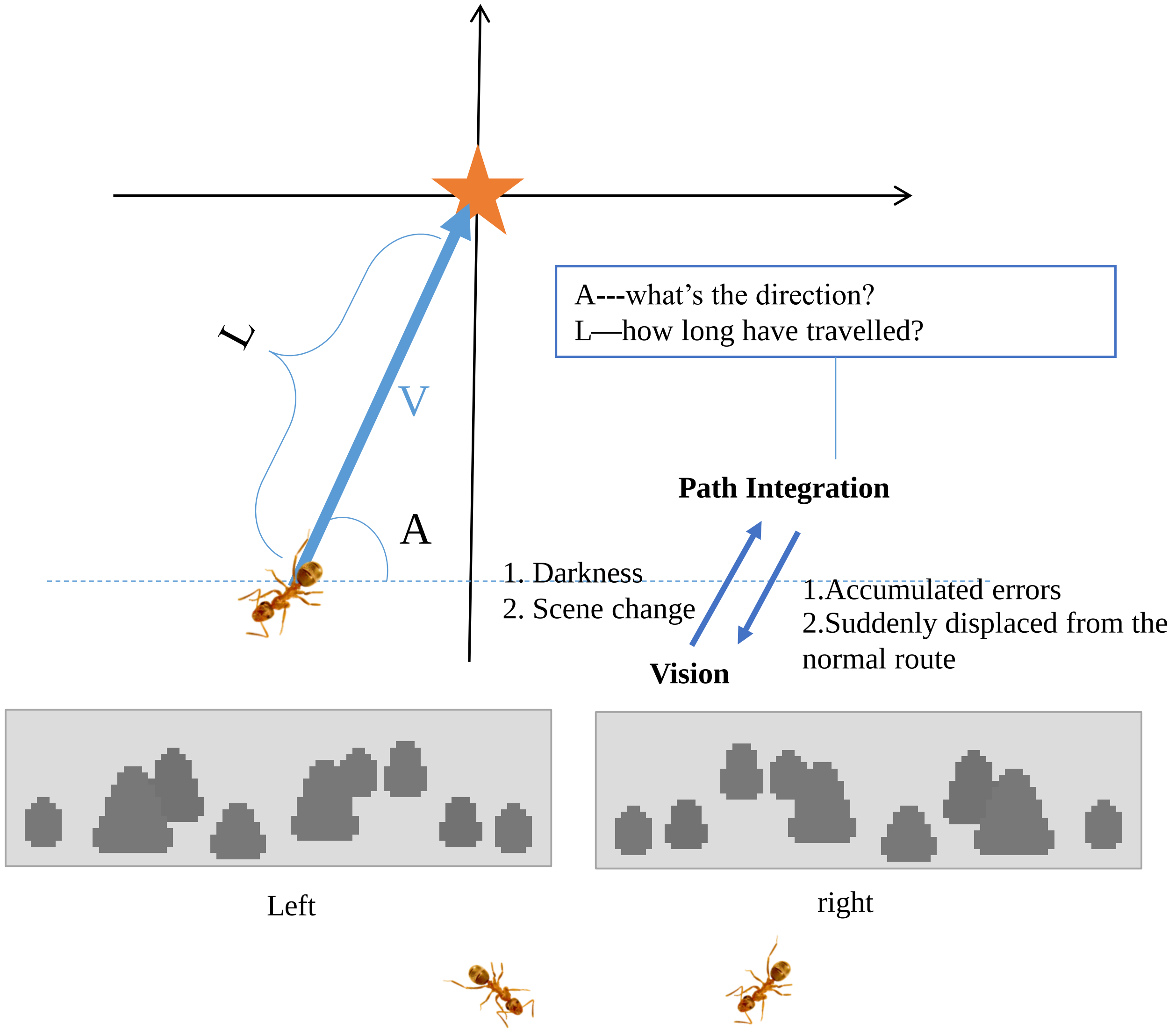
The desert ants can travel hundreds of meters for food, and return home directly with high accuracy.

Bees can develop efficient line routes around multiple food sources

The Monarch Butterflies can travel 3600km as the migrant

Introduction – Insect Navigation Toolkit (desert ants case)





Which direction is the nest's direction?

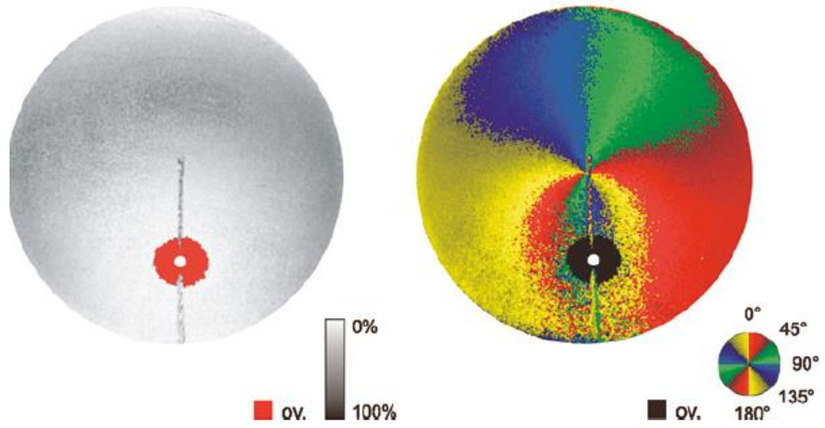
Müller, M., & Wehner, R. (1988). Path integration in desert ants, Cataglyphis fortis. Proceedings of the National Academy of Sciences, 85(14), 5287-5290.

Introduction – Insect Navigation- Path Integration

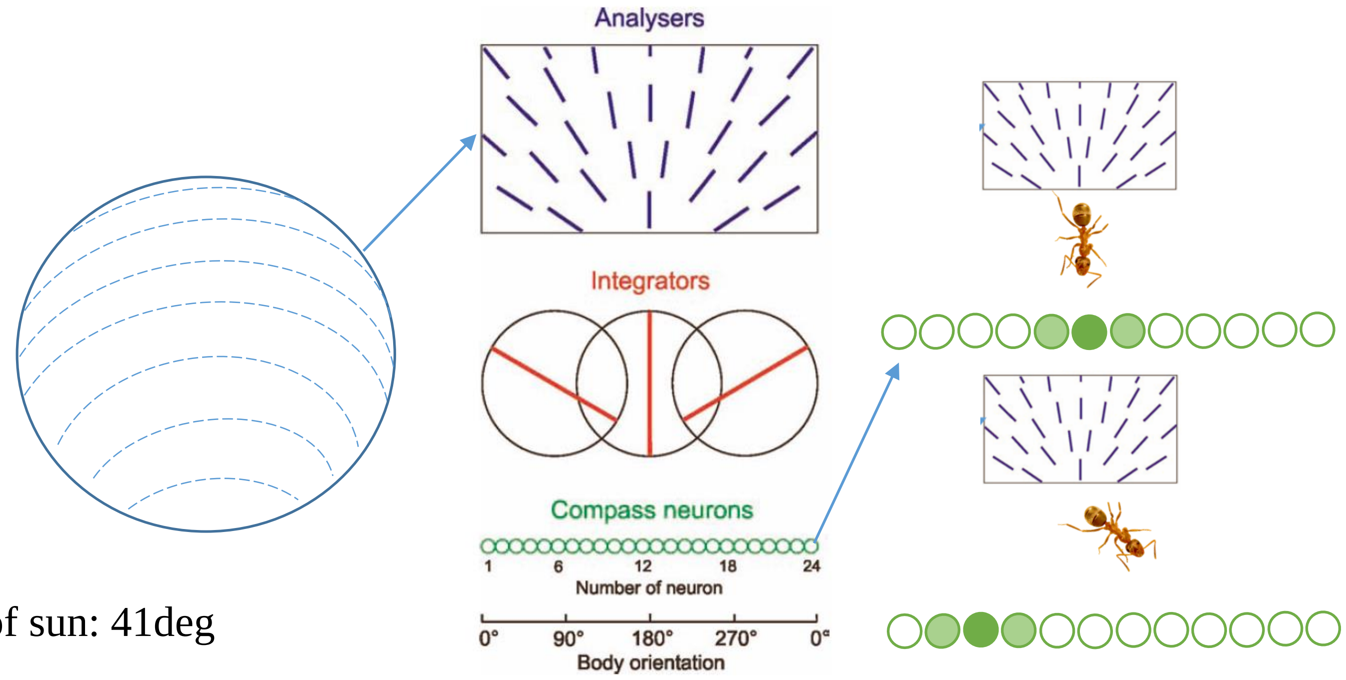
Theory calculation: $L = \int v\,dt$ $A = \int \omega\,dt$

We can also put them together by vectorization, then the Home Vector $\vec{V}(T) = \int_0^T \vec{v}(t)\,dt$

Sensory system



Skylight polarization when Elevation of sun: 41deg



3.For magnitude of the velocity:

Ants: Step Count, Optic Flow
Bees: Optic Flow

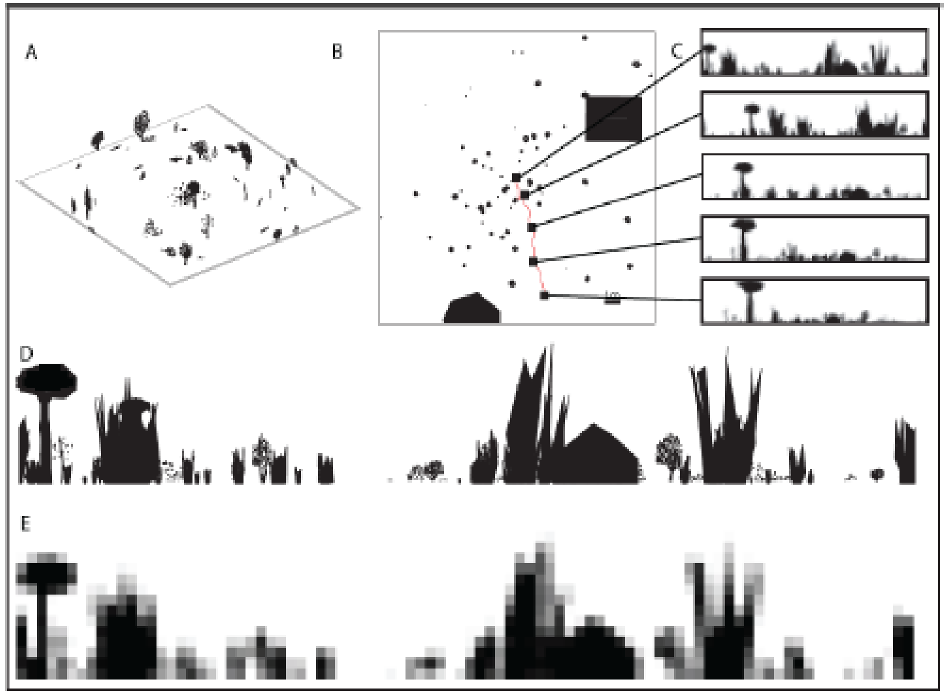
R. Wehner. *Desert ant navigation: how miniature brains solve complex tasks,* J Comp Physiol A 189: 579–588, 2003

Introduction – Insect Navigation- Vision

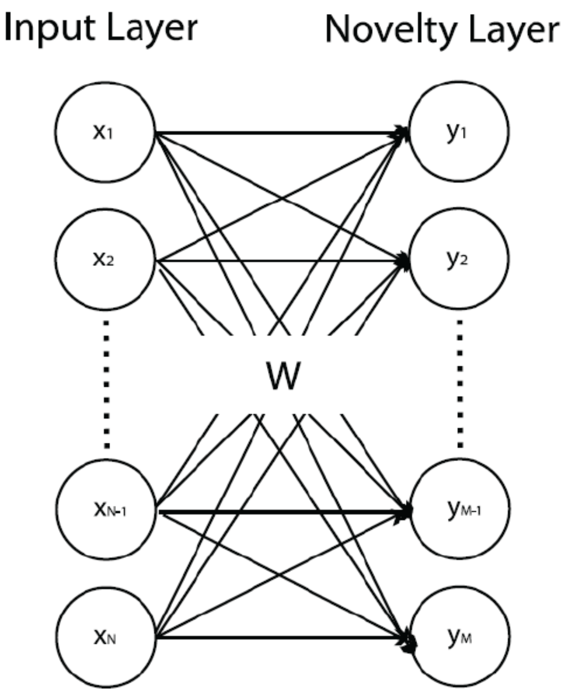
How do insects process the visual information for navigation? By now, know some about it. But far from enough.

An Neuron Network for Homing Using Vision.

1. Generate many homing journeys and get the images of the scenes

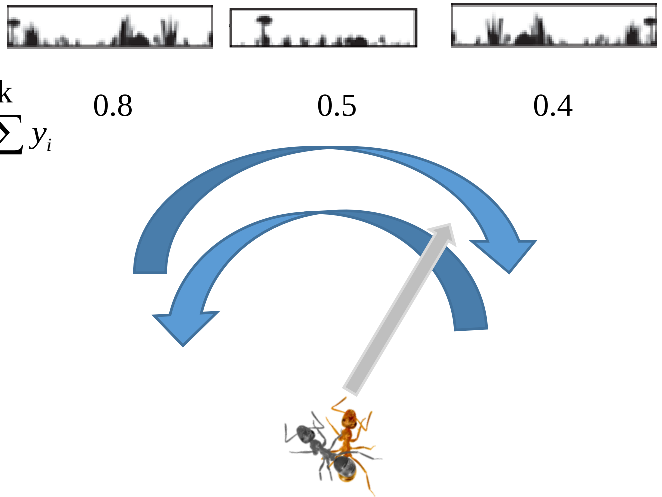


2. Use these images to train a simple neural network



3. Searching and use the trained model to calculate the unfamiliarity and choose the direction with the smallest scene unfamiliarity.

Network Output $\sum y_i$



4. Perform well but is not bio-plausible.(too many artificial ingredients)

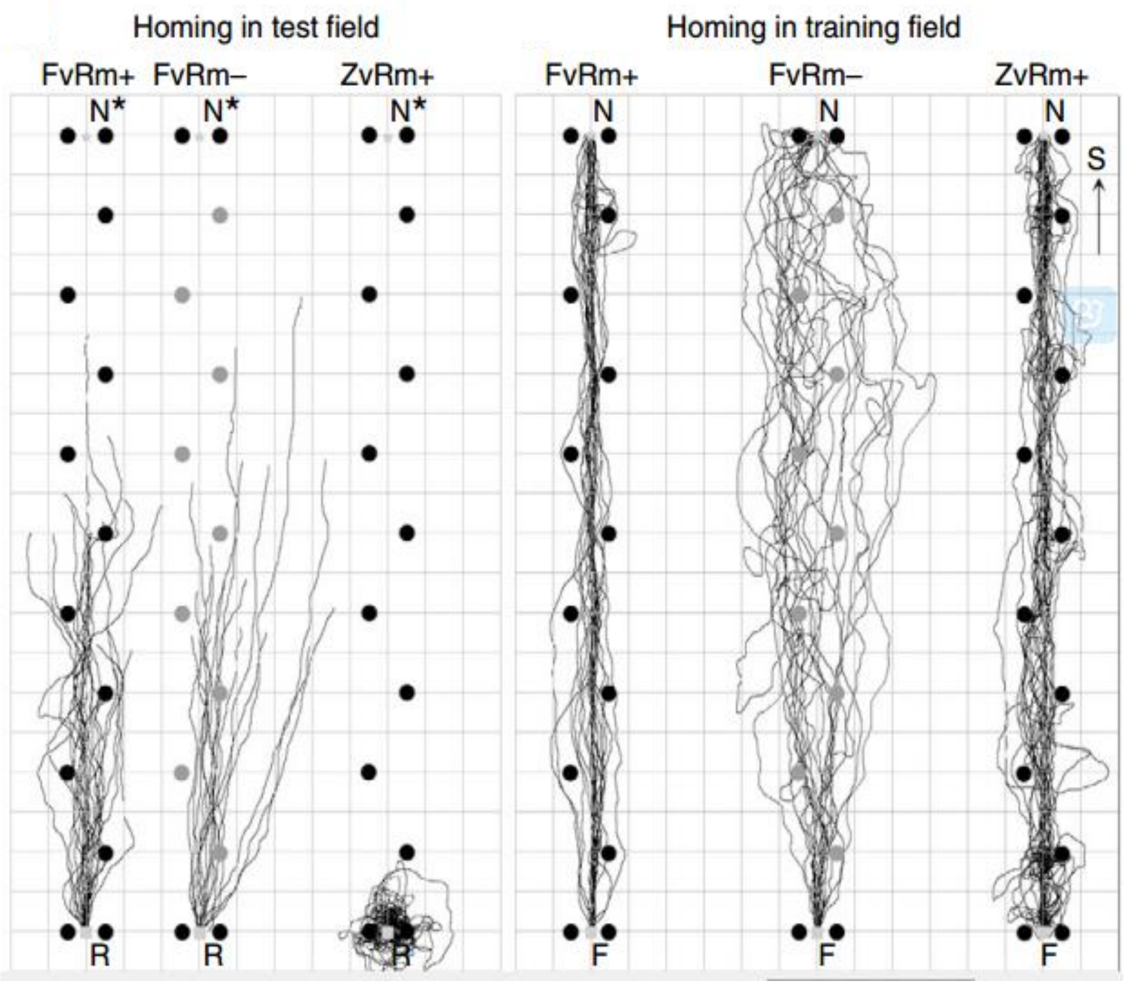
Baddeley B, Graham P, Husbands P, Philippides A, *A Model of Ant Route Navigation Driven by Scene Familiarity*, PLoS Comput Biol 8(1), 2012.

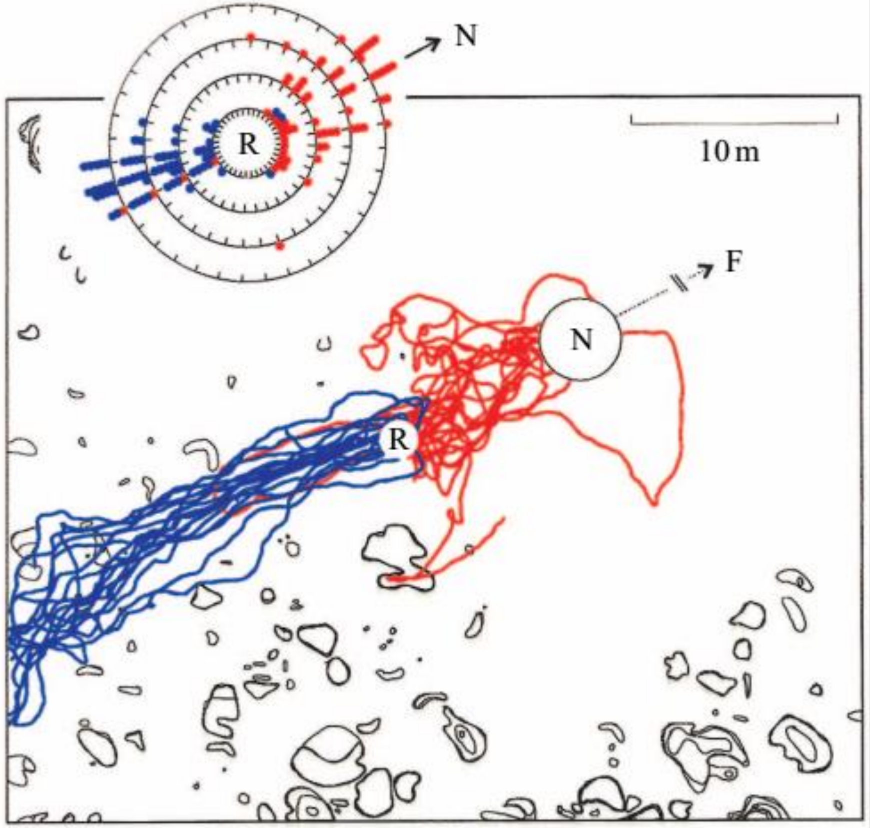
Introduction – Cues integration in **INSECTS**

Fv/Zv : Full home Vector (with path integration), Zero home Vector(No path integration)

Rm+/Rm- : With Route landmark(+) / without Route landmark (-)

Melophorus bagoti

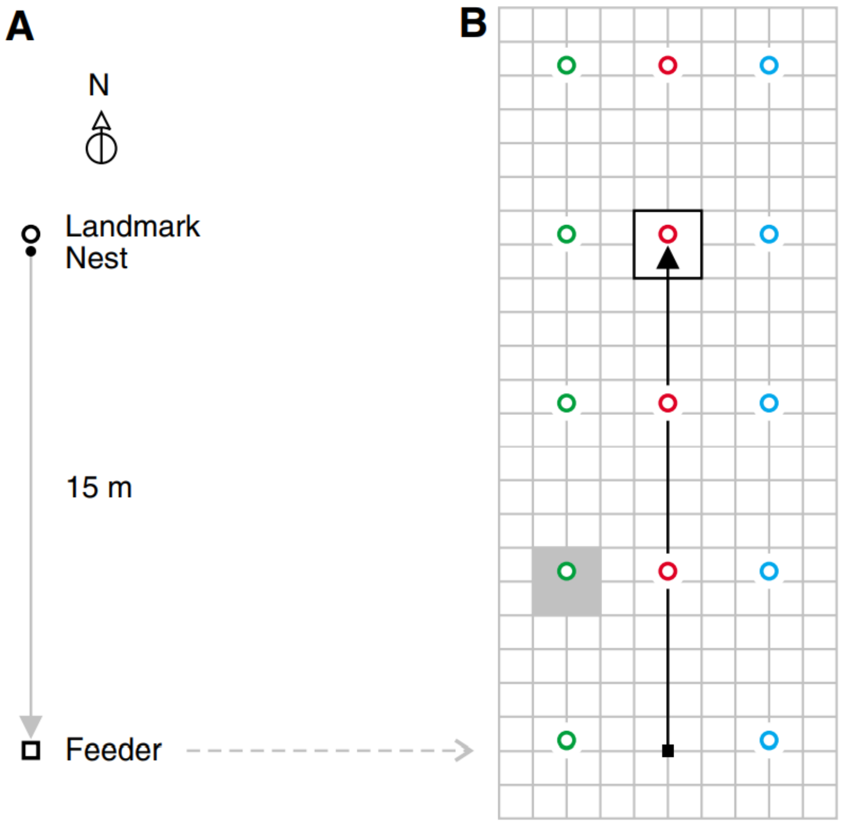


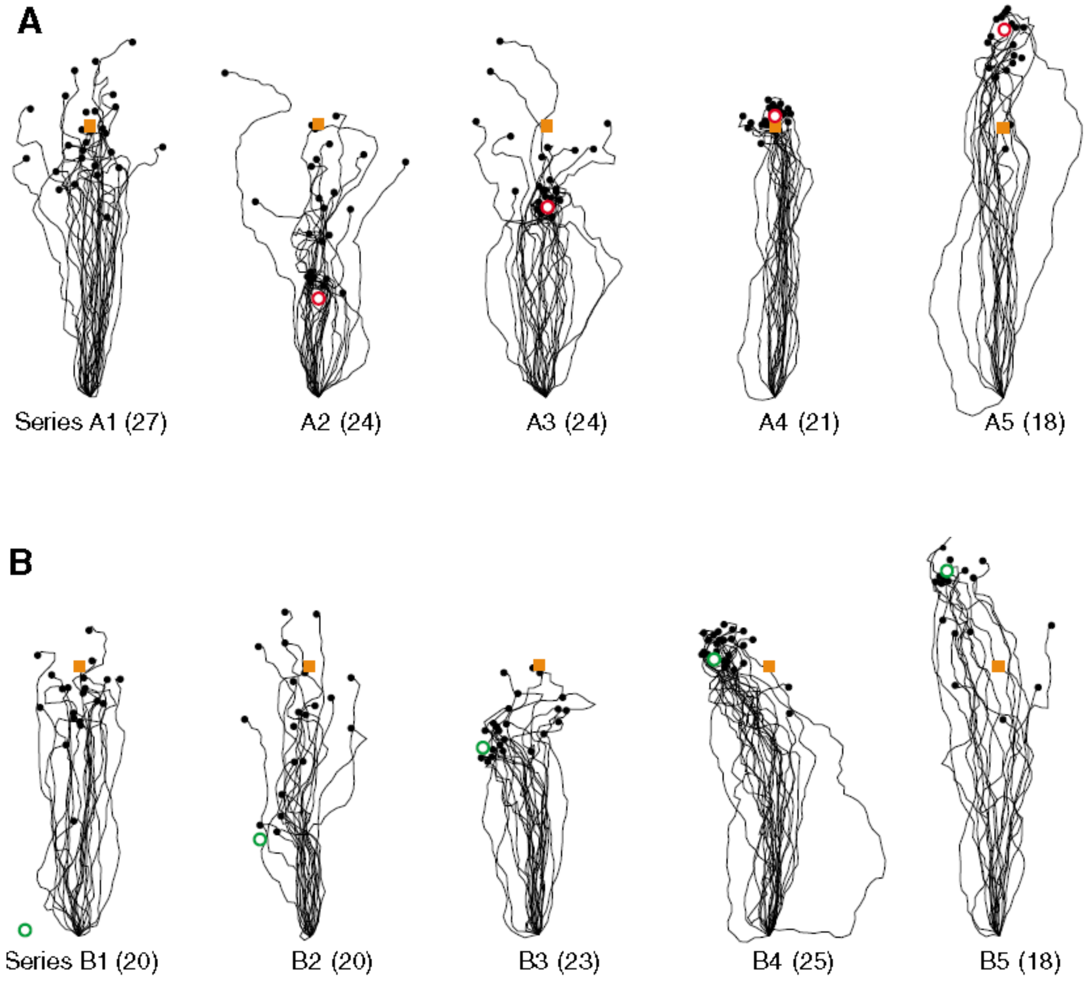


Ajay Narendra, *Homing strategies of the Australian desert ant Melophorus bagoti. II. Interaction of the path integrator with visual cue information,* J. Exp. Biol. 210, 1804-1812, 2007.

Introduction – Cues integration in **INSECTS**

Cataglyphis fortis

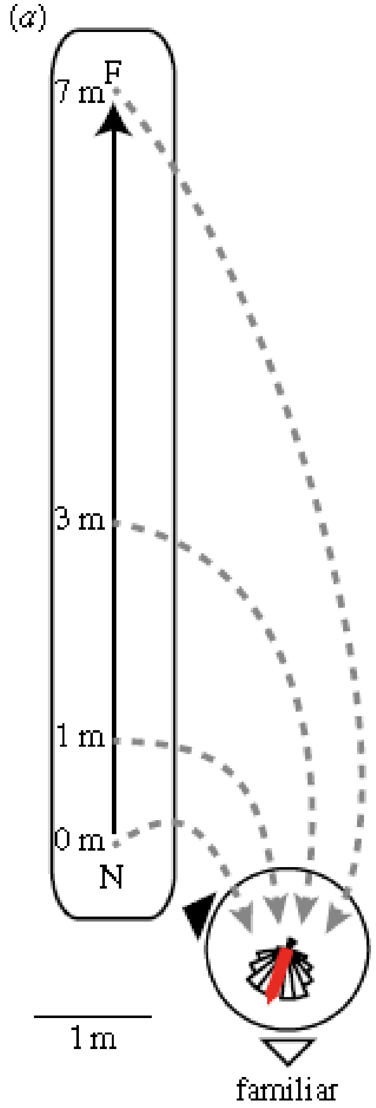


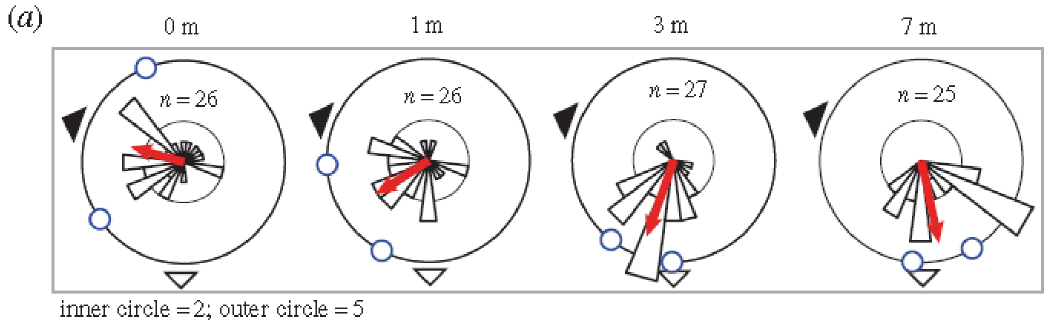


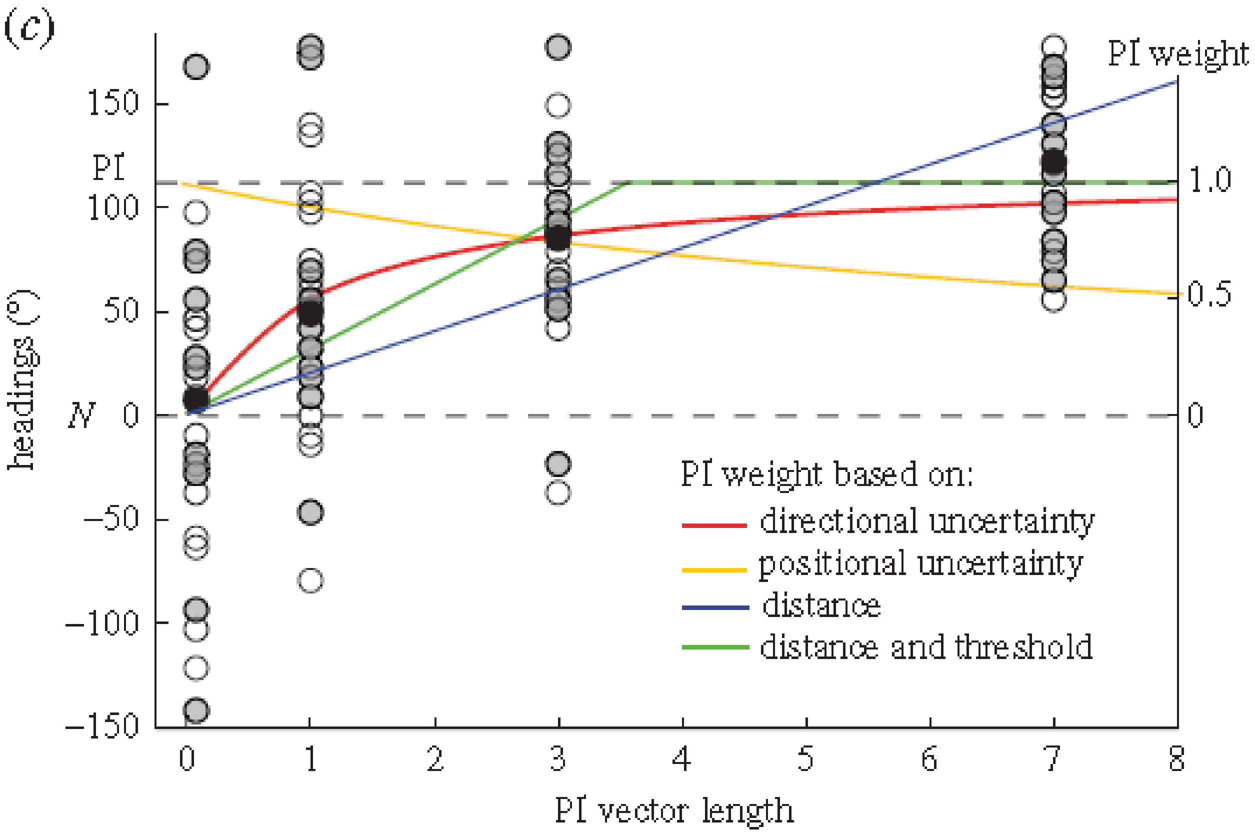
Bregy P, Sommer S, Wehner R (2008) Nest-mark orientation versus vector navigation in desert ants. J Exp Biol 211:1868–1873.

Introduction – Cues integration in **INSECTS**

Cataglyphis velox







Wystrach A, Mangan M and Webb B, Optimal cue integration in ants. Proc. R. Soc. B 282: 20151484. 2015.

Introduction – Inspiration - Cues integration in animal and human

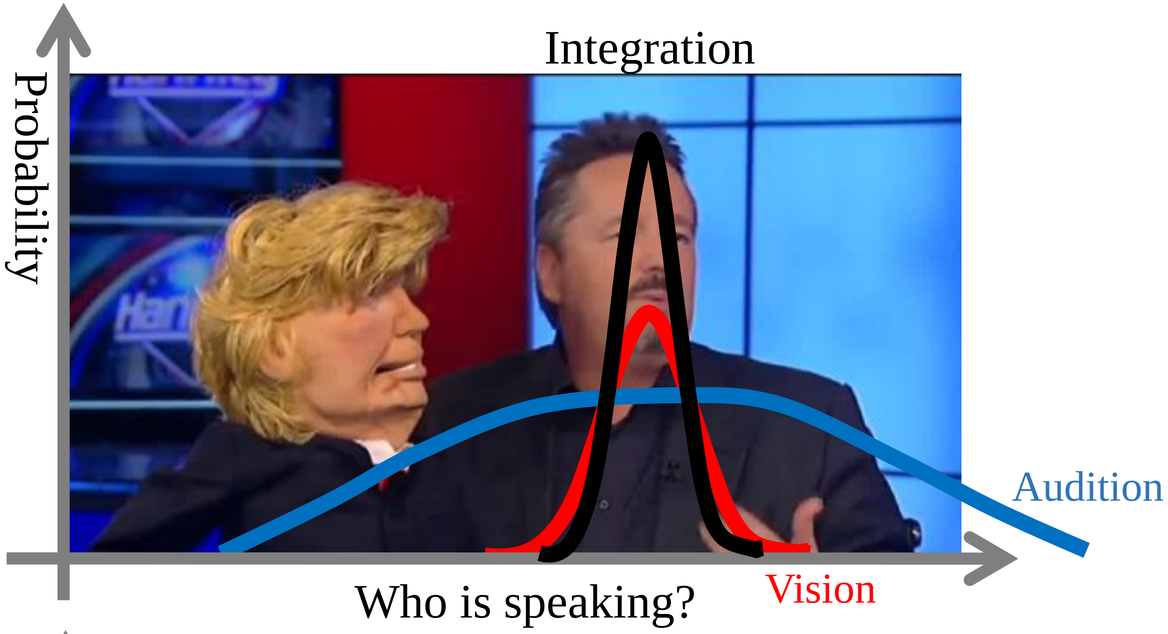
Who is speaking?

How dose other intelligent creatures do the cues integration tasks?

Who is speaking?

Fox News. (2016, May 26). Terry Fator adds 'Donald Trump' to his Las Vegas lineup [Video]. https://www.youtube.com/watch?v=HoZ_Jq5LN7Q

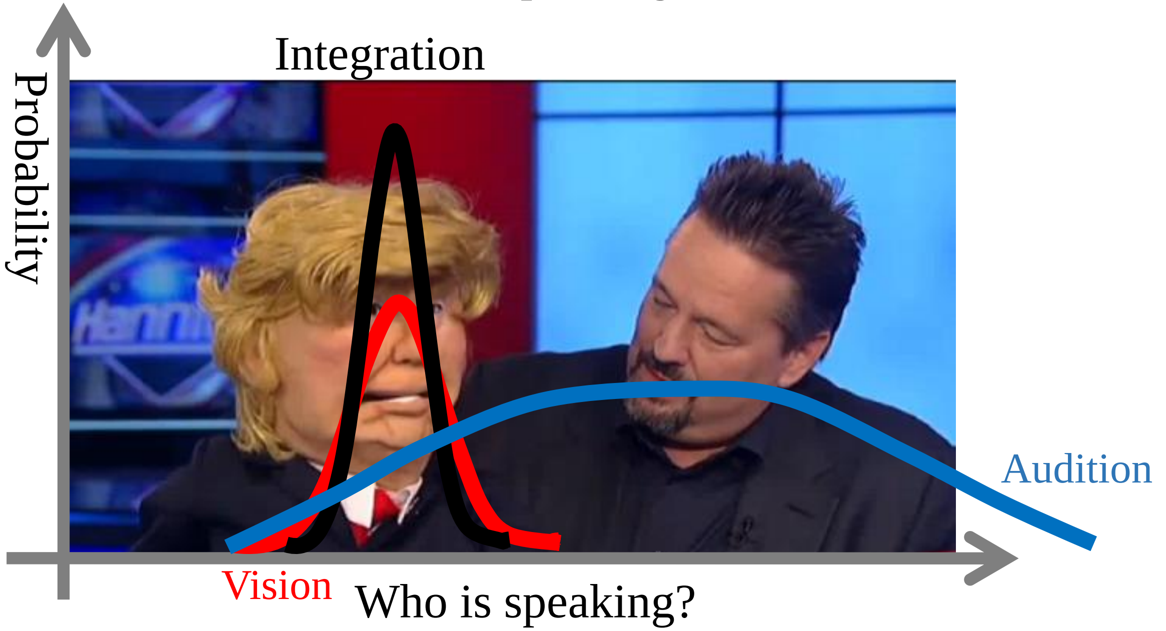
Introduction – Cues integration in animal and human



When the cues are close, the brain is optimal.

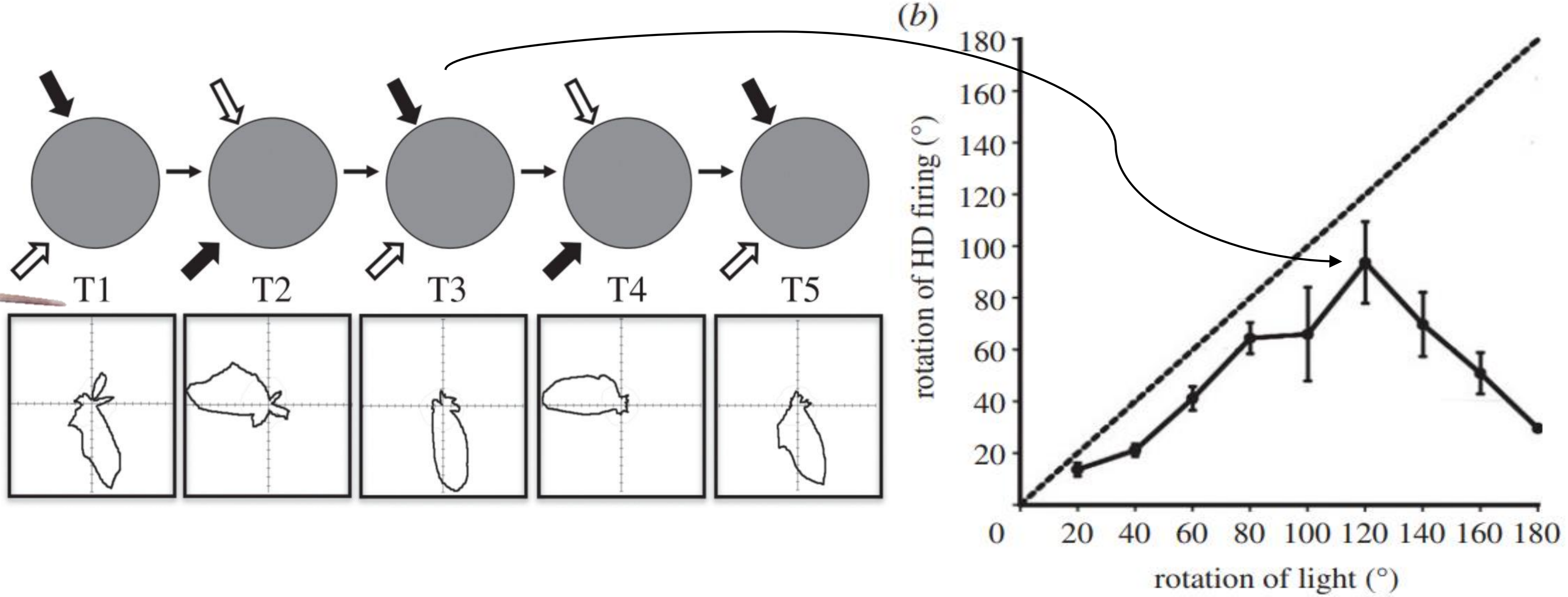
$$X = X_V W_V + X_A W_A$$

$$W_A = \frac{\sigma_V^2}{\sigma_V^2 + \sigma_A^2} \qquad W_V = \frac{\sigma_A^2}{\sigma_V^2 + \sigma_A^2}$$



When the cues are distant, the brain choose winner-take-all strategy:
Selecting the more reliable cue!

Lister Hooded



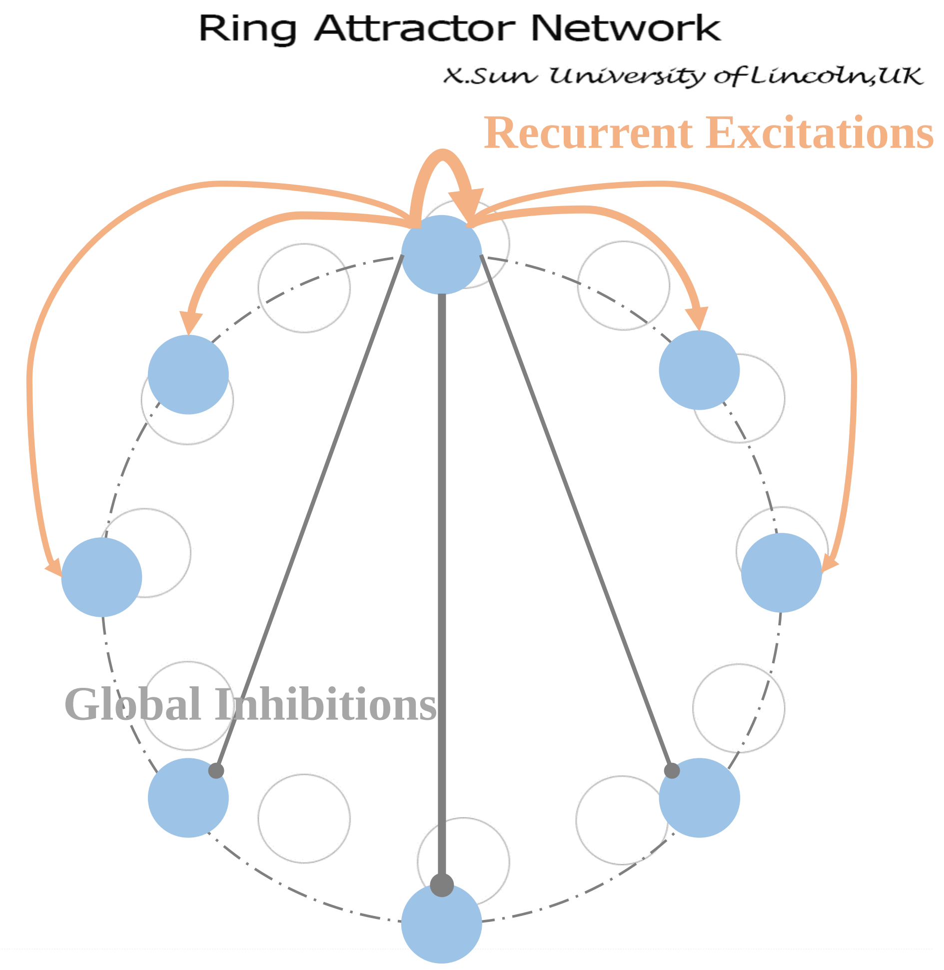
- **Performs optimal integration for cues with small difference.**
- **Switches to winner-take-all for cues with large difference.**

Knight, R., Piette, C. E., Page, H., Walters, D., Marozzi, E., Nardini, M., ... &Jeery, K. J. (2014). Weighted cue integration in the rodent head direction system. Philosophical Transactions of the Royal Society of London B: Biological Sciences,369(1635), 20120512.

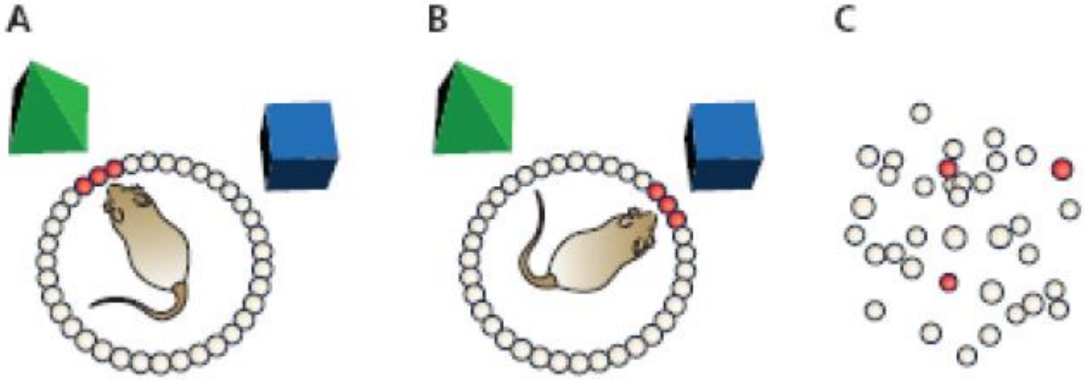
Introduction – Problems

- How does creatures do cues integration in a neural level, and for insects?
- What kind of neural network have similar properties (optimal and winner-take-all)?
- Is there a quite simple but efficient neuron network? And if so,
- Where it located in the insect’s brain and what inspirations can they give us for robotics application?

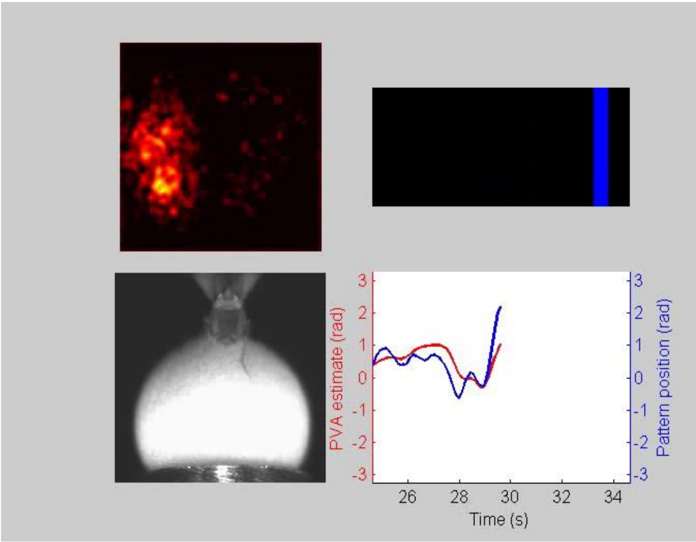
Models and Methods – Ring attractor network



Neurons arranged to a ring and have some specific properties



We found ring attractor properties in rats' brain.



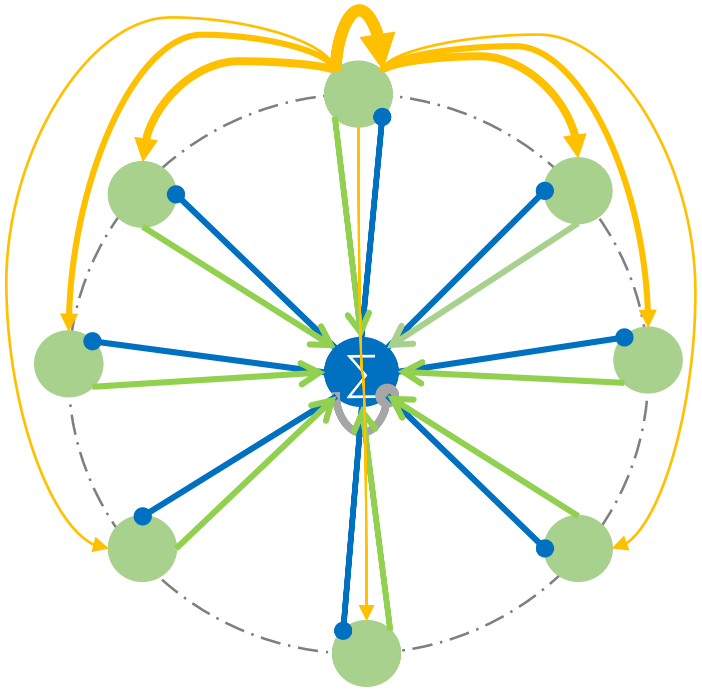
We also found ring attractor network in insect's brain.

Touretzky, D. S. (2005). Attractor network models of head direction cells. Head direction cells and the neural mechanisms of spatial orientation, 411-432.

Jeffery, K. , Page, H. J., Stringer, S. M. (2016). Optimal cue combination and landmark-stability learning in the head direction system. The Journal of physiology, 594(22), 6527-6534

Seelig JD, Jayaraman V, *Neural dynamics for landmark orientation and angular path integration*, Nature 521(7551):186–191, 2015.

Models and Methods – Ring attractor for integrating cues



Touretzky ring attractor

Integration Neurons

Uniform Inhibition Neurons

Excitation Connections

Inhibition Connections

All neurons are CTRNN neurons, so the membrane potential c_i

$$\tau \frac{dc_i}{dt} = -c_i + I_i$$

I_i is the total current injected to the neuron

$$I_i = \sum_{j=1}^{n} W_{ij} O_j + X_i = \sum_{j=1}^{n} W_{ij} g\,(c_i) + X_i$$

$$g(c_i) = \max(0, \theta + c)$$

W is the connection weights, and the recurrent excitation weights is defined by the Gaussian function

$$W_{ji}^{E\to E} = e^{\frac{-d_{ji}^2}{2\sigma^2}}$$

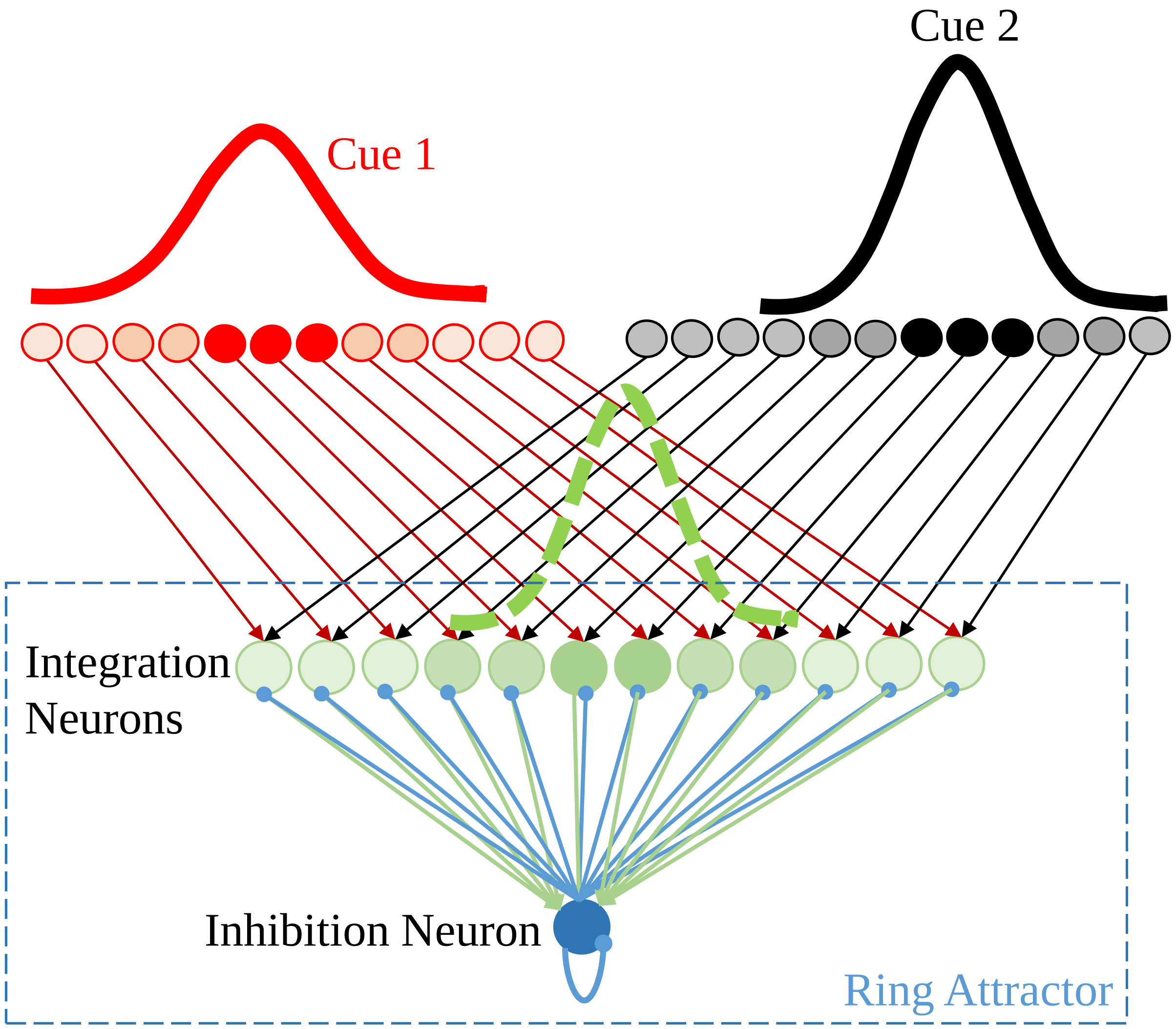
d_{ji} is the difference between the preference of i and j neuron

g is the activation function to guarantee the nonlinear property

X_i is the external input

The uniform inhibitory neuron sums all the integration activations and feedback the same inhibition to all the neurons

Touretzky, D. S. (2005). Attractor network models of head direction cells. Head direction cells and the neural mechanisms of spatial orientation, 411-432.



Cues are defined by the Gaussian function as:

$$F(i) = \frac{K}{\sqrt{2\pi}\sigma} e^{\frac{-(p_i - u)^2}{2\sigma^2}} + \xi N(0,1)$$

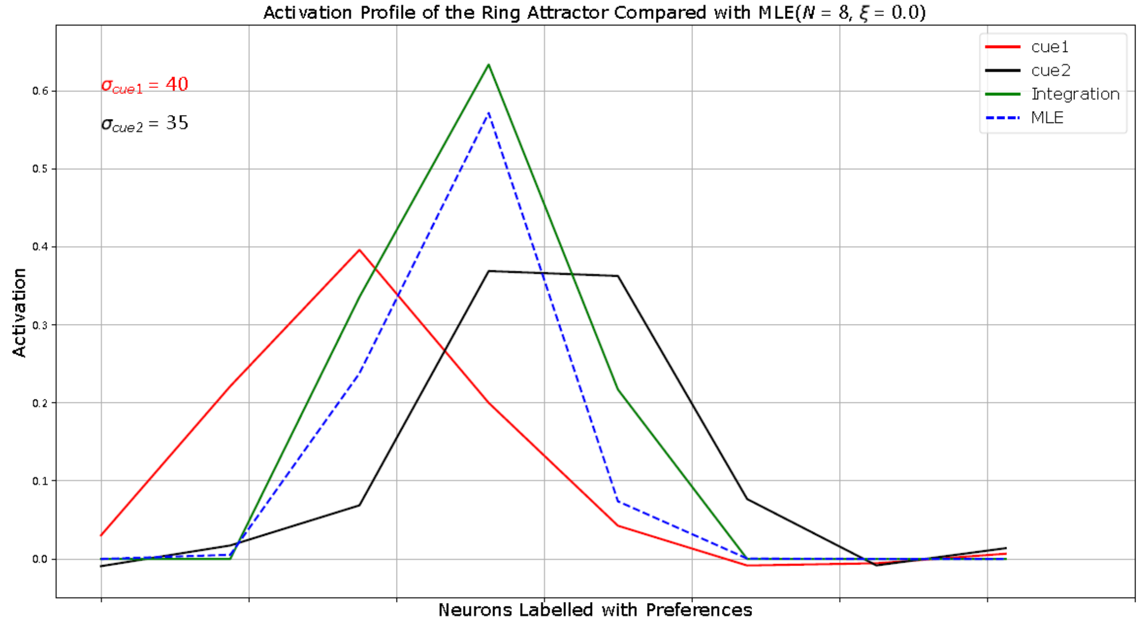
We input the two cues at the same time, so the time evolution equation of the membrane potential of the integration neurons becomes:

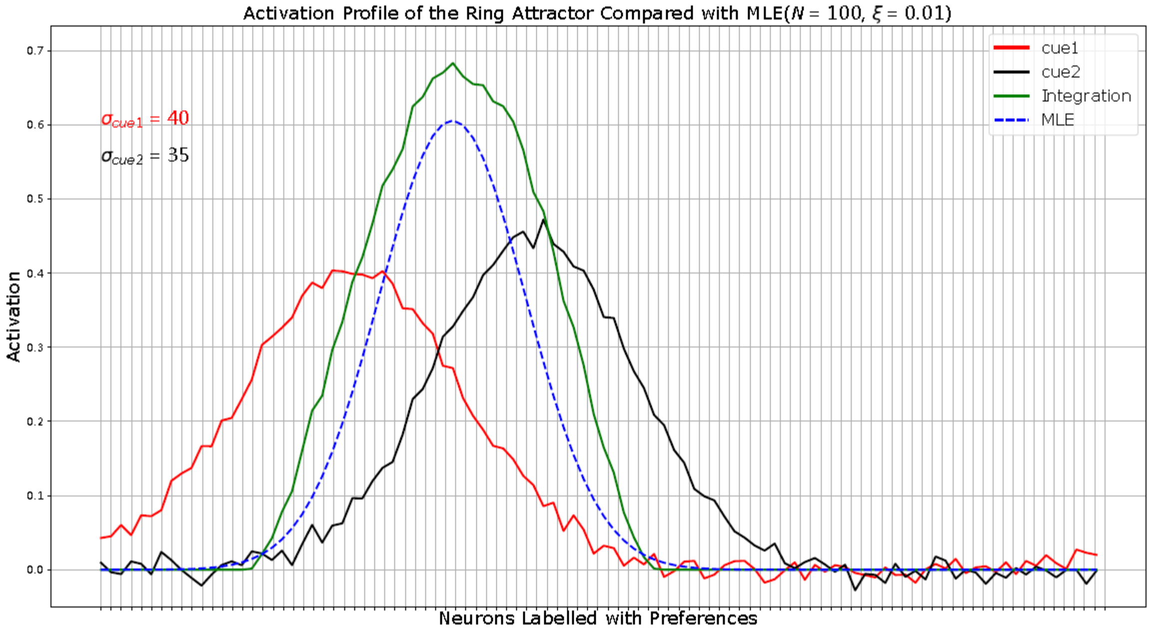
$$\tau \frac{dc_i}{dt} = -c_i + g(\sum_{j=1}^{n} W_{ji}^{E\to E} c_j + X1_i + X2_i + W^{I\to E} u)$$

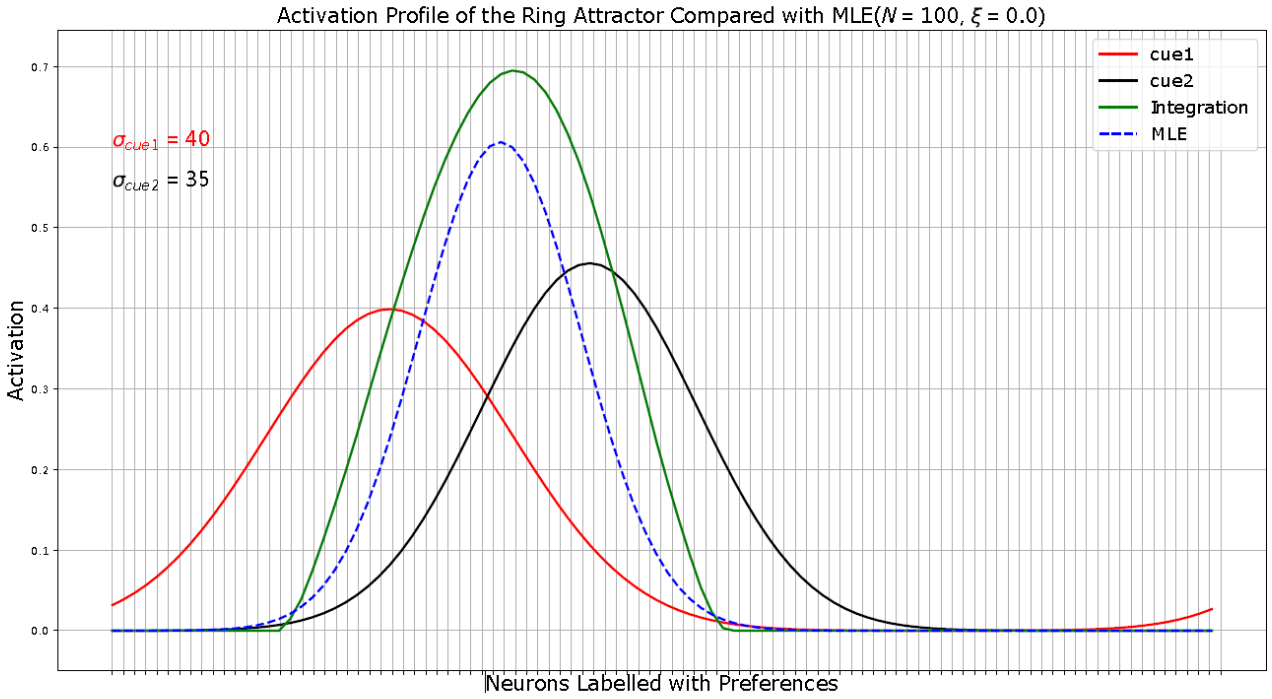
And the time evolution equation of uniform inhibition neuron is:

$$\tau \frac{du}{dt} = -u + g(W^{I\to I} u + W^{E\to I} \sum_{k=1}^{n} c_k)$$

Experiments and Results – Activation Profile



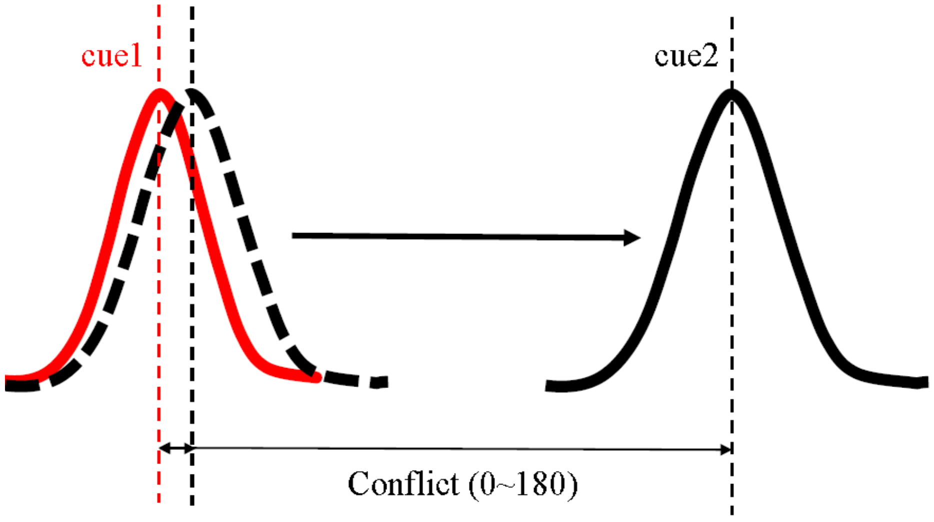


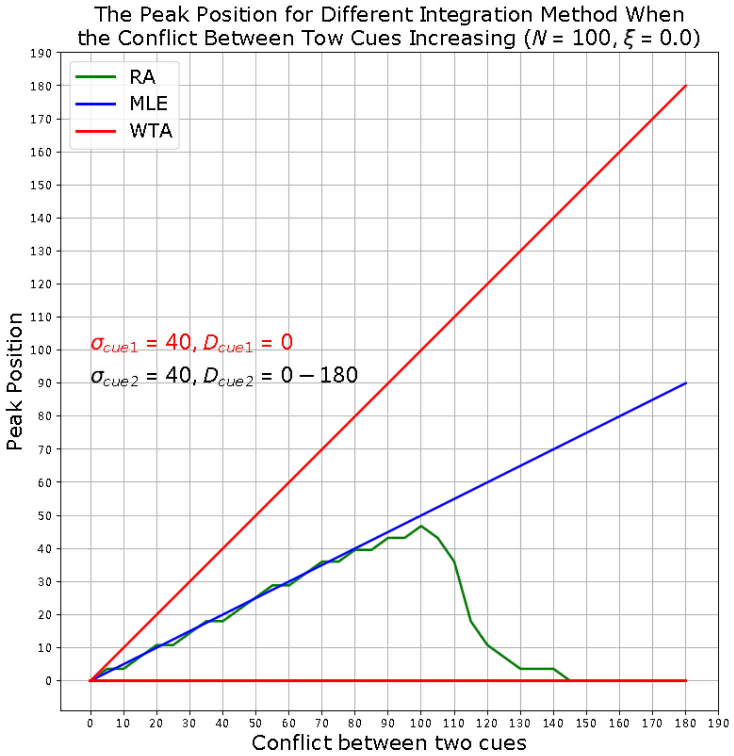


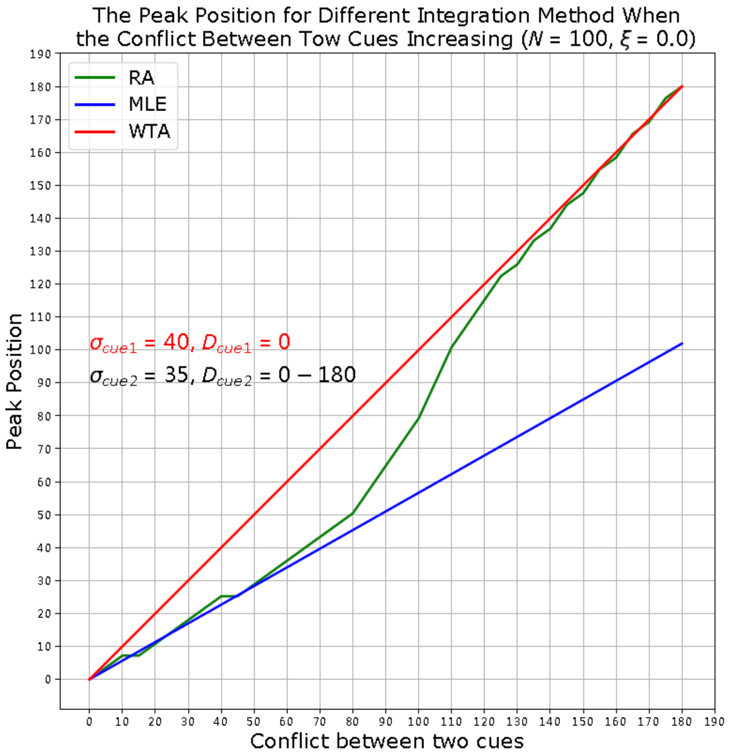
(1) Integration of conflicting cues by a ring attractor network shows that the response approaching the optimal integration.

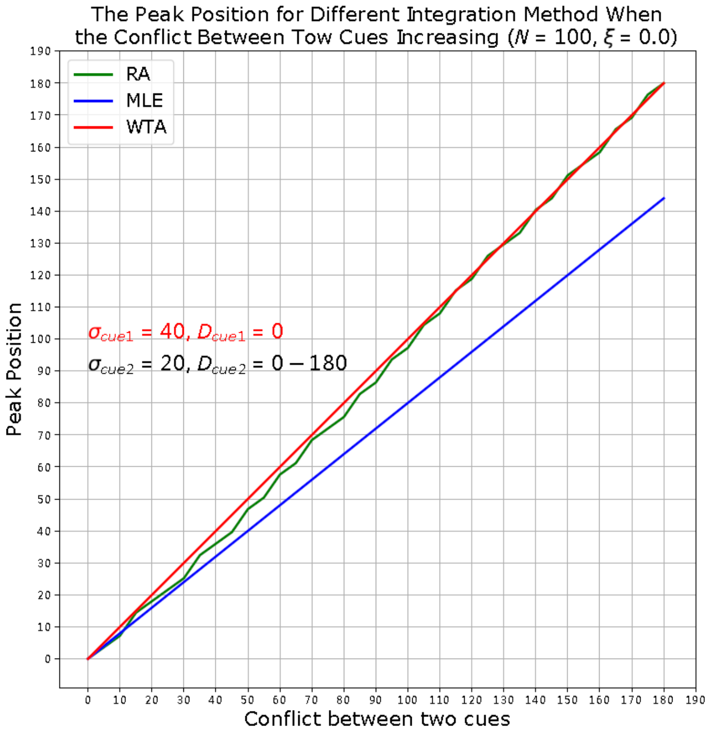
(2) The model remained stable despite the white noise and obvious loss of resolution in the Gaussian functions.

Experiments and Results – Increasing the conflicts of input cues





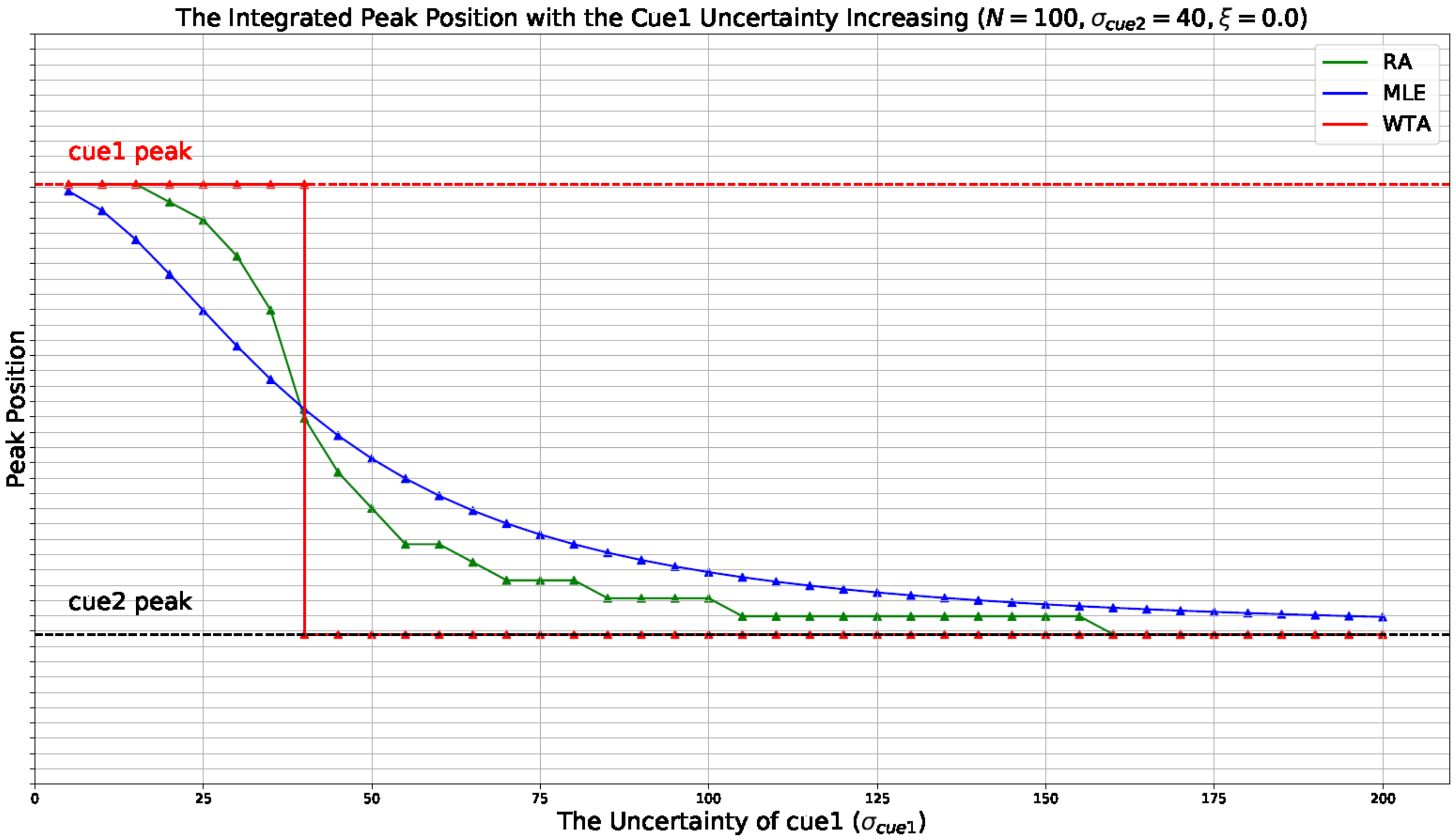




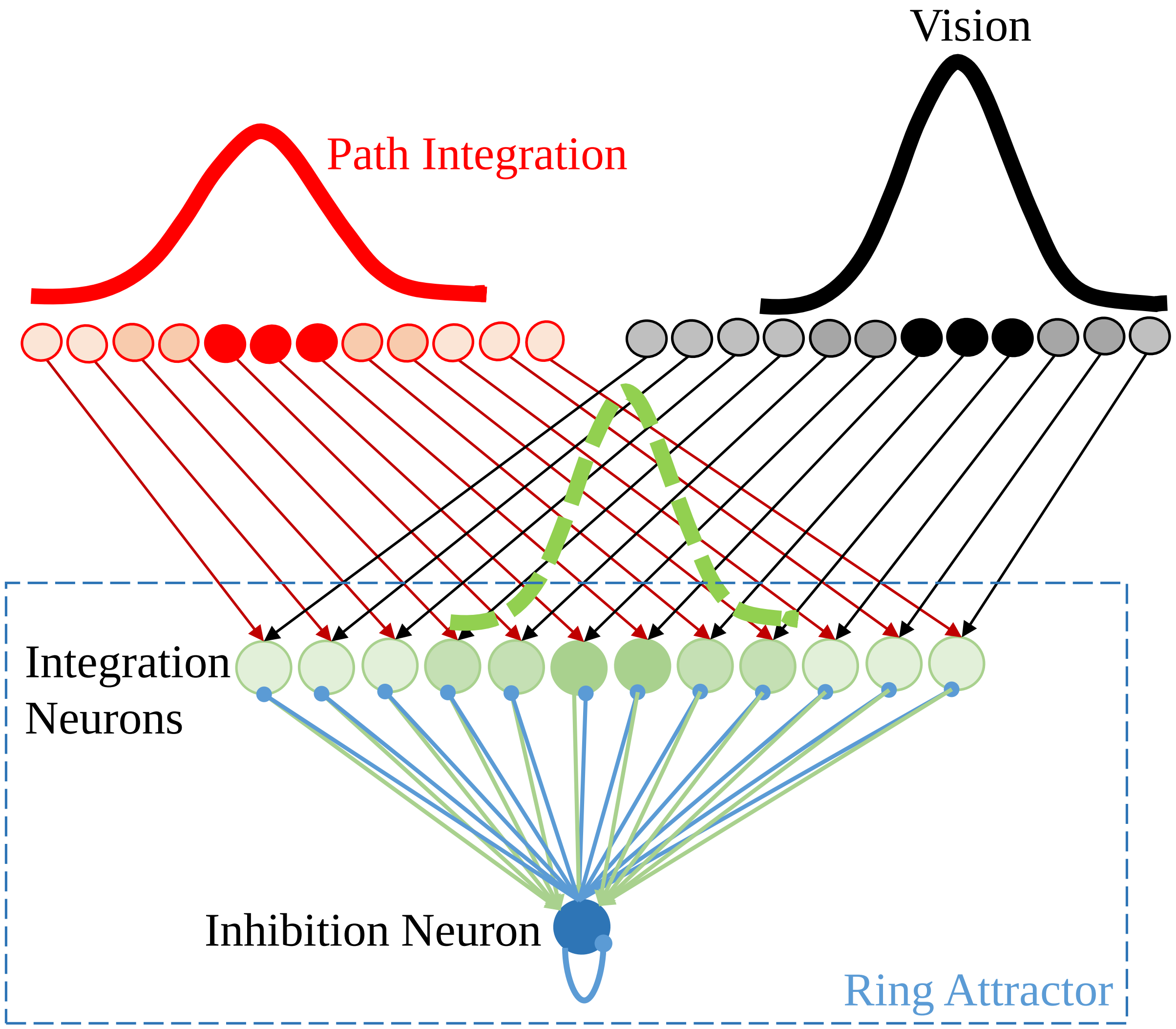
(1) Within a range of cues conflicts, the ring attractor model perform the optimal (or approximately) cues integration, when the two cues are enough different, the model shifts to the winner-take-all (WTA) scenario.

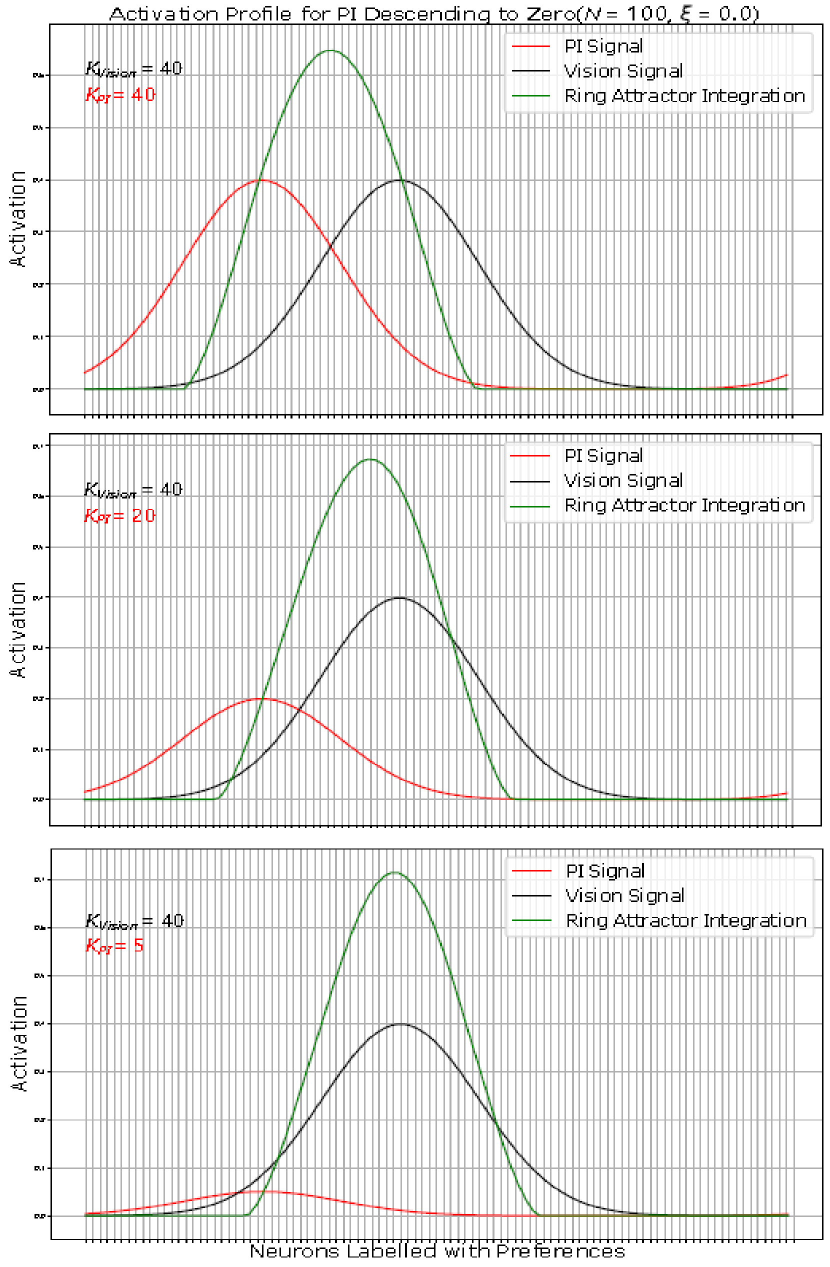
(2) The difference between the uncertainty of two cues also strongly affect the model output.

Experiments and Results – The effect of cues uncertainty



Experiments and Results – Repeat the biology experiments





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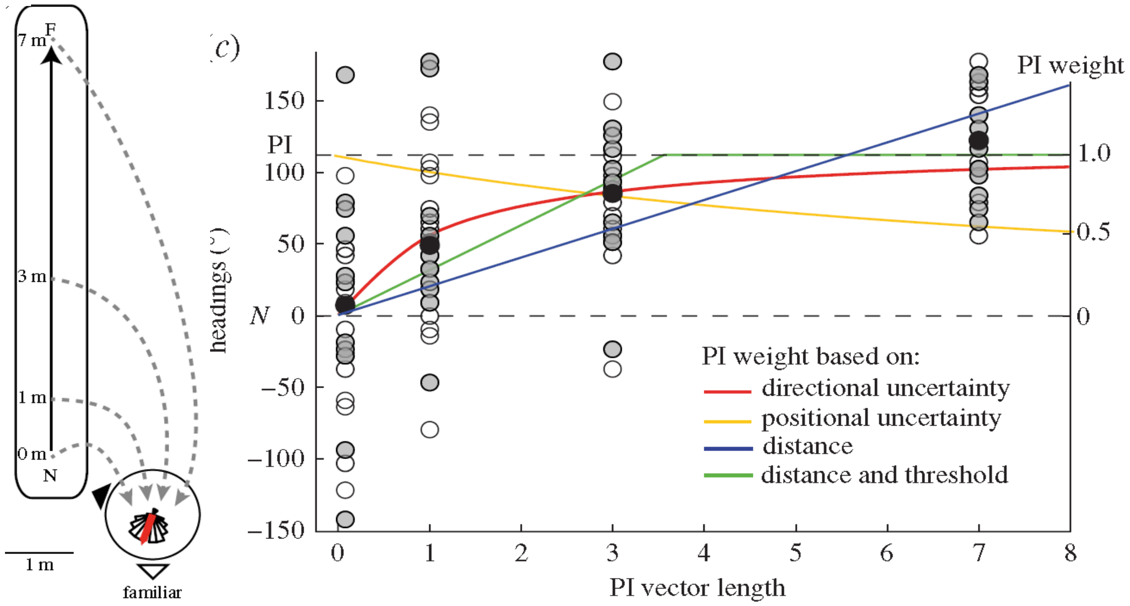
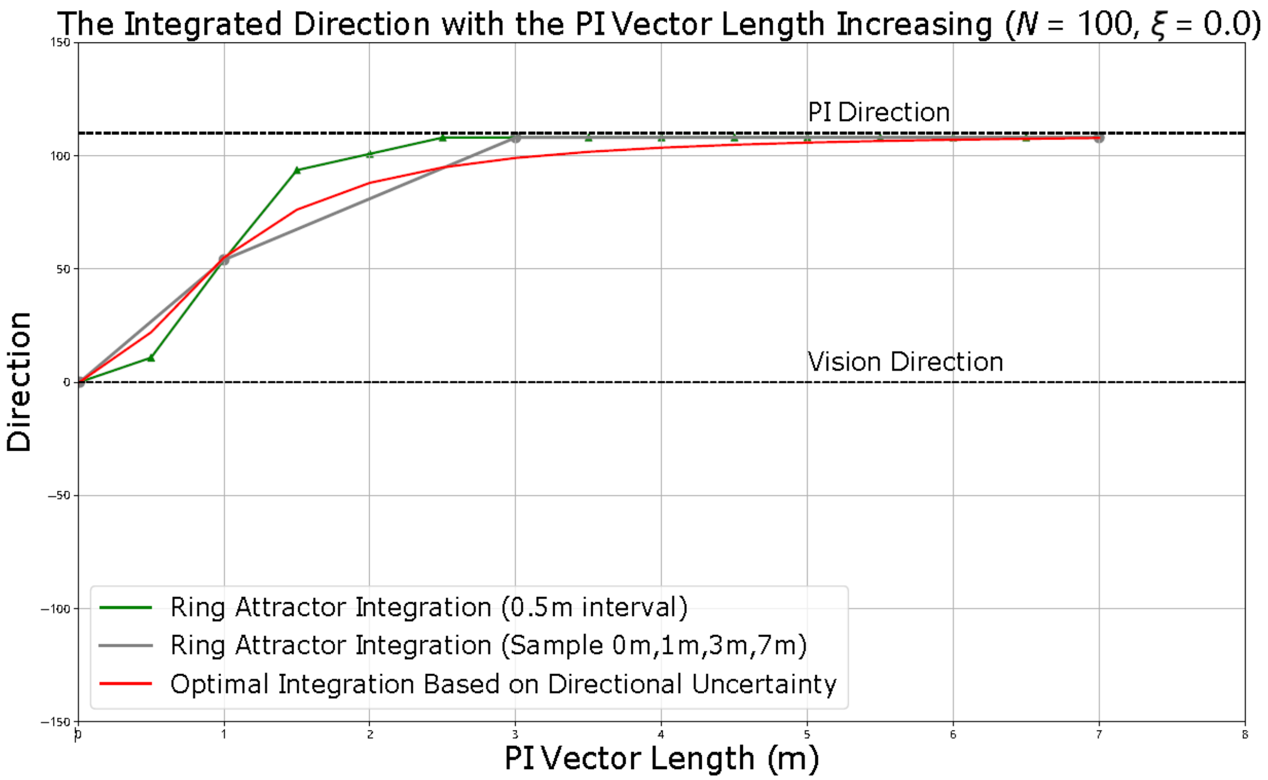
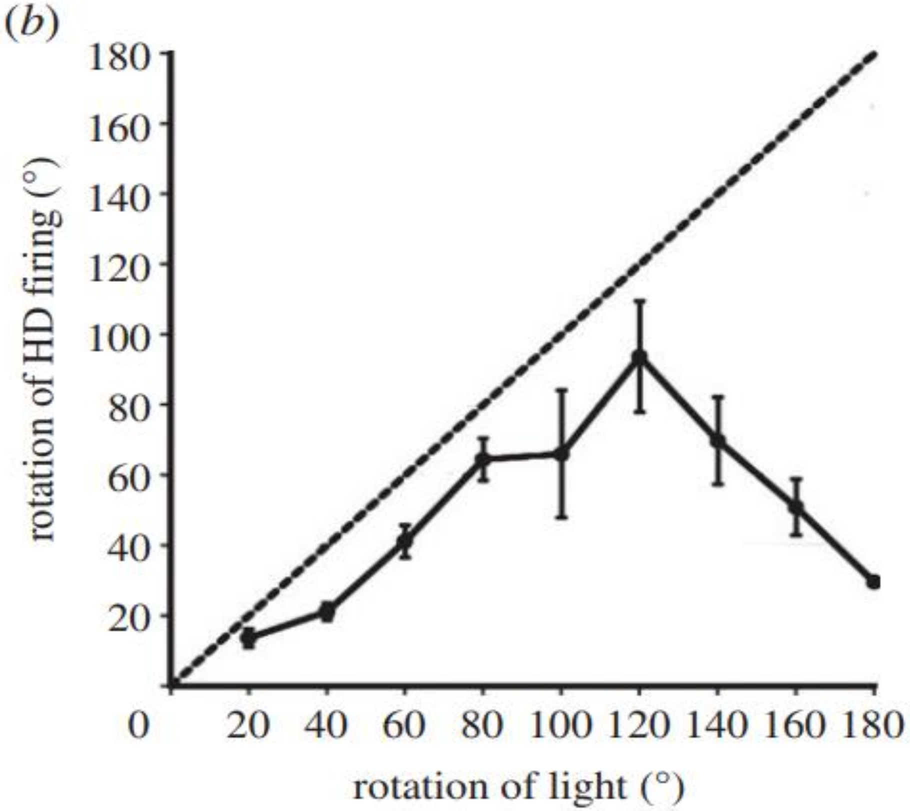
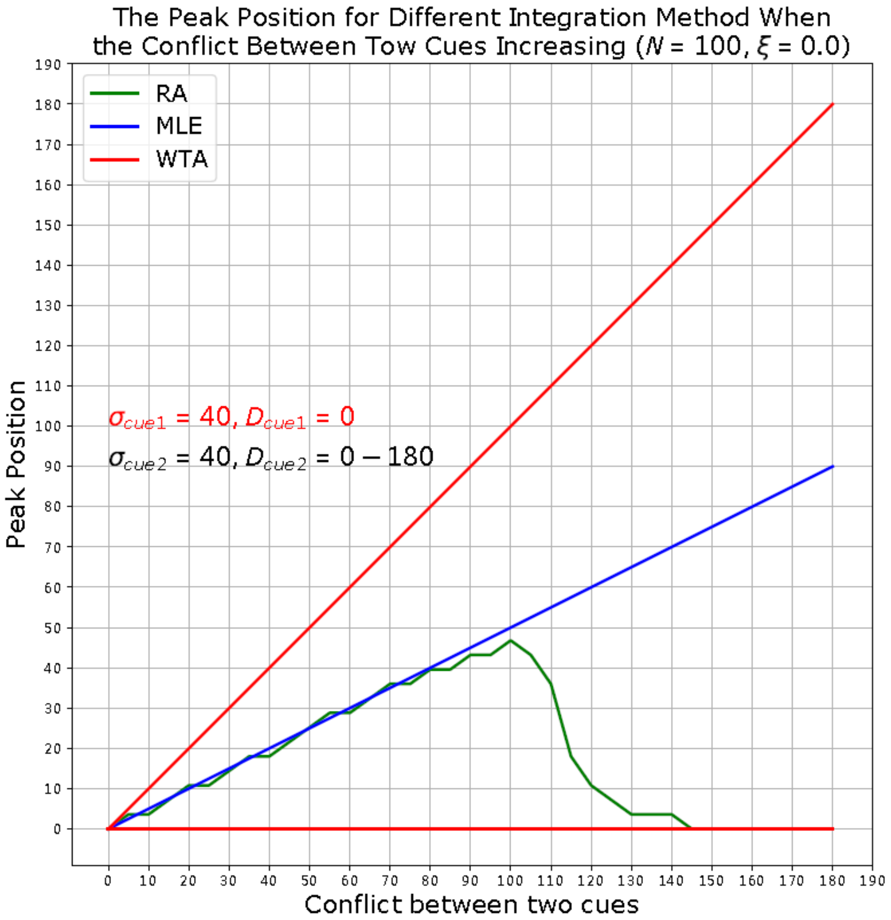




Experiments and Results – Repeat the biology experiments

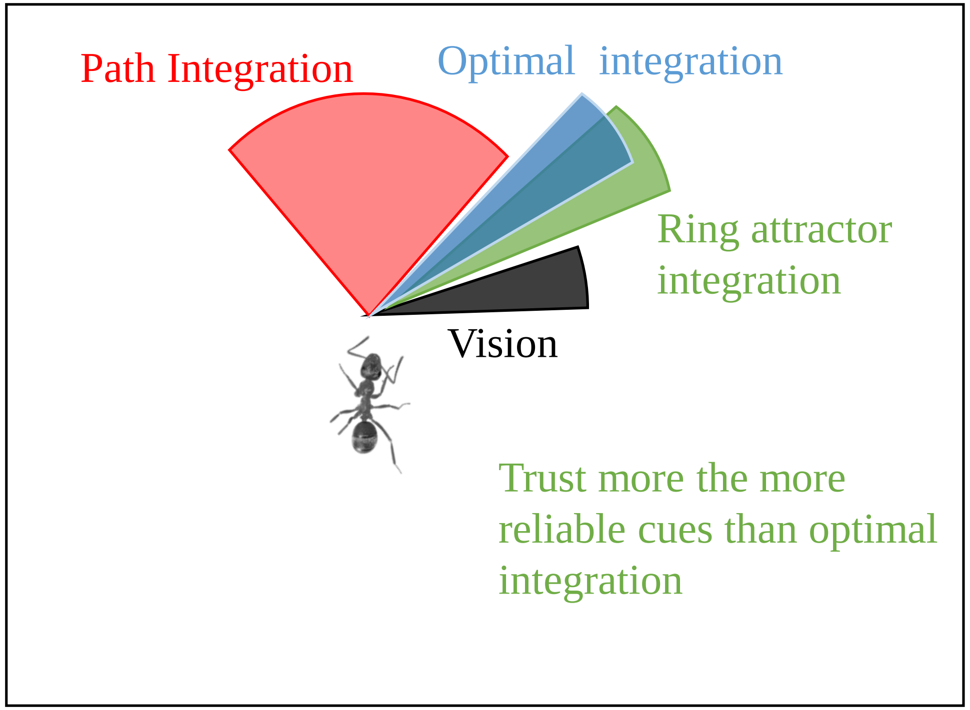


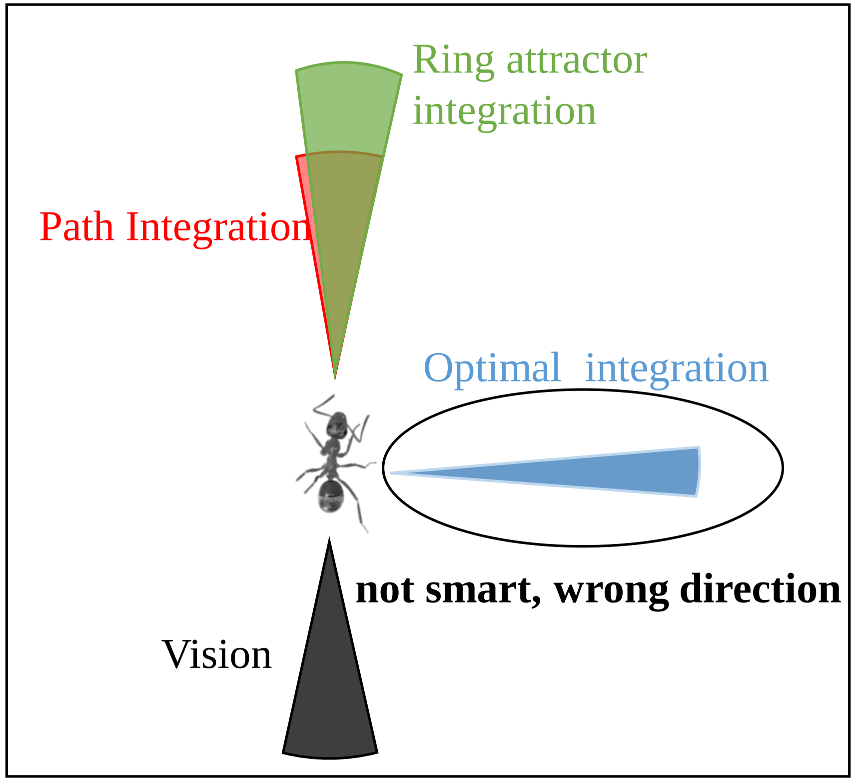


Knight, R., Piette, C. E., Page, H., Walters, D., Marozzi, E., Nardini, M., ... &Jeery, K. J. (2014). Weighted cue integration in the rodent head direction system. Philosophical Transactions of the Royal Society of London B: Biological Sciences,369(1635), 20120512.

Summary of the results for the ring attractor network

1. **Can ring attractor perform optimal integration for cues with small difference? YES**
2. **Can it also perform winner-take-all for cues with large difference? YES**





3. **Even when miniaturized and with noise Good Properties.**
4. **Have similar performances with biological experiments Biology plausible.**

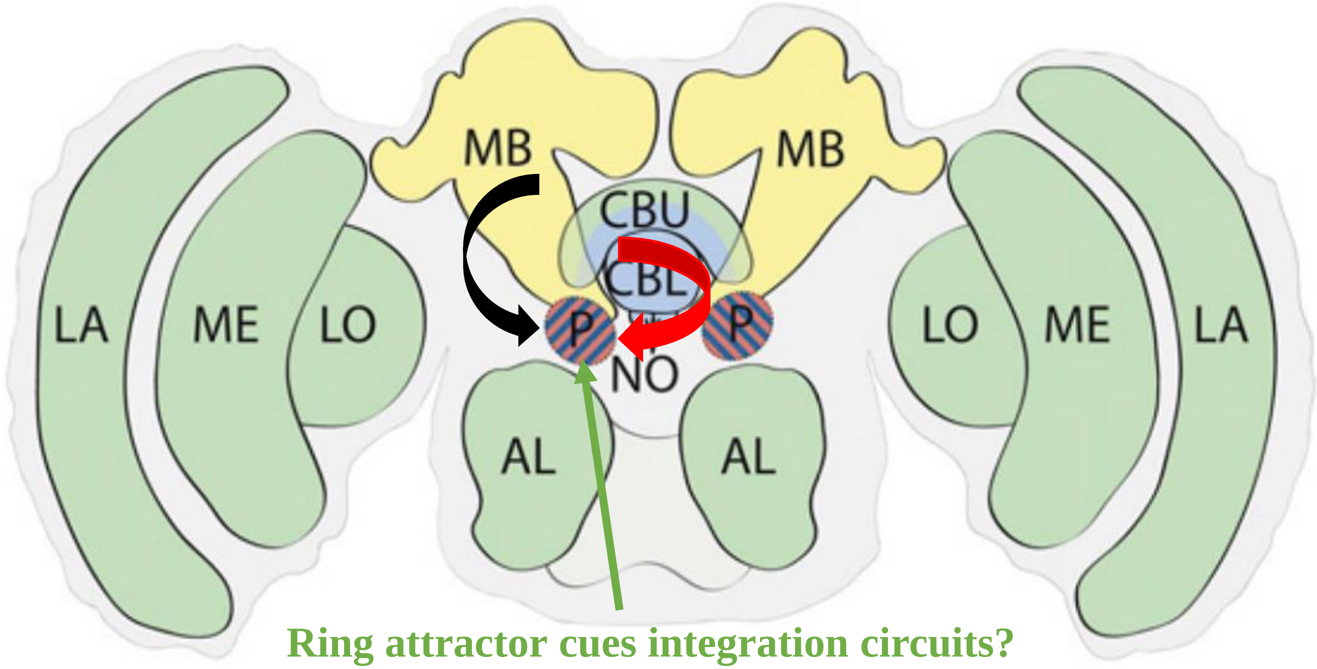
Discussion- Aid search for integration networks in animals

(1) Information integration in the LAL

Insect brain:

MB mushroom body
CBU central body upper
CBL central body lower
NO noduli
P protocerebrum (with LAL in it)
LAL lateral accessory lobe
AL antennal lobe

Optic Lobe
- LA-Lamina
- ME-Medulla
- LO-Lobula



Ring attractor cues integration circuits?

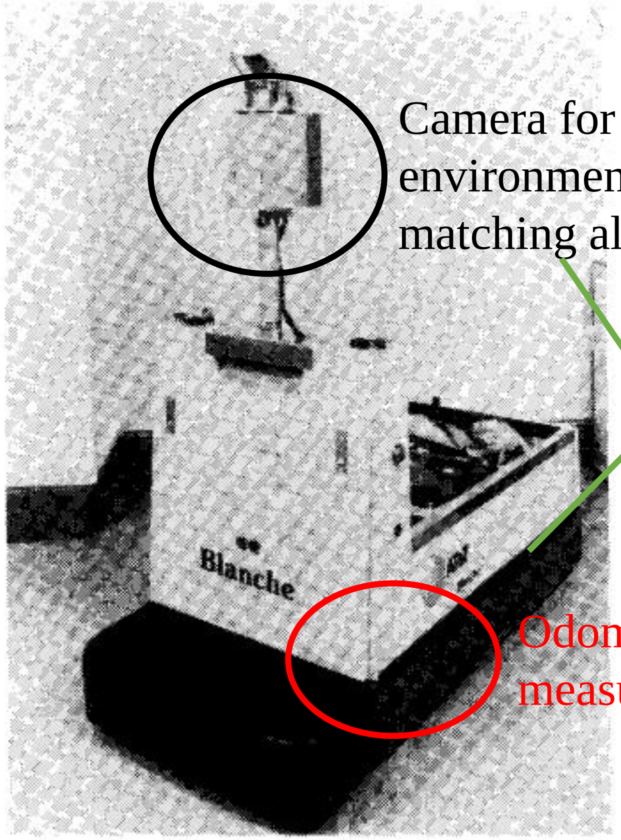
(2) Other areas that needs information combining. Ring attractor network may be a ubiquitous circuits in animals' brain.

Andrew B. Barrona, Colin Kleinb, *What insects can tell us about the origins of consciousness*, Proceedings of the National Academy of Sciences, 113 (18), 2016

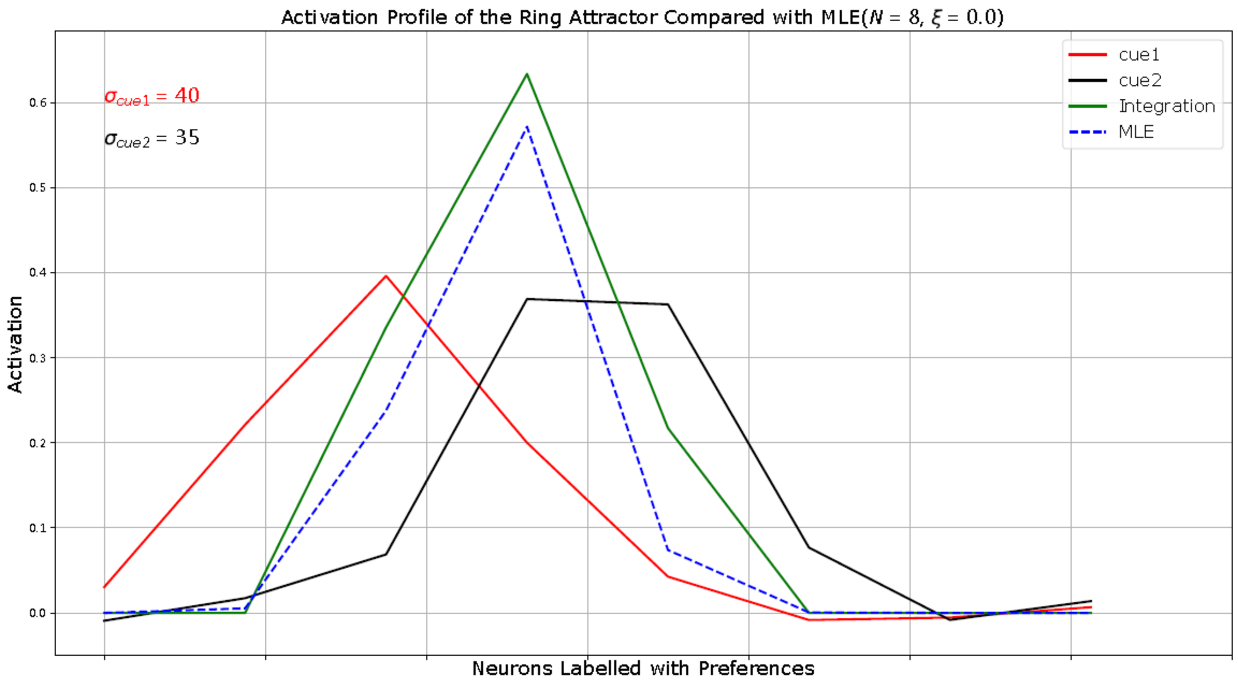
Discussion- Robot application

Sensory Fusion

(1) Can do the optimal-like integration

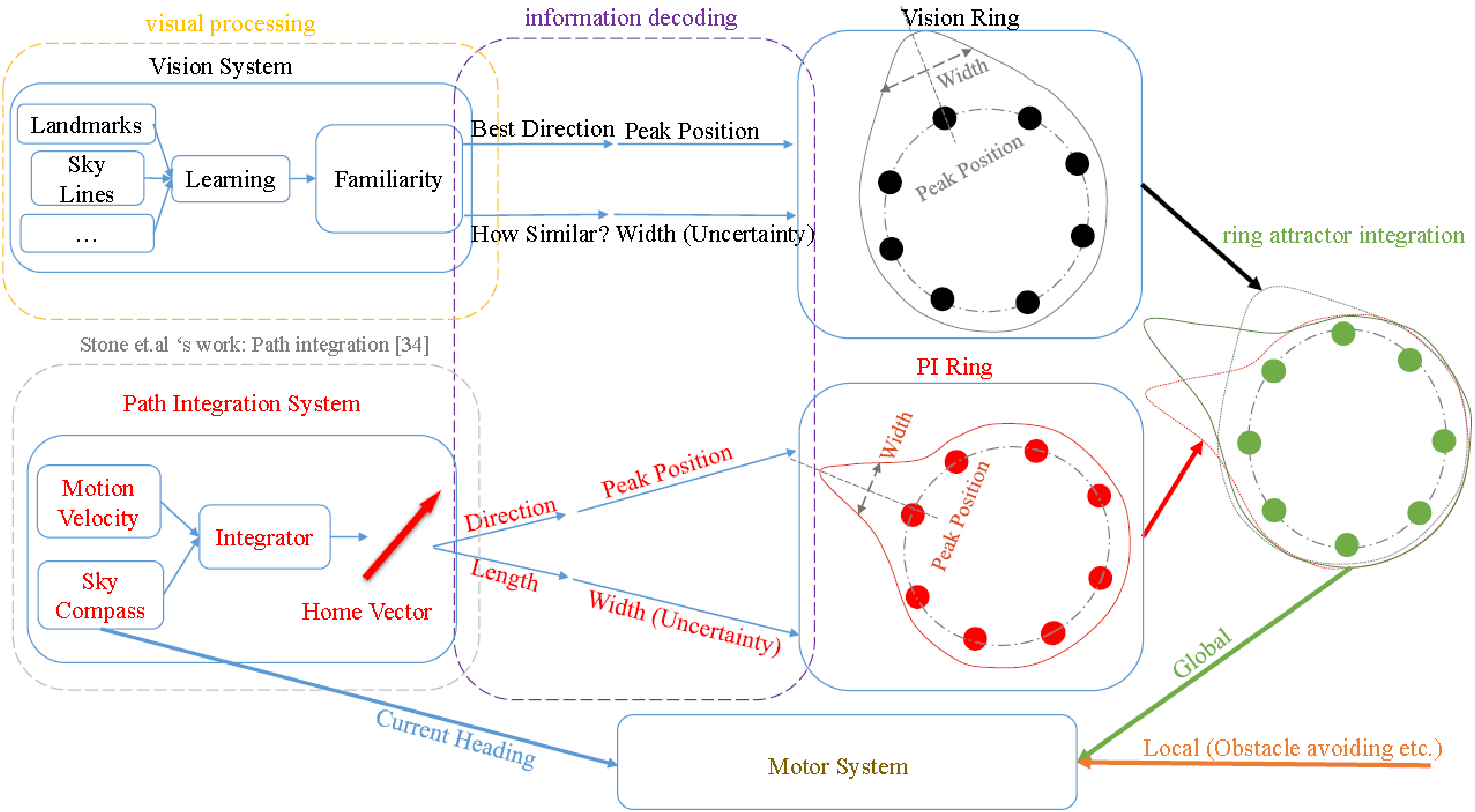


(2) Cost very little computing resources (8 neurons can still work well), make it possible for applying Bayesian method on small, cheap robot platforms

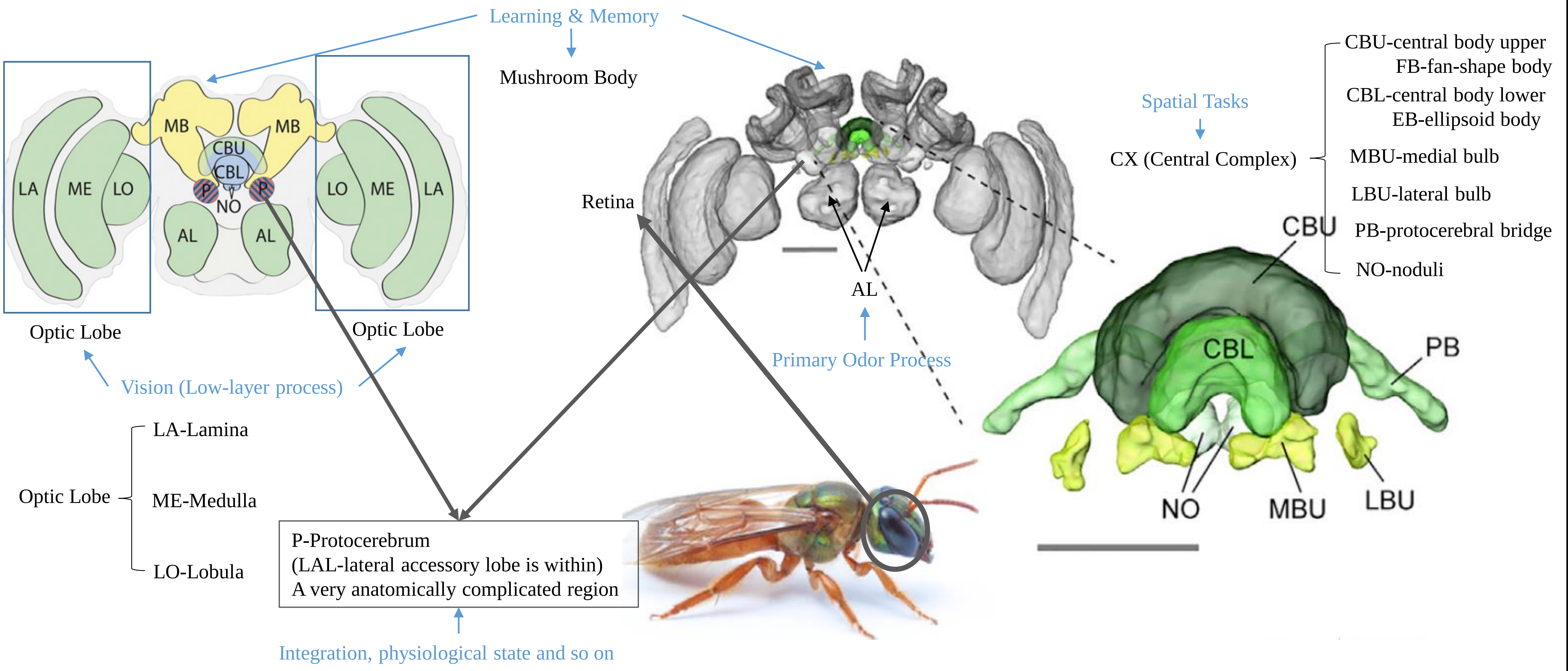


Cox, I. J. (1991). Blanche-an experiment in guidance and navigation of an autonomous robot vehicle. IEEE Transactions on robotics and automation, 7(2), 193-204.
Kam, M., Zhu, X., & Kalata, P. (1997). Sensor fusion for mobile robot navigation. Proceedings of the IEEE, 85(1), 108-119.

Future Plan – The holistic toolkit of insect navigation



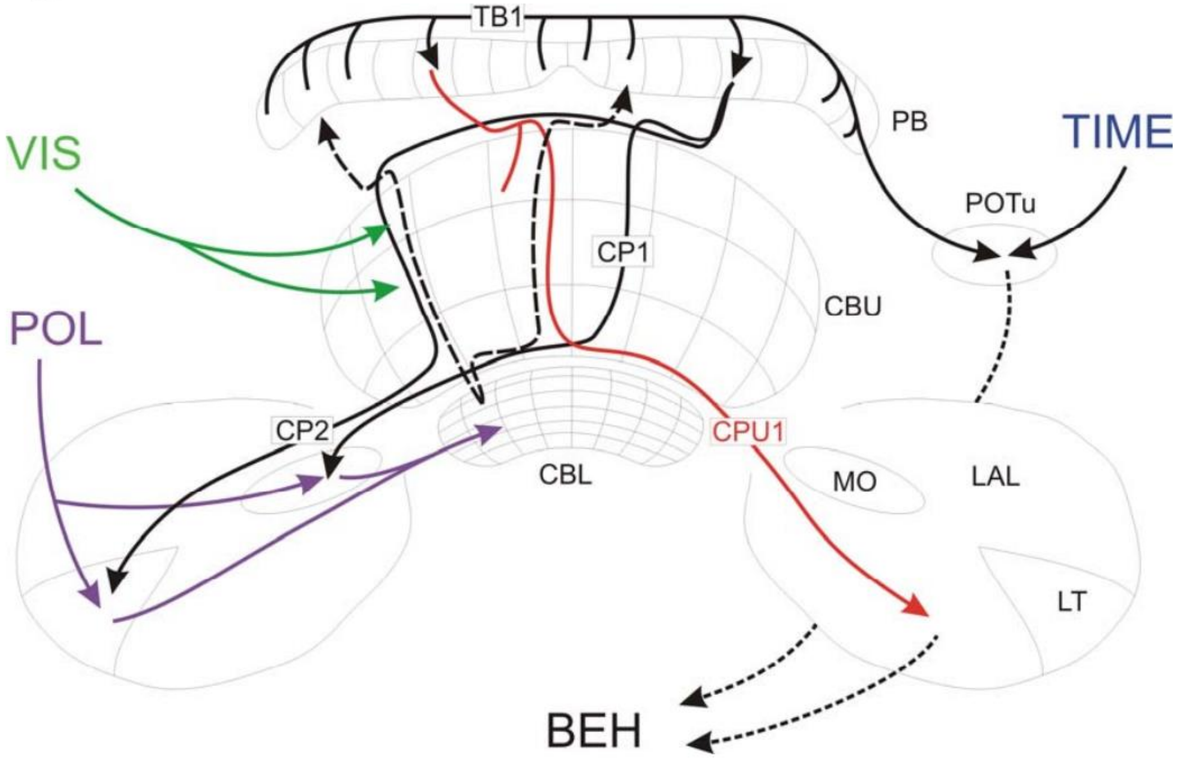
Future Plan – The holistic toolkit of insect navigation



Andrew B. Barrona, Colin Kleinb, *What insects can tell us about the origins of consciousness*, Proceedings of the National Academy of Sciences, 113 (18), 2016

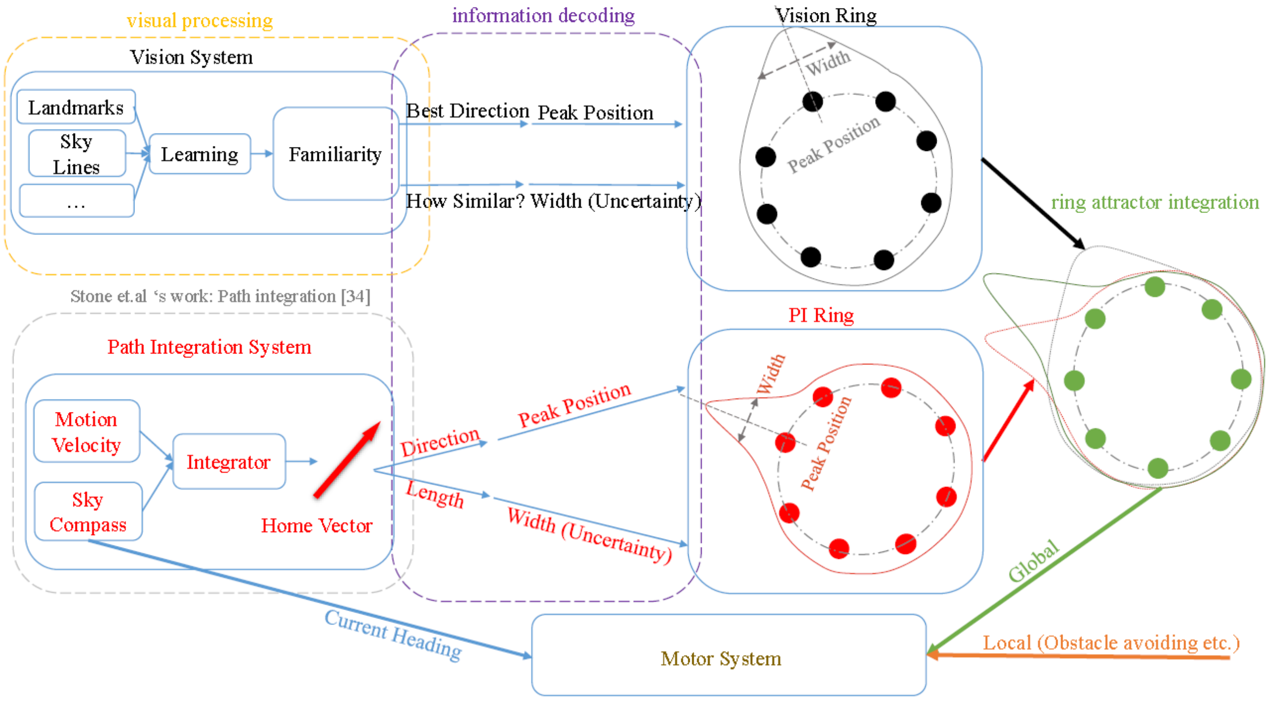
Thomas Stone, Barbara Webb, et.al, *An Anatomically Constrained Model for Path Integration in the Bee Brain*, Current Biology 27, 3069–3085, October 23, 2017

Future Plan – The holistic toolkit of insect navigation



Predict physiological performances

Give supported evidences

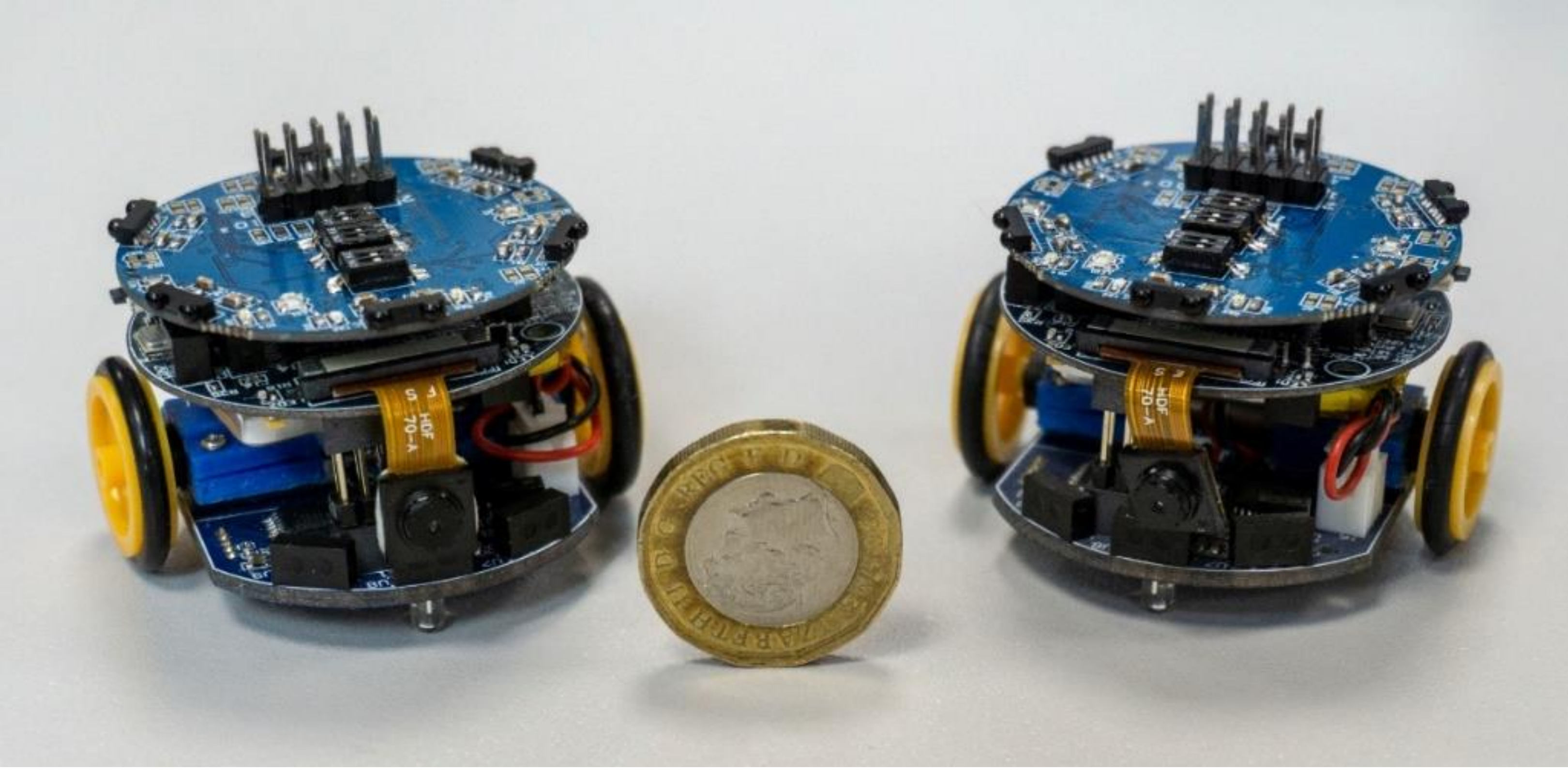


Heinze, S., and Homberg, U. (2007). Maplike representation of celestial E-vector orientations in the brain of an insect. Science 315, 995–997.

Future Plan – The Implementation on Robot

Implement the whole insect navigation toolkit on robot to test the effectiveness of biological strategy in real world:

- The first insect navigation inspired automatous robot.
- Give convincing explanation for insects’ navigational behaviors
- Give insights into the understanding of how small brain solve complex navigation tasks



Colias-IV, Computational Intelligent Lab, University of Lincoln, UK

EU HORIZON 2020 PROJECT STEP2DYNA WORKSHOP

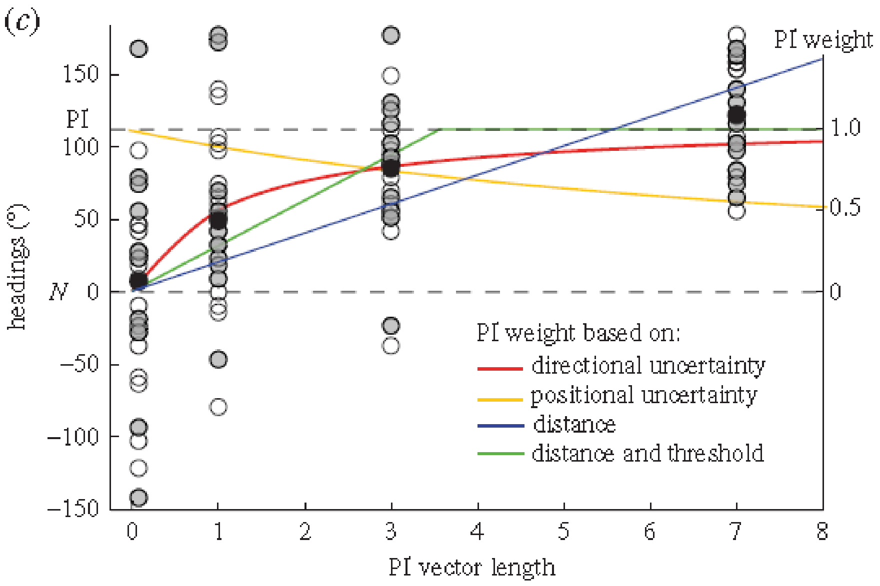
Thanks!

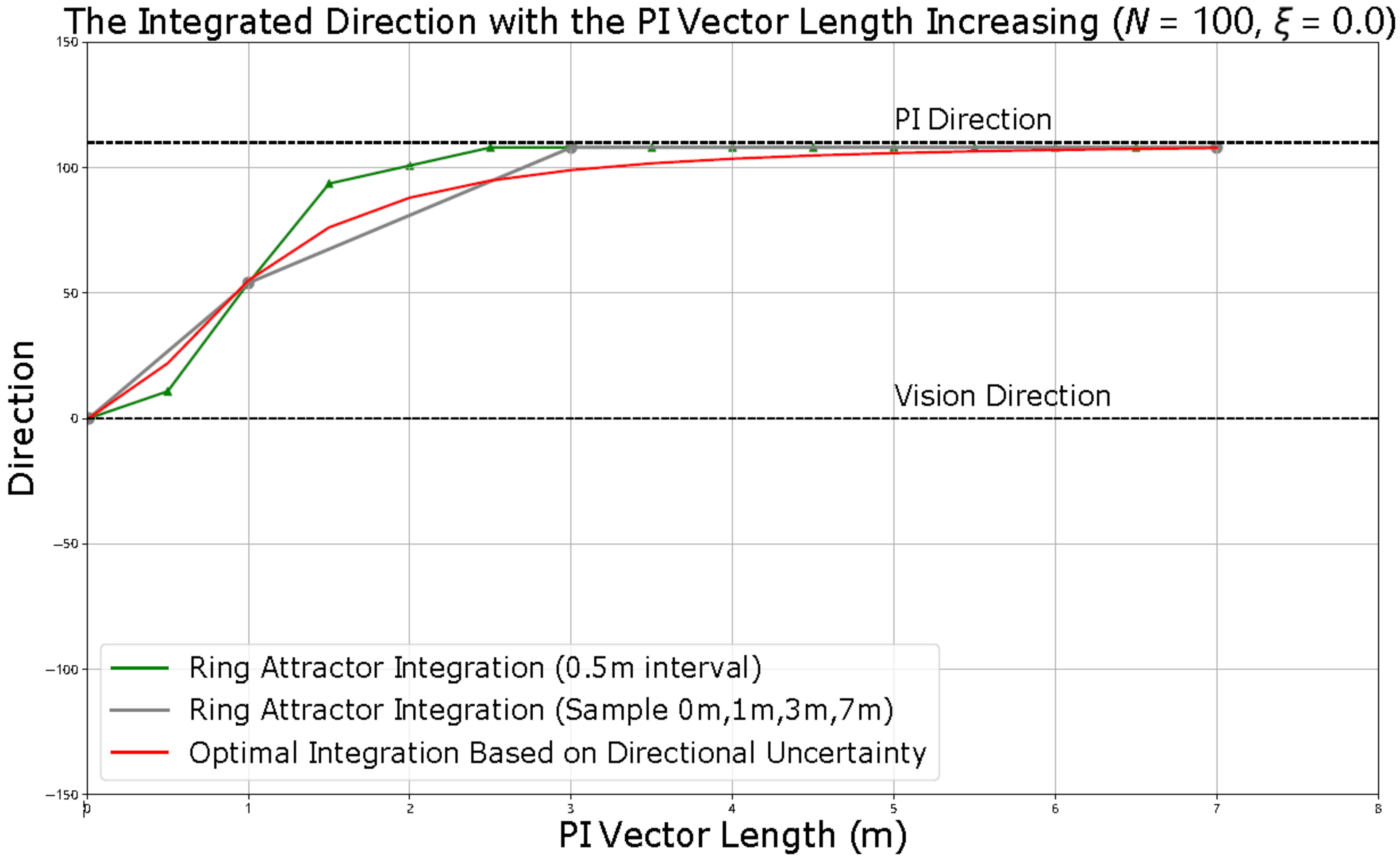
Xuelong Sun

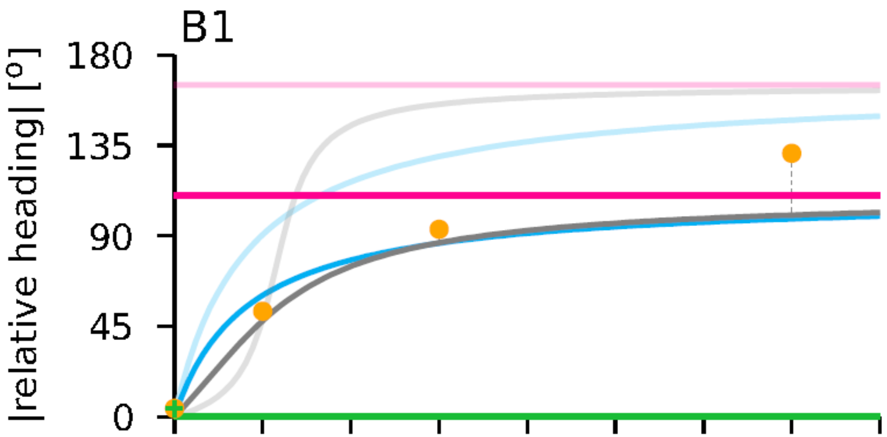
Wednesday, 16th Oct, 2018

University of Lincoln, Lincoln, UK

3. Repeat Biological Experiments







[1] Hoinville, T., & Wehner, R. (2018). Optimal multiguidance integration in insect navigation. Proceedings of the National Academy of Sciences, 115(11), 2824-2829.

Conclusions

- Our implementation of the classic ring attractor can perform optimal-like cue integration when presented with conflicting cues.
- The network output is also shown to be robust to noise on the sensory input and reduction in size to the 8 neurons that encode direction in insects.
- Sweep tests showed both the variance and distance between conflicting cues strongly affect the network properties.:

(1) With equal or small differences in variance of cues the network performs a weighted average for small cue conflicts, but switches to a winner-take-all response for larger conflicts.

(2) larger differences the network switches to WTA responses at much small conflicts.

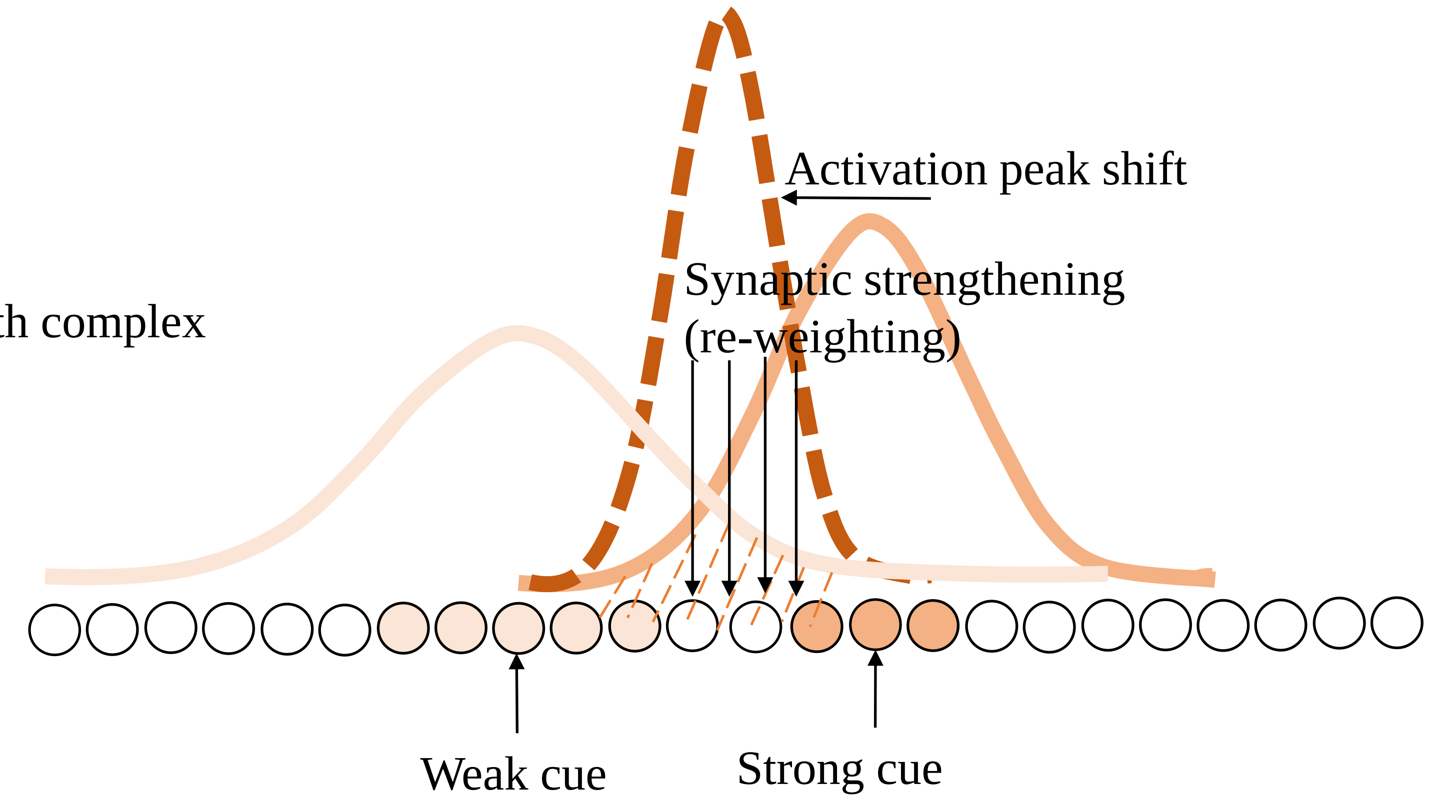
- Simple ring attractor network possesses the capacity of smartly switching from optimal integration to winner-take-all shows a similar properties of animals' behavior supported by some biological experiments.
- With the advantage of small size and simple structure, it can be applied in small and cheap robot needing sensory fusion.

Existing Method – Re-weighting mechanism

>> Jeffery et.al has proposed that ring attractor can be a cue integration network but **require complex re-weighting function.**

1. Constrained by the biological evidence of rodents

2. Neurons should have learning ability and circuits with complex mechanism



Jeffery, K. J., Page, H. J., Stringer, S. M. (2016). Optimal cue combination and landmark-stability learning in the head direction system. The Journal of physiology, 594(22), 6527-6534