AFOSR Annual Report: The Cronin Laboratory

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THE UNIVERSITY OF MARYLAND BALTIMORE COUNTY

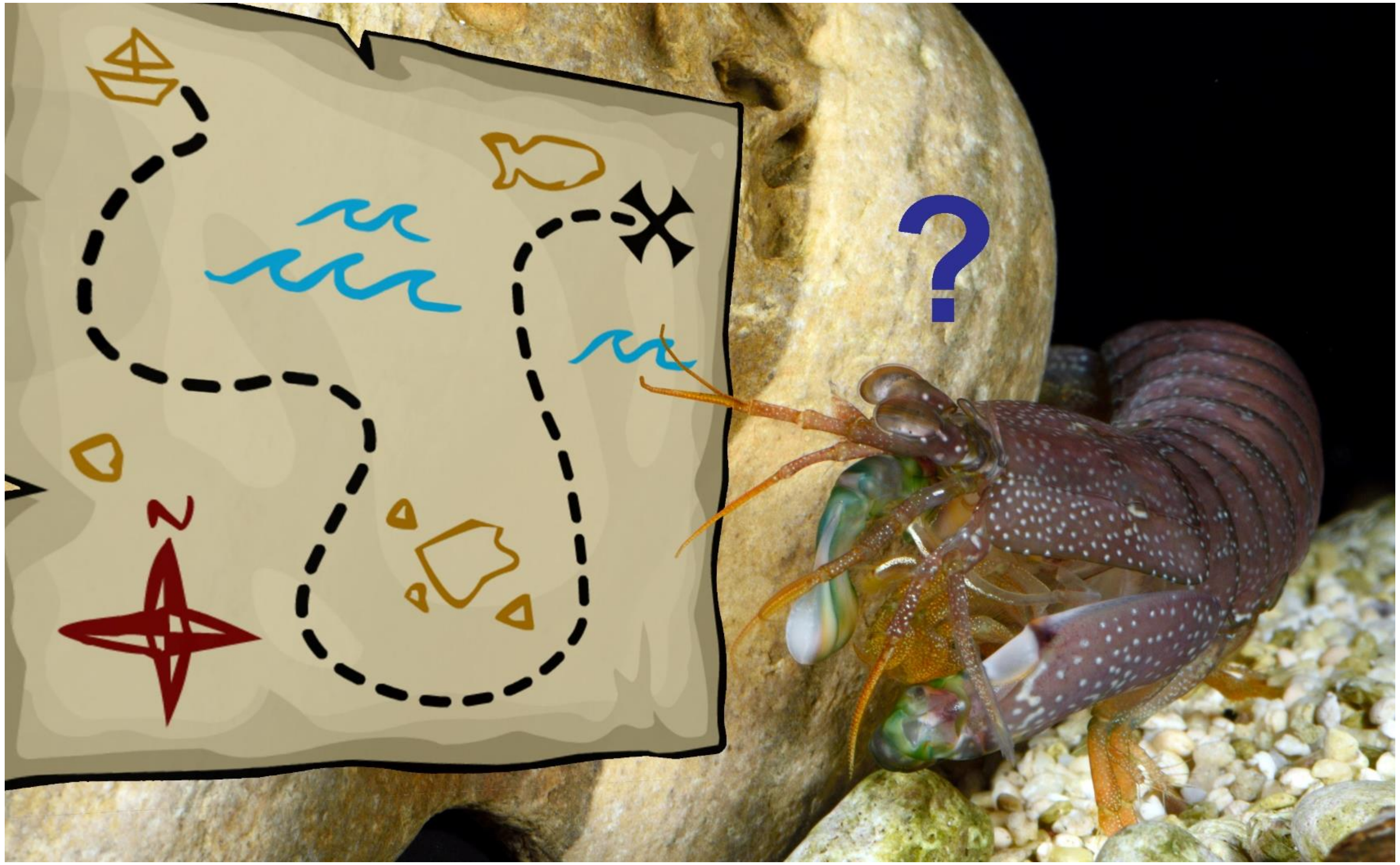
Mantis Shrimp

Photos: Roy Caldwell and Mike Bok

Burrows

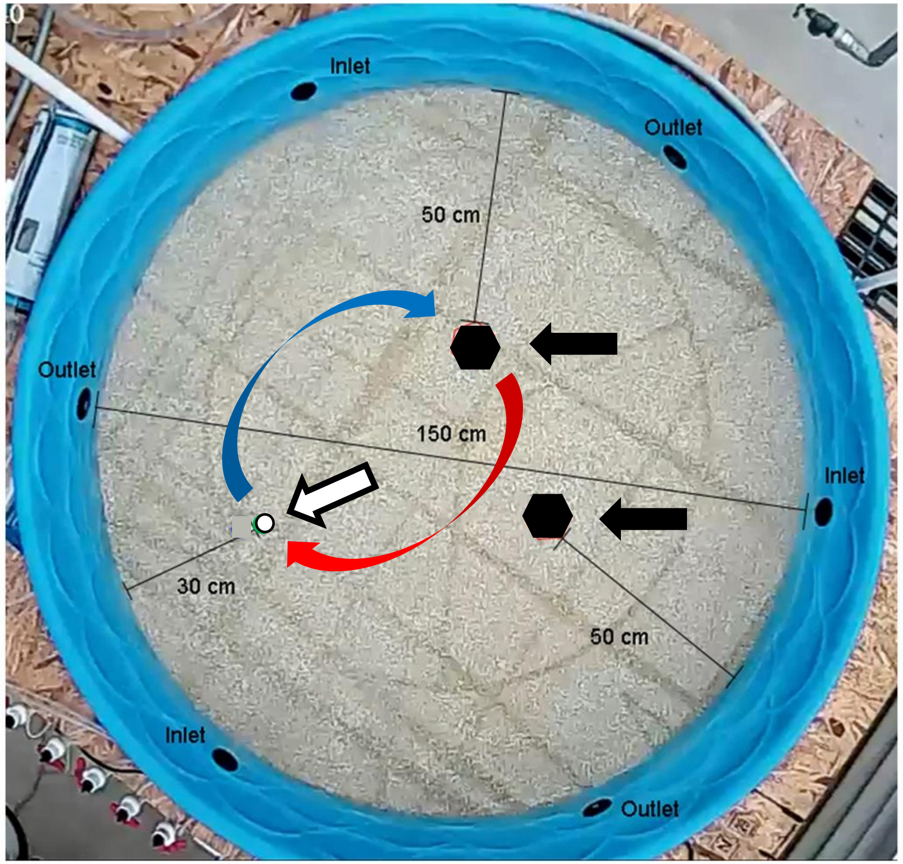
Neogonodactylus oerstedii travel up to 4m away from their burrows during foraging. (Animals 30-50 mm long)

How do Mantis Shrimp Navigate back to their burrows after foraging excursions ?



Original Photo: Roy Caldwell

Navigation Arenas



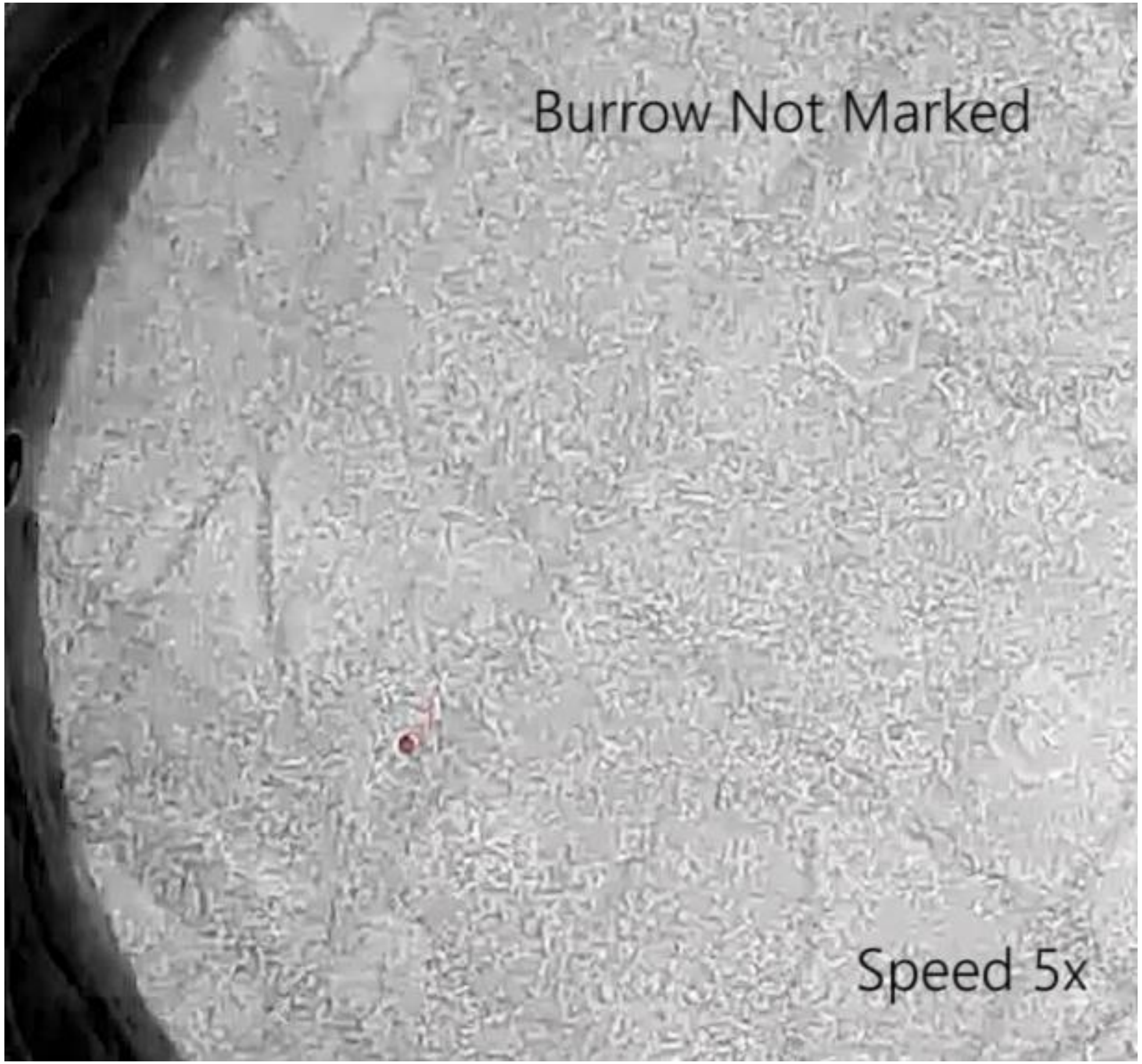
White: Burrow Black: Food Placement

Arenas were filled with sand and salt water

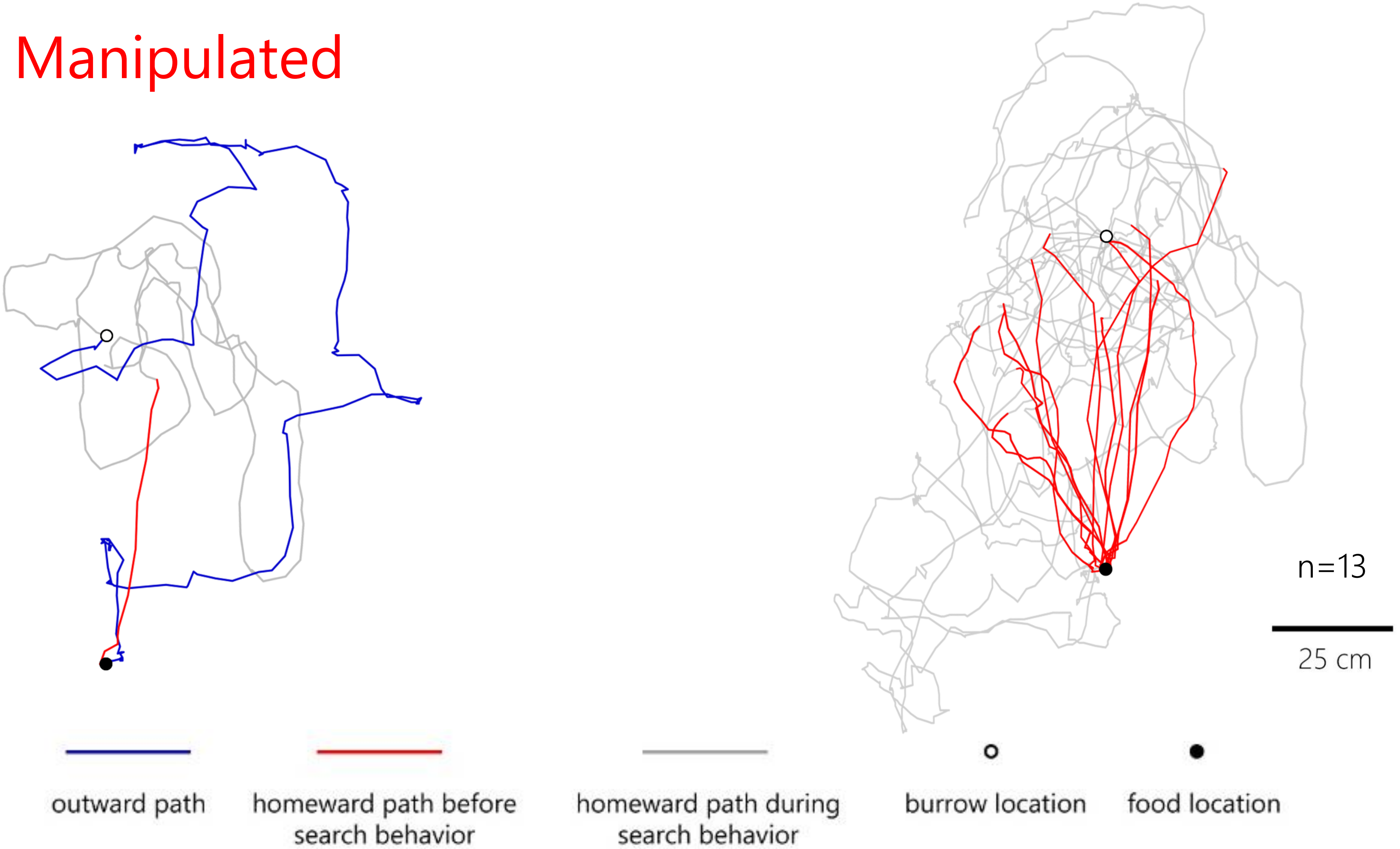
Burrows were visually unidentifiable at range.

Empty snail shells were stuffed with food pieces and placed at fixed locations

Outward and homeward paths between the burrow and these fixed locations were observed.


Burrow Not Marked
Speed 5x

Not Manipulated



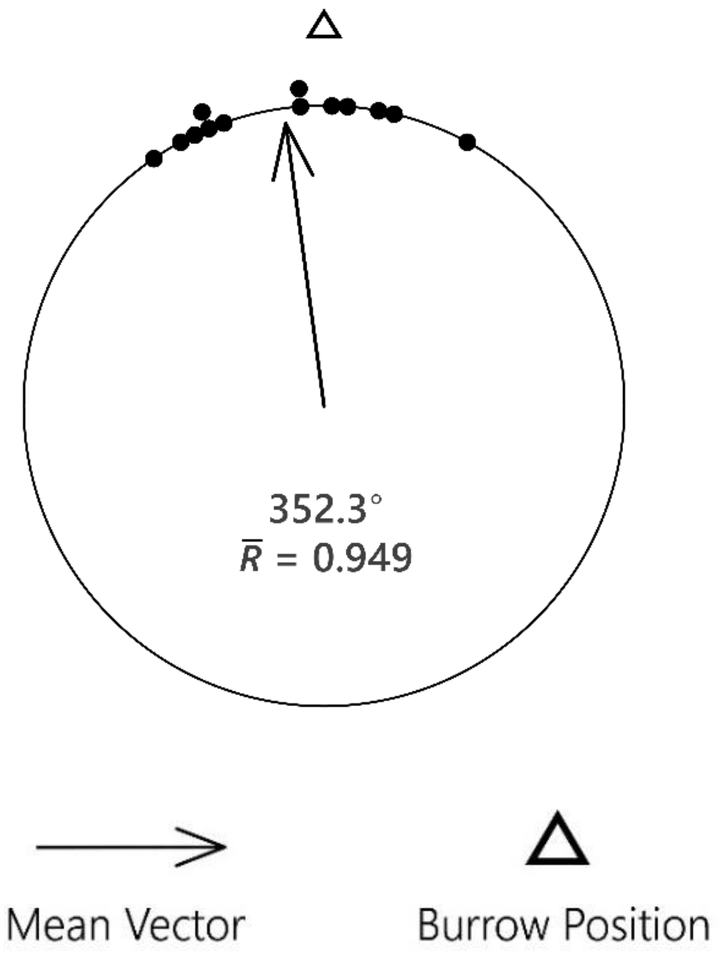
Not Manipulated

Homeward paths were generally oriented towards the burrow.

Initial Homeward
Path Orientations

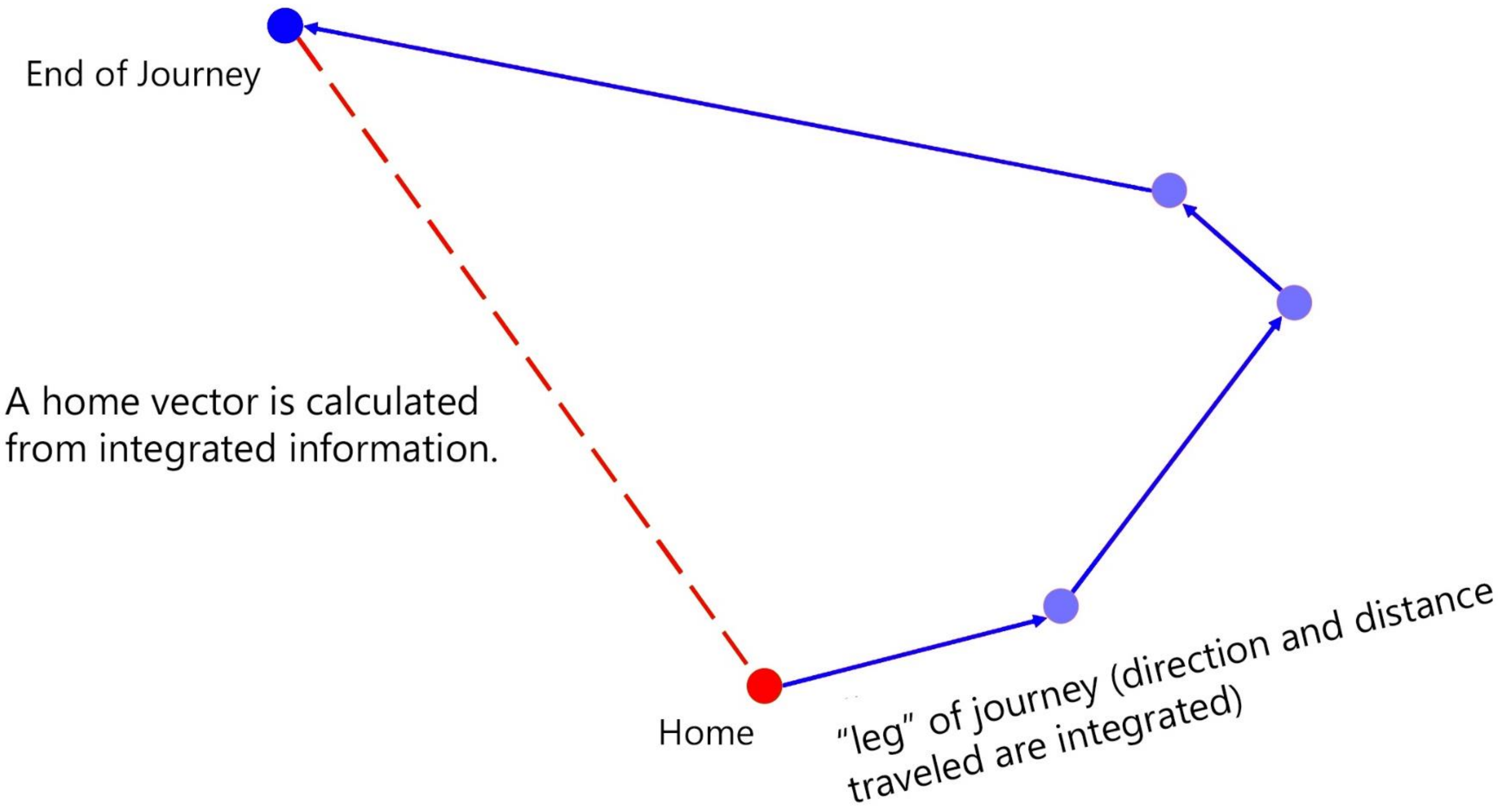
(1/3 beeline distance)

$p < 0.001$



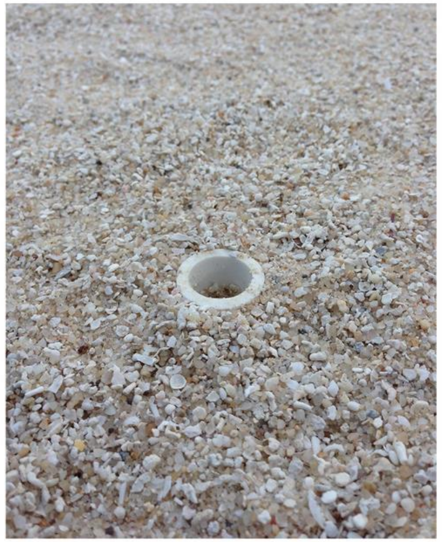
Path Integration

(Dead Reckoning)

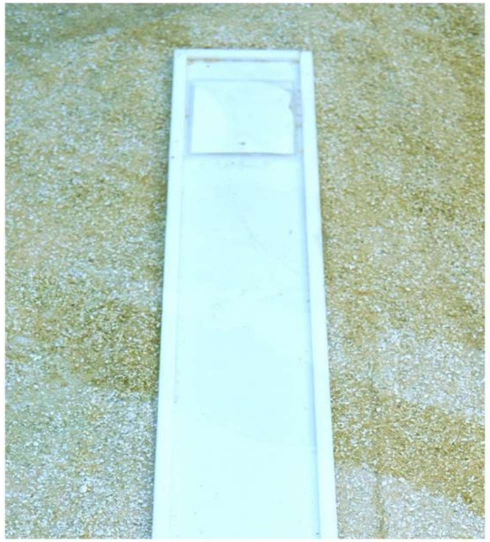


Experimental Conditions

Not Manipulated

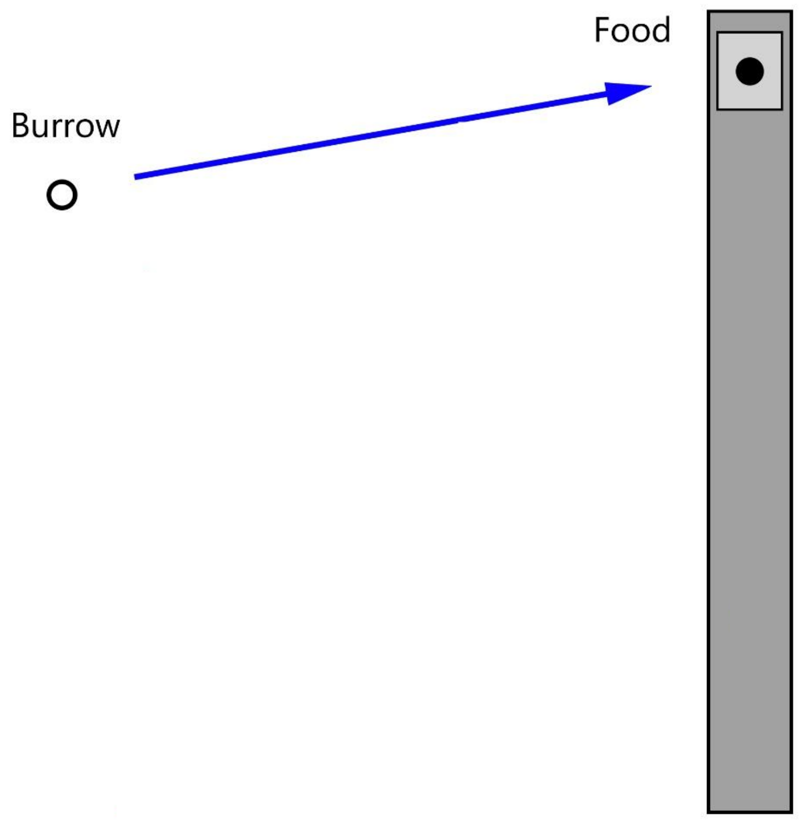


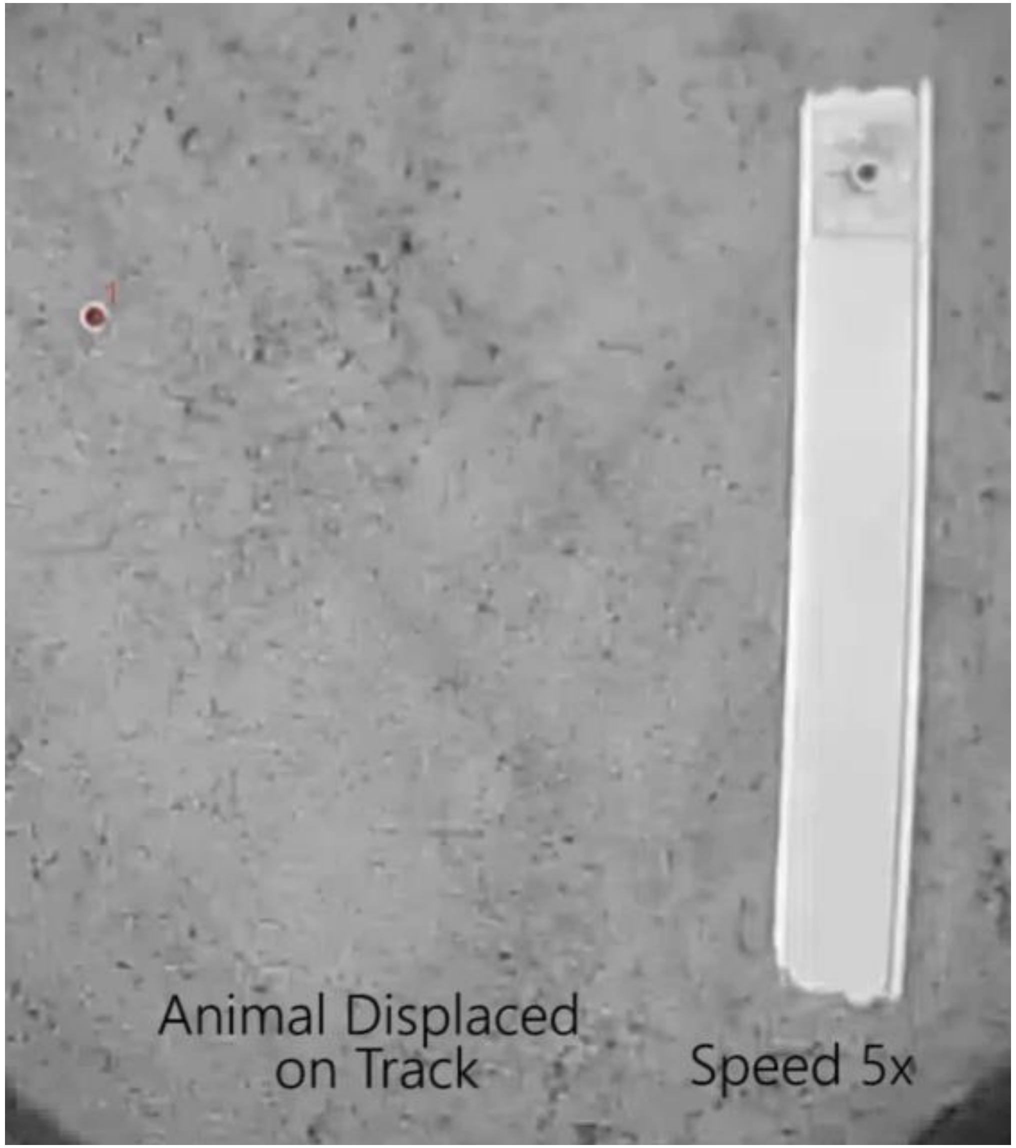
Animal Displaced



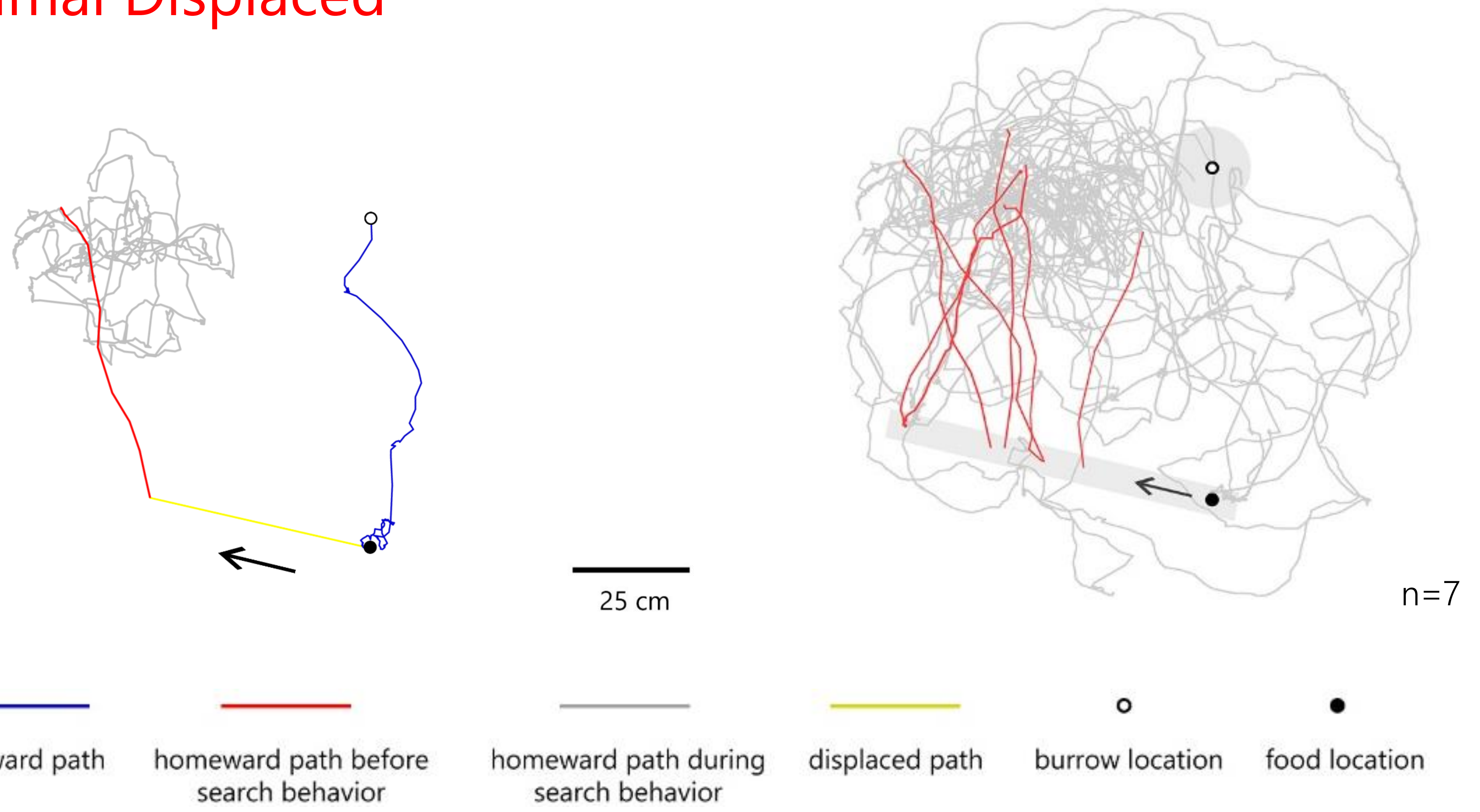
During displacement experiments, animals were displaced on a platform along a track.

Animal Displaced

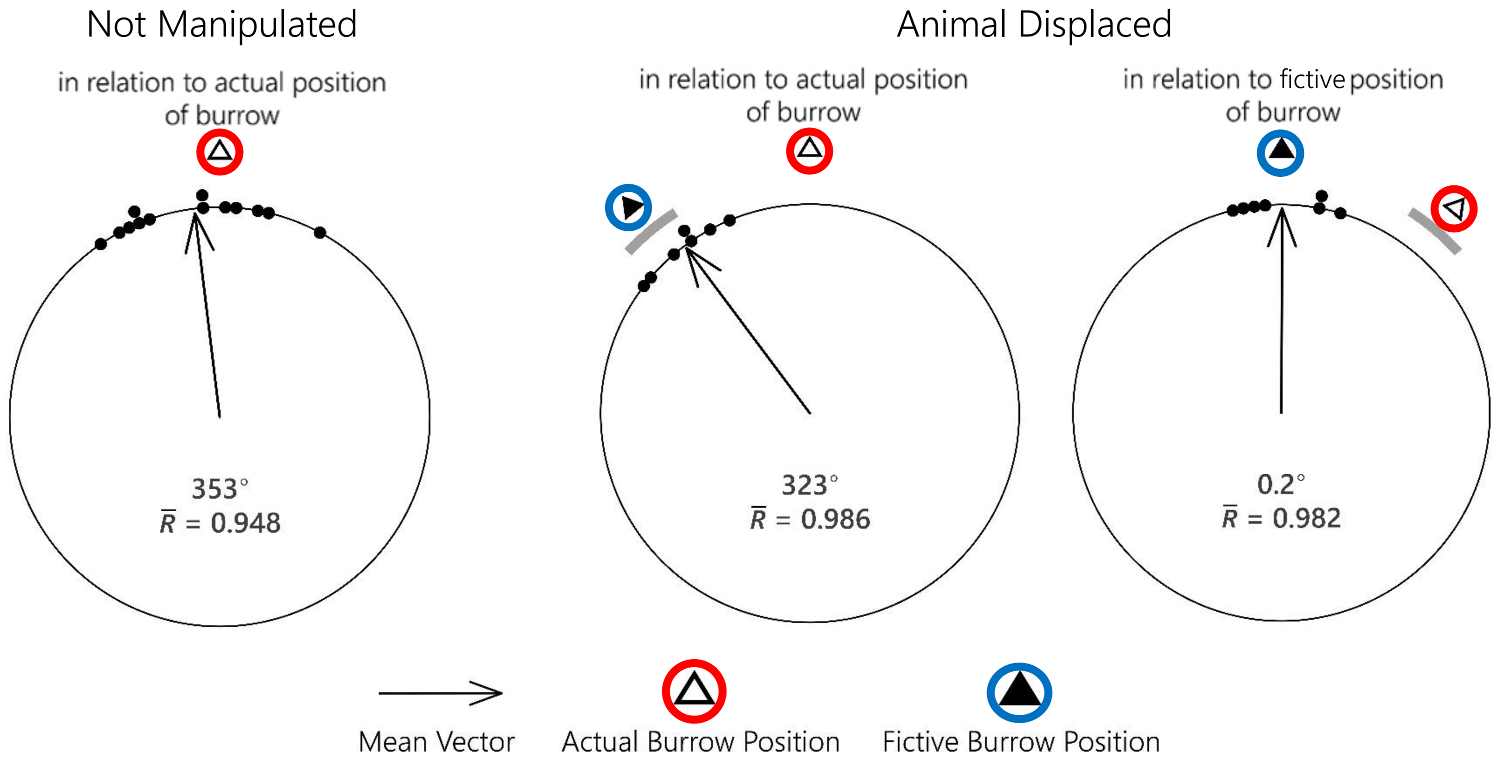


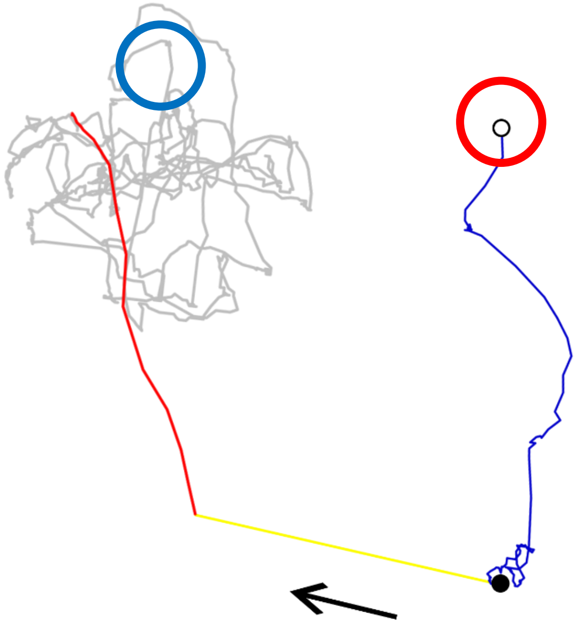


Animal Displaced



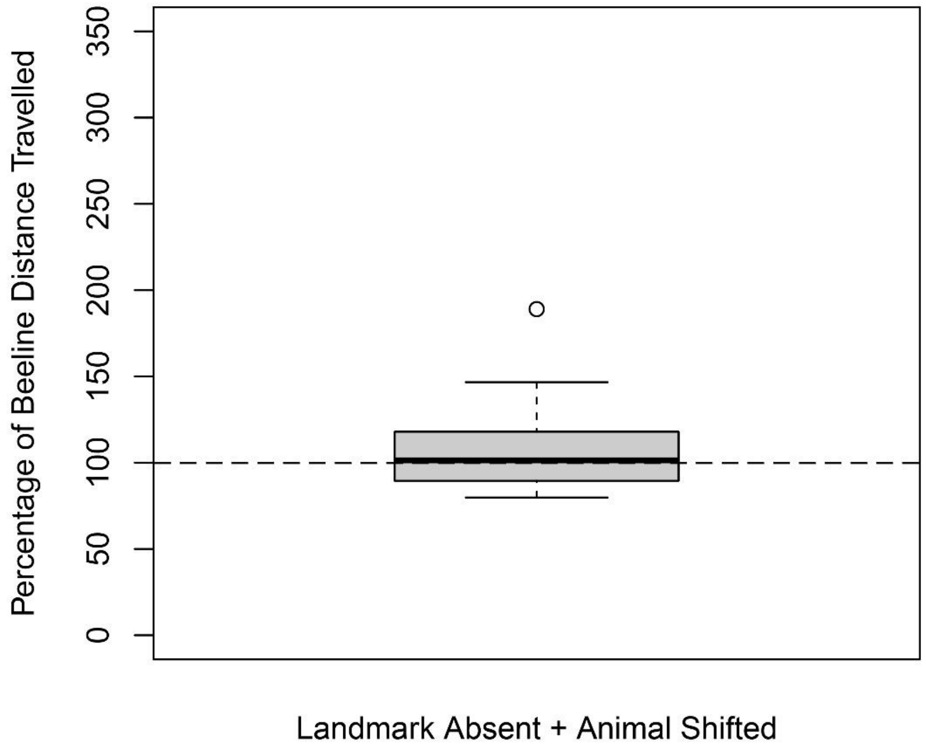
When animals were displaced, homeward paths were oriented in the direction of the fictive burrow's position rather than towards the actual direction of the burrow.





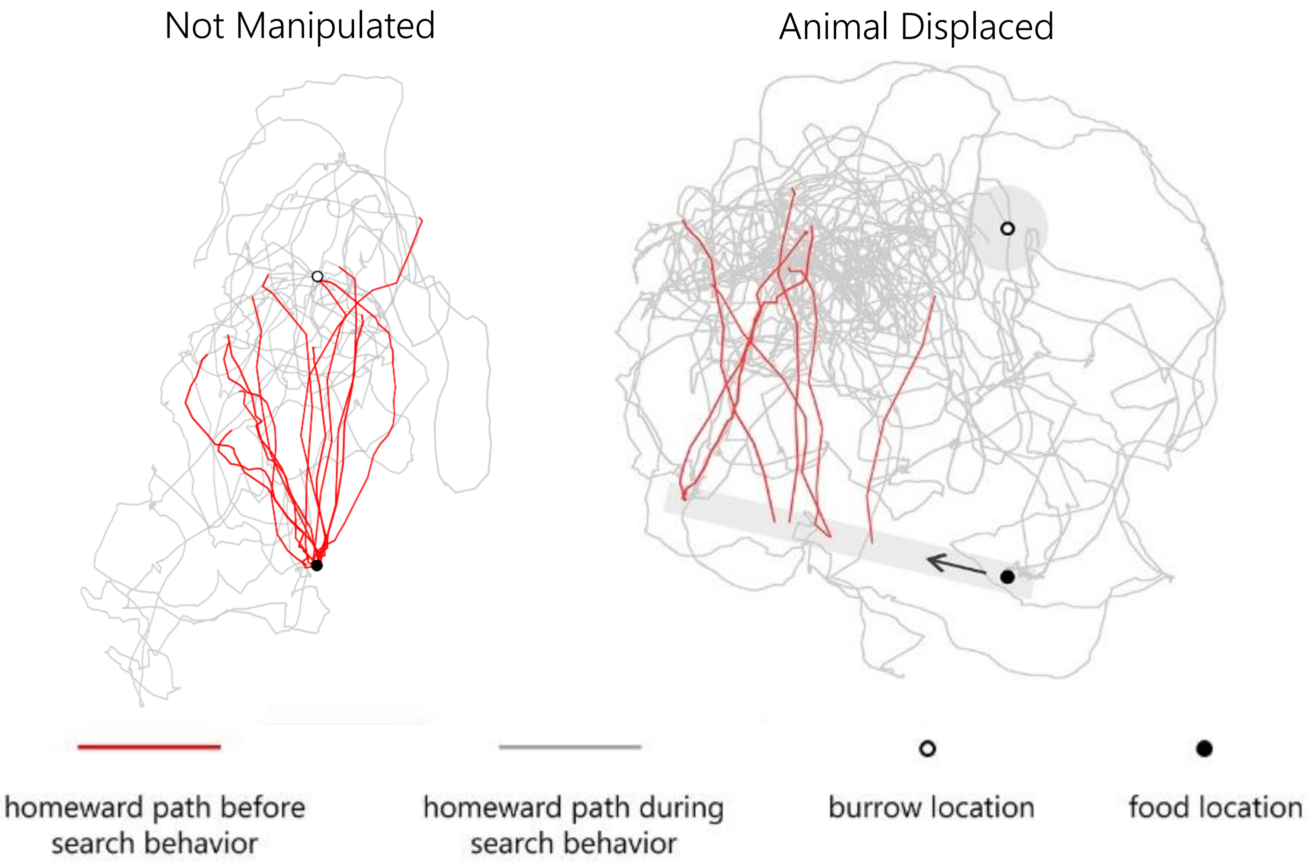
Not Manipulated vs. Animal Displaced (actual burrow): $p < 0.001$
Not Manipulated vs. Animal Displaced (fictive burrow): $p > 0.3$

Homeward path lengths were similar in length to the beeline distance to the burrow before search behaviors were initiated.



Indistinguishable from ±15% Beeline Distance

$p < 0.05$ $n = 20$



How are mantis shrimp orienting during path integration？

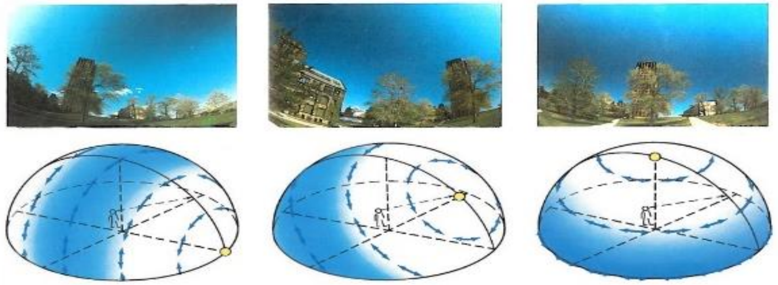
Path Integration

Compass

Odometer

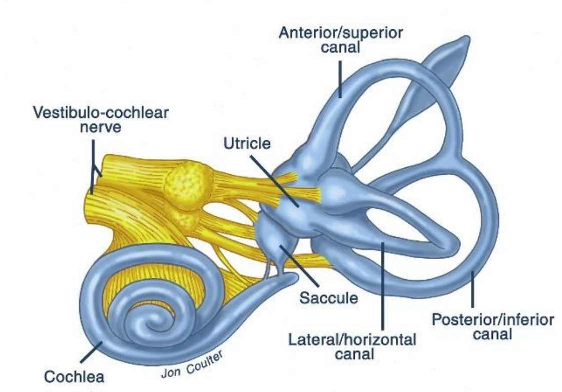
Sun Compass

Celestial Polarization Compass



Adapted from Waterman, 1989

Inertial Compass



Panorar

www.nature.com

www.friendsofthehoneybee.com

Wikimedia Commons

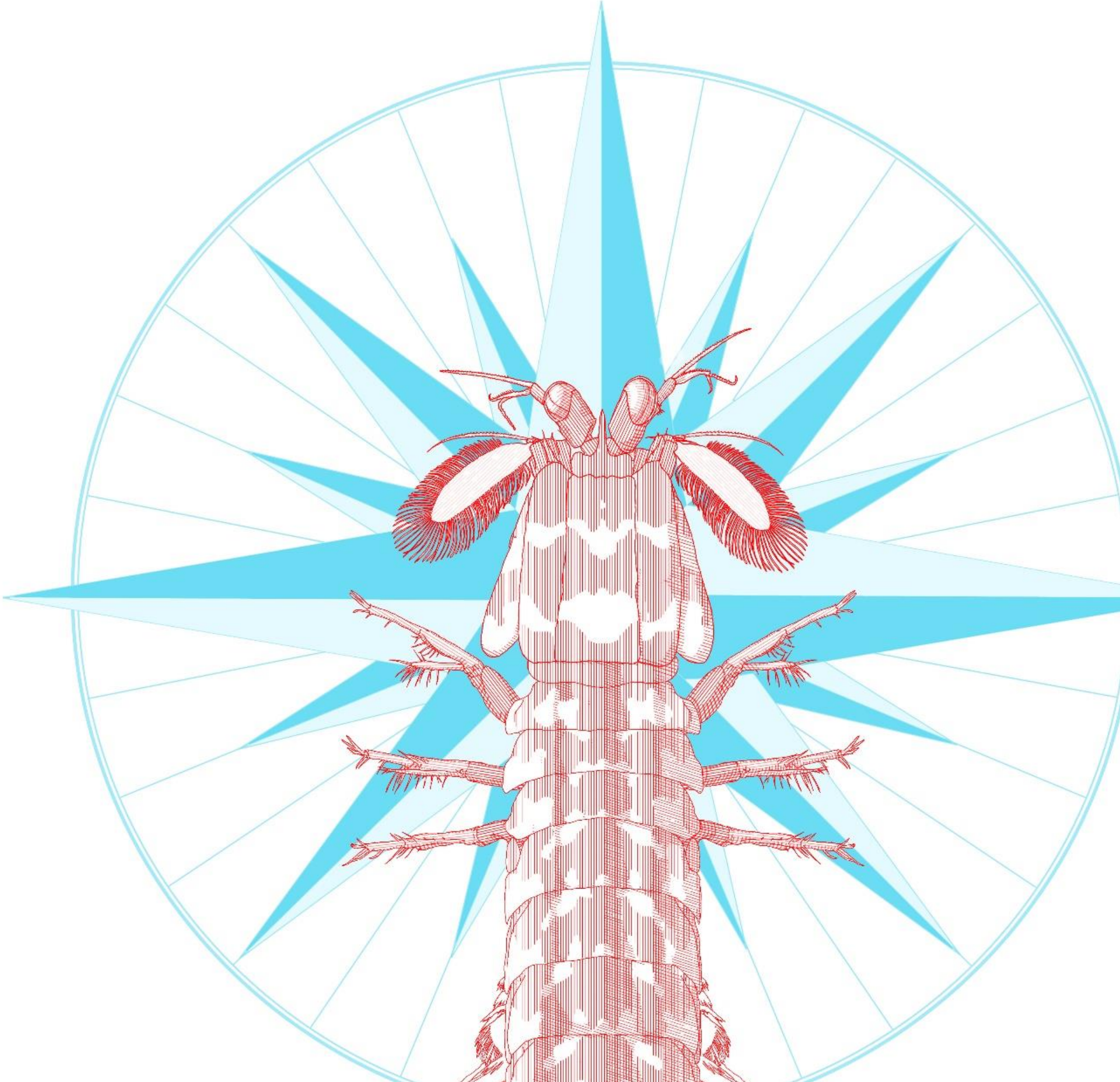
Compass

Online Science Mail

What Compasses are Mantis shrimp using for orientation ?

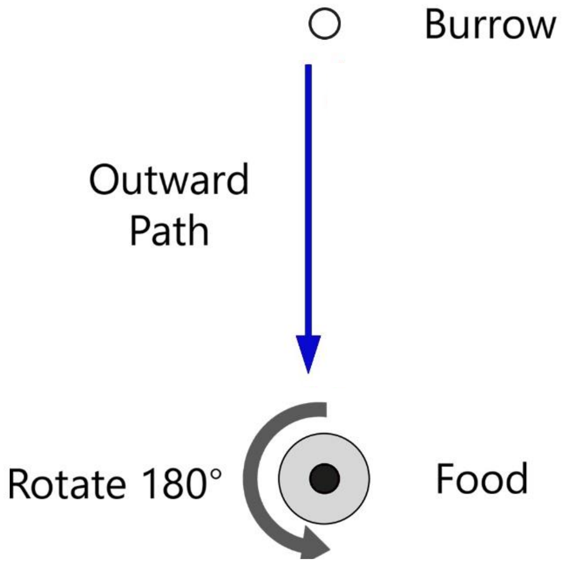
Allothetic (External) Compass: informed by externally anchored stimuli
(ex. celestial compasses, magnetic compass)

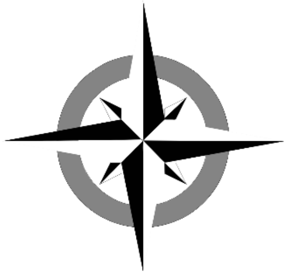
Idiothetic (Internal) Compass: informed by stimuli anchored in the body
(ex. proprioceptive compass informed by the vestibular system in mammals)



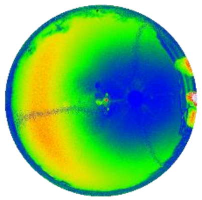
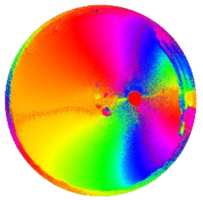
Navigation Arenas

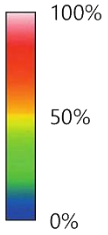
COMPASS- allothetic or idiothetic?

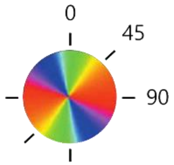




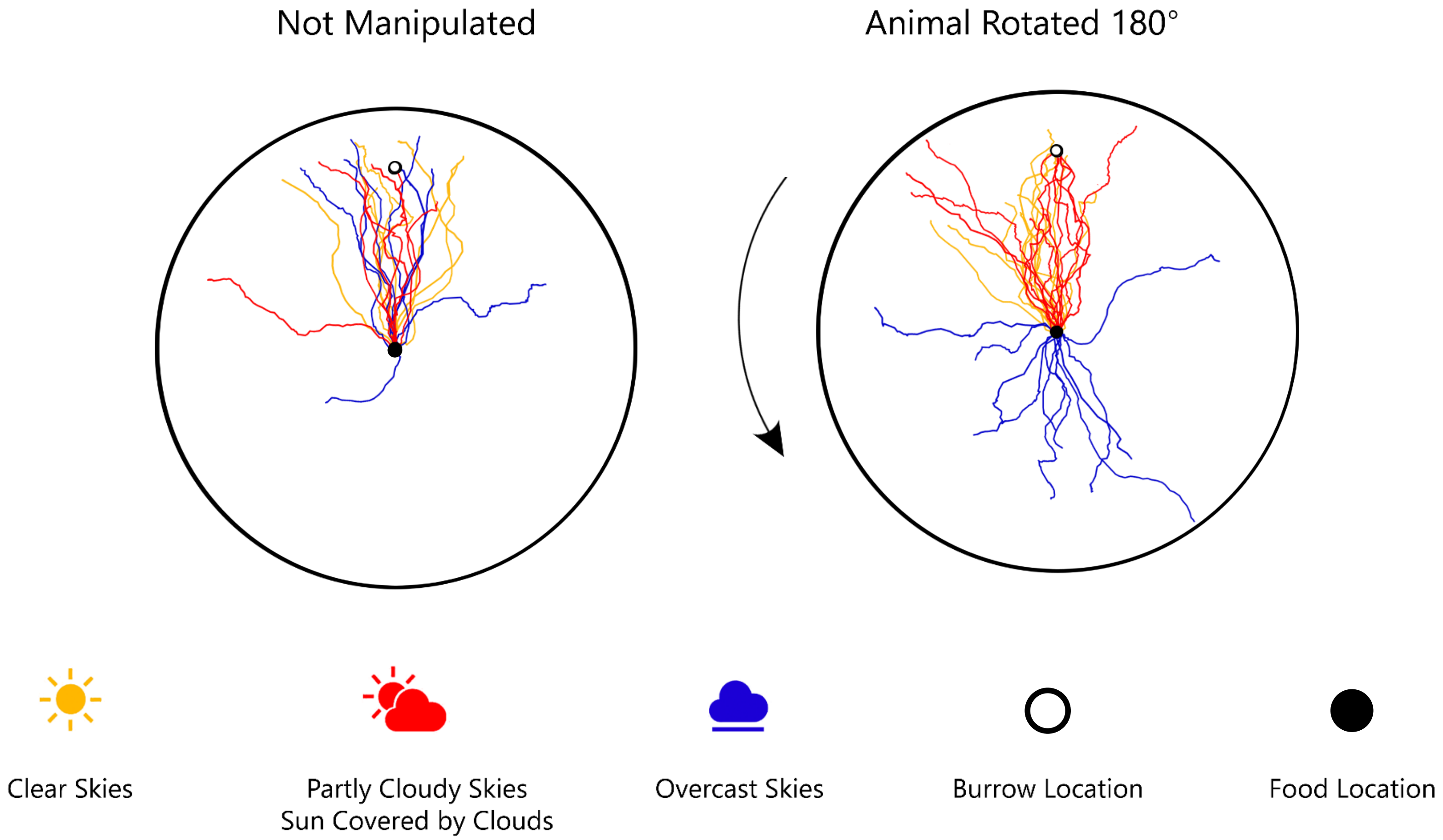
Environmental Conditions

	Photograph with Polarizer	Percent Polarization	e-Vector Angle
 Clear Skies			

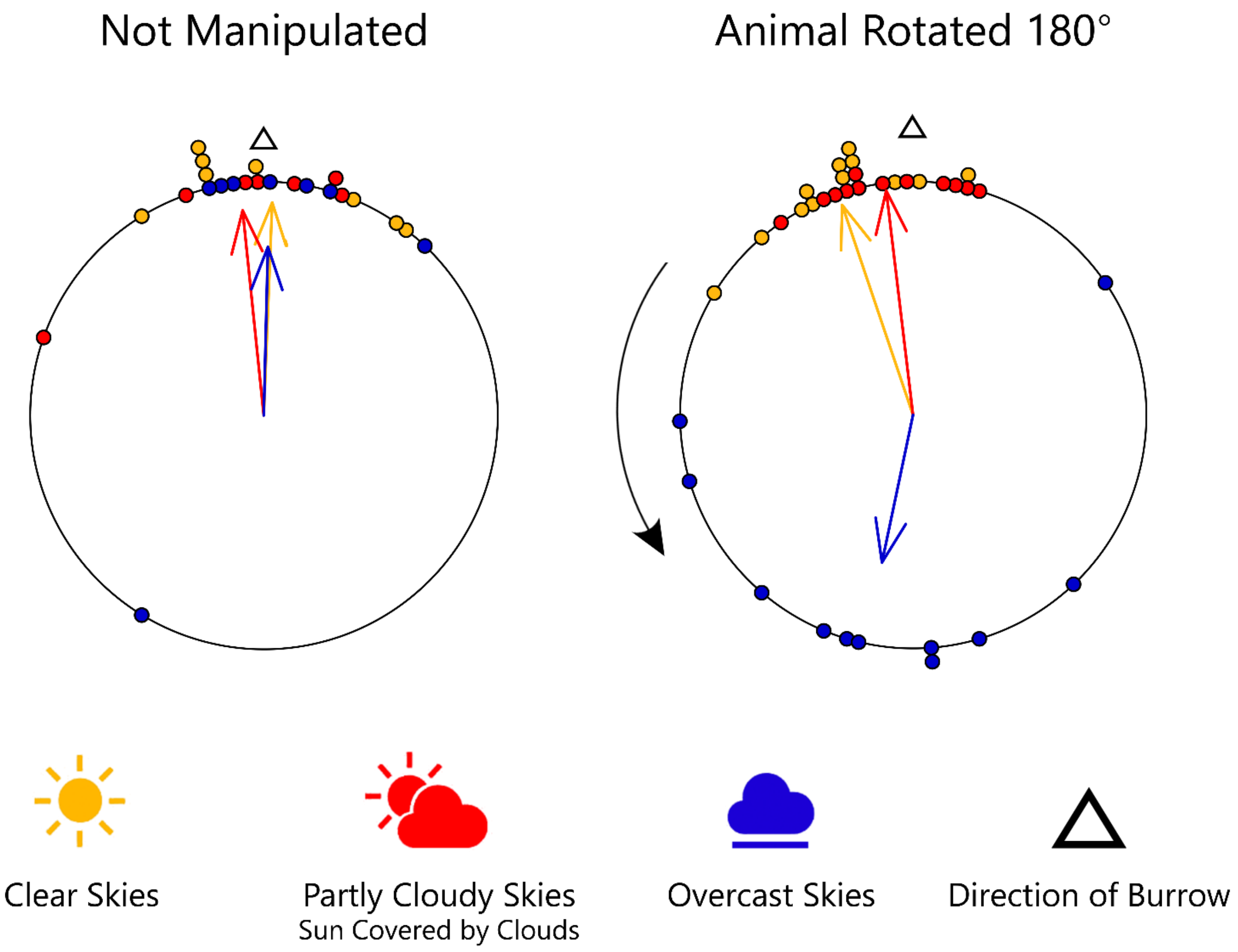




Outdoor Compass Experiments: Homeward Path Tracings

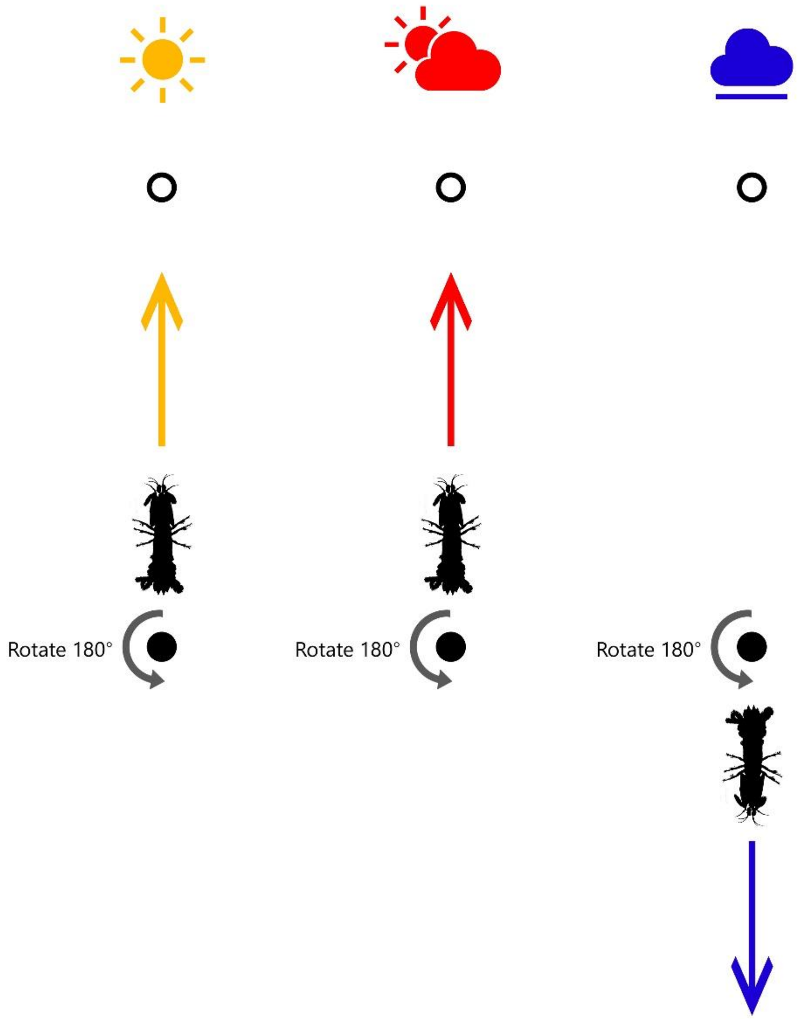


Outdoor Compass Experiments: Homeward Path Orientations



All groups significantly oriented ($p<0.01$)

Outdoor Compass Experiments



Allothetic Compasses are Celestial

Celestial Compass:

Solar azimuth?

Celestial Compass:

Celestial polarization patterns? Celestial gradients?

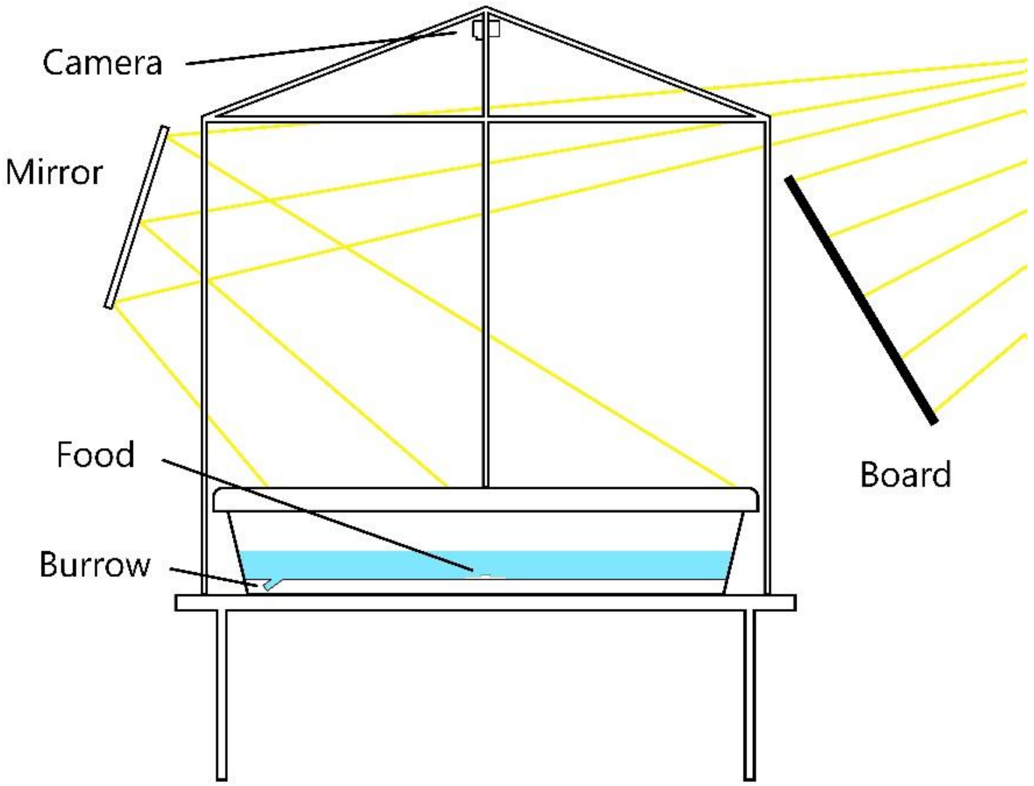
Idiothetic Compass:

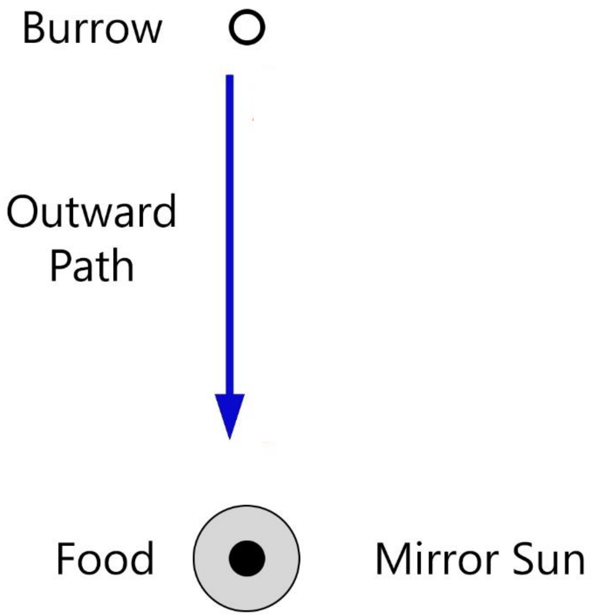
Accelerometers? Optic flow?

What Celestial Cues are being used for orientation ?

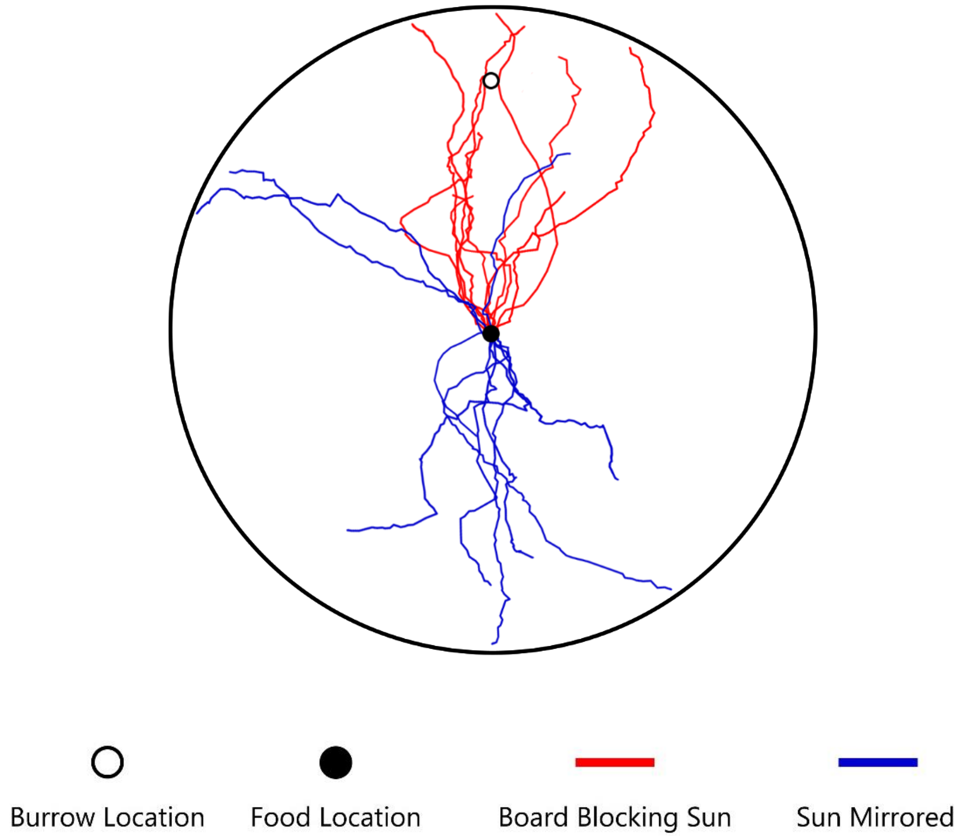
Sun Compass

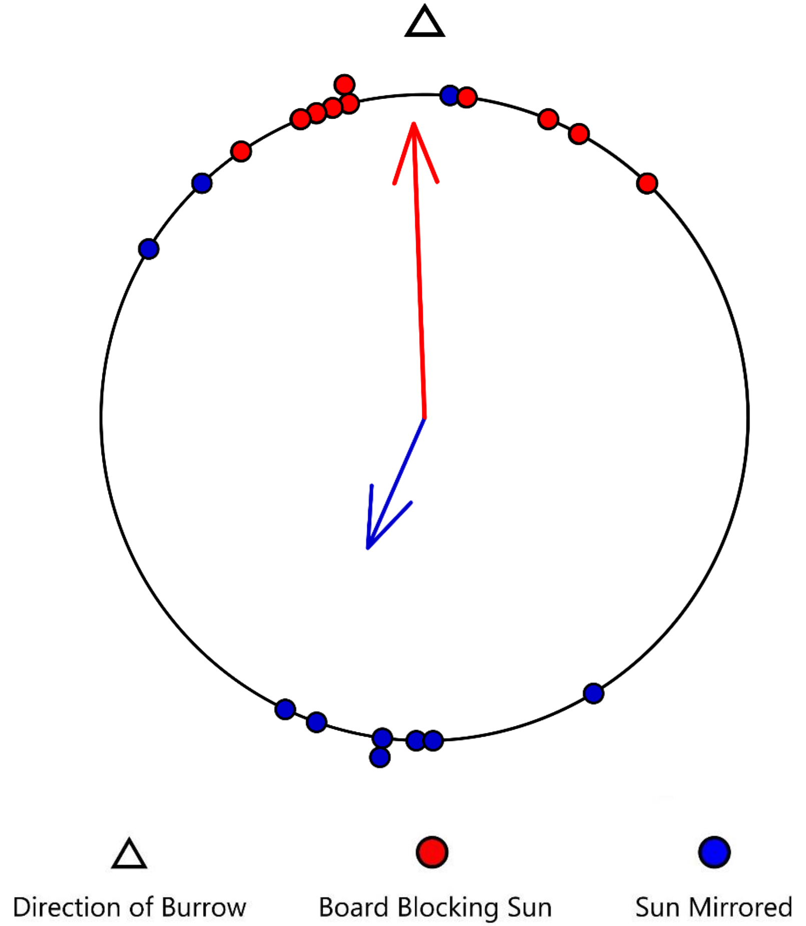
Displace Sun





Sun Compass





Sun Blocked: $p < 0.001$ Sun Mirrored: $p = 0.023$

SUBMARINE Polarization Patterns

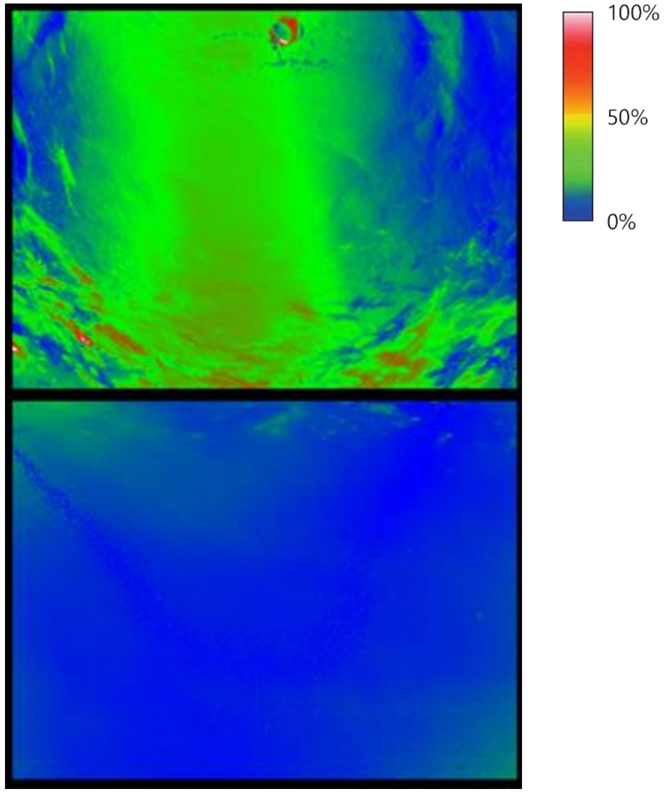
Horseshoe Reef , Lizard Island at a 5 meter depth at sunset.

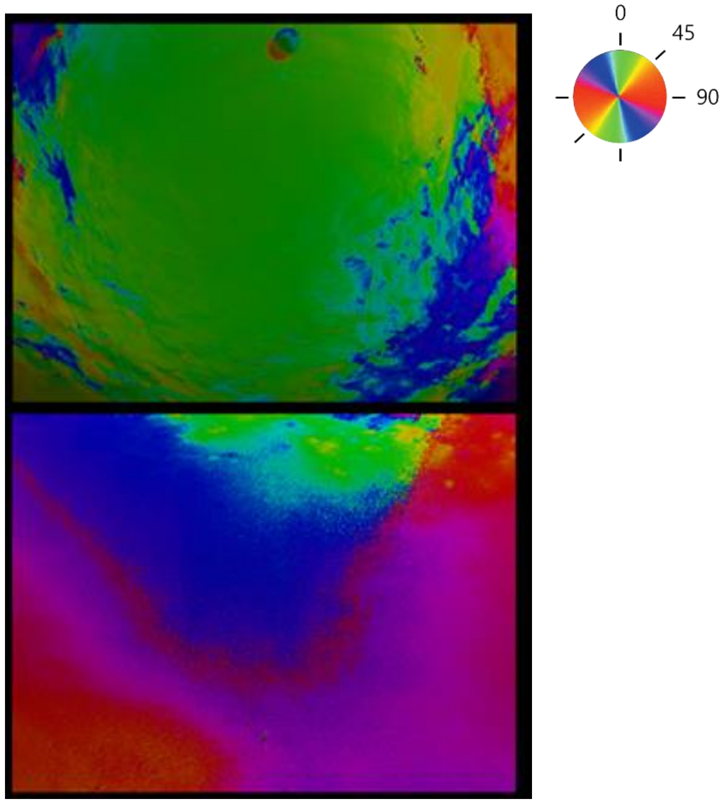
Degree of Polarization

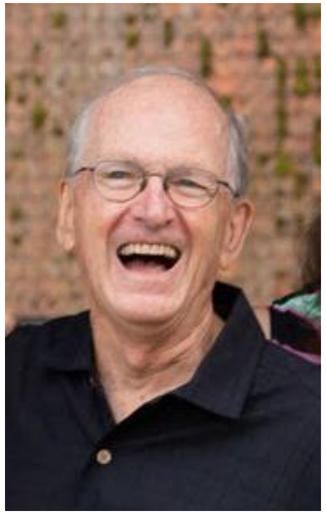
Angle of Polarization

View of Zenith

View of Horizon

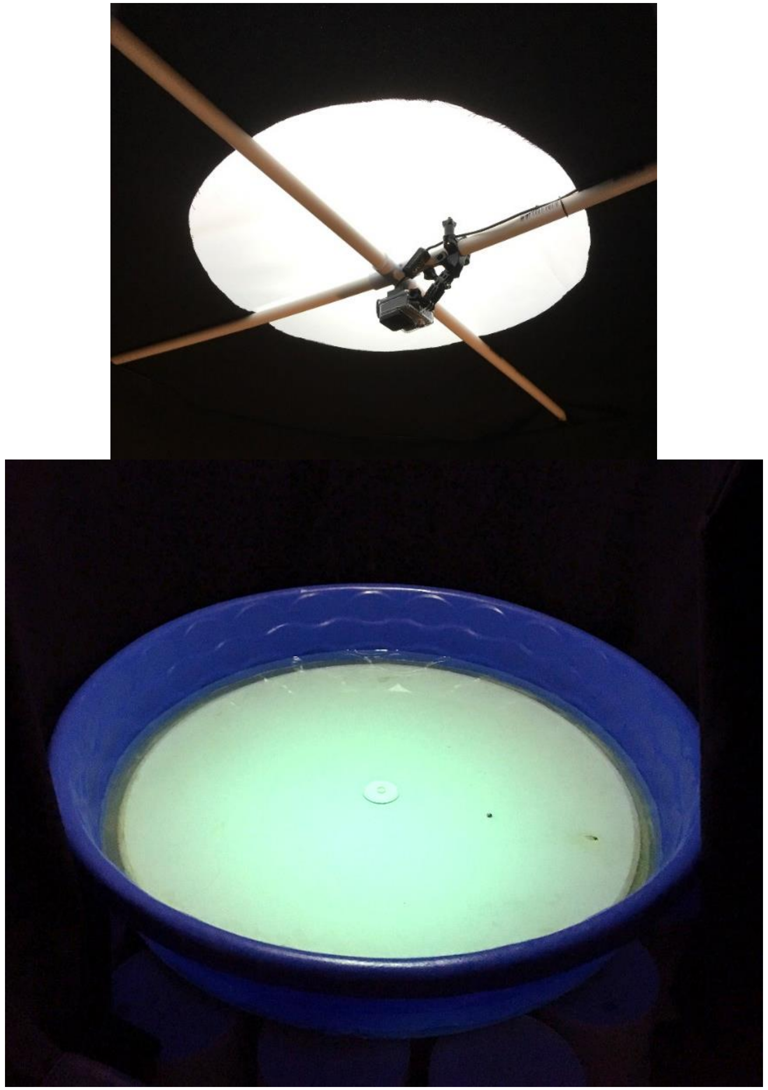


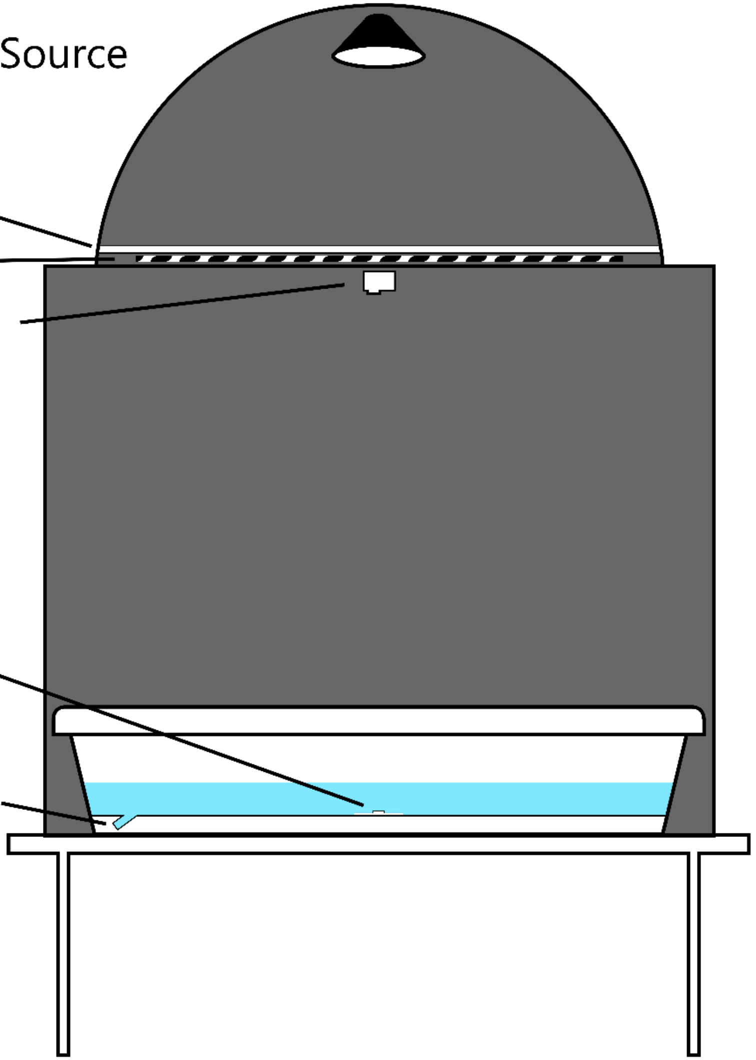




Tom Cronin

Polarization Compass

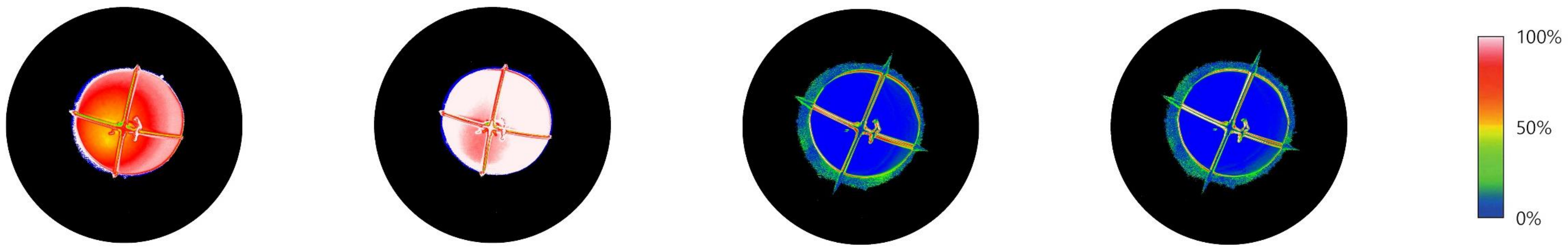




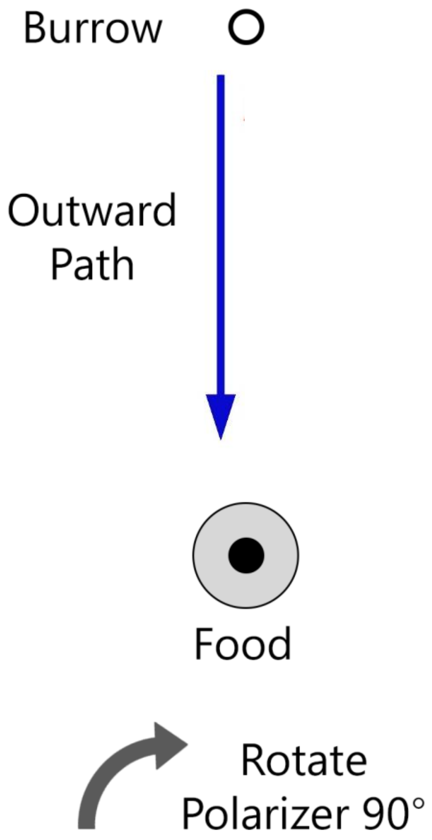
Celestial Polarization Compass

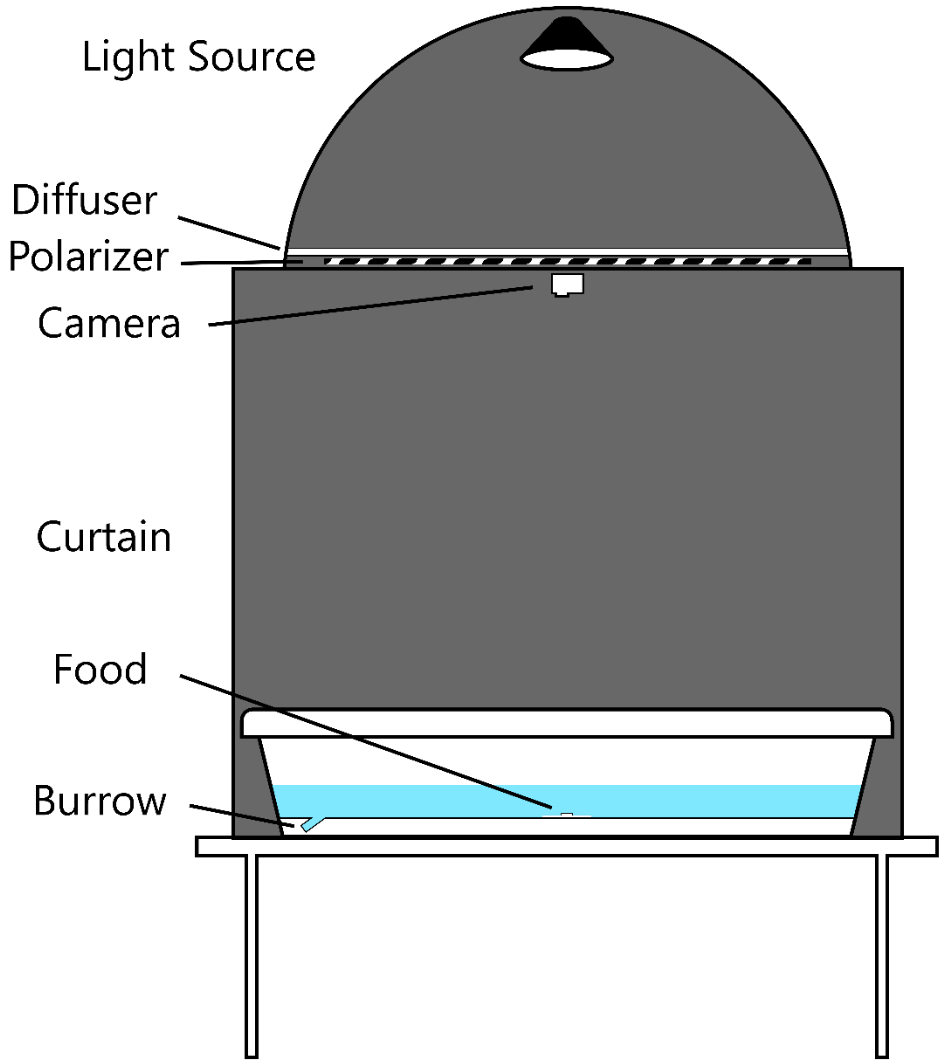
Polarized Field Static | Polarized Field Rotated 90° | Depolarized Field Static | Depolarized Field Rotated 90°

Percent Polarization

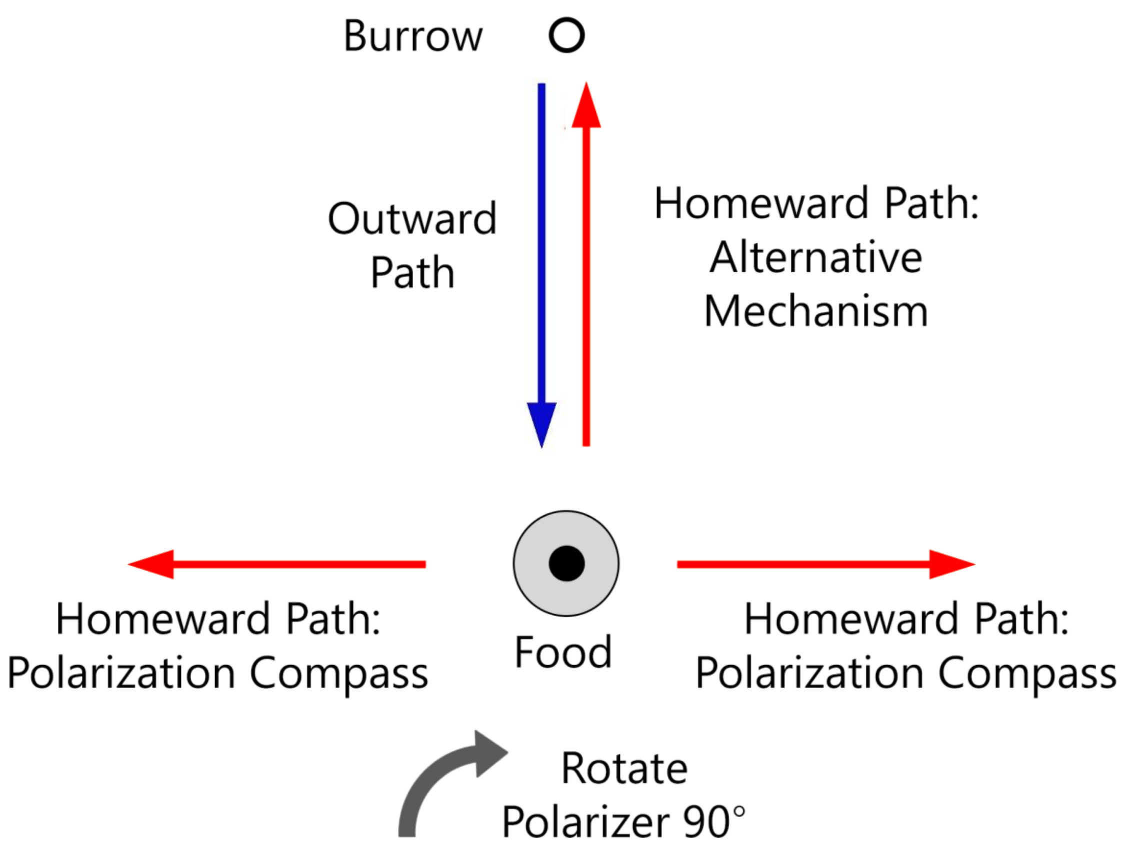


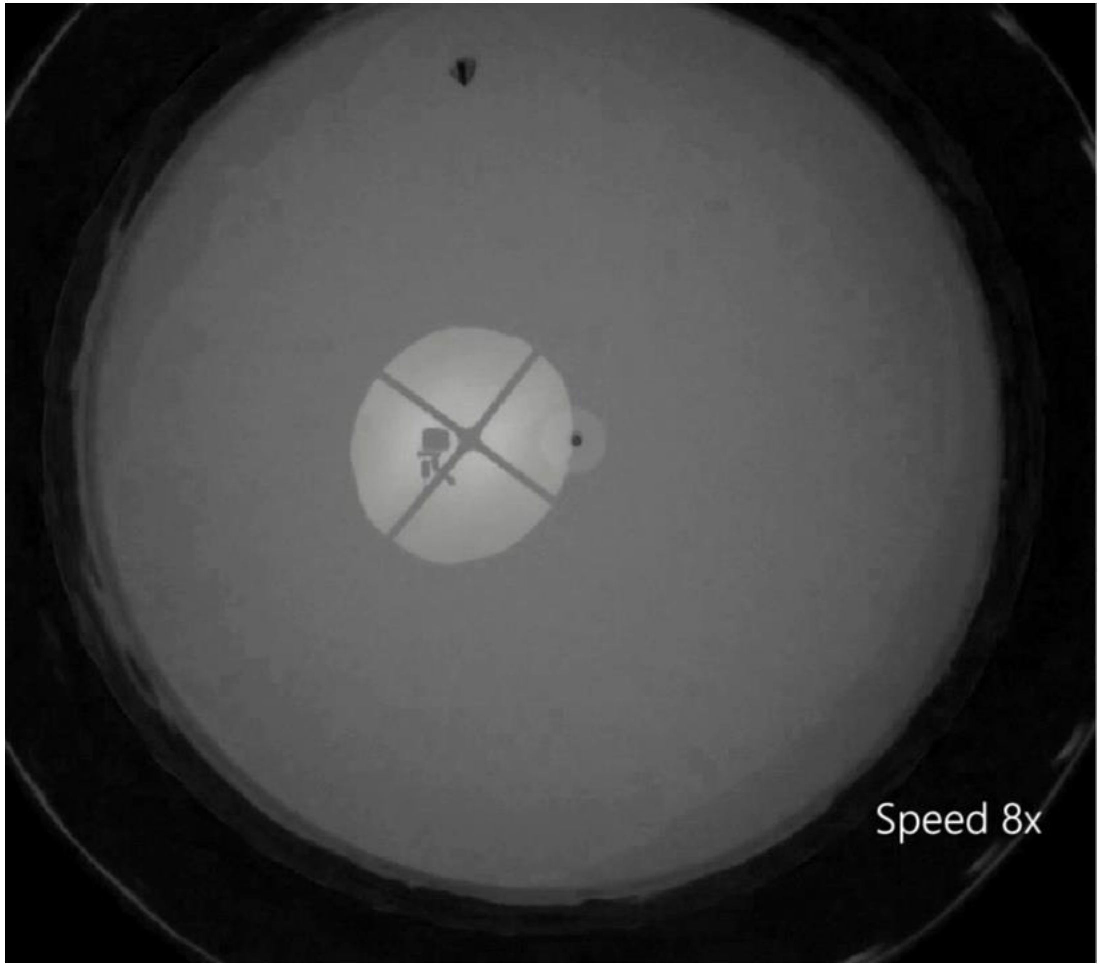
Polarization Compass



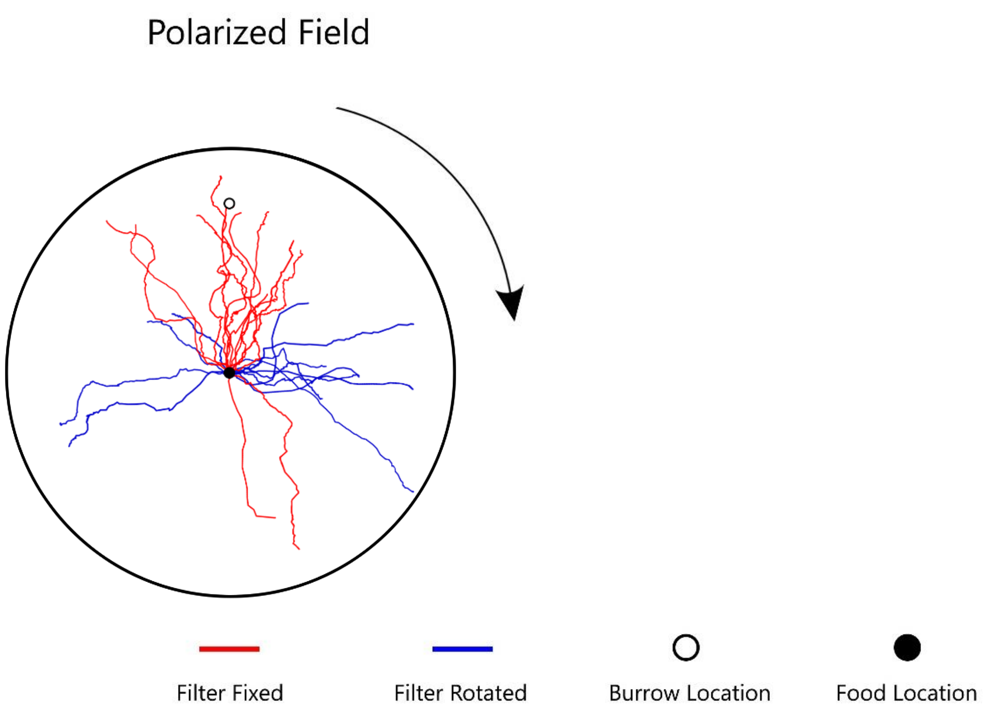


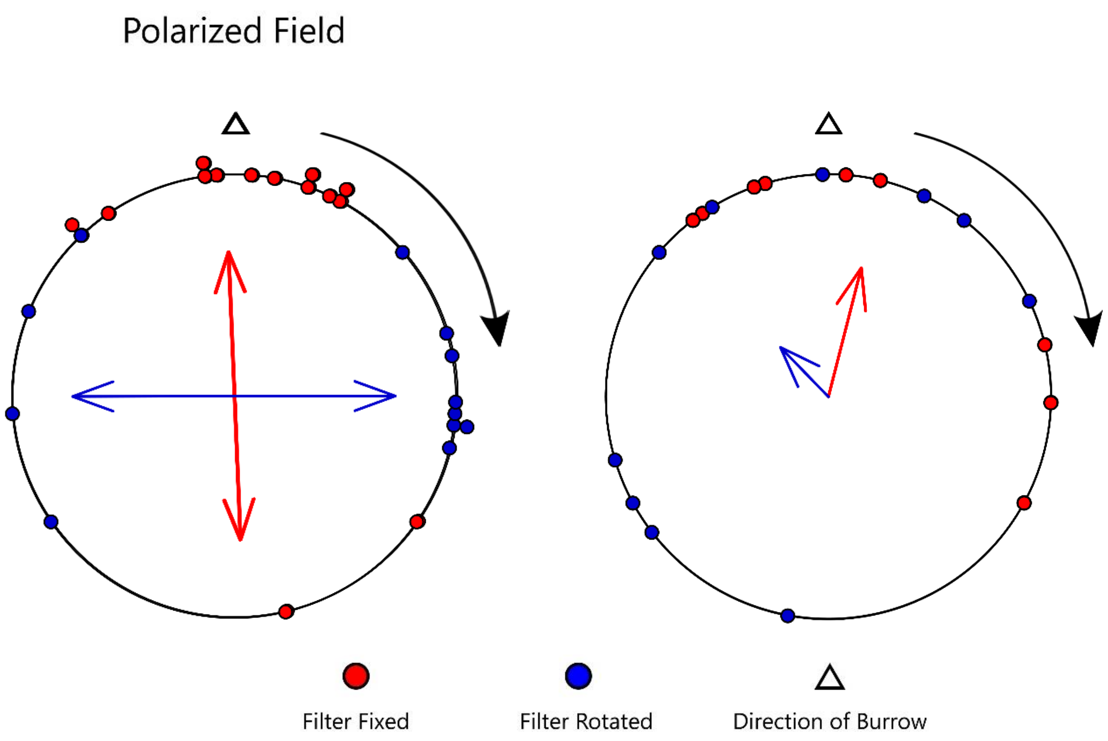
Celestial Polarization Compass





Celestial Polarization Compass





Polarized Field: $p < 0.01$ both; different $p < 0.001$

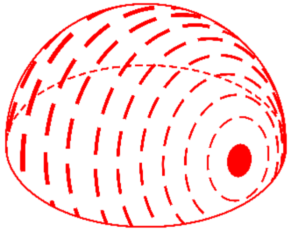
Depolarized Field: fixed $p = 0.12$, rotated $p = 0.39$

Hierarchy of Compass Cues

Clear Skies

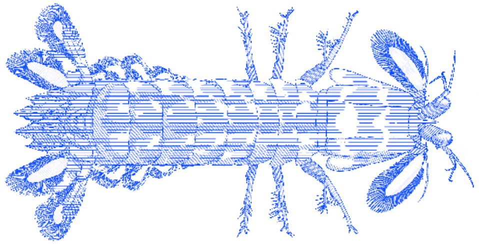
Solar Azimuth
(for the majority of individuals)

Partly Cloudy Skies
Sun Covered by Clouds



Celestial Polarization Patterns

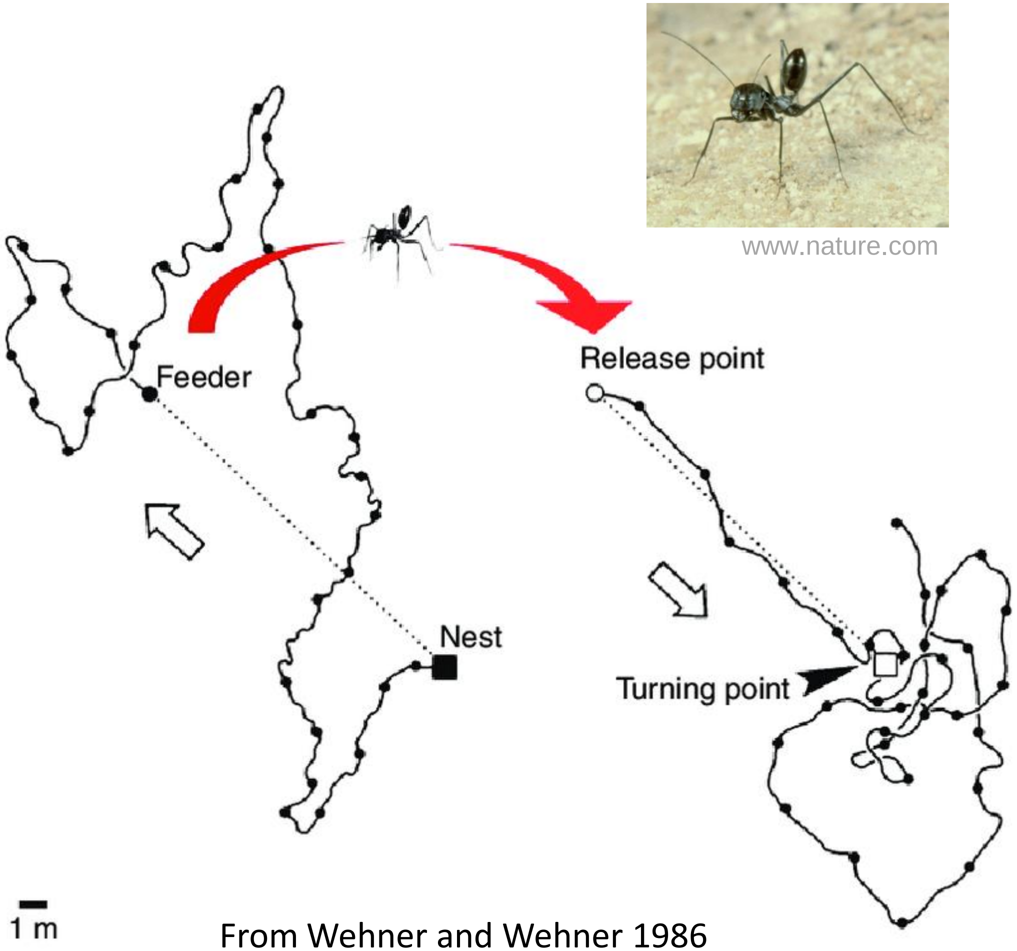
Overcast Skies



Idiothetic Cues

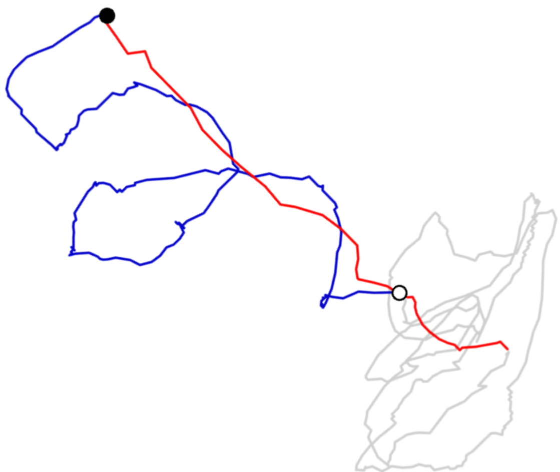
CONCLUSIONS

Desert Ant

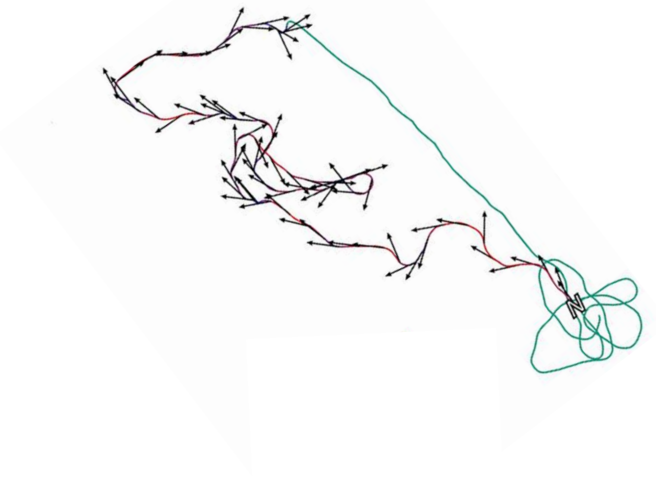


From Wehner and Wehner 1986

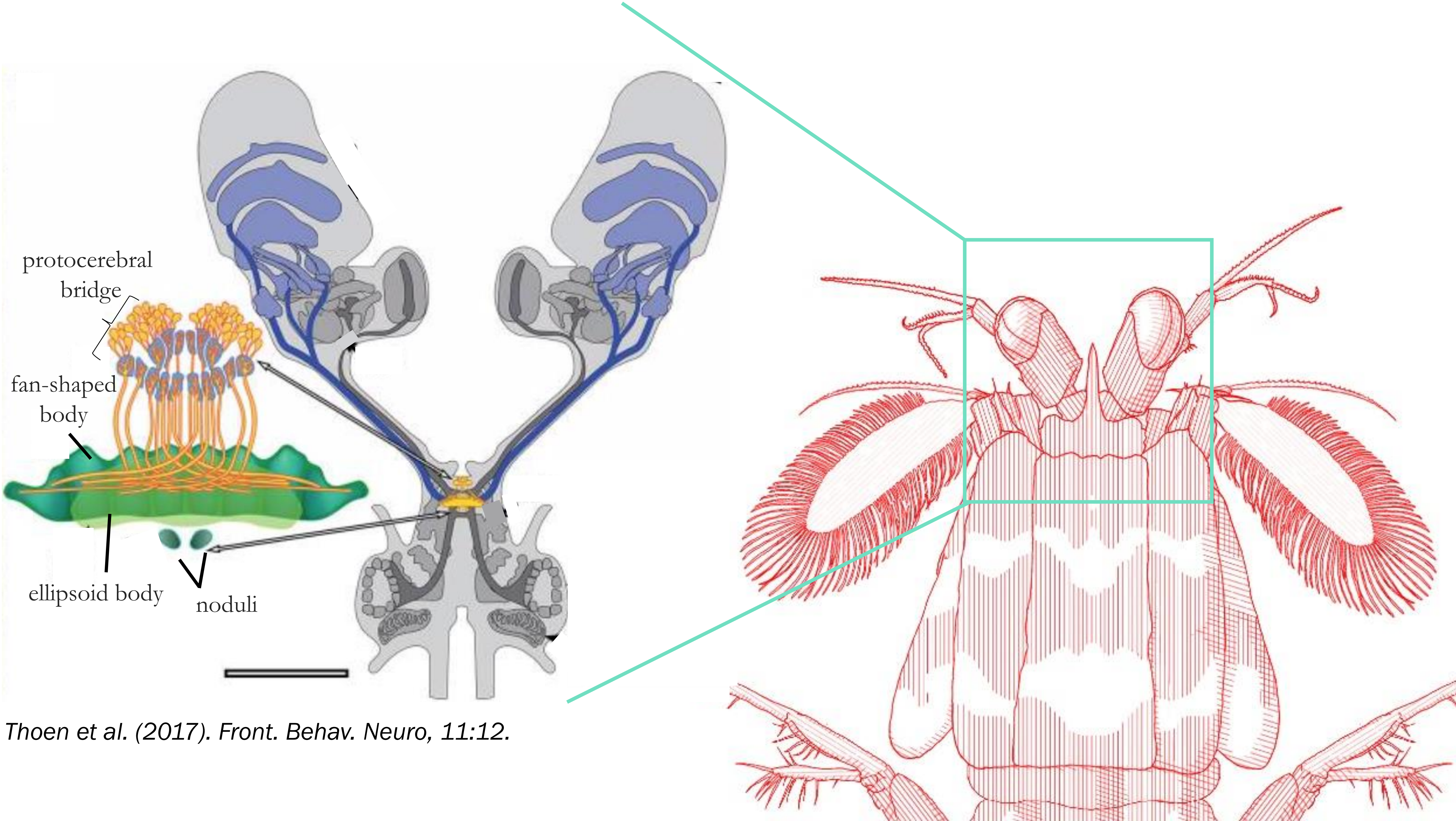
Stomatopod



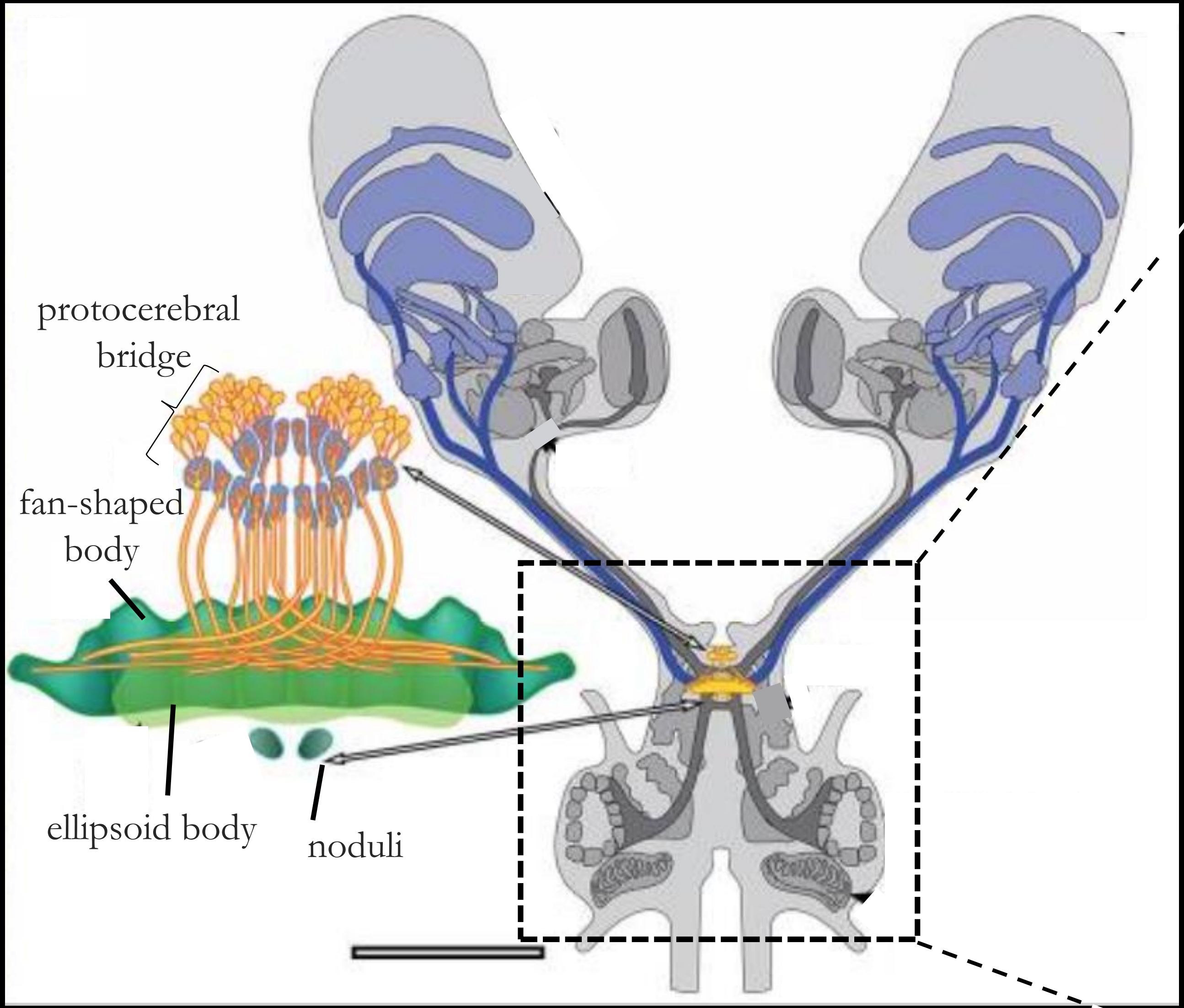
Simulation of a Biologically Constrained Computational Model Performing Path Integration



From Stone et al. 2017



Thoen et al. (2017). Front. Behav. Neuro, 11:12.



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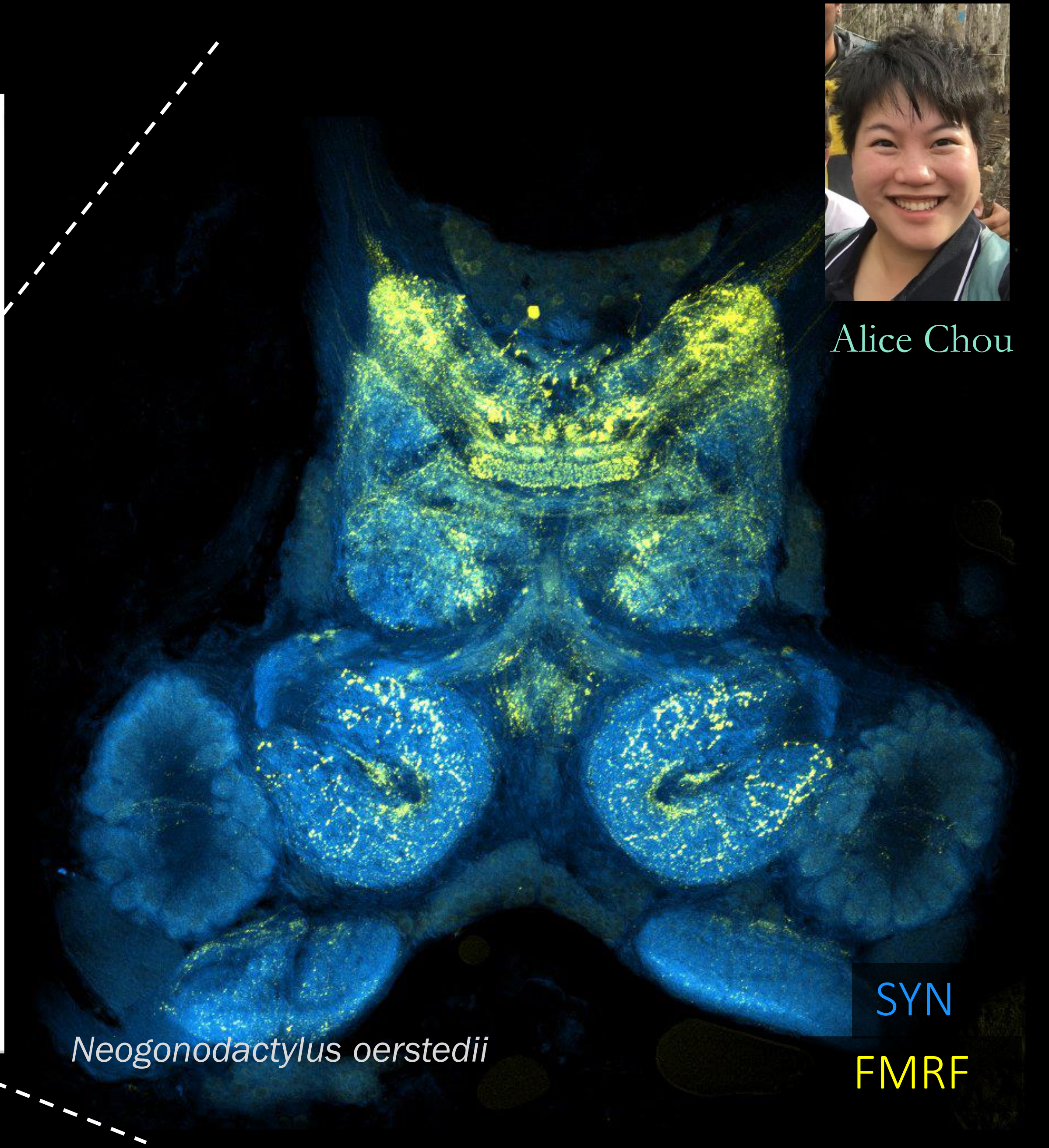
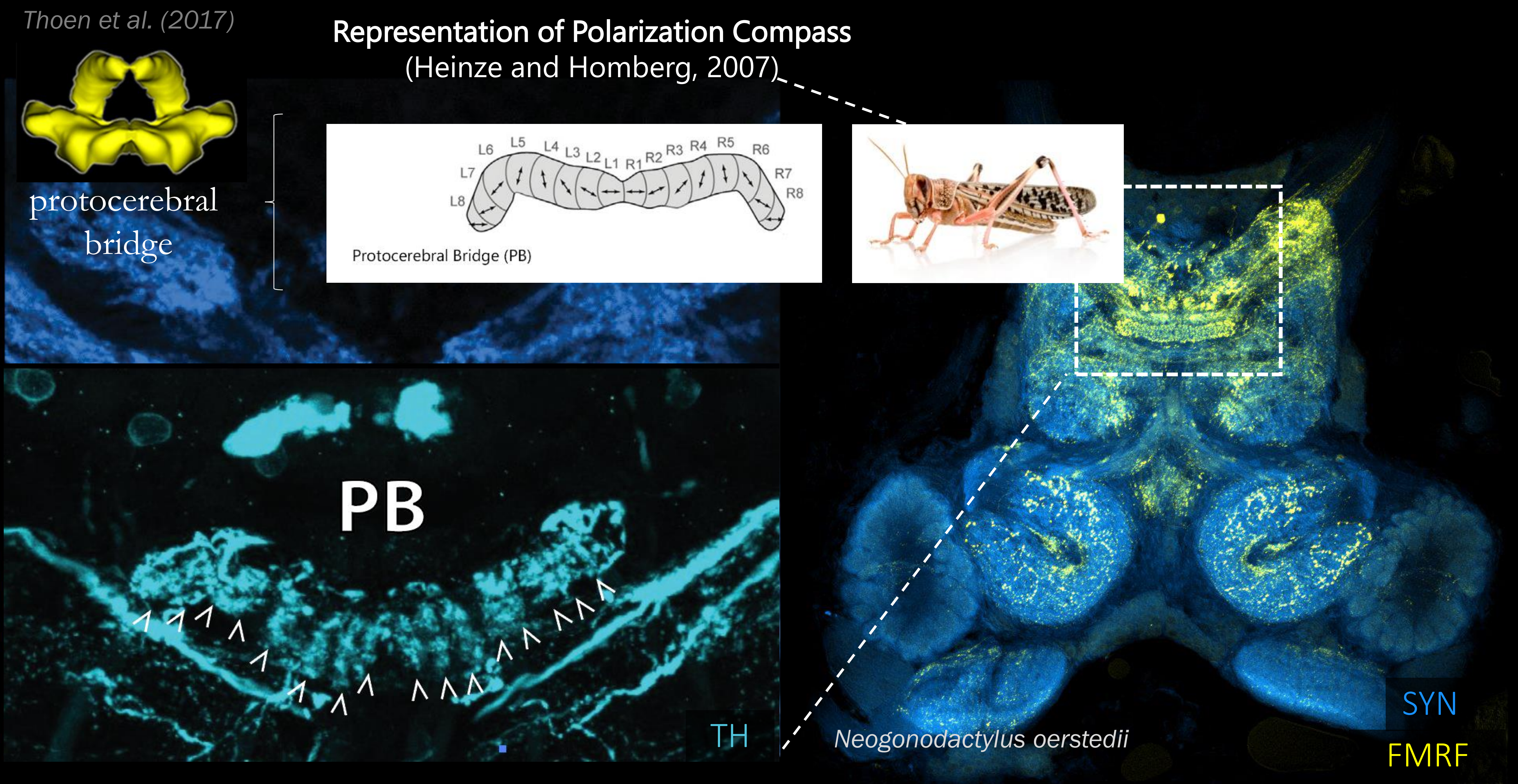
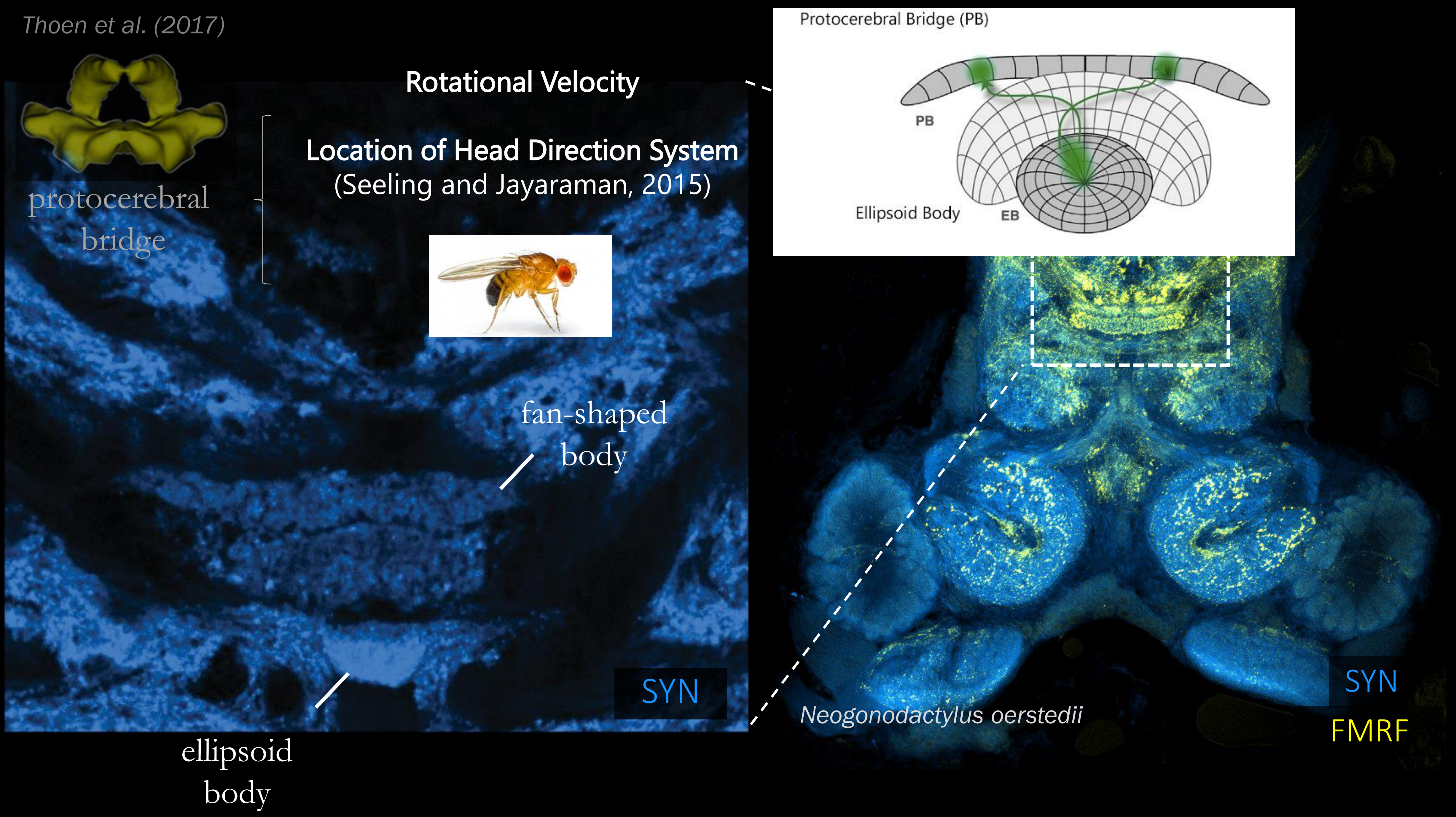
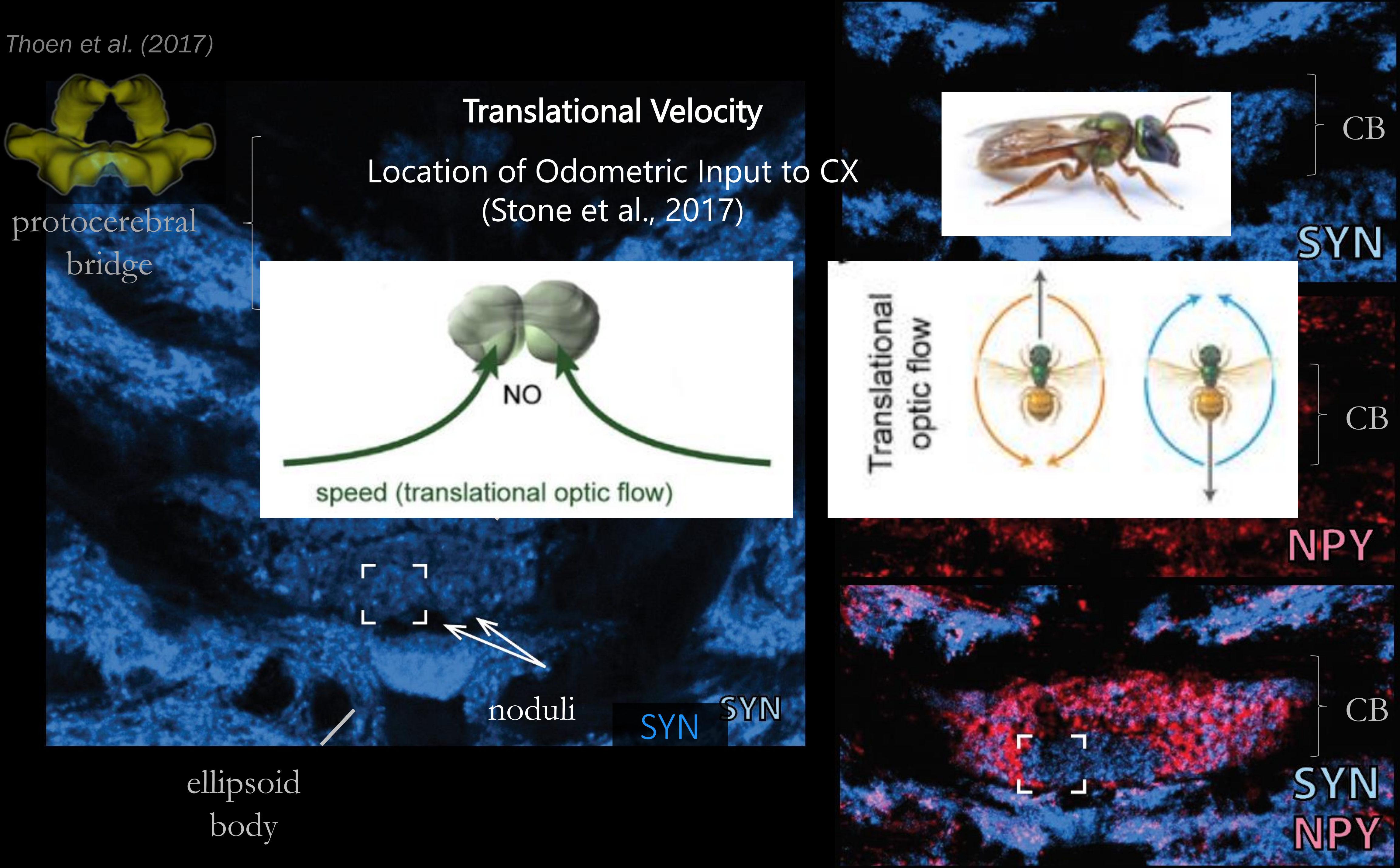


Alice Chou



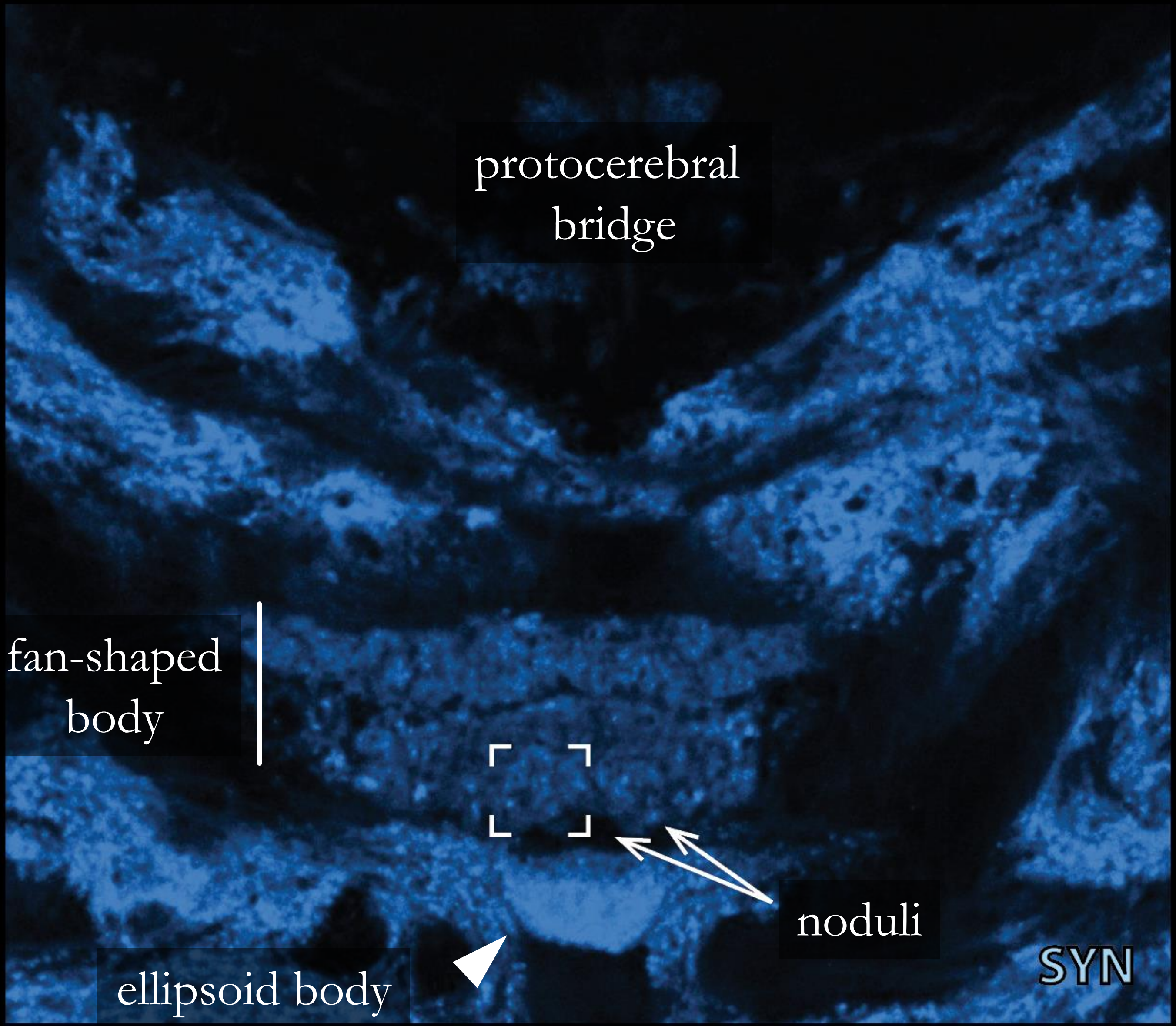
Representation of Polarization Compass
(Heinze and Homberg, 2007)
Thoen et al. (2017)
protocerebral bridge
L6 L5 L4 L3 L2 L1 R1 R2 R3 R4 R5 R6
L7 R7
L8 R8
Protocerebral Bridge (PB)
PB
TH
Neogonodactylus oerstedii
SYN
FMRF


Thoen et al. (2017)
protocerebral
bridge
Rotational Velocity
Location of Head Direction System
(Seeling and Jayaraman, 2015)
fan-shaped
body
ellipsoid
body
SYN
Protocerebral Bridge (PB)
PB
Ellipsoid Body
EB
Neogonodactylus oerstedii
SYN
FMRF



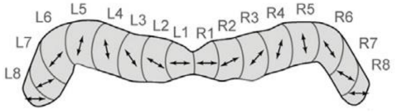
Thoen et al. (2017)
Translational Velocity
Location of Odometric Input to CX
(Stone et al., 2017)
protocerebral
bridge
NO
speed (translational optic flow)
Translational
optic flow
CB
SYN
CB
NPY
CB
SYN
NPY
noduli
SYN
SYN
ellipsoid
body

stomatopod central complex



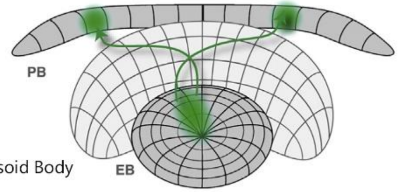
The Neural Basis of Behavior

Insects



Protocerebral Bridge (PB)

Representation of Polarization Compass
(Heinze and Homberg, 2007)

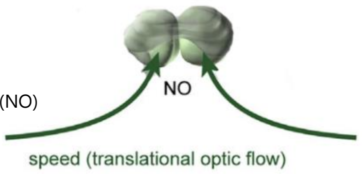


Ellipsoid Body

Rotational Velocity

Location of Head Direction System
(Seeling and Jayaraman, 2015)

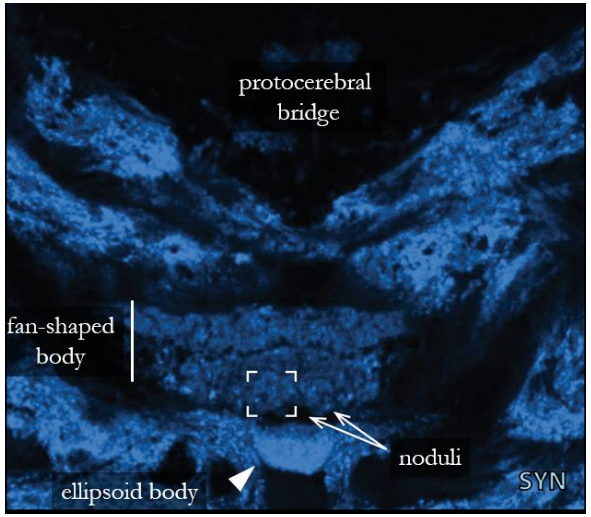
Noduli (NO)



Translational Velocity
Location of Odometric Input to CX
(Stone et al., 2017)

Adapted from Heinze 2017

Stomatopod



Are these behaviors and neural architecture an amazing convergence?
or are they ancient homologs- A Cambrian strategy for navigation?

Desert Locust: http://jgi.doe.gov Drosophila: www.yourgenome.org Megalopta: Heinze 2017

SUMMARY

- *Neogonodactylus oerstedii* is the first described fully aquatic path-integrator.

- *N. oerstedii* is the first described animal to use polarization patterns for dynamic navigation underwater (as opposed to fixed directional orientation).

- The insect central complex possess neuropils crucial for navigation.

- Mantis shrimp possess a central complex with the full set of the neuropils found in insects- a first in non-insect crustaceans.

ACKNOWLEDGEMENTS

Thank you !

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- John Cohen and the Cohen Lab (especially Victoria Simmons) and University of Delaware CEOE

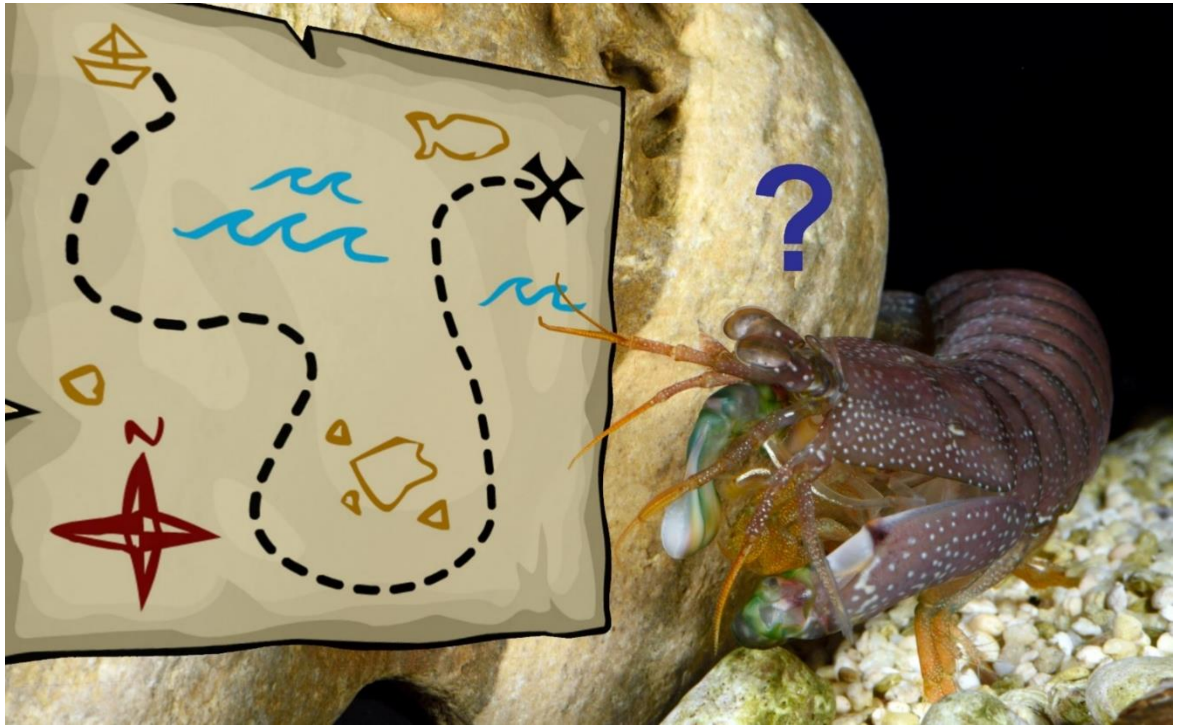
-Nicholas Strausfeld and the Strausfeld Lab (especially Marcel Sayre) at the University of Arizona

-Natalie Roberts (a BIG help, especially during sun compass experiments), Jong Park, and Sam Hulse.

-Tagide de Carvalho and Jeremy Swan: UMBC Imaging Support

-John Cataldi: UMBC Machining

-Roy Caldwell and Mike Bok for included animal photographs



Original Photo: Roy Caldwell

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Navigating disparate environments

Depths/ Tubidity/ Wave action

activeanglingnz.com

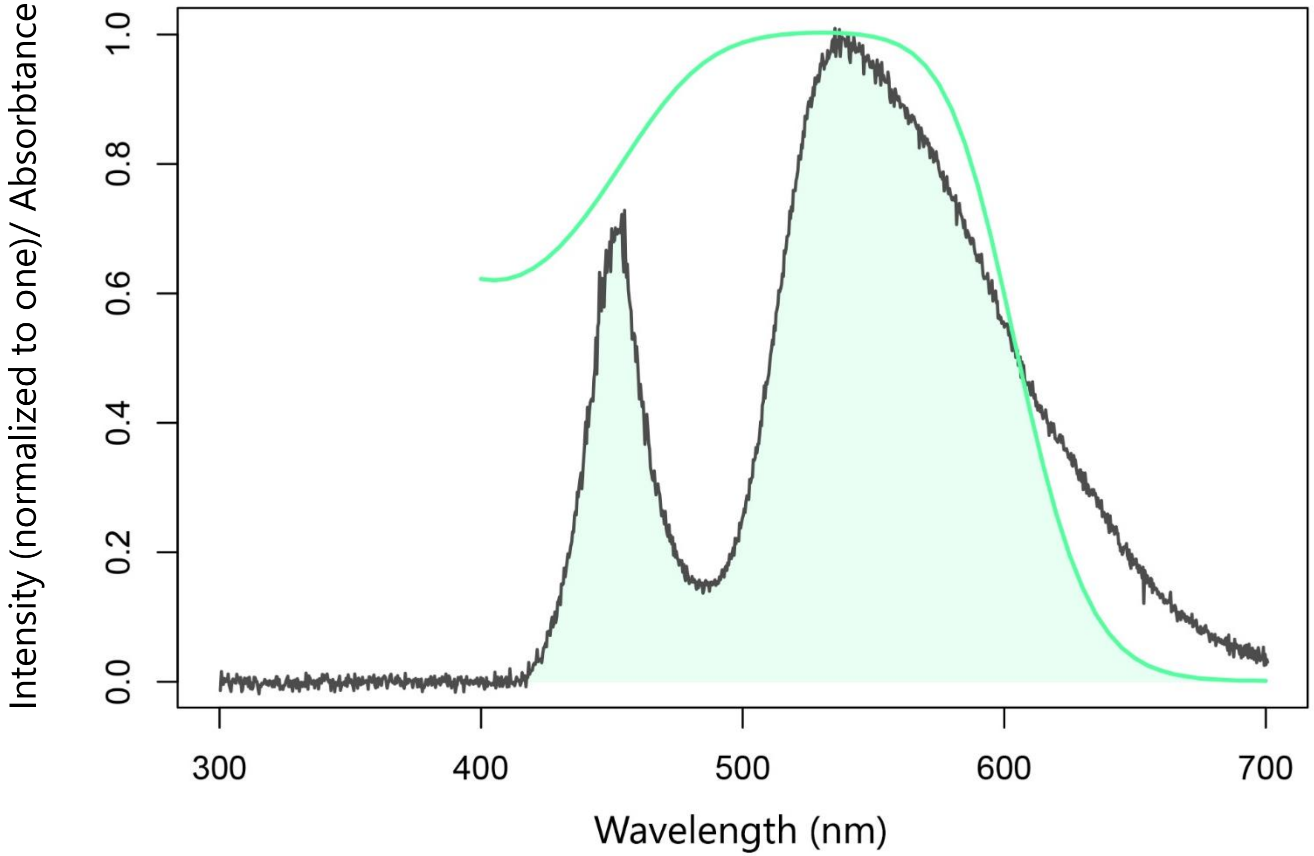
Low Intertidal – 15 m

15- 30m, up to 50m deep

Mike Bok

Celestial Polarization Compass

Spectral Environment in POL Arena



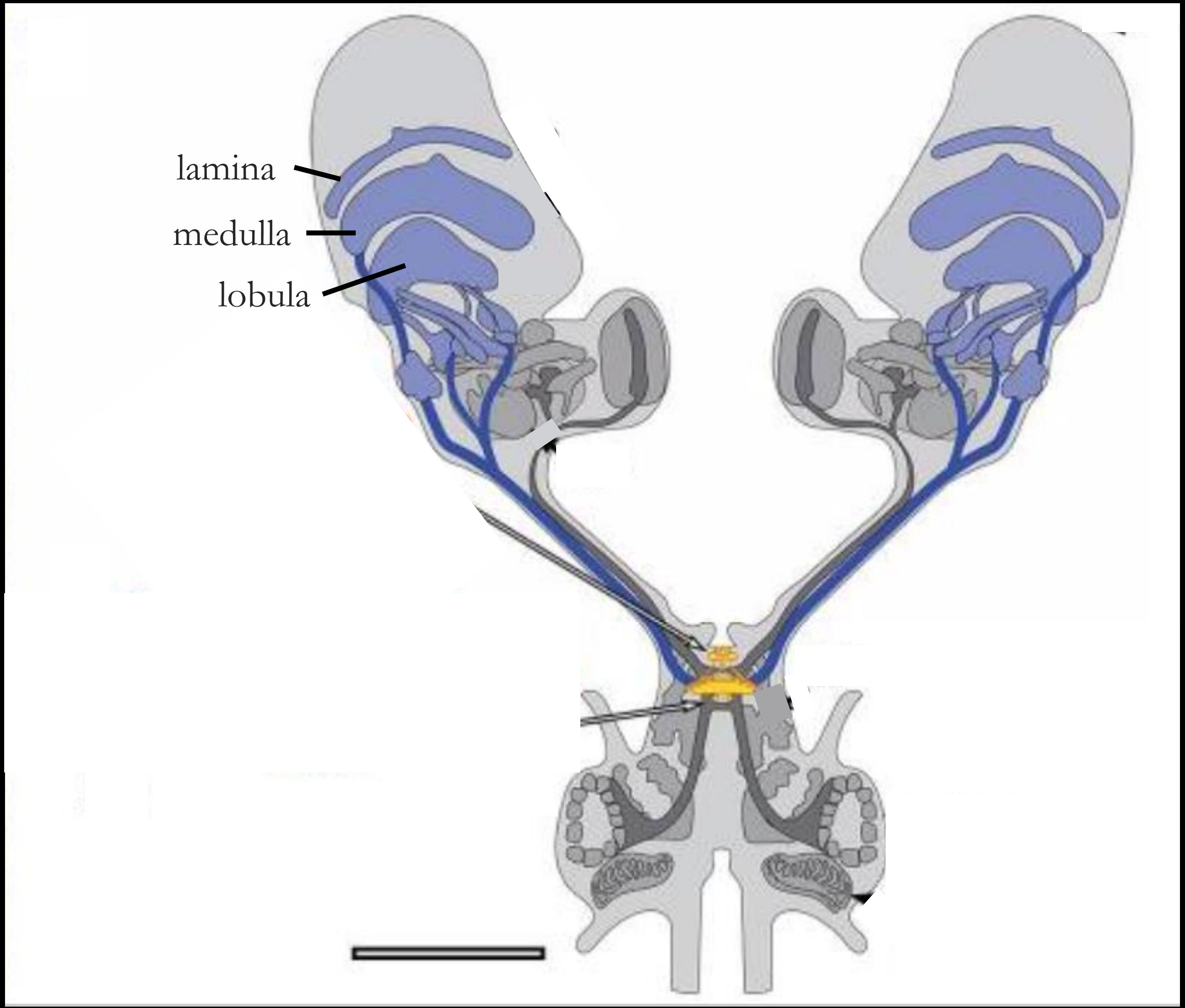
Irradiance curve measured from the center of the arena

Absorbtance of main rhabdom photoreceptors (R1-7) in the peripheral hemispheres of the eye of *N. oerstedii*

(from Cronin and Marshall 1989)

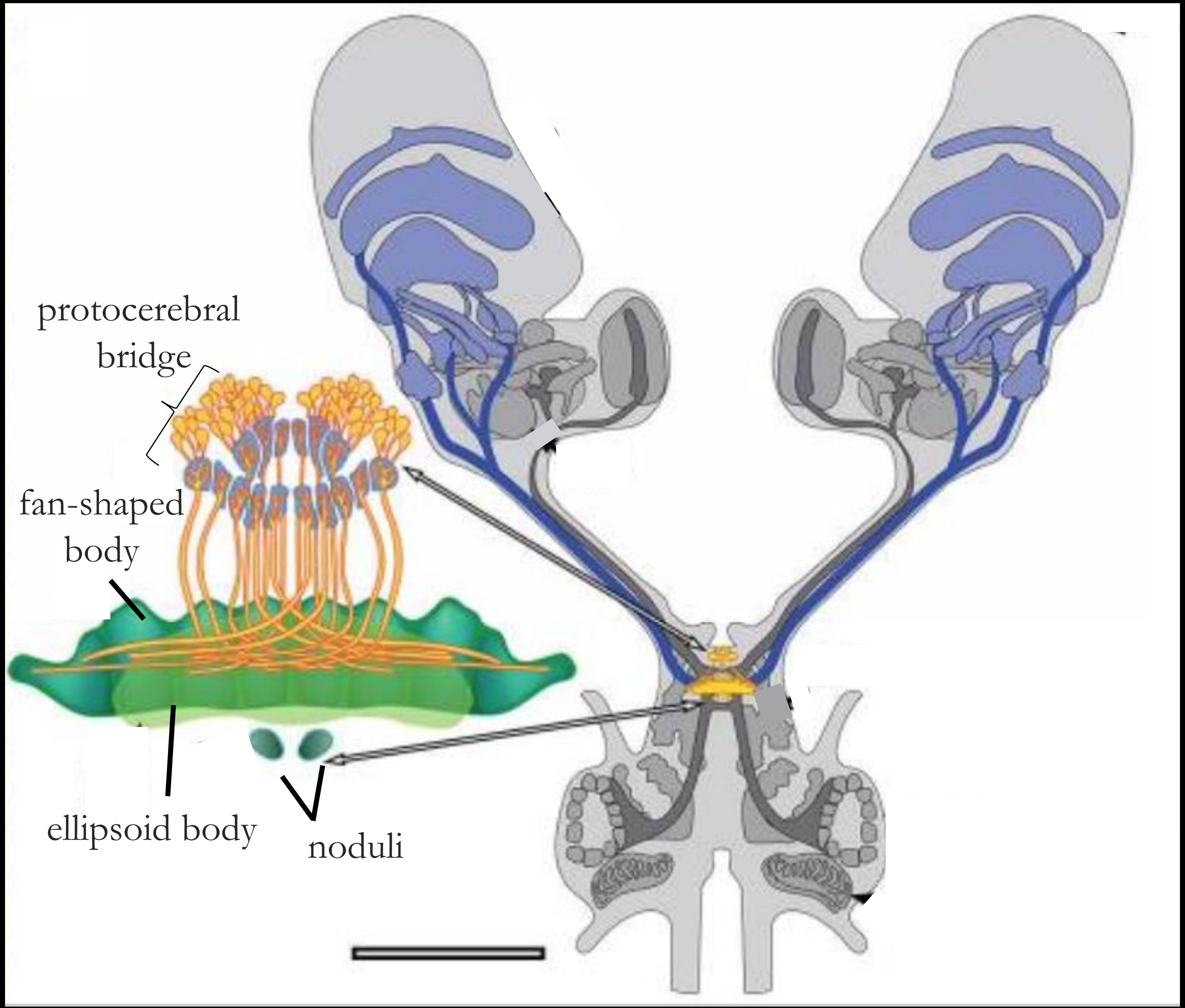
Central complex

anterior view of *Megalopta genalis* brain
(Stone et al., 2017)



Thoen et al. (2017). Front. Behav. Neuro, 11:12.

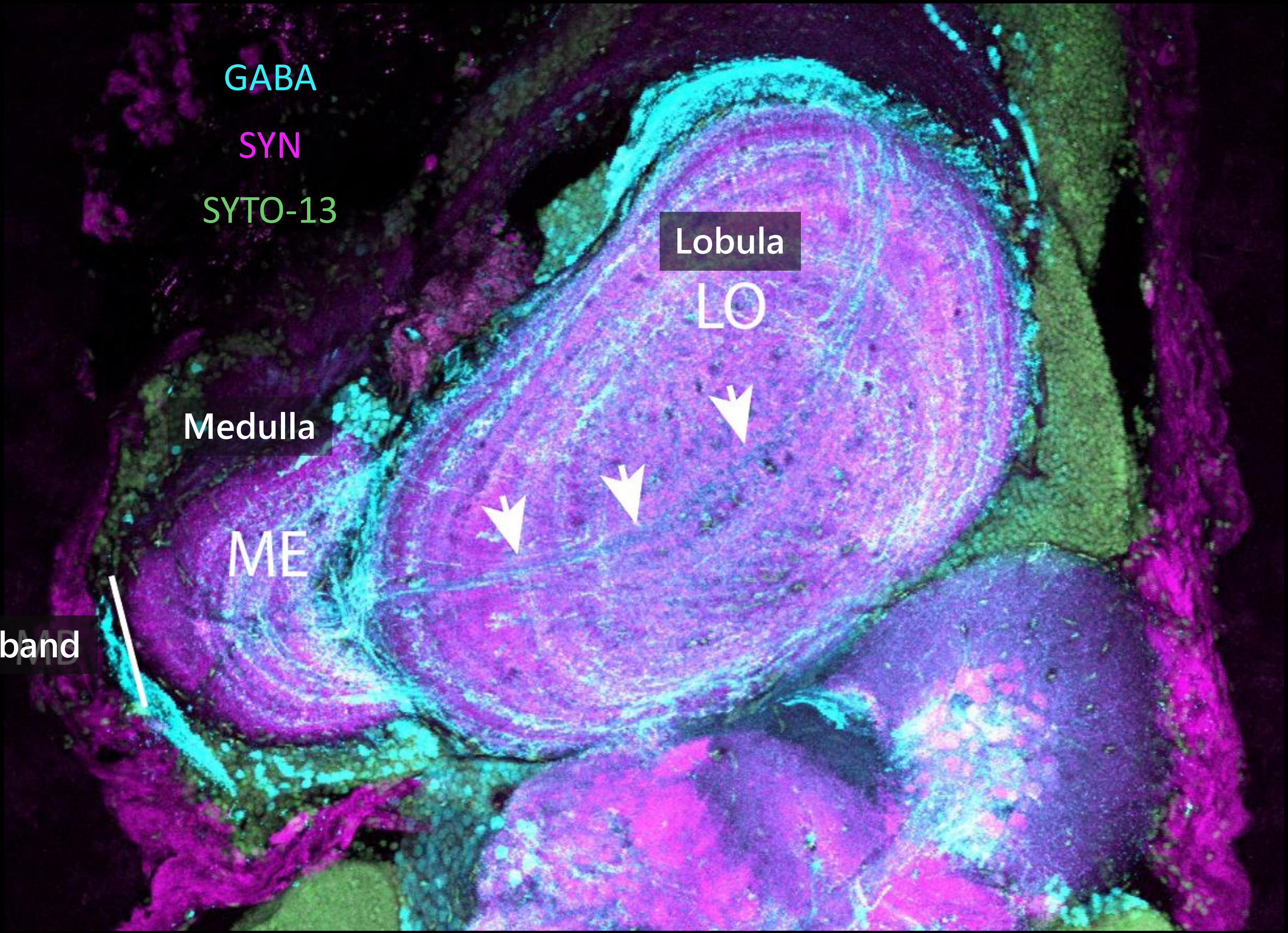
Squilla empusa



Thoen et al. (2017). Front. Behav. Neuro, 11:12.

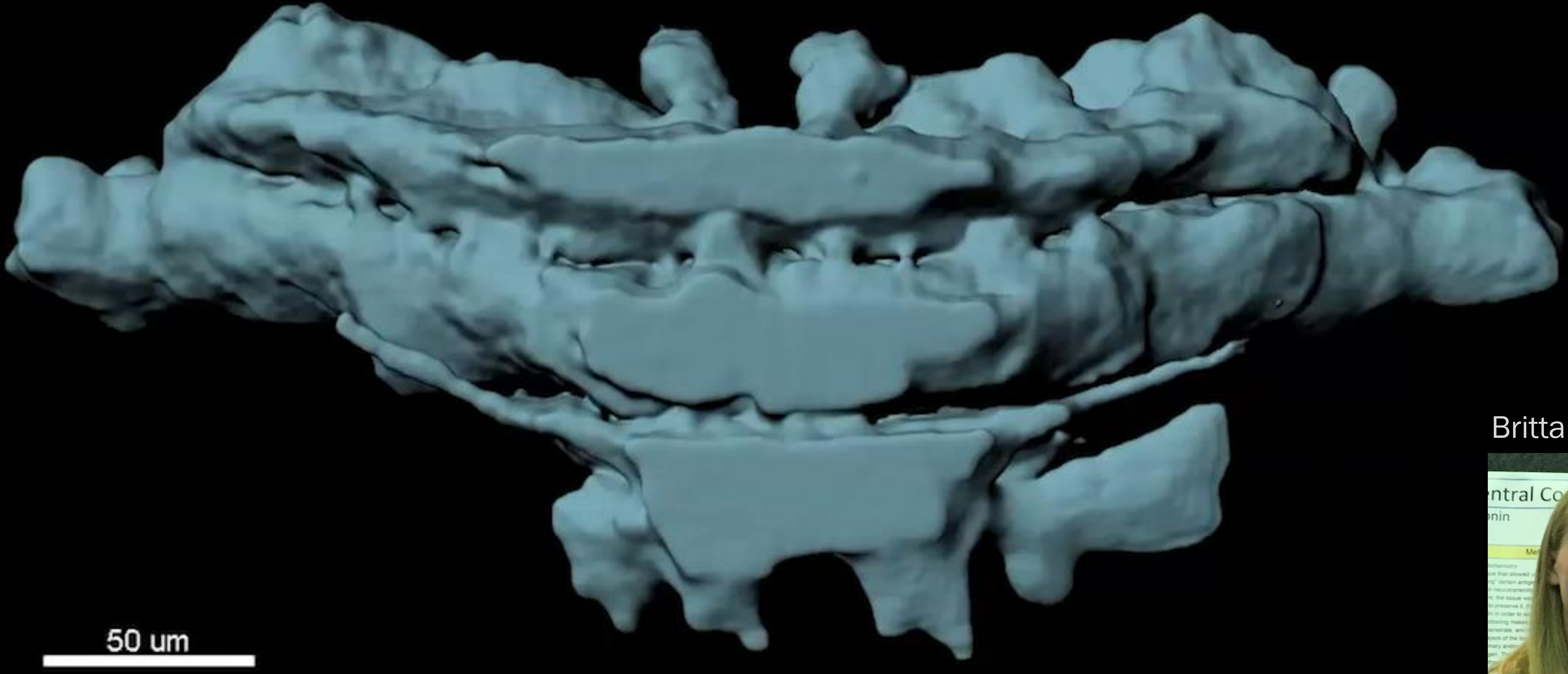
Squilla empusa

Visual Organization Appears to be Retained in the Neural Structure of the Optic Lobes



Chan Lin

Columnar organization apparent in EB-like neuropil and upper and lower sections of the Fan-shaped body



Brittany Driscoll