Olfactory navigation: using odors to orient in space and time

Deconstructing the Sense of Smell
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“Far better an approximate solution to the right question than an exact answer to the wrong question, which can always be made more precise.”

John Tukey

SPATIAL MAPPING EVOLVED UNDERWATER

In a world defined by chemicals

first
universal
only remote
still expensive

Spatial orientation

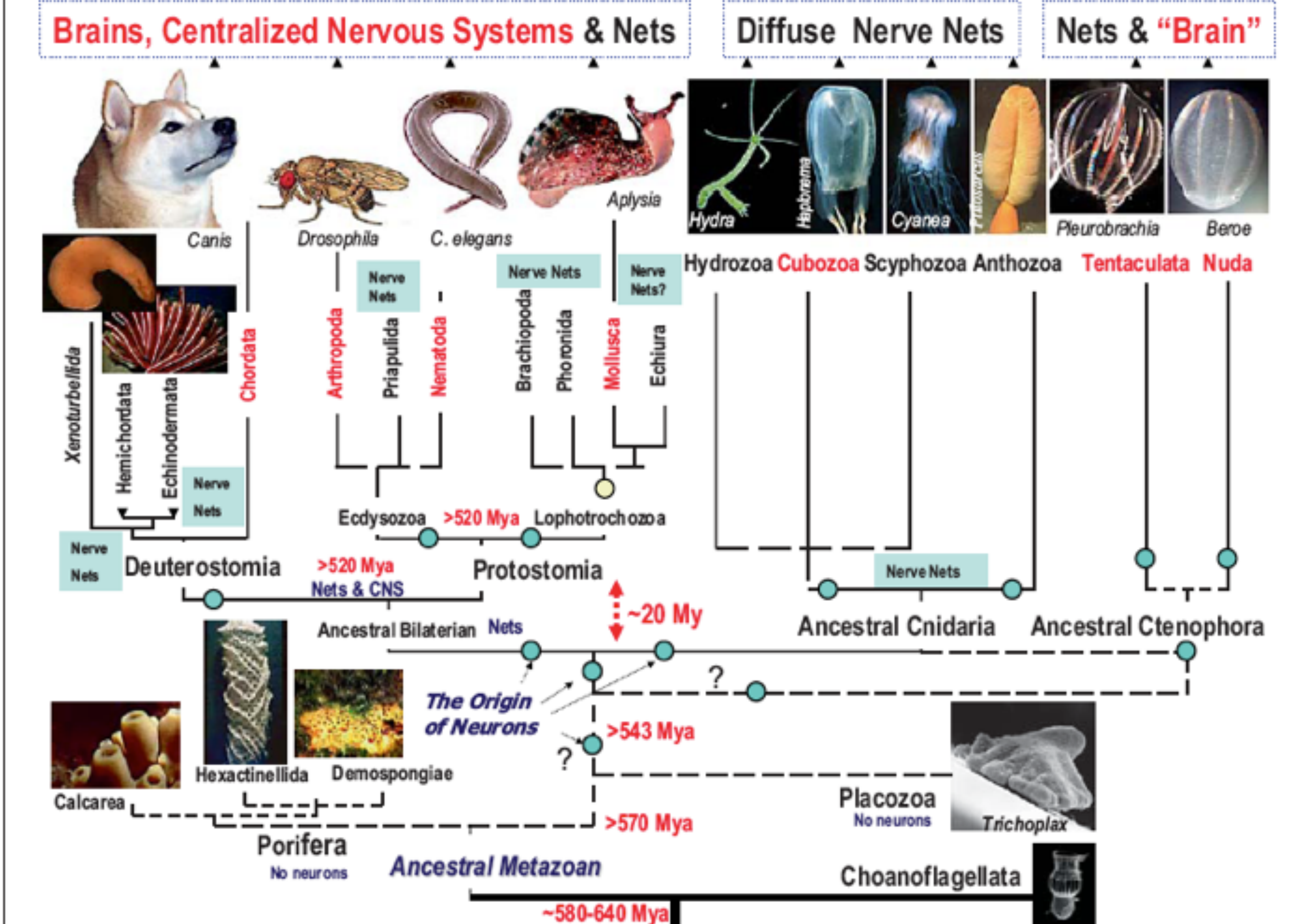
Egocentric

- Learned reaction to objects
- Beacon; turning algorithm
- Unanchored; cumulative errors

Allocentric

- Self is object in landscape
- Anchored in absolute space
- Expensive but resilient

When did this evolve?



Moroz, L. 2009 On the independent origins of complex brains and neurons Brain Behav Evol 74: 177-190

Why did this evolve?

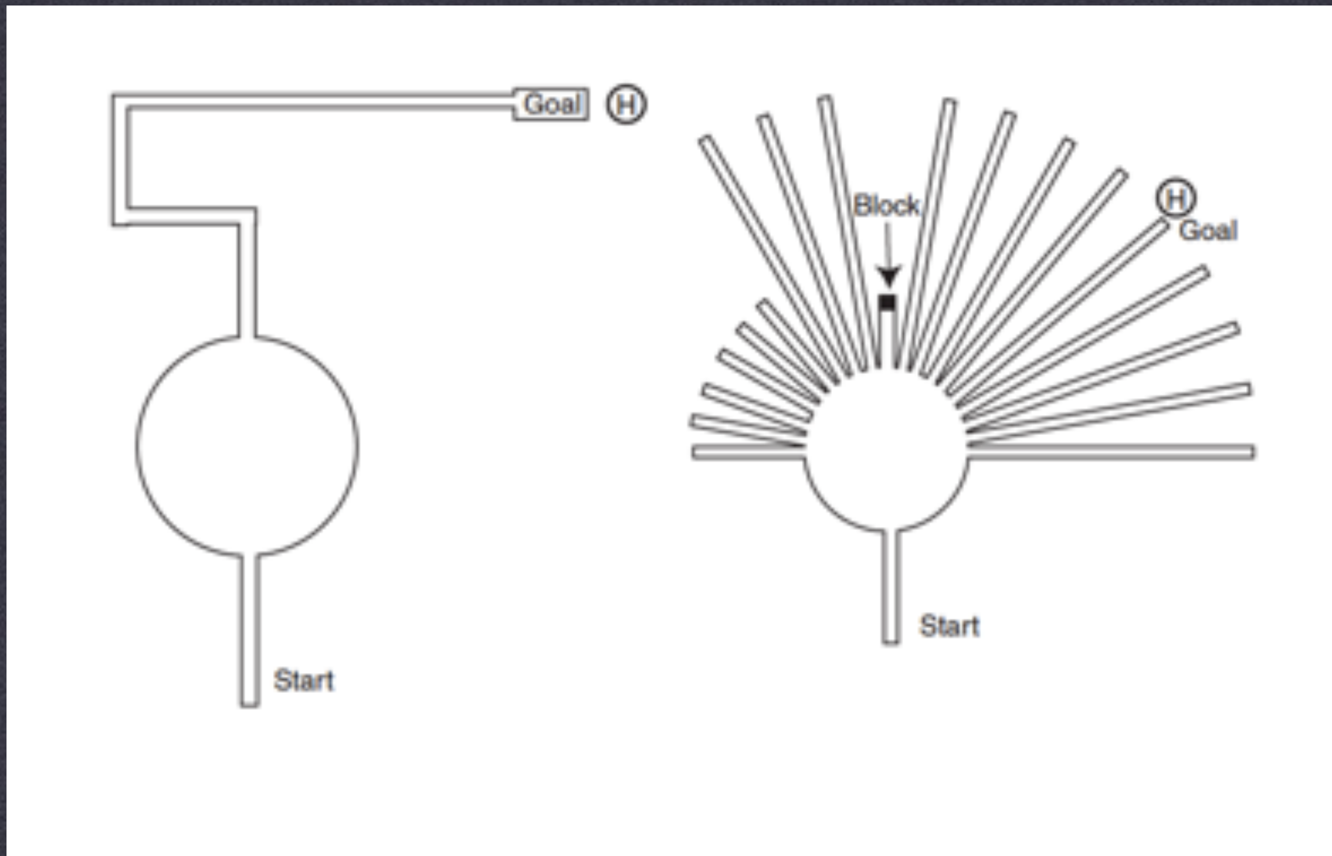
Cambrian explosion

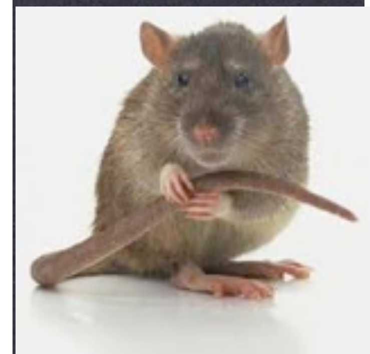
www.johnsibbick.com

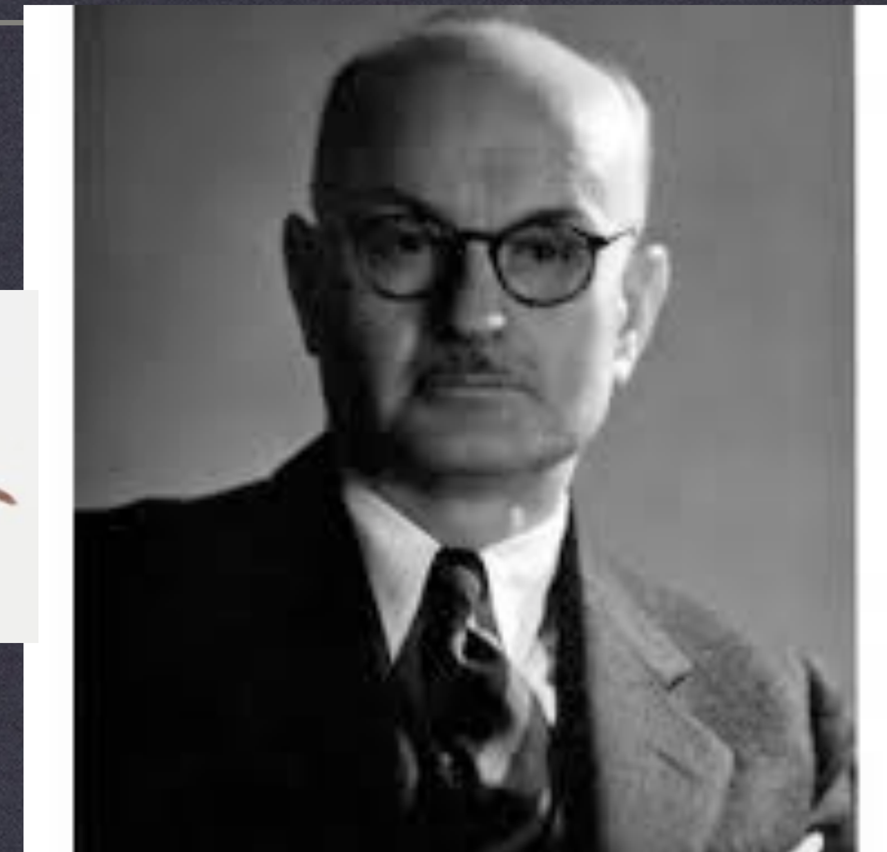
What is true navigation?

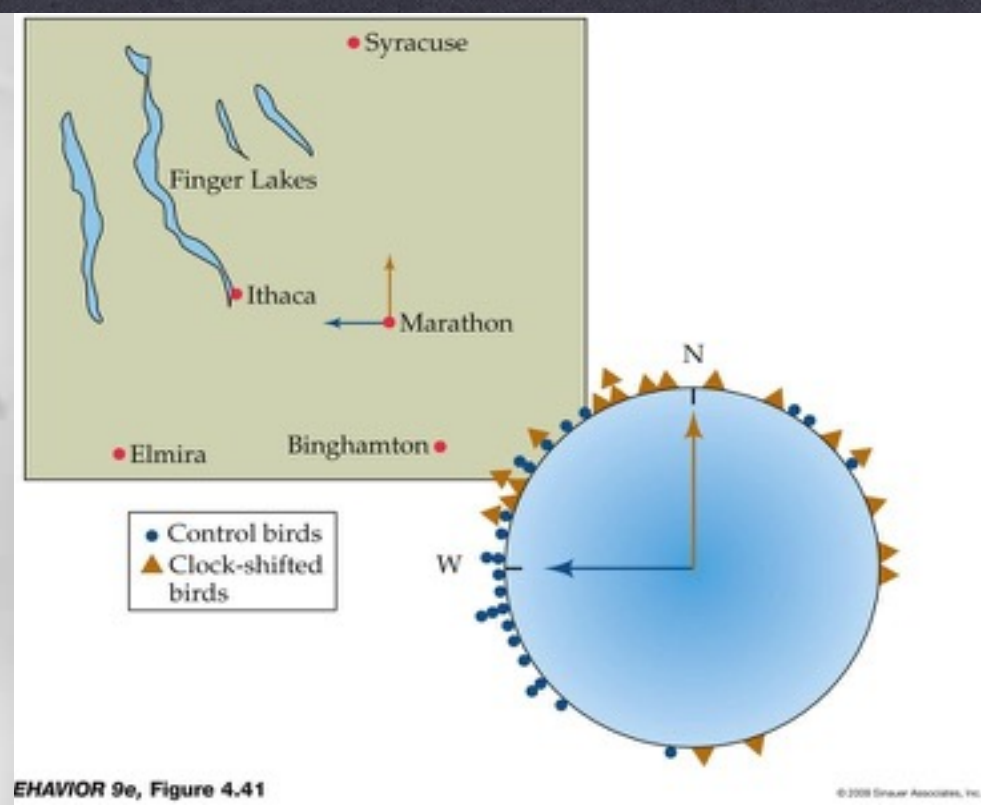
Not egocentric (S-R)
Not memorized allocentric (route)

Creating novel path across untravelled space, in the absence of beacons.



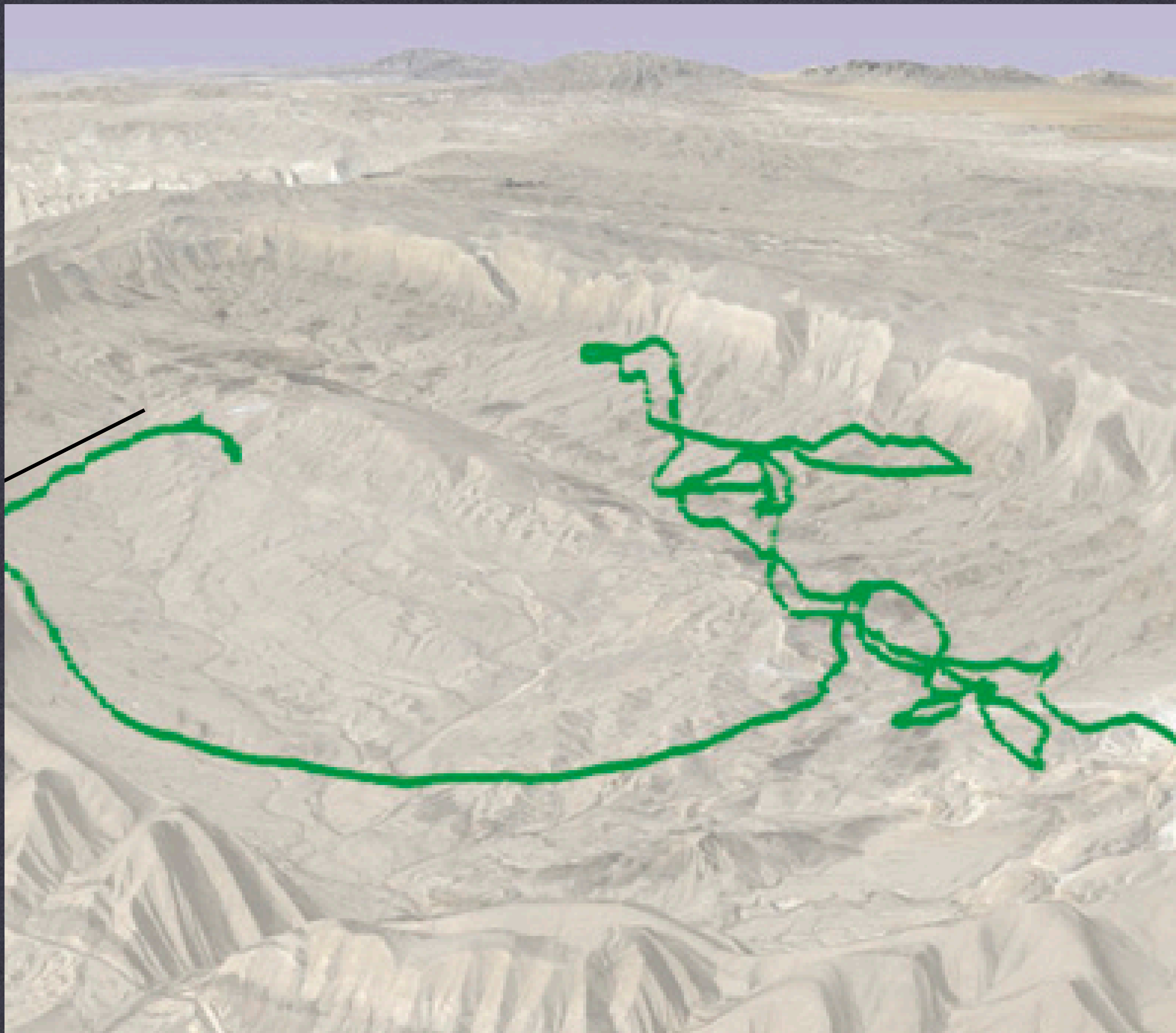






1949: ANIMALS MAKE MAPS

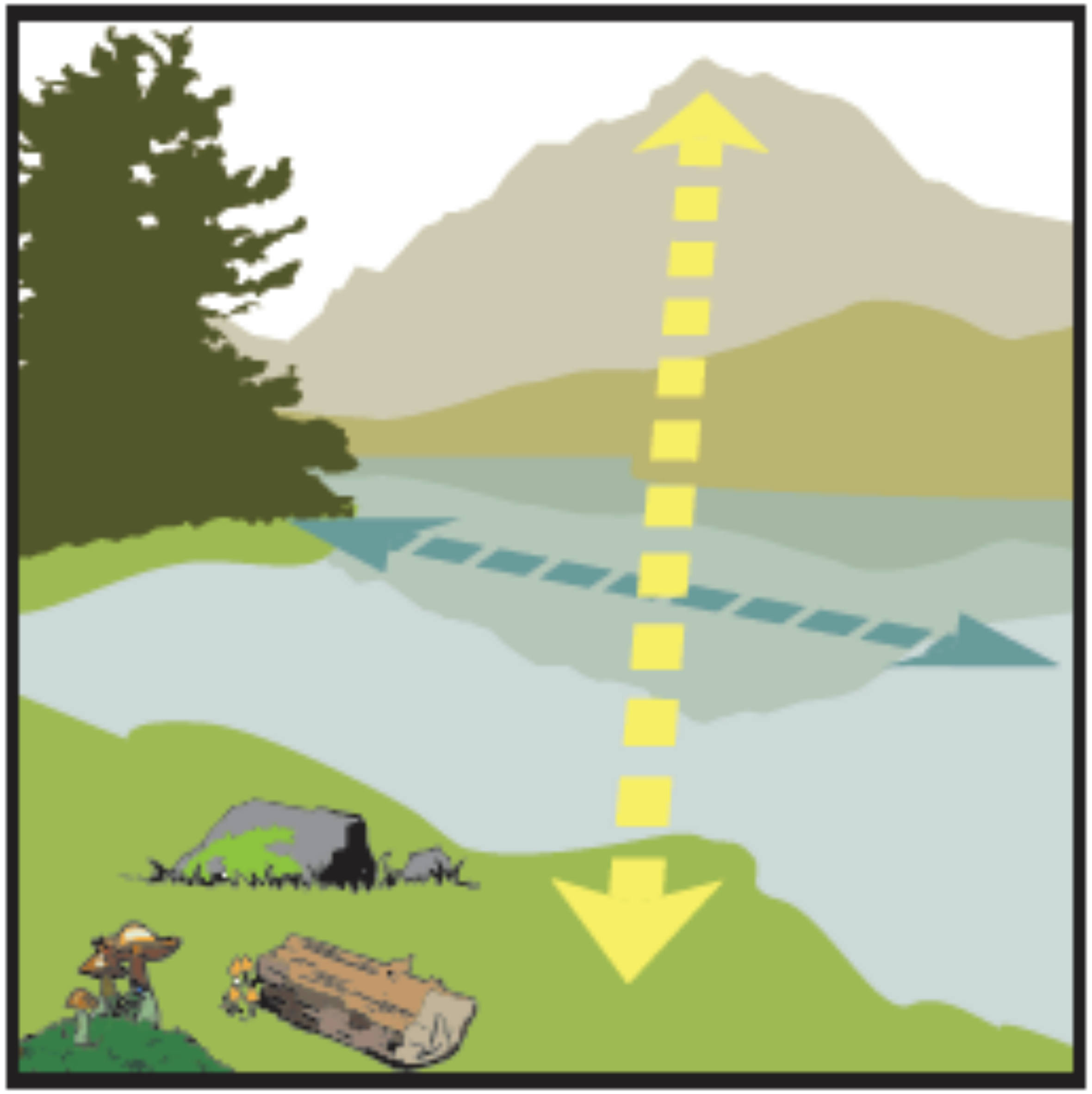
EDWARD TOLMAN AT BERKELEY: CONVERGENCE WITH GUSTAV KRAMER IN WEST GERMANY

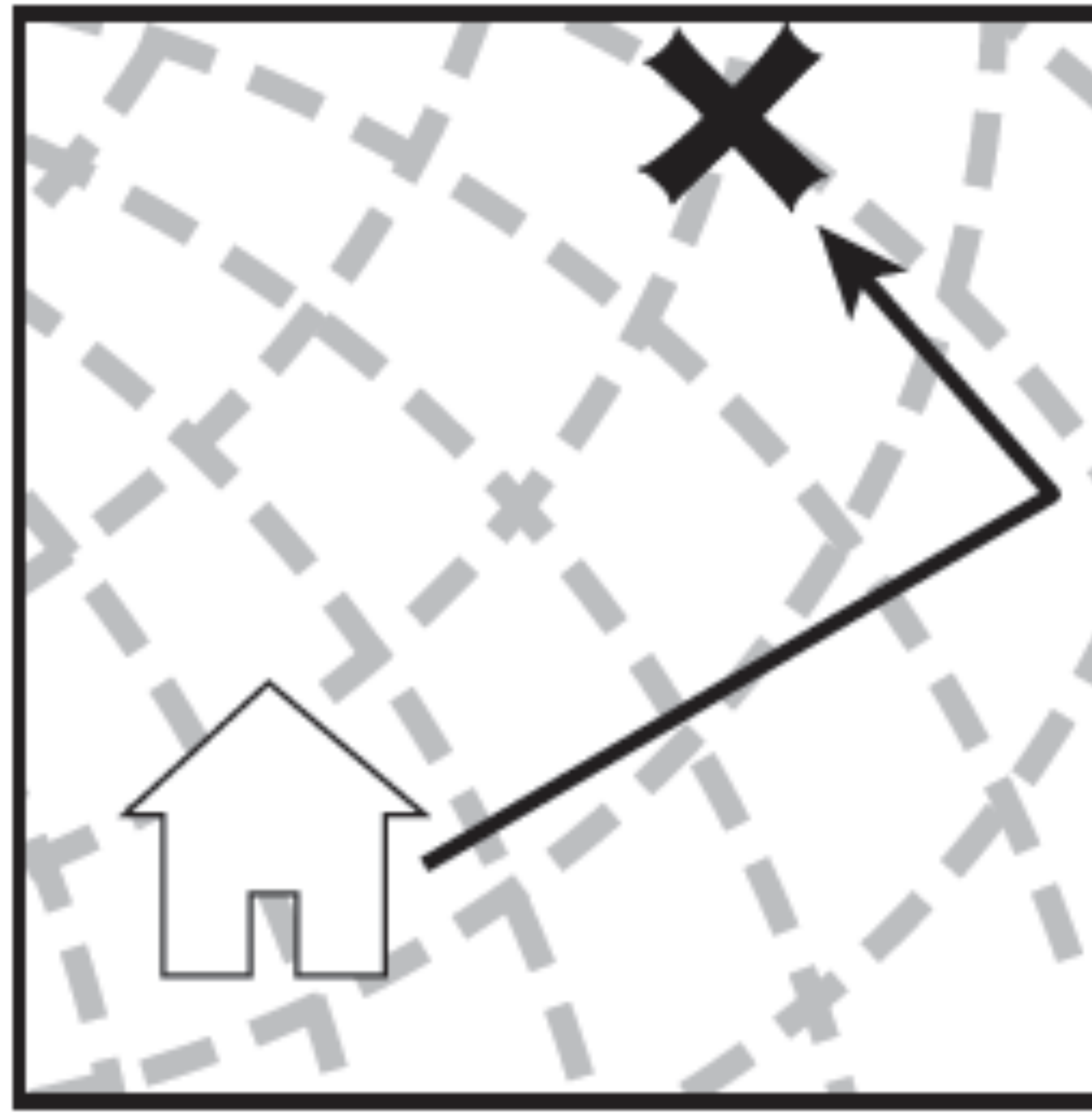


PIGEON-LIKE NAVIGATION IN A FLYING MAMMAL

EGYPTIAN FRUIT BAT IN THE NEGEV DESERT (TSOAR ET AL. 2011 PNAS)

THE BEARING MAP

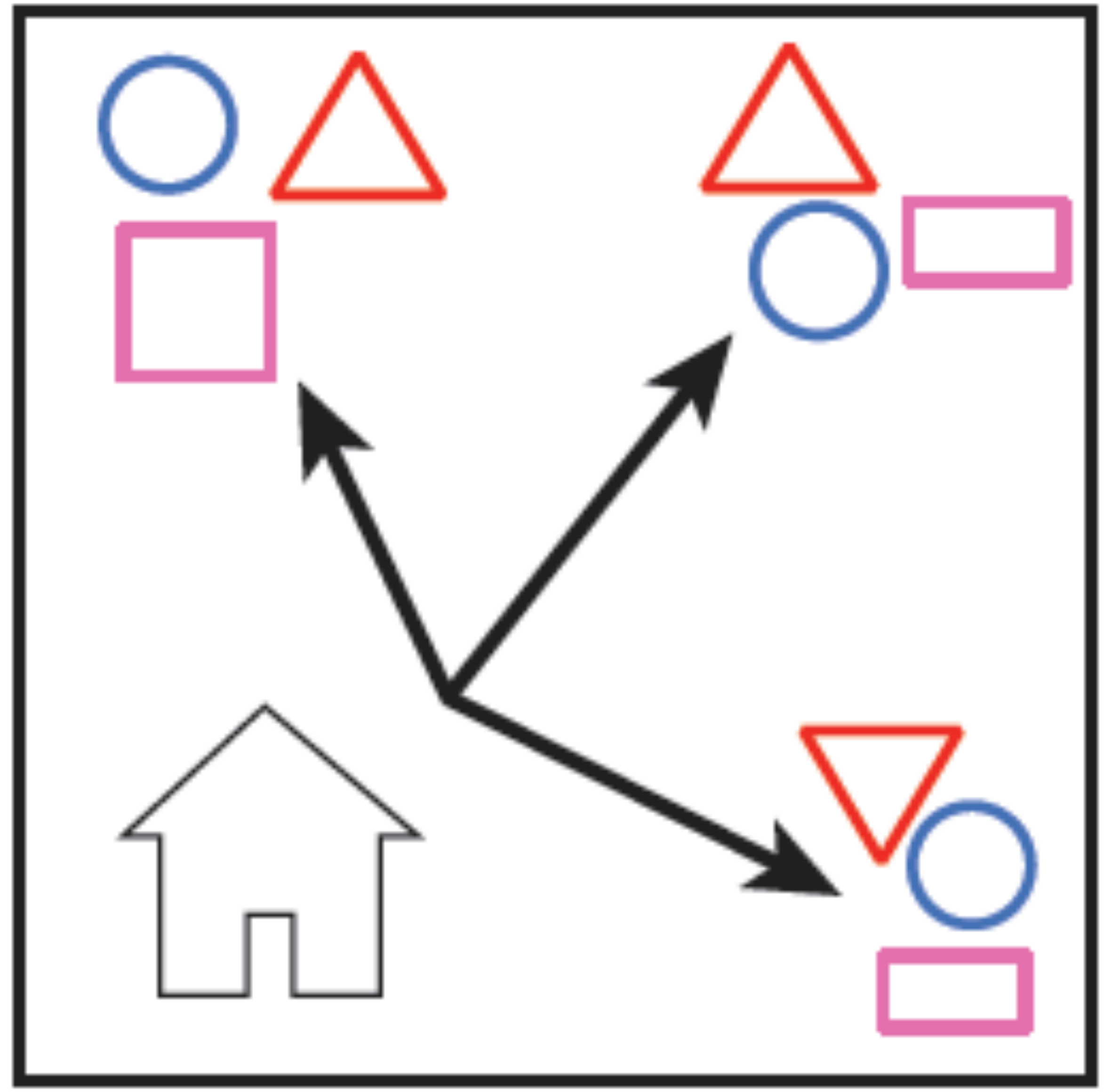




Directional (gradient) cues - gradients, slope, shapes

Dentate gyrus subfield

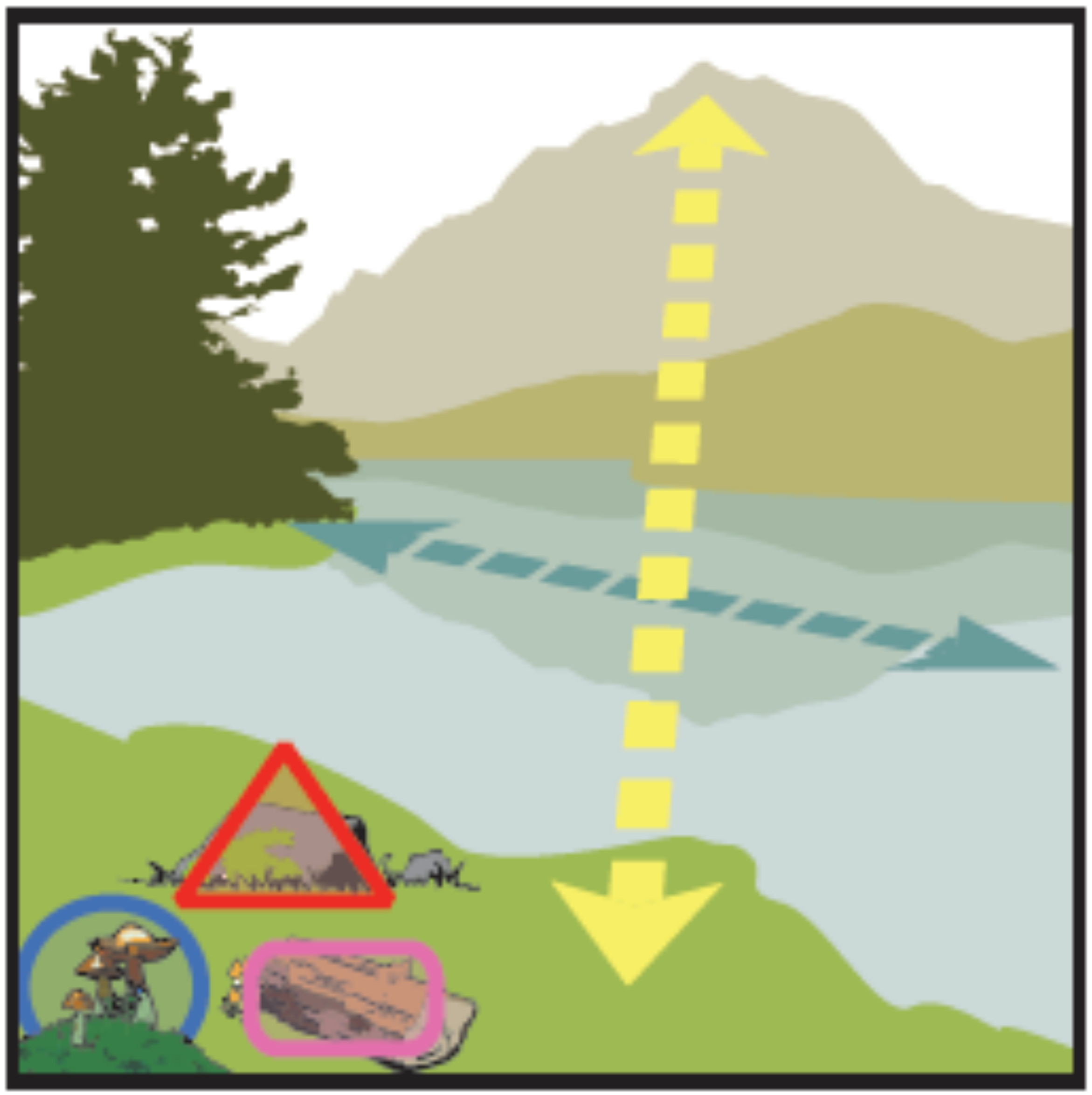
THE SKETCH MAPS

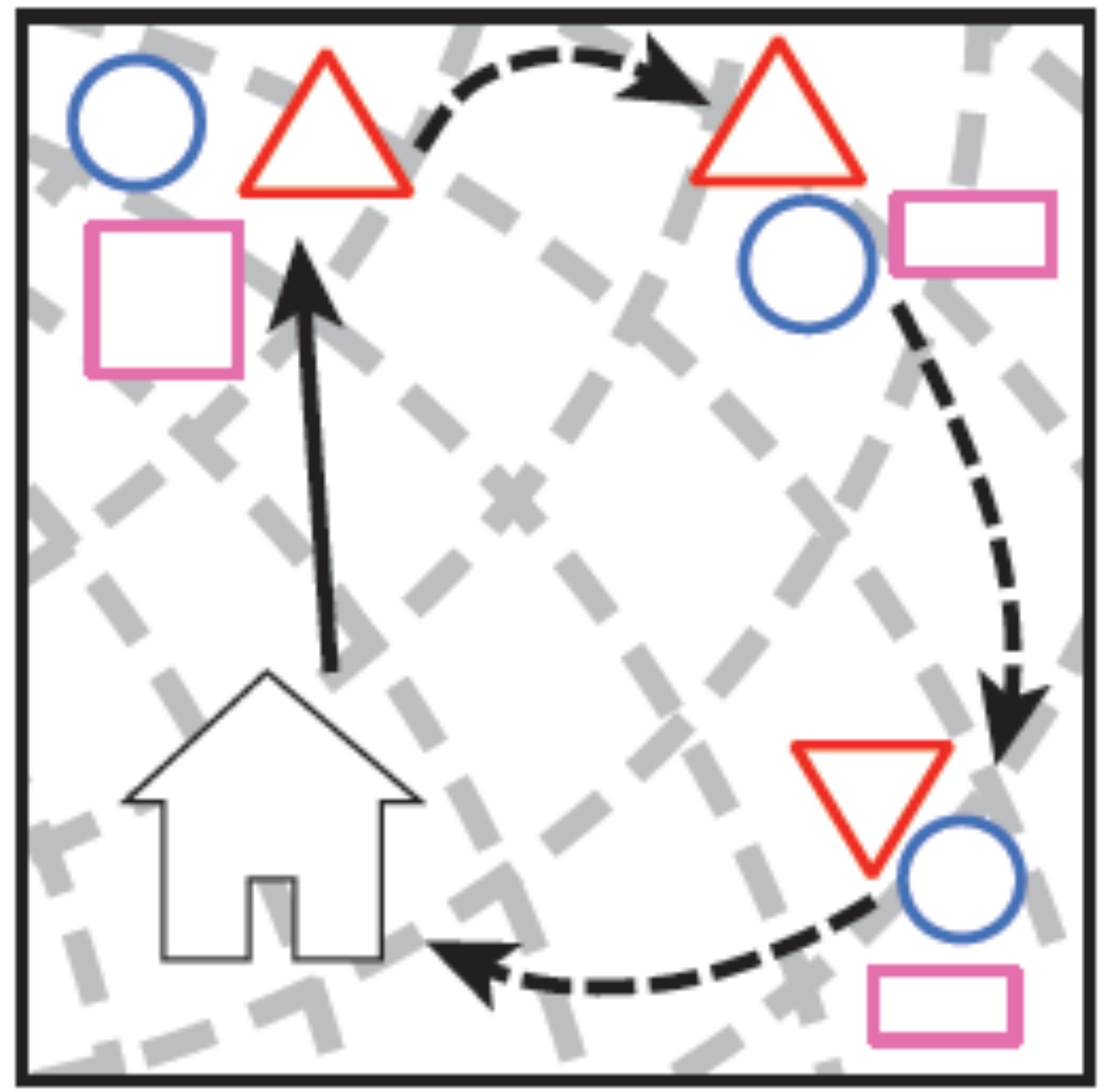


Positional (landmark) cues – local objects in unique constellations

CA1 Subfield

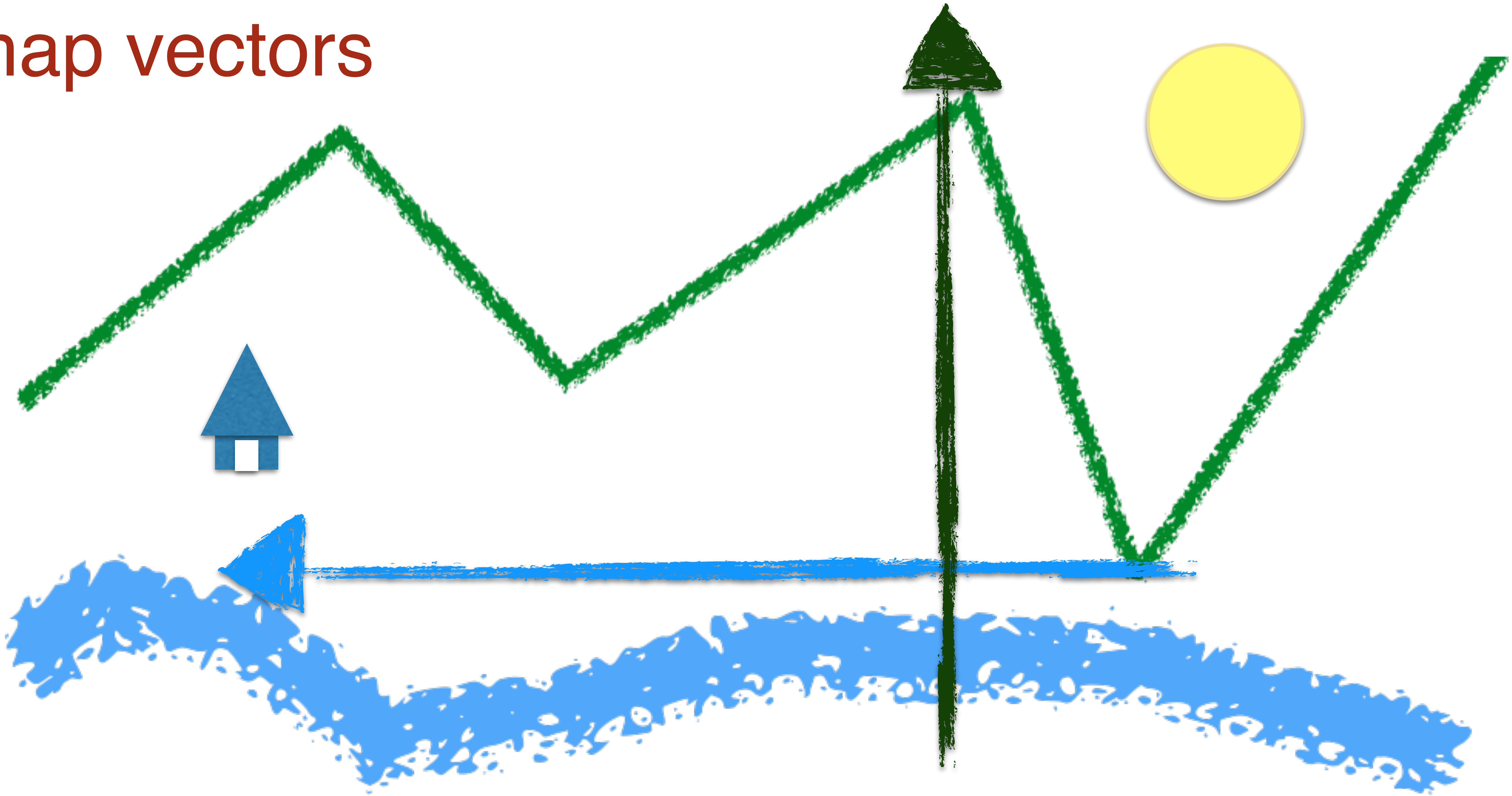
THE INTEGRATED (COGNITIVE) MAP





Sketch Maps recoded in Bearing Map coordinates
CA3 Subfield of Ammon's Horn

map vectors

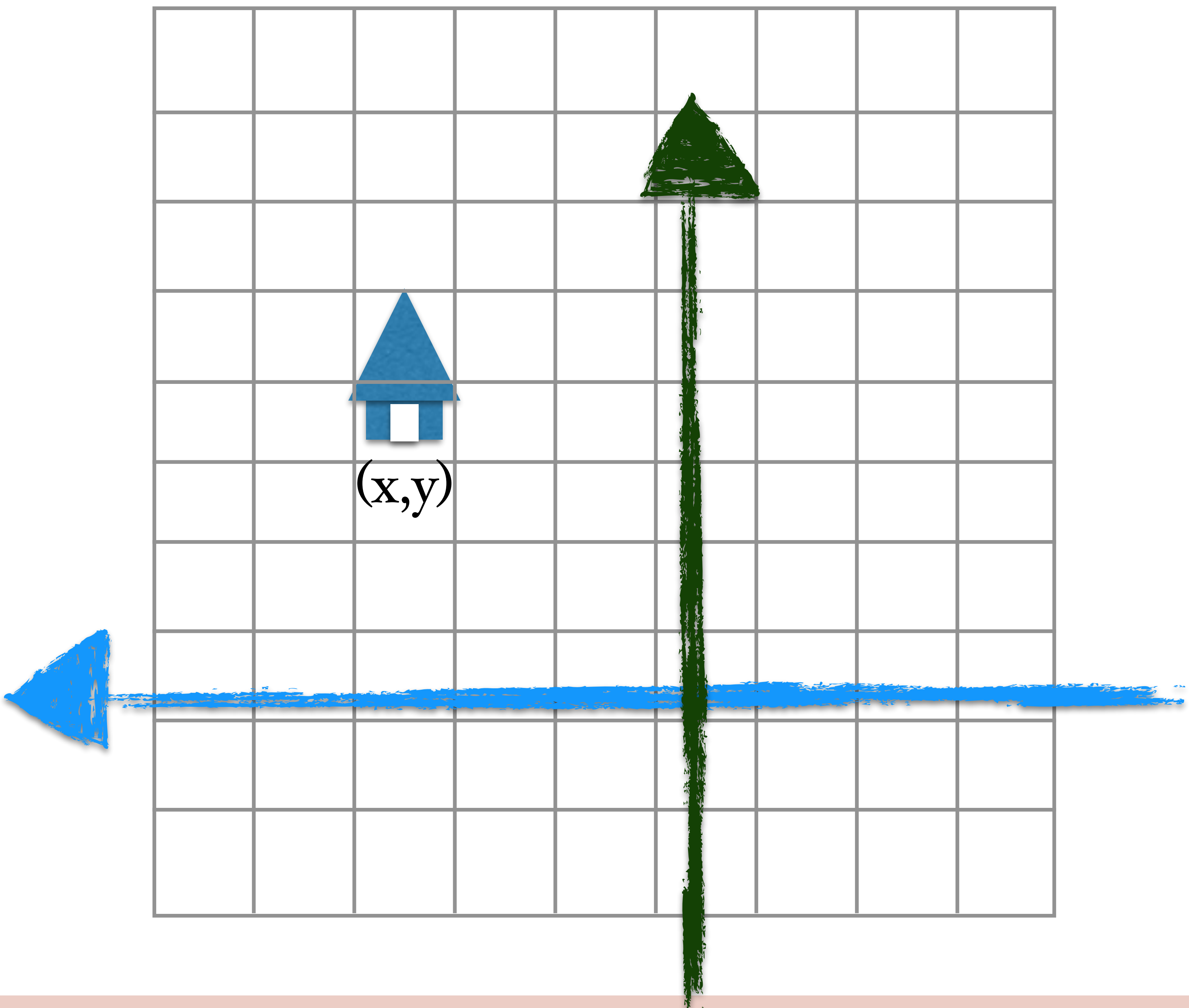


COMPASS or DIRECTIONAL CUES

- **gradients:** odor, sound, magnetic field
- **polarization:** landscape shapes, objects, slope

Jacobs & Schenk. 2003. Unpacking the cognitive map: the parallel map theory of hippocampal function. *Psych Rev*

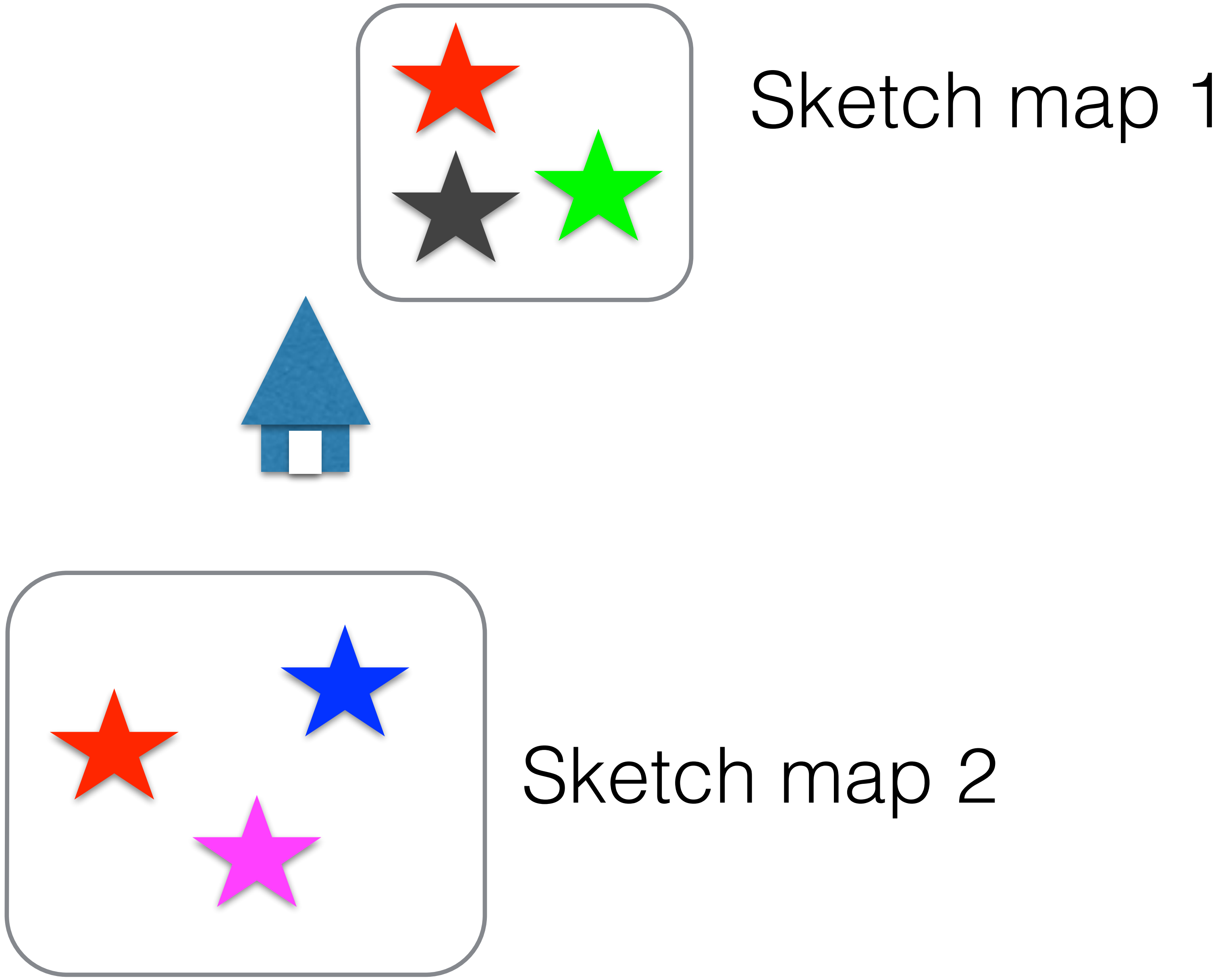
Construct grid from vectors



Location defined in absence of unique landmarks

Jacobs & Schenk. 2003. Unpacking the cognitive map: the parallel map theory of hippocampal function. *Psych Rev*

Add positional cues



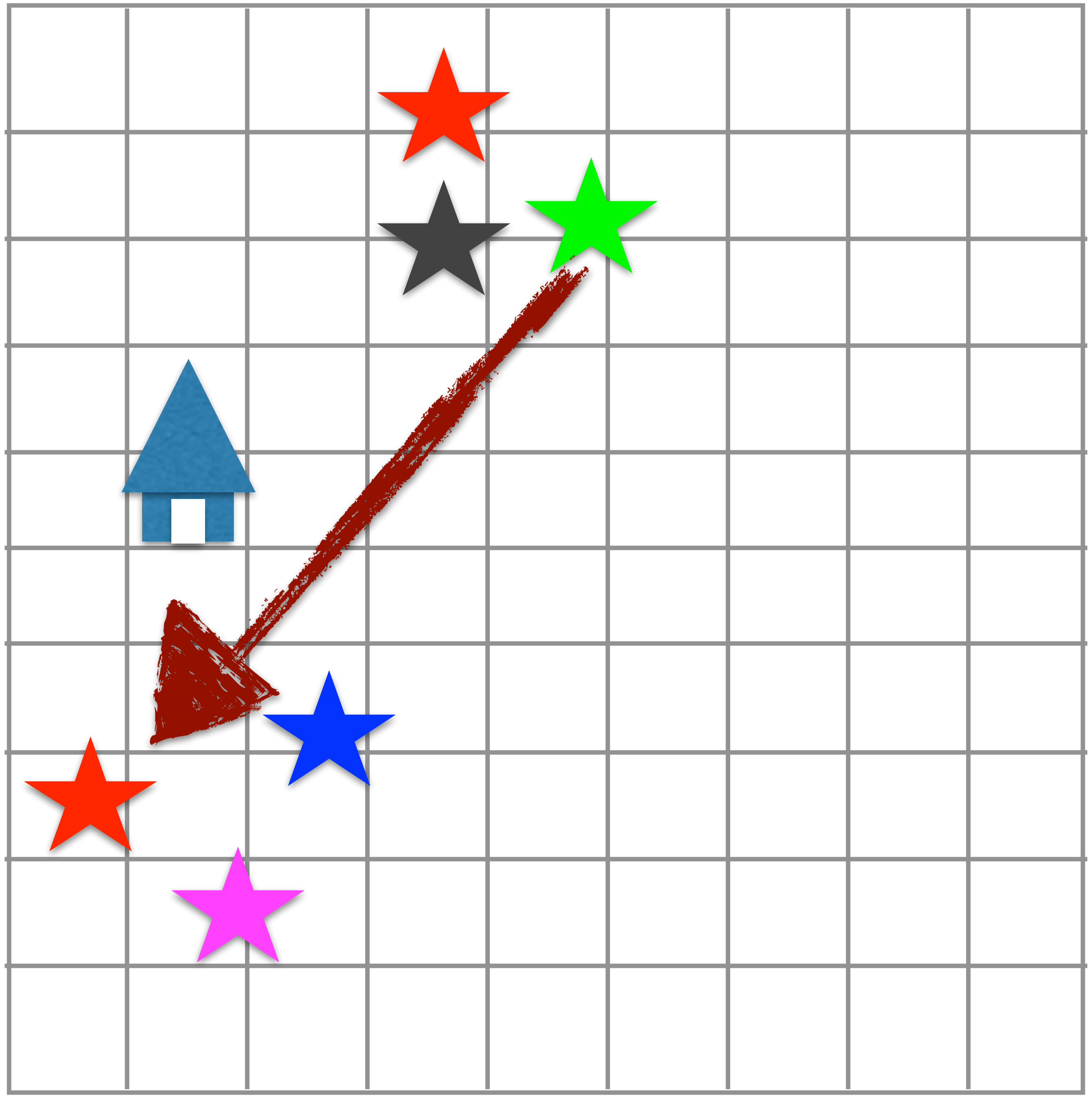
ARRAYS of positional cues form SKETCH MAPS

close arrays of unique learned objects

Jacobs & Schenk. 2003. Unpacking the cognitive map: the parallel map theory of hippocampal function. *Psych Rev*

Integrate directional and positional cues

Encode positional cues in directional cue coordinate system

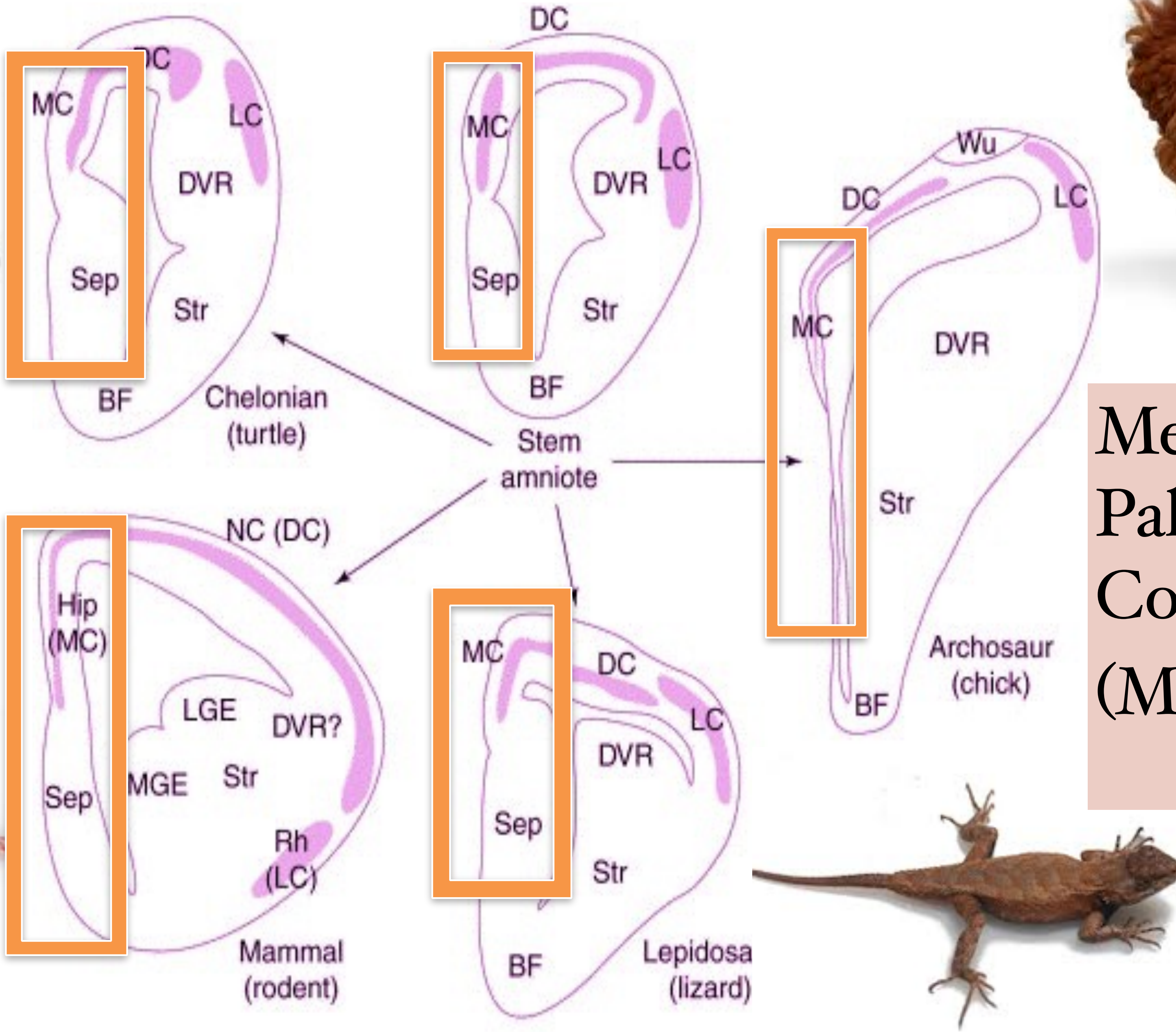


Compute novel shortcut to imperceptible goal

Parallel map theory

Jacobs & Schenk. 2003. Unpacking the cognitive map: the parallel map theory of hippocampal function. *Psych Rev*

ALL VERTEBRATES: Bearing Map



Medial Pallium or Cortex (MC)

Bar, I., Lambert de Rouvroit, C., and Goffinet, A. M. (2000). The evolution of cortical development. An hypothesis based on the role of the Reelin signaling pathway. *TRENDS in Neurosciences* 23, 633–638.

Bird Maps

Standard model (Wallraff 2005)

Navigational Map

HP independent; need olfaction

Familiar Area Map

HP dependent; need vision

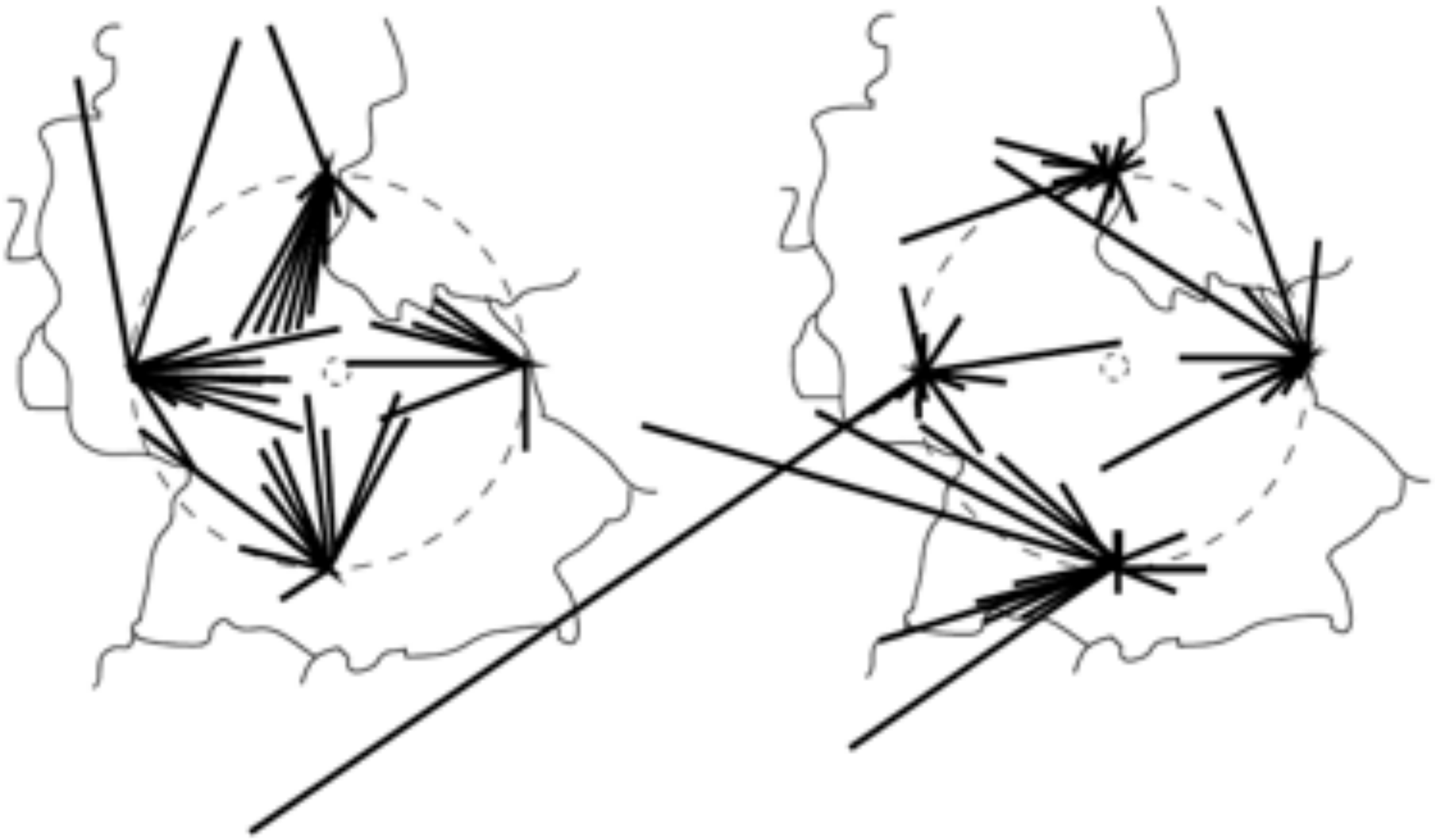
Floriano Papi (1970); Hans Wallraff, Anna Gagliardo, et al.

Domestic Pigeon, trained artificially

- Olfaction > Magnetic

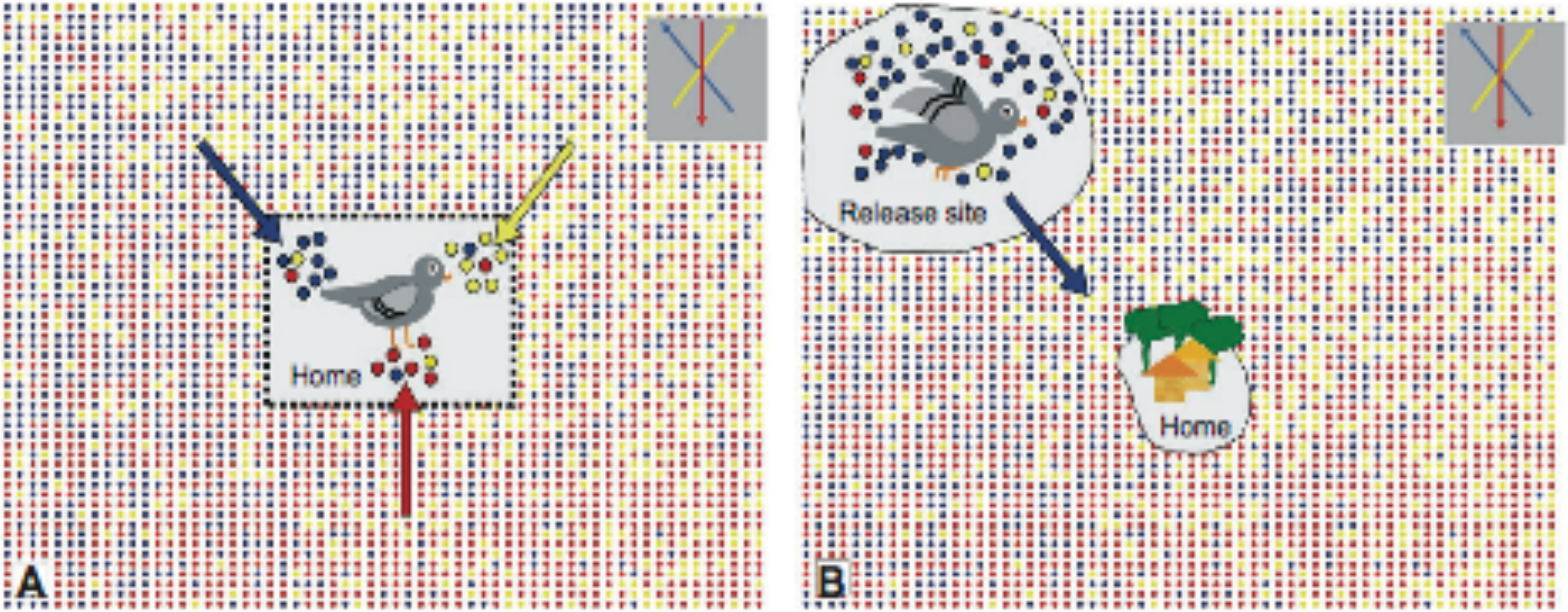
Wild Catbird, natural migration

- Olfaction > Magnetic



Mehlhorn, J., & Rehkämper, G. (2009). Neurobiology of the homing pigeon—a review. *Naturwissenschaften*.

Holland, R. A., Thorup, K., Gagliardo, A., …& Wikelski, M. (2009). Testing the role of sensory systems in the migratory heading of a songbird. *Journal of Experimental Biology*.



From Gagliardo et al. (2013) J. Exp. Biol. 216: 2165-2171; Figure 1.

Distort olfactory learning during development (add baffles; add odors)

Lesion or anesthetize (OE, OB, piriform)

An alternative to the ‘Navigational Map’

HP lesioned bird could

- use reference memory for odor
- this supplies initial bearing
- only disoriented in familiar area
  (working memory required)

Jacobs & Menzel, R. (2014). Movement Ecology.

Suggested by the only two exceptions to HP-pigeon orienting from UNFAMILIAR SITE:

Bingman, & Yates. (1992). Behavioral Neuroscience

- raised in Maryland, tested in Ohio
- 800 km displacement

WRONG MAP

Bingman, et al. (1990). Behavioral Neuroscience, 104(6), 906–911.

- HP lesioned before learning loft area odors

NO MAP

If correct…

Hippocampal function homologous in birds (natural scale, olfactory) and rodents (small scale, olfactory also?)

Parallel map architecture general solution

Jacobs & Menzel, R. (2014). Movement Ecology.

Olfactory navigation in mammals?

Rat HP place fields controlled by spatial array of odors; rotation.

Zhang & Manahan-Vaughan (2015). *Cerebral Cortex.*

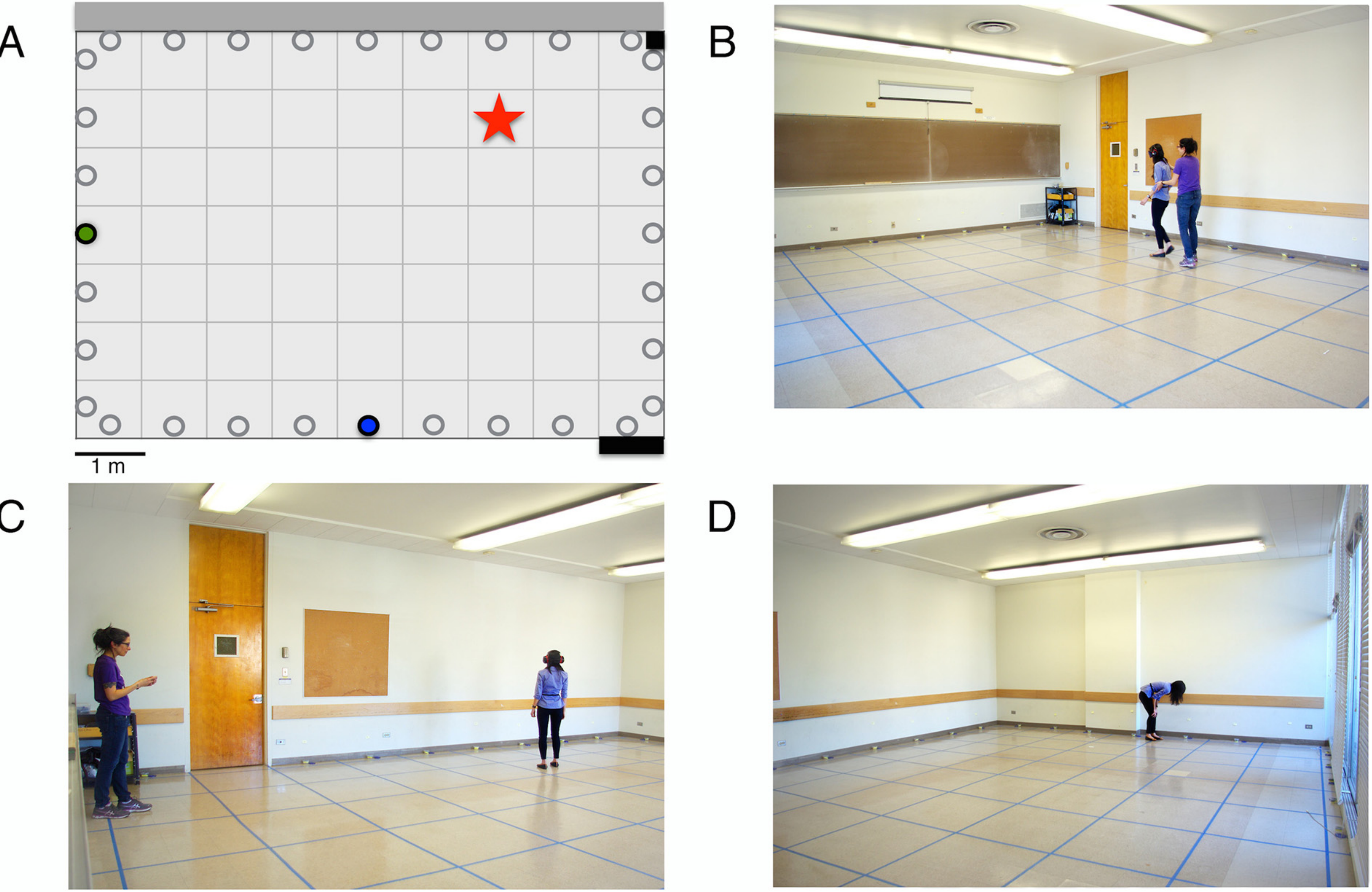
Humans?

Porter, J., et al. (2006). Mechanisms of scent-tracking in humans. Nature Neuroscience, 10, 27–29.

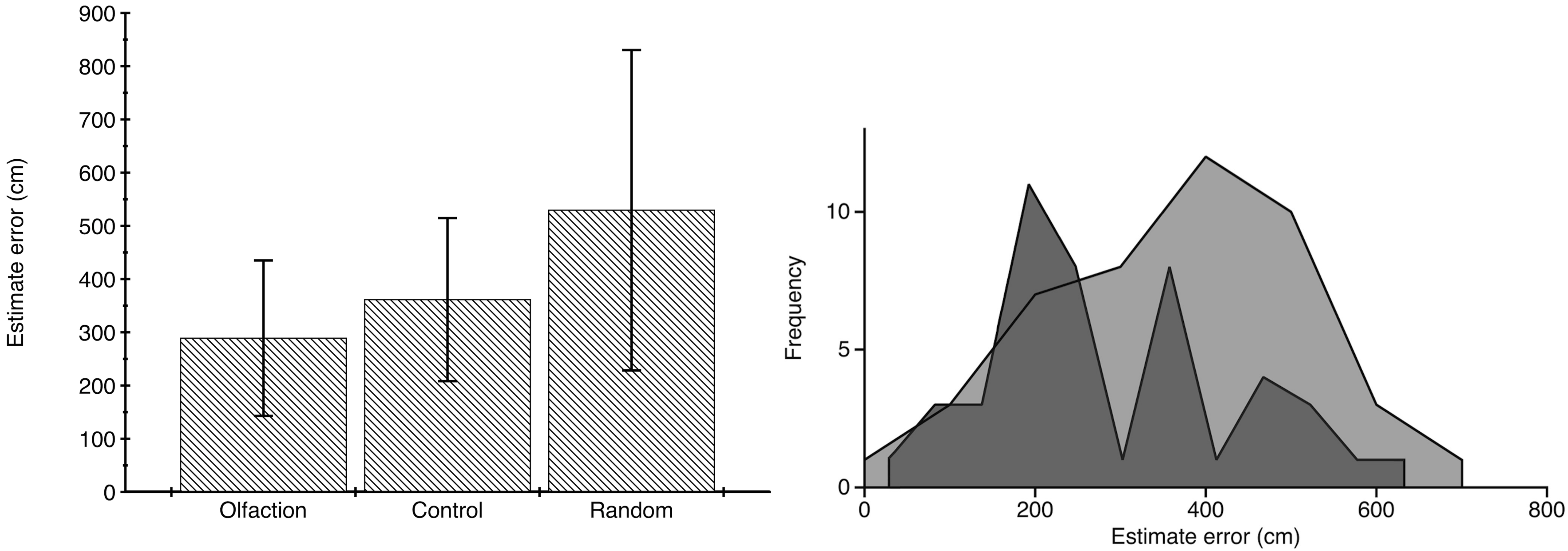
But can humans using **working memory** to map an **arbitrary location** in a purely **olfactory** landscape?

Procedure

- **Olfaction condition:** Mask vision, audition.
- Disorient enroute to location.
- One minute sampling.
- Disorient and return to start.
- Remove masks.
- Return to sample location.
- **Task validation:** vision only
- **Control condition**: no sensory input.
    - Within subject, fixed order


A
B
C
D
1 m

Humans can map an arbitrary location using only odor



Jacobs, Arter, Cook & Sulloway (2015)PLoS ONE

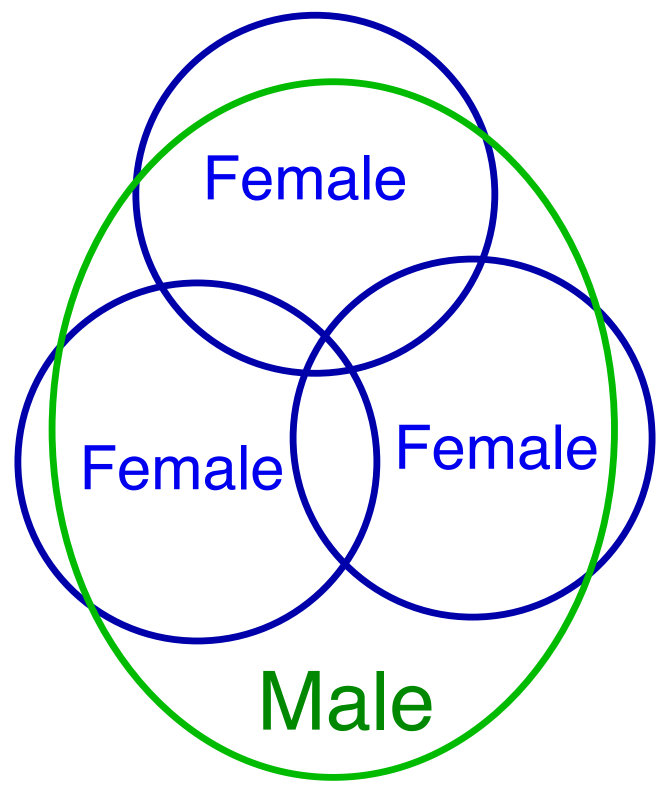
Implications

- First demonstration of olfactory orientation to arbitrary location, in any species.
- Assume pigeons use this for navigation.
- If in humans, could be a general mechanism for orientation.

So far

- Hippocampus may be homologous in structure and function in birds and mammals.
- Elements of olfactory navigation can be demonstrated in birds, rats and humans.
- Do olfactory systems scale with navigational demand, as does hippocampus?

Hippocampal size larger when creating flexible new routes



DATA FROM DIFFERENT VERTEBRATE GROUPS

Correcting for brain size and phylogeny

Olfactory bulb size increases with

- Home range size, terrestrial carnivores (*mammals*)
- Predatory theropod species (*dinosaurs*)
- Secondary nocturnality (*birds*)
- Navigational ability
  - (*domesticated pigeons*)

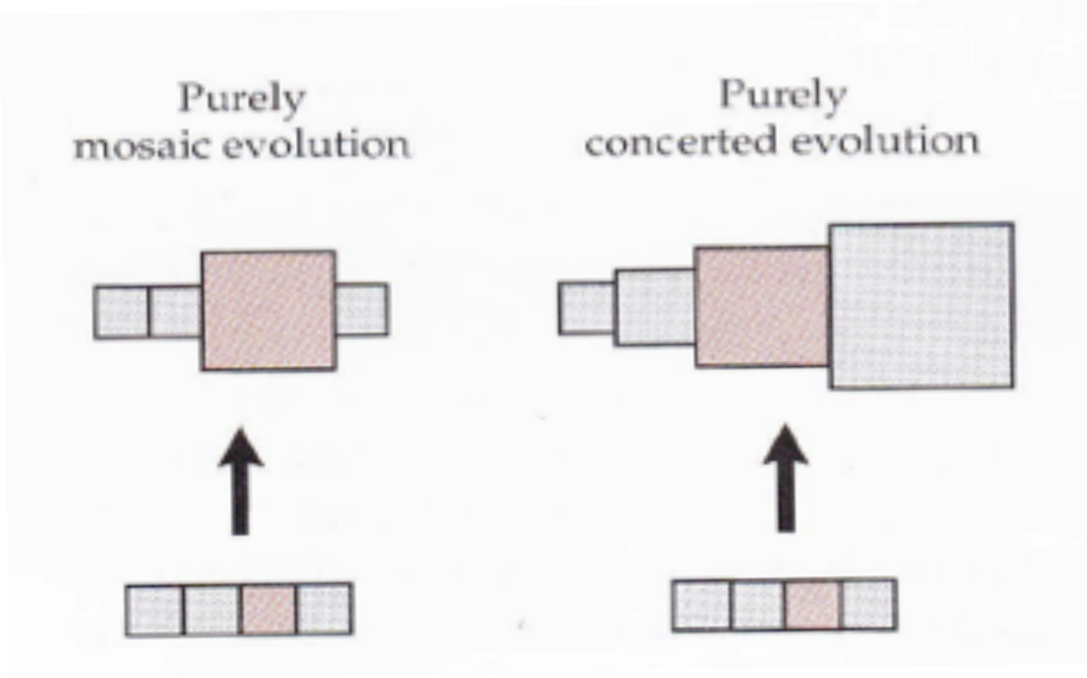
Gittleman, J. L. (1991). Carnivore olfactory bulb size: allometry, phylogeny and ecology. *J. Zoology.*

Zelenitsky, D., Therrien, F., & Kobayashi, Y. (2009). Olfactory acuity in theropods: palaeobiological and evolutionary implications. *Proc Roy Soc B.*

Healy, S. D., & Guilford, T. (1990). Olfactory-bulb size and nocturnality in birds. *Evolution.*

Mehlhorn, J., & Rehkämper, G. (2009). Neurobiology of the homing pigeon—a review. *Naturwissenschaften.*

MOSAIC EVOLUTION OF OLFACTORY SYSTEM



Finlay & Darlington analyses:

Mammals

Sharks (basal vertebrate)

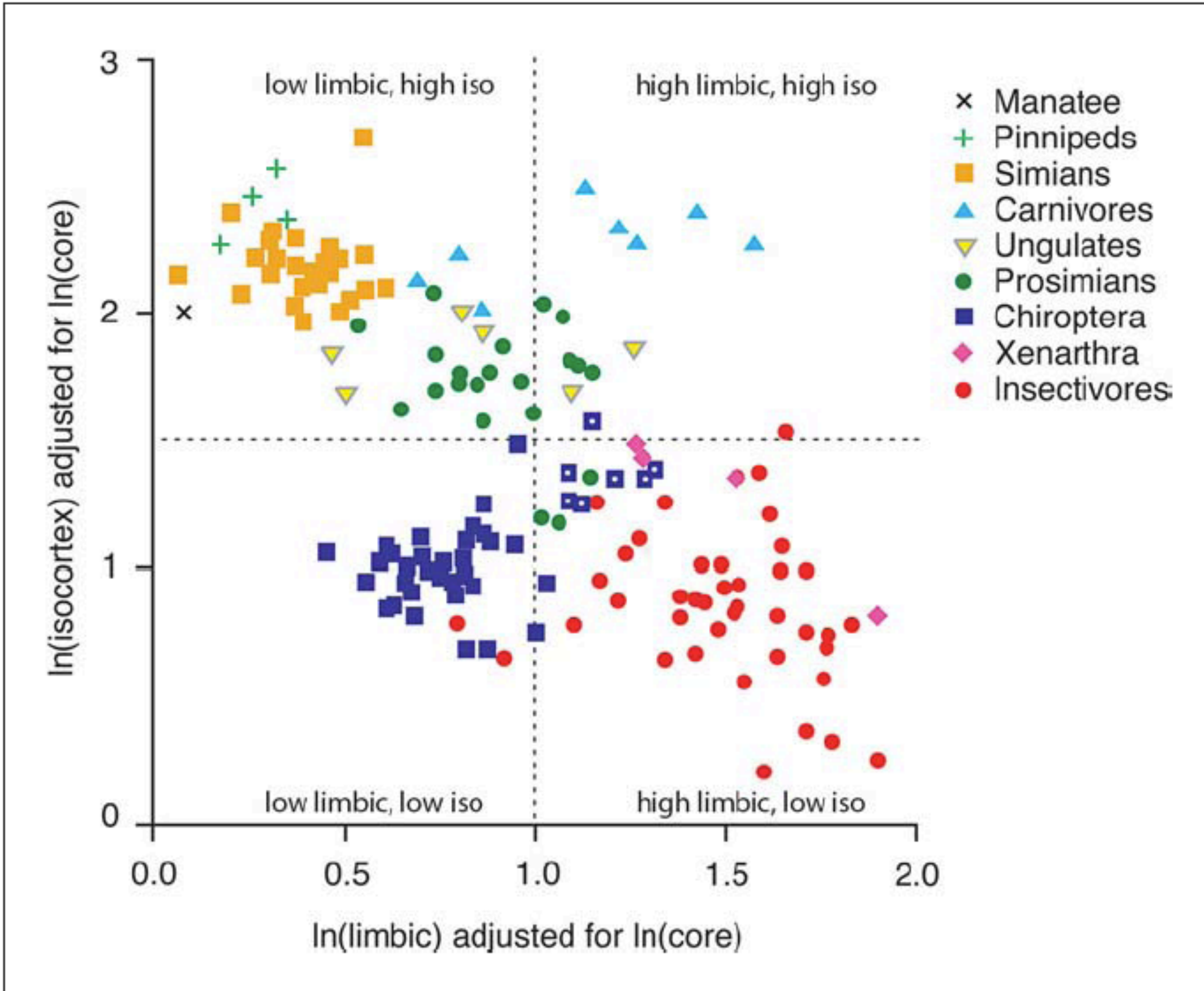
90-97% variance brain structure size explained by size of whole brain

3-10% olfactory system

Finlay, B. & Darlington, R. 1995. Linked regularities in the development and evolution of mammalian brains. *Science*.

Yopak, K. E., …and Finlay, B. L. (2010). A conserved pattern of brain scaling from sharks to primates. *PNAS*

Striedter, G 2005. PRINCIPLES OF BRAIN EVOLUTION. Sinauer.



3
2
1
0
0.0
0.5
1.0
1.5
2.0
low limbic, high iso
high limbic, high iso
low limbic, low iso
high limbic, low iso
ln(isocortex) adjusted for ln(core)
ln(limbic) adjusted for ln(core)
Manatee
Pinnipeds
Simians
Carnivores
Ungulates
Prosimians
Chiroptera
Xenarthra
Insectivores

BEHAVIORAL HYPOTHESIS

Detector Strategy

prey location either obvious or impossible to predict

Predictor Strategy

with sufficient data, prey location can be predicted in space and time – *increase isocortex size*

Predict using odorants - increased limbic size

Emphasize other sensory - decreased limbic size

Detector

Limbic

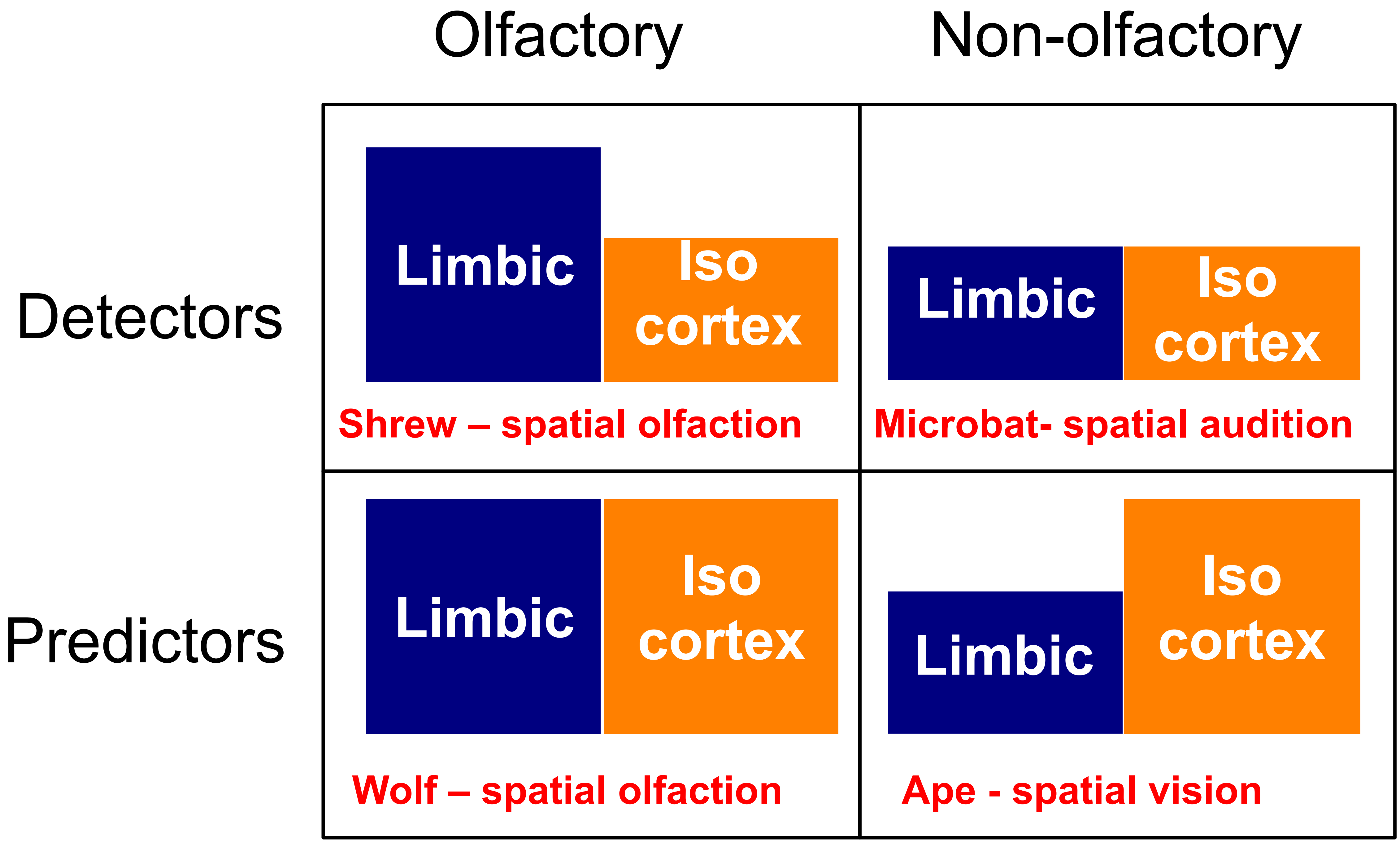
Iso cortex

Predictor

Limbic

Iso cortex

PATTERNS IN LIMBIC ALLOCATION COINCIDE WITH OLFACTION AND PREDATORY STRATEGY



Jacobs, L. (2012) From chemotaxis to the cognitive map: the function of olfaction. *PNAS.*

HIPPOCAMPAL NEUROGENESIS COVARIES WITH SPATIAL OLFACTION, NOT JUST SPATIAL BEHAVIOR

ONLY two locales of adult neurogenesis found in **all vertebrates…**

- **Olfactory Bulb (OB)**
- **Hippocampus (HP)**

Echolocating microbats and whales/dolphins (sonar)

- **small/absent OB size, low/absent HP neurogenesis**

Simple/non-echolocating (mega) bats:

- **intermediate OB size, intermediate HP neurogenesis**



Amrein, I., Dechmann, D. K., Winter, Y., & Lipp, H.-P. (2007). Absent or Low Rate of Adult Neurogenesis in the Hippocampus of Bats (Chiroptera). *PLoS ONE*.

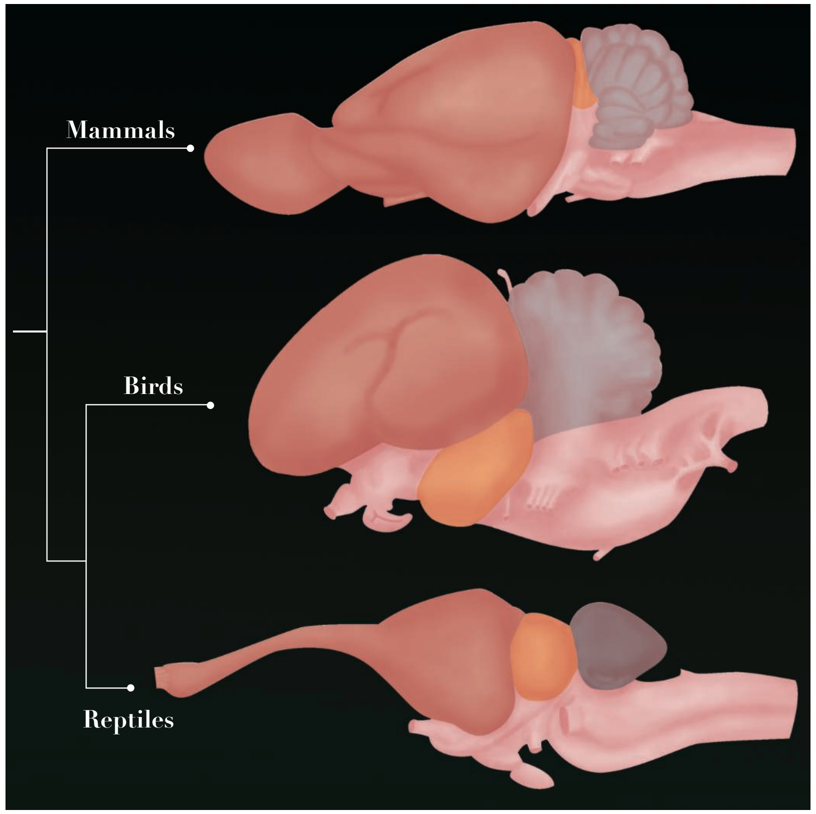
Gatome, C. W., Mwangi, D. K., Lipp, H.-P., & Amrein, I. (2010). Hippocampal neurogenesis and cortical cellular plasticity in Wahlberg's epauletted fruit bat: a qualitative and quantitative study. *Brain, Behavior and Evolution.*

BRAIN EVOLUTION REVOLUTIONS

"The mammalian neocortex with its protean powers has evolved from the olfactory forebrain of primitive vertebrates. Perhaps because olfaction demands a neural architecture preadapted to learning complex input patterns."

Daniel Osorio, Wayne Getz and Jurgen Rybak. 1994. Insect vision and olfaction: different neural architectures for different kinds of sensory signal? From animals to animats 3. MIT Press.

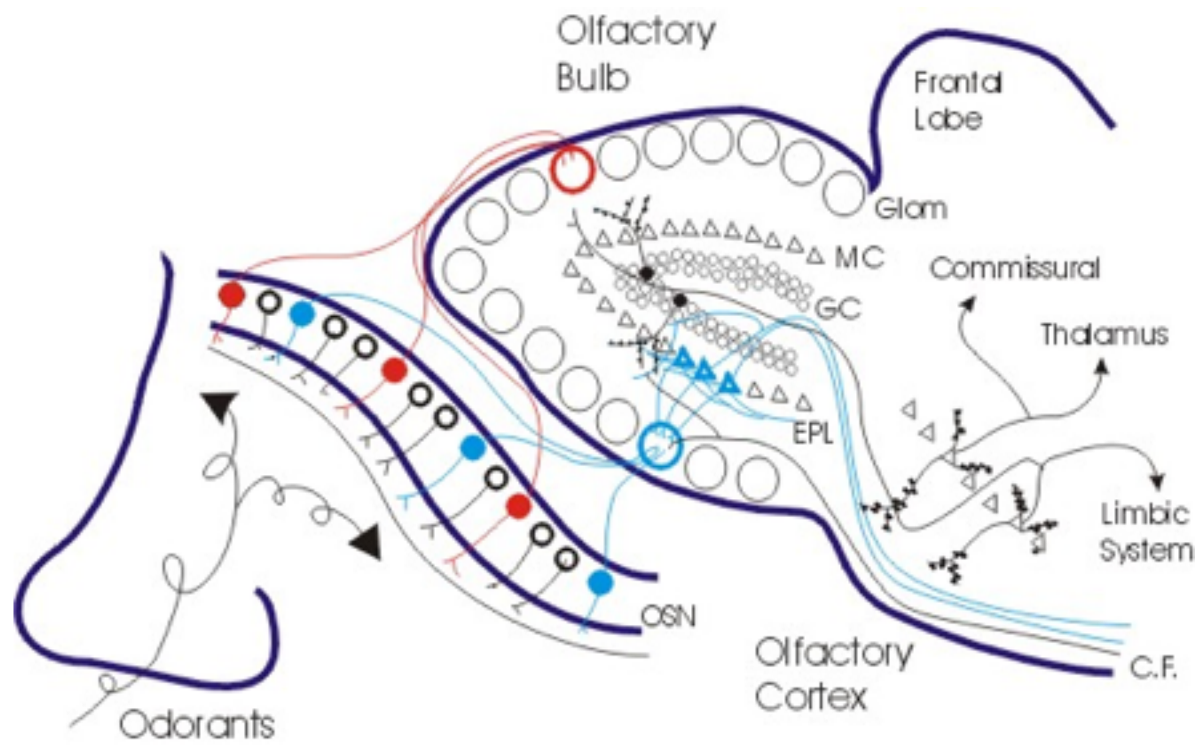
3 'pulses' of olfactory enhancement preceded increases in total brain size in Early Jurassic

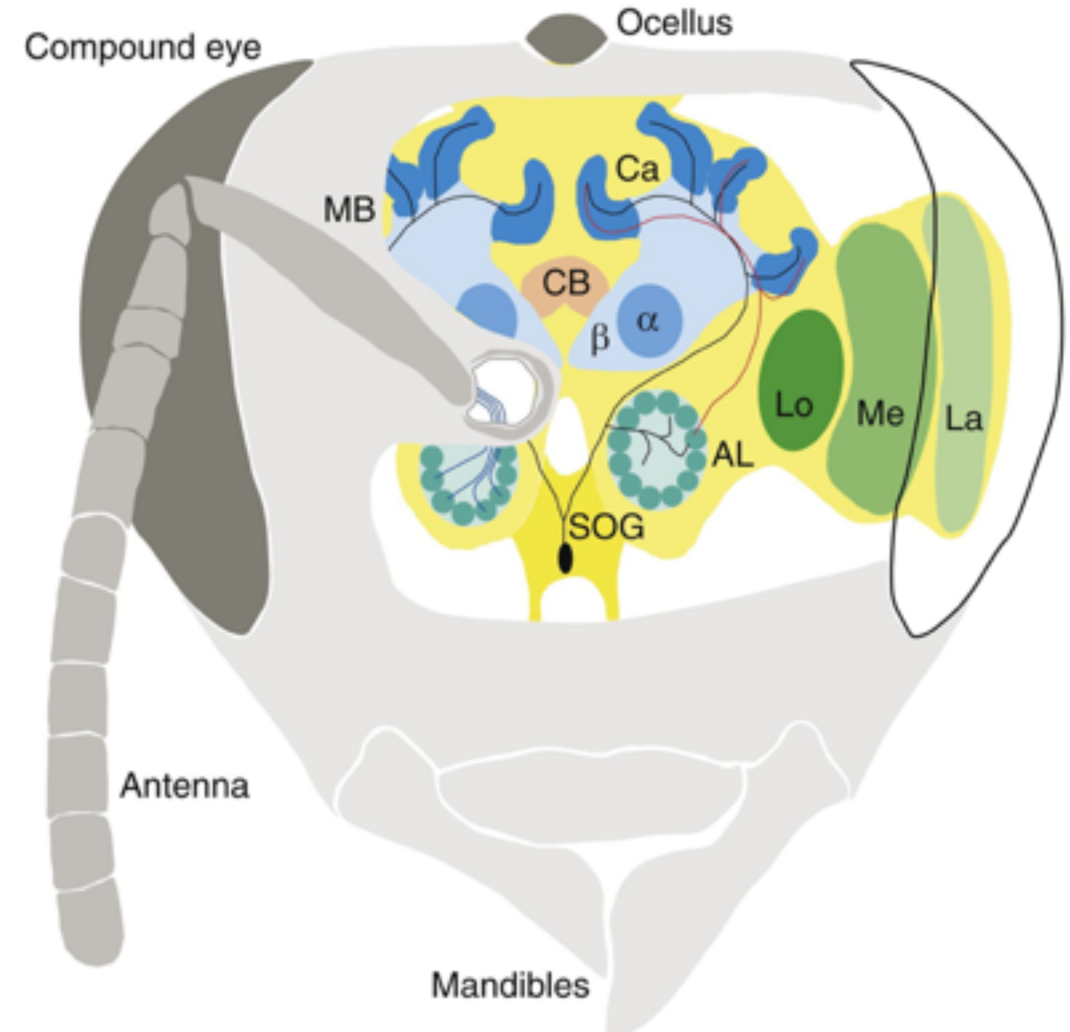


Rowe, T. B., Macrini, T. E., and Luo, Z.-X. (2011). Fossil Evidence on Origin of the Mammalian Brain. *Science* 332, 955–957.

Is this more general?

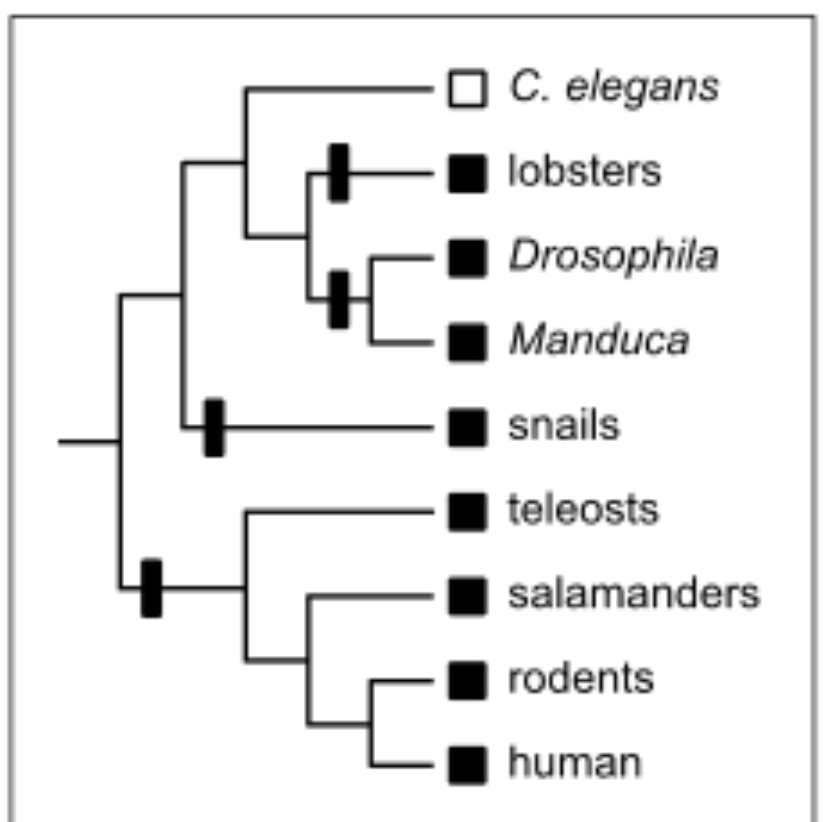
SIMILARITIES IN OLFACTORY SYSTEMS





Olfactory Glomerulus Present

Eisthen BBE (2002)



Nematode
Crustacean
Insects
Mollusk
Bony Fish
Amphibian
Rodent
Human

PNAS

Honey bees navigate according to a map-like spatial memory

Randolf Menzel*†‡, Uwe Greggers*†, Alan Smith†§, Sandra Berger*, Robert Brandt*, Sascha Brunke*, G
Sandra Hülse*, Tobias Plümpe*, Frank Schaupp*, Elke Schüttler*, Silke Stach*, Jan Stindt*, Nicola Stol
and Sebastian Watzl*

*Institut für Biologie, Neurobiologie, Freie Universität Berlin, Königin-Luise-Strasse 28/30, 14195 Berlin, Germany; and §Plant and Inv
Rothamsted Research, Harpenden, Herts AL5 2JQ, United Kingdom

Communicated by Charles R. Gallistel, Rutgers, The State University of New Jersey, Piscataway, NJ, November 25, 2004 (received for re

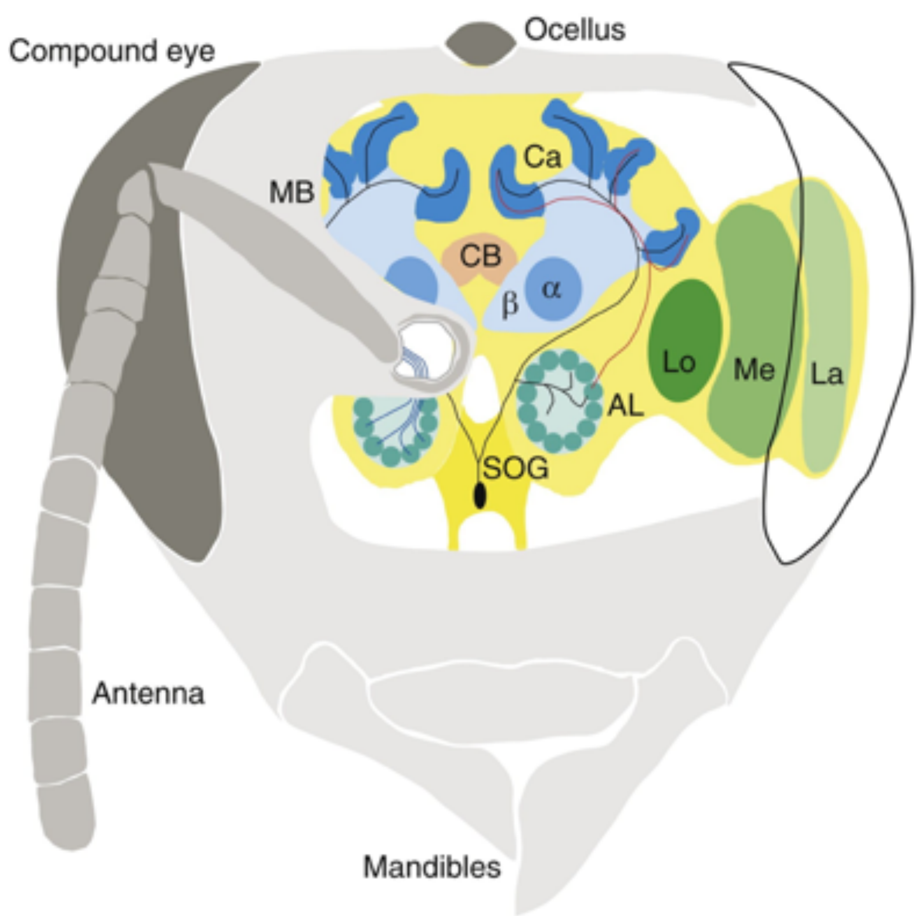
True navigation and magnetic maps in spiny lobsters

Larry C. Boles & Kenneth J. Lohmann

Department of Biology, University of North Carolina, Chapel Hill, North Carolina 27599, USA

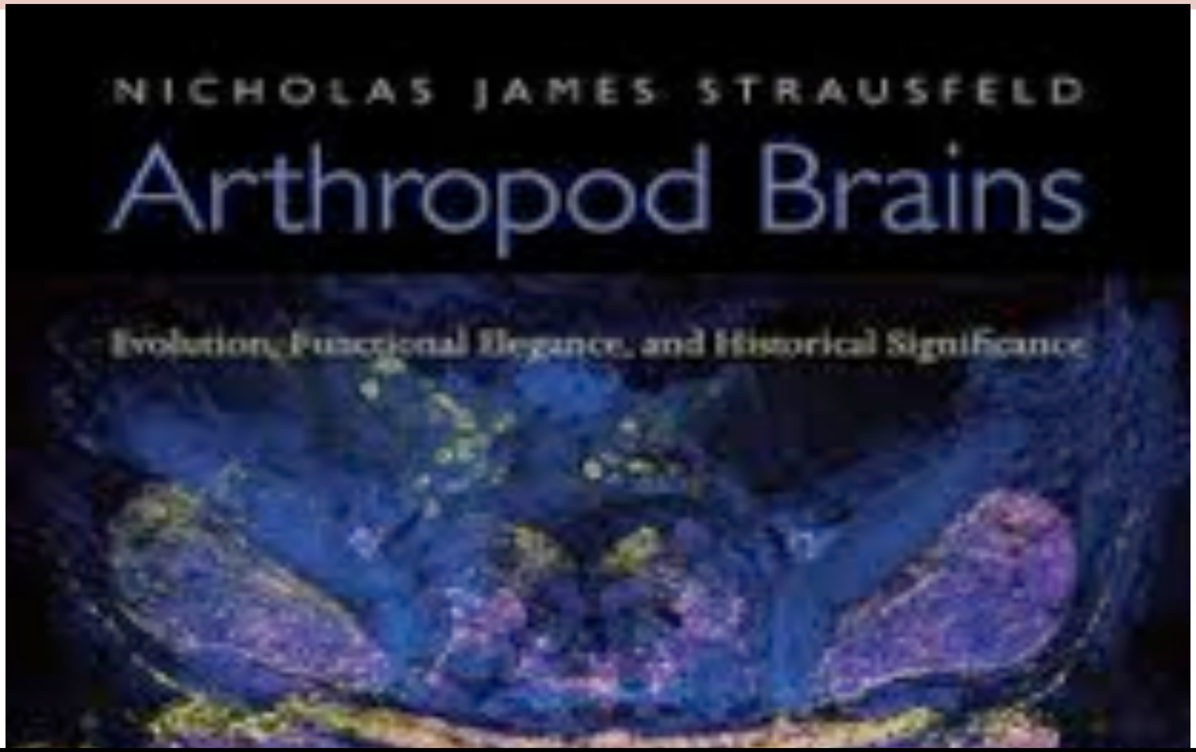
HONEY BEES AND LOBSTERS MAP…SANS HIPPOCAMPUS

INSECT BEARING MAP?



Insect MUSHROOM BODY primarily olfactory, input from ANTENNAL LOBE

Water-Striders: reduced AL, robust MB: sensory substitution

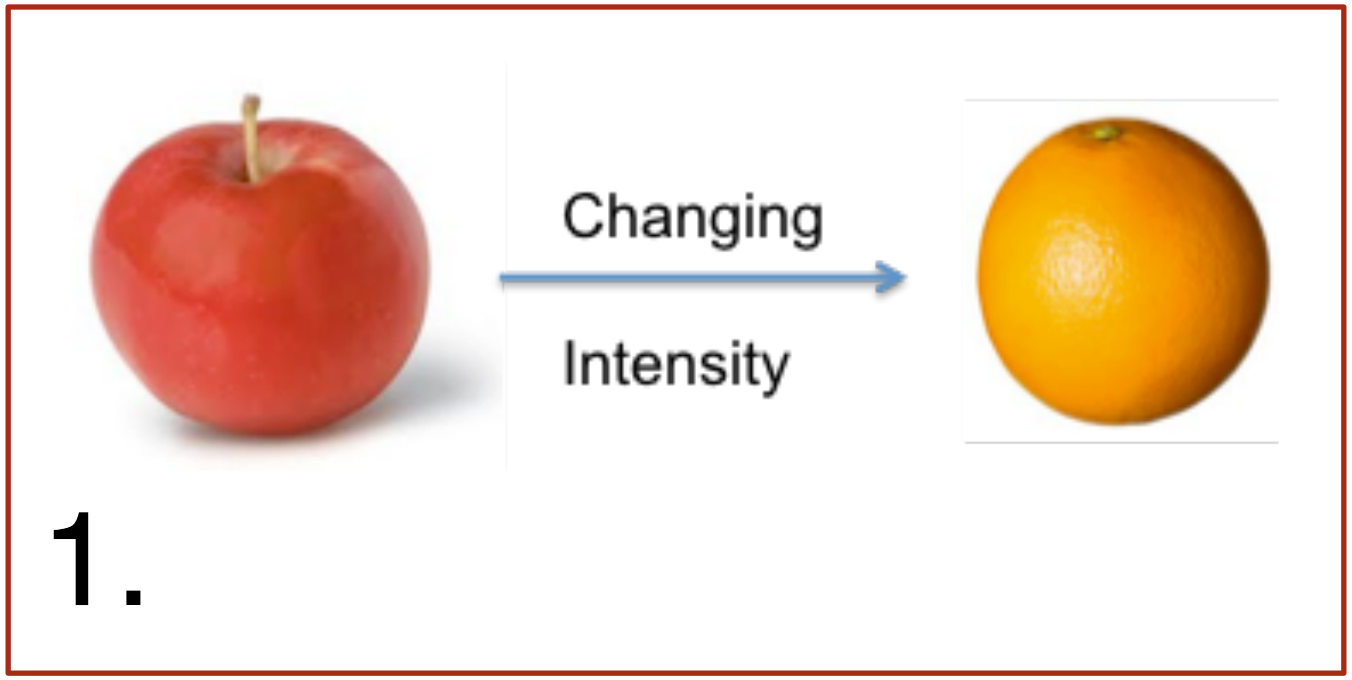


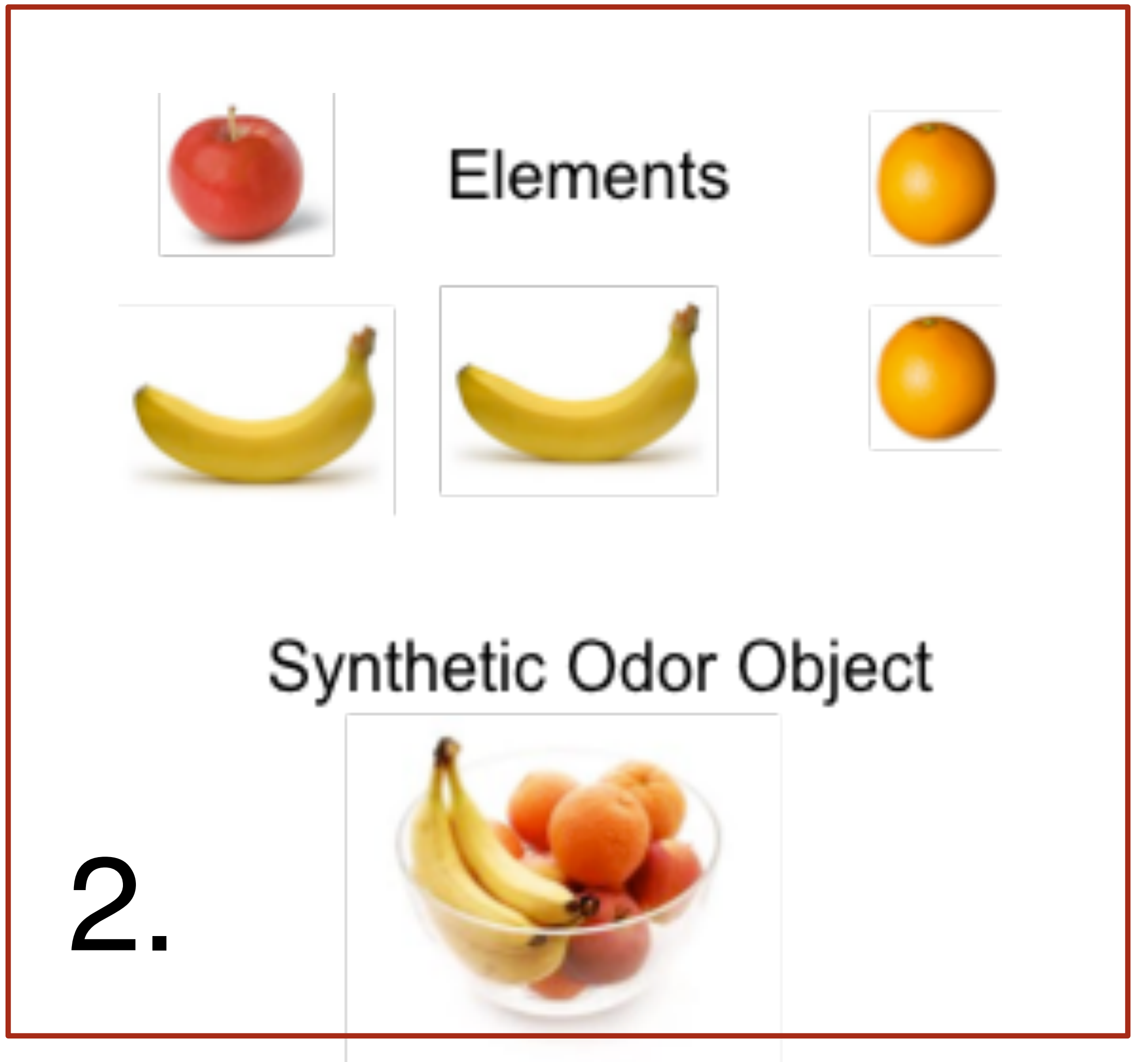
Strausfeld, N. J., Sinakevitch, I., Brown, S. M., & Farris, S. M. (2009). Ground plan of the insect mushroom body: Functional and evolutionary implications. *J. Comp. Neurol.*

Implications

- Demand for spatial olfaction may explain patterns of allometry and plasticity across diverse taxa.
- Olfactory circuits could thus be constructed not only to identify but also to map odors for the purpose of spatial navigation.

COULD THESE PERCEPTUAL PHENOMENA HAVE SPATIAL FUNCTIONS?

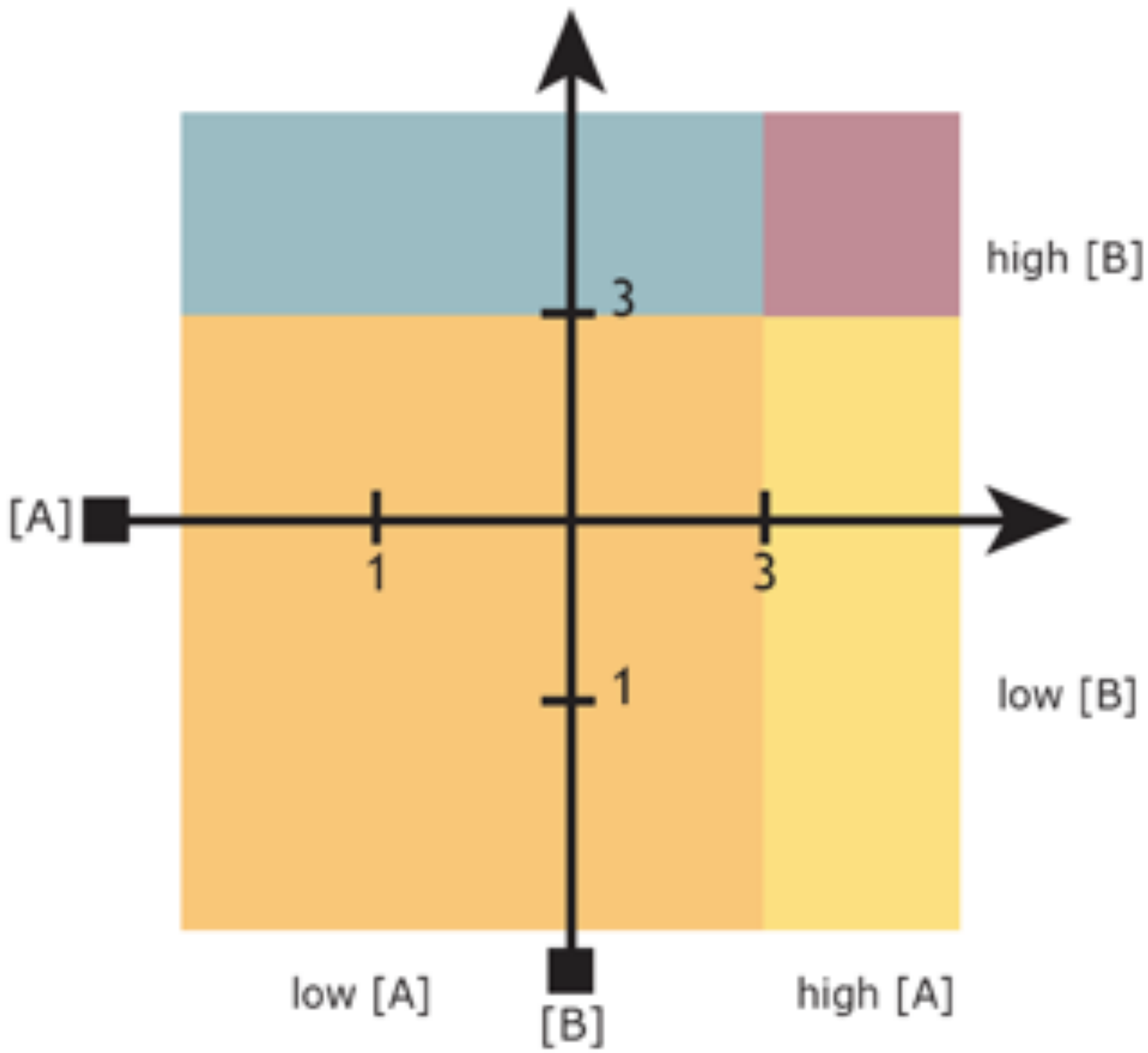




ODOR PERCEPT COULD CREATE GLOBAL ORGANIZATION

Intensity gradients demarcated

- High and low concentration percepts
- Creates neighborhoods in olfactory space



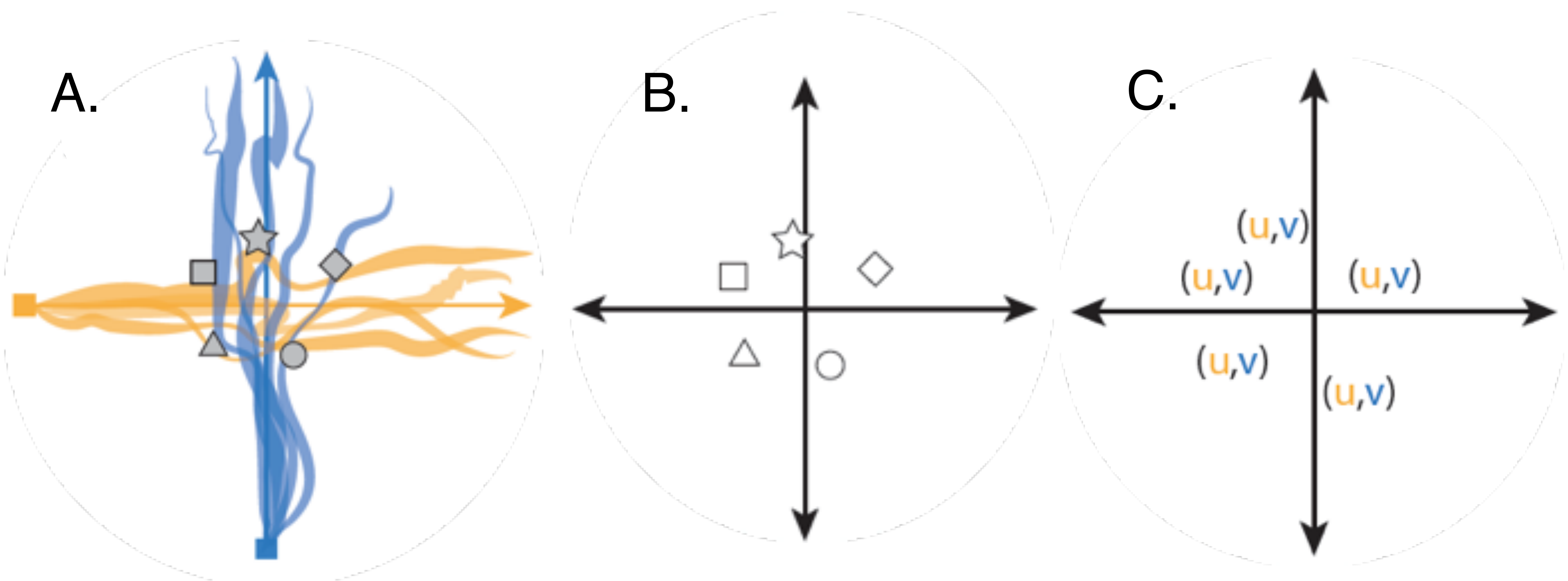
ODOR OBJECTS COULD BE PERCEIVED AS POSITIONAL CUES (LANDMARKS)

Confluence of odorant plumes

A. Unique ratios located in olfactory space

B. Perceived as Synthetic Odor Object

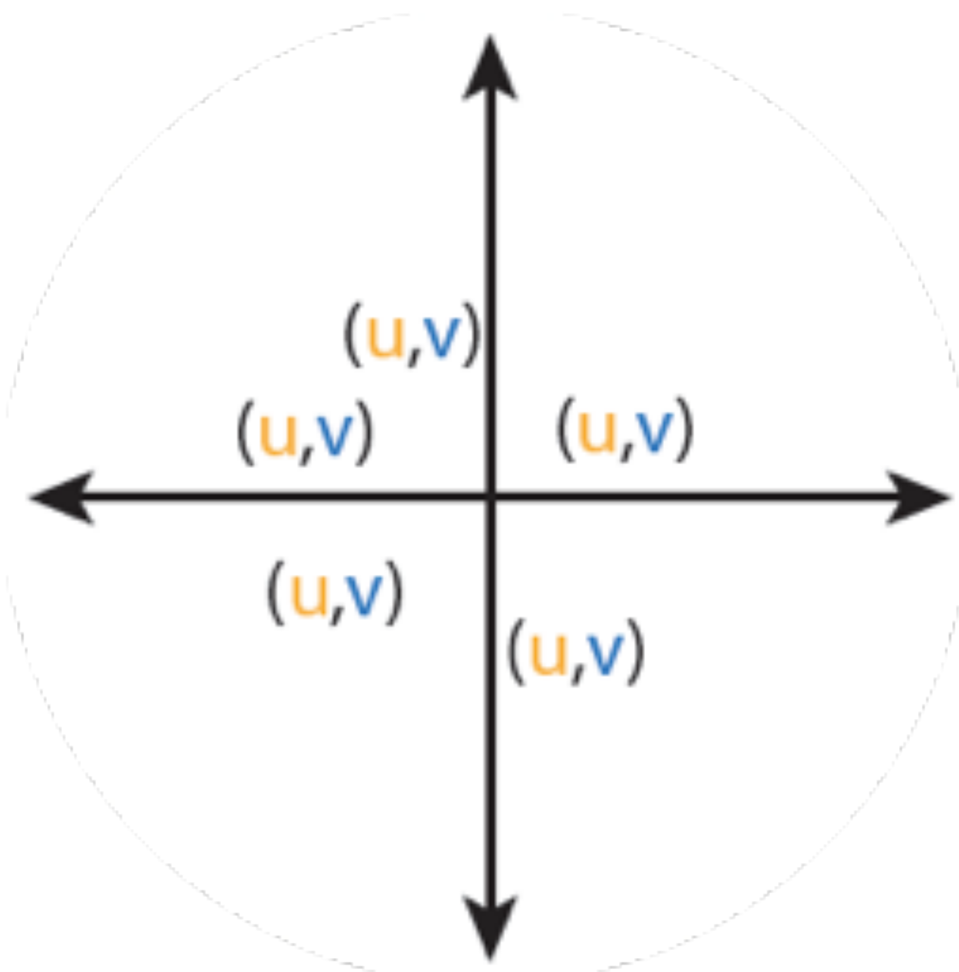
C. Perceived as Mixture of Elements

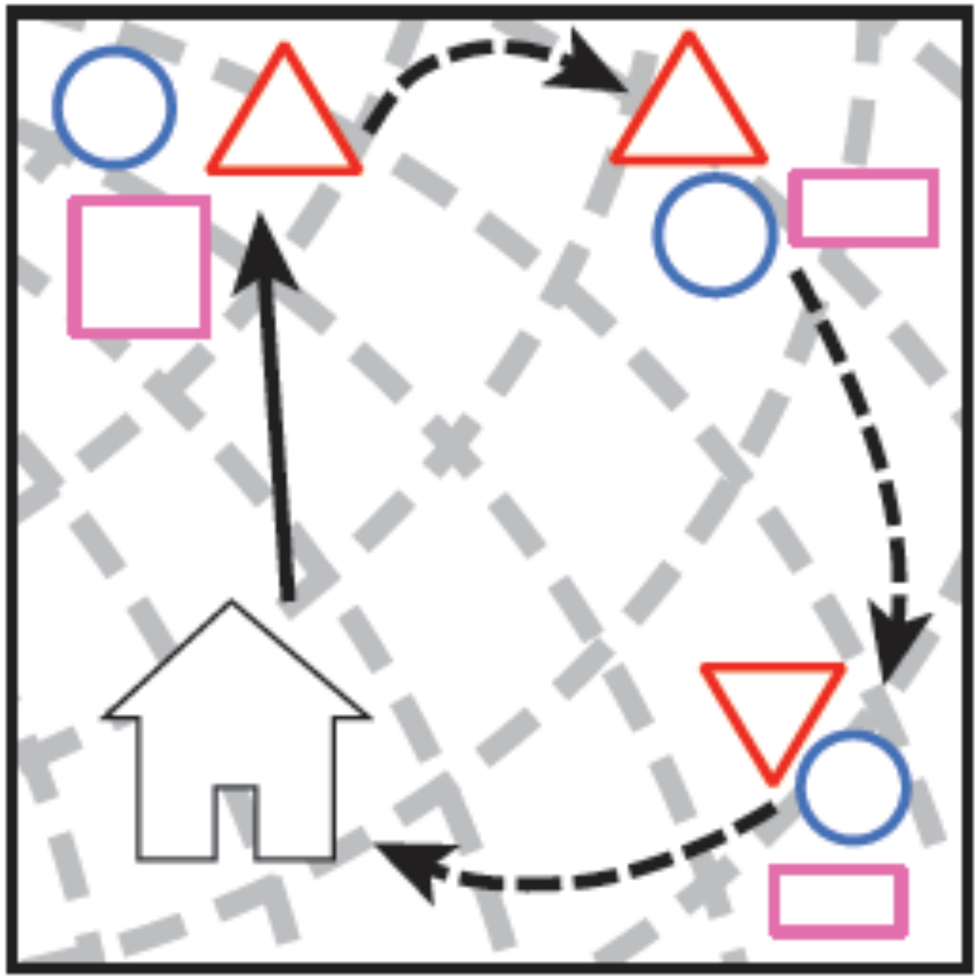


OLFACTION COULD USE PARALLEL MAP STRUCTURE TO STORE AND EXTRAPOLATE

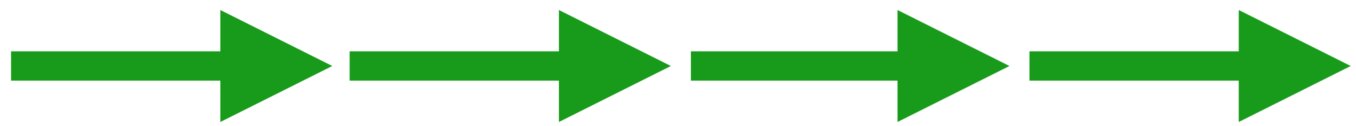
Has necessary information – origin of hippocampal logic?

- Objects re-coded in grid coordinates
- Flexible short-cutting





What other properties are needed to map gradients?



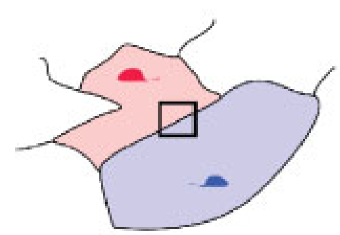
- MUST KNOW
  - Rate of locomotion
  - Rate of sampling (respiration)
- DECODE fluid direction and speed, using measurements from other systems (vibrissae, rhinarium, etc.)

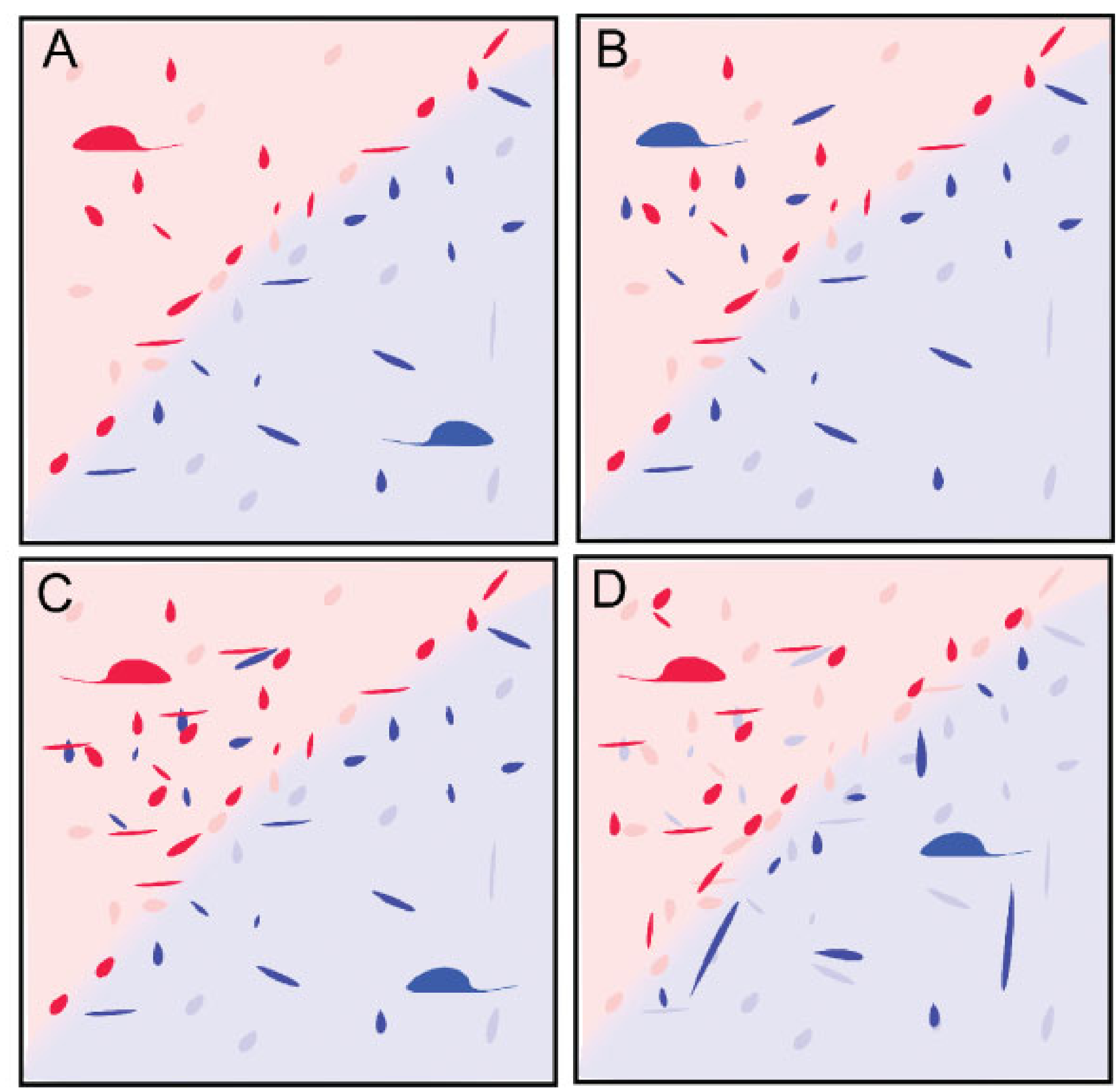
Space and Time

Review articles

Scent wars: the chemobiology of competitive signalling in mice

Jane L. Hurst* and Robert J. Beynon





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