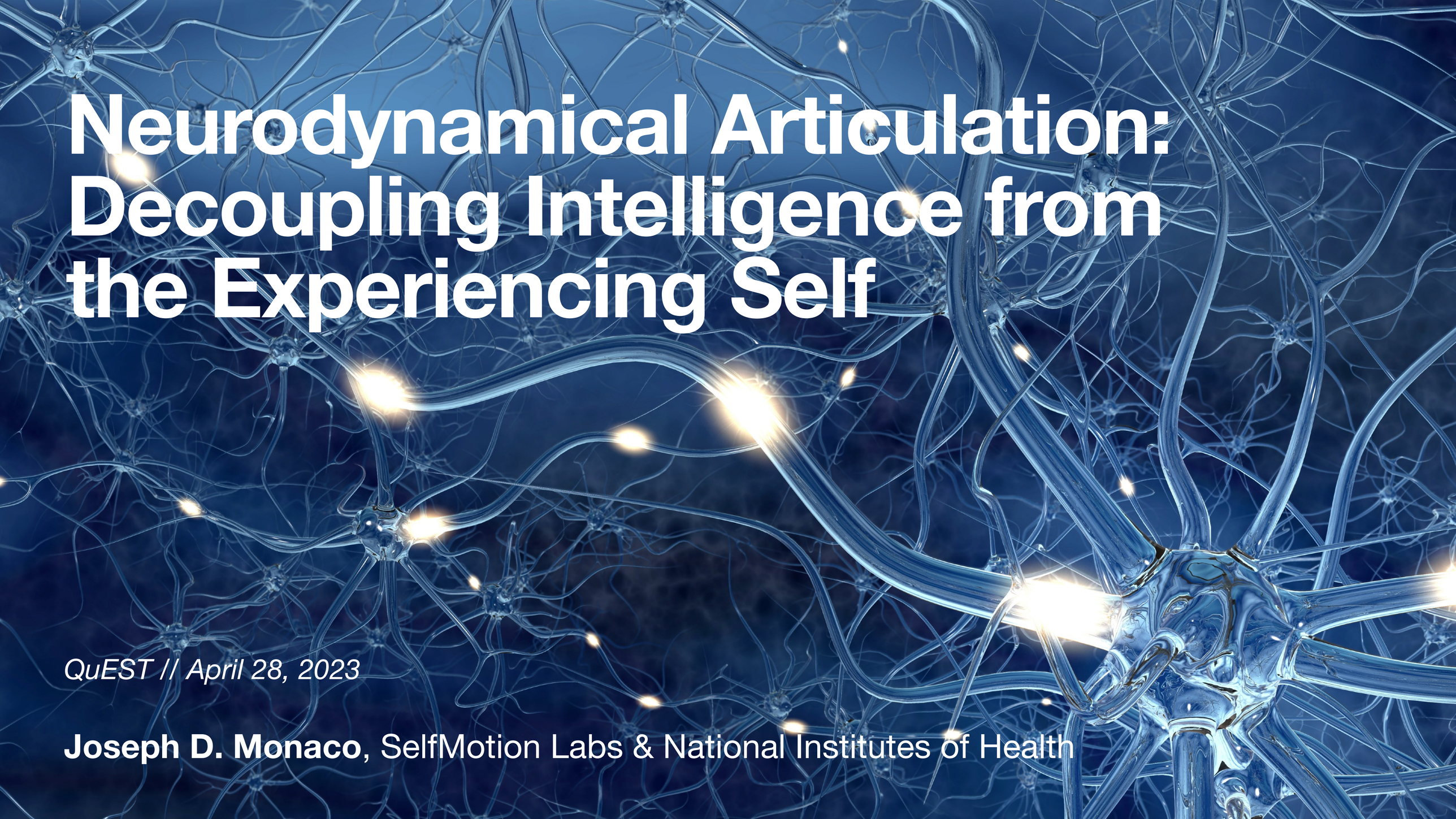


Neurodynamical Articulation: Decoupling Intelligence from the Experiencing Self

QuEST // April 28, 2023

Joseph D. Monaco, SelfMotion Labs & National Institutes of Health

Intelligence vs. conscious experience

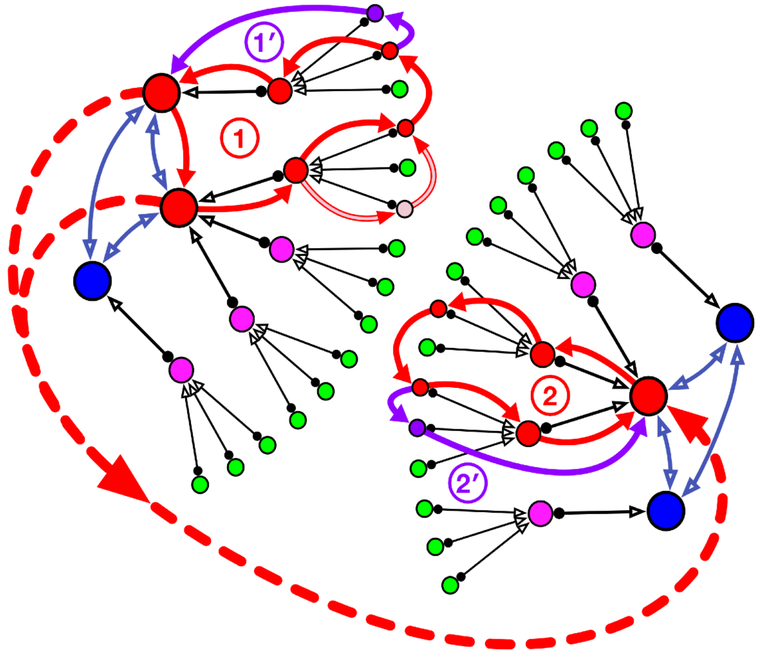
Minded vs. unminded competence, calculative rationality, and computation

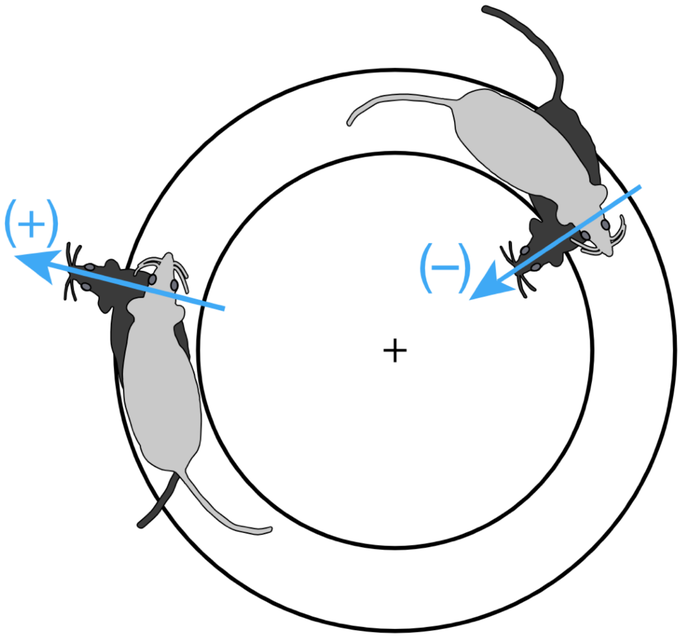
- The BIG questions…
  - What is intelligence and what is it for?
  - What is consciousness and what is it for?

Neurodynamical computing

A dynamical control framework for biological intelligence

1. Briefly review disciplinary approaches to formalizing biological intelligence
    - Highlight persistent gaps in concepts, theories, and hypotheses
2. Motivate a perceptual control framework for resolving external observer bias
    - Informational implications for cognitive computing with neural dynamics
3. Synthesize structure and temporal properties of mammalian hippocampal-cortical networks
    - Oscillations, dynamical articulation, and agency

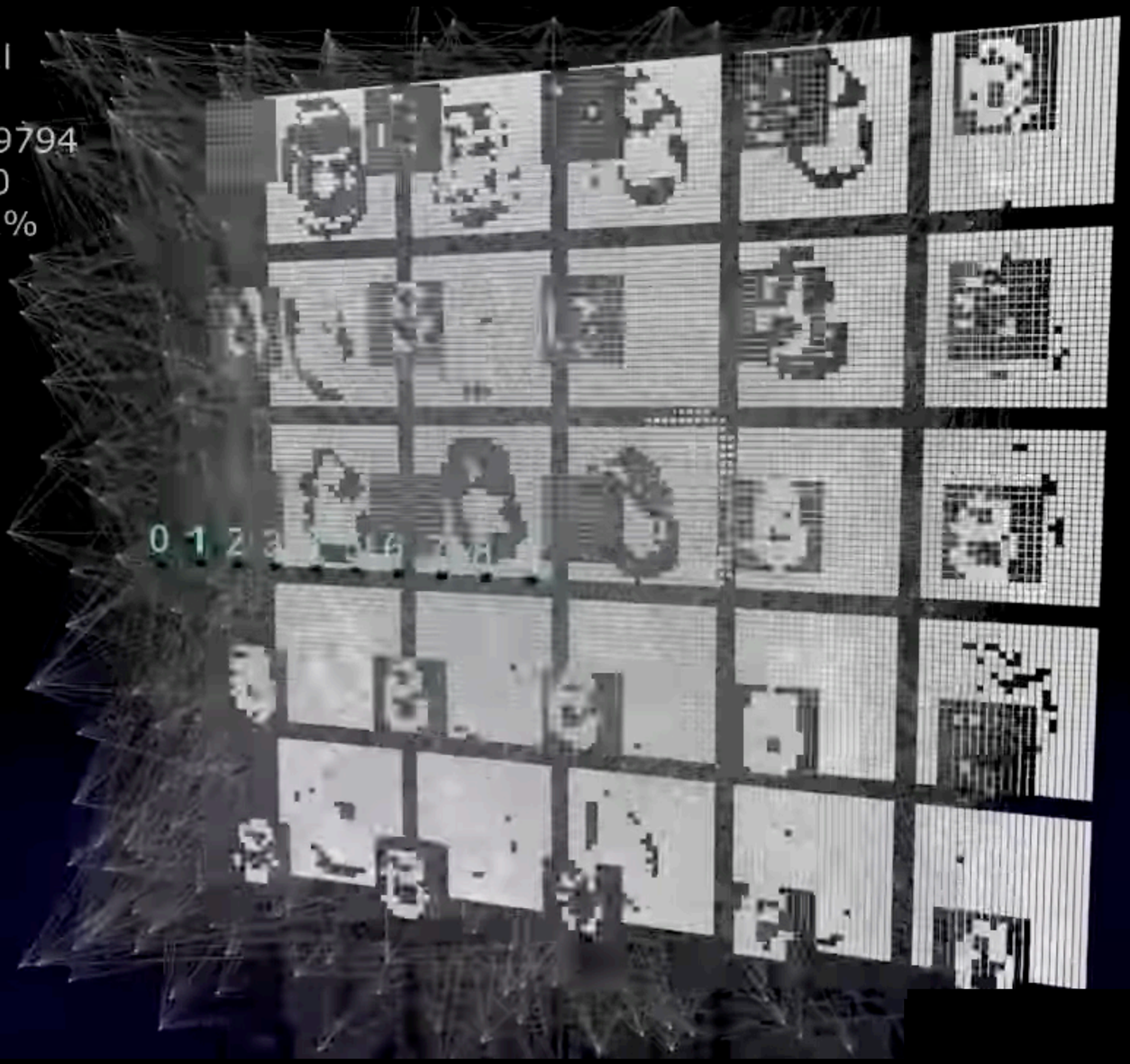


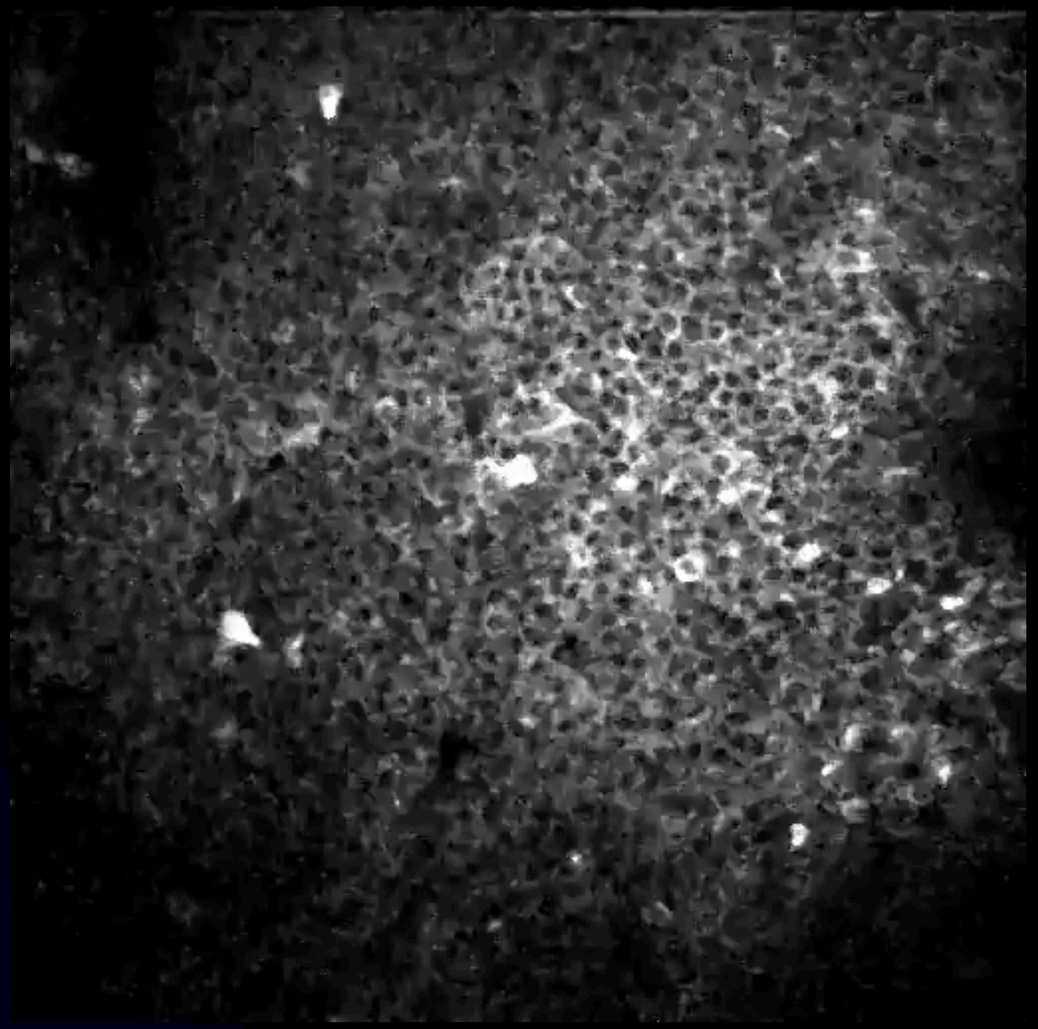


Three paths…

Framing an integrative (computational) neuroscience of intelligence

- Cybernetics→
  Cognitive Science
- GOFAI→
  “Third Wave” AI learning and reasoning
- Behaviorist Psychology→
  Mainstream neuroscience
  - Physics of neural systems→
    Computational neuroscience





500x500 μm f.o.v. over mouse CA1 of synapsin-driven GCaMP6f during training in an olfactory working-memory task.

Video Credit: J. Taxidis

External observer bias

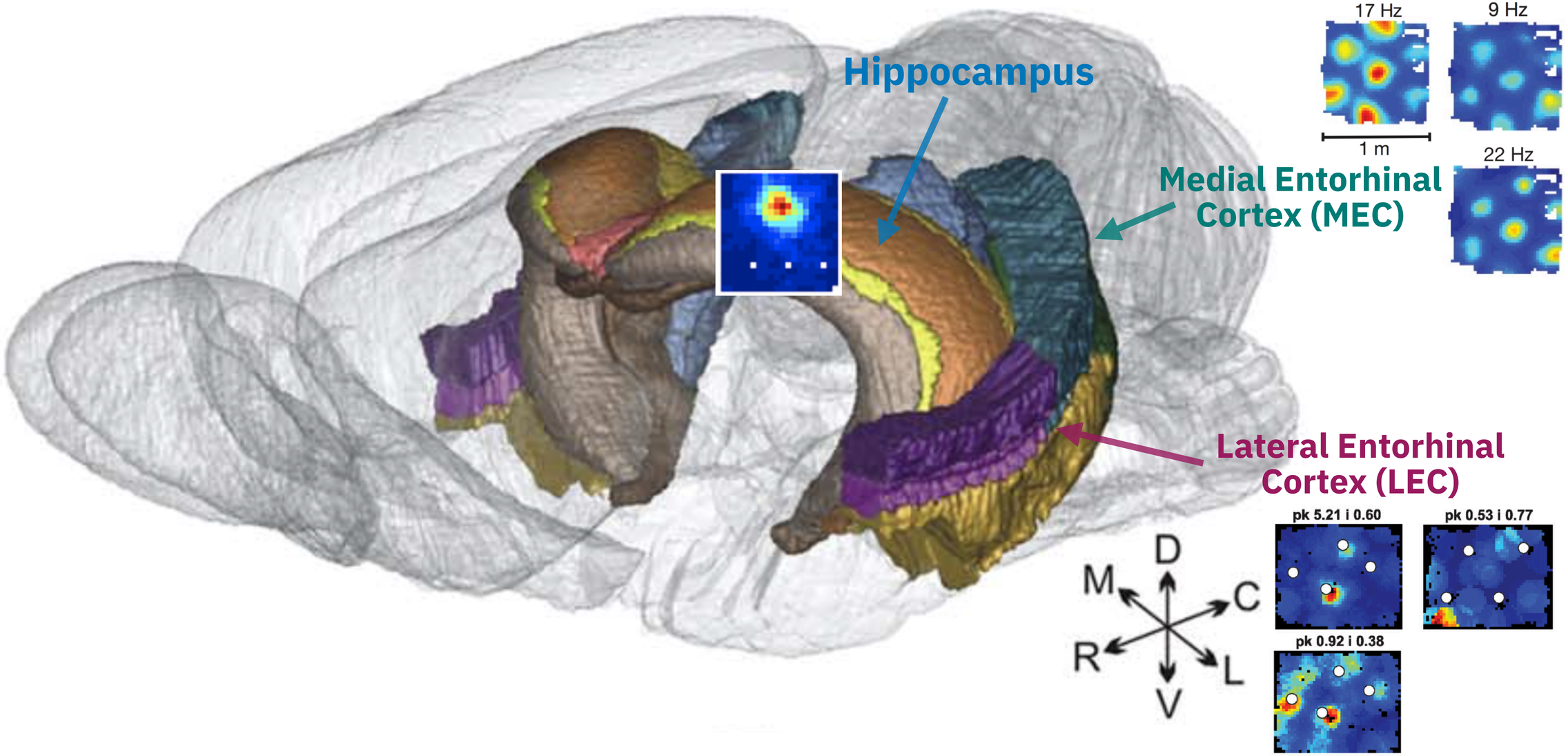
Inverting the input-output paradigm

1. Computational metaphors for the brain have entrenched the behaviorist bias that externally observable output is the endpoint of brain function

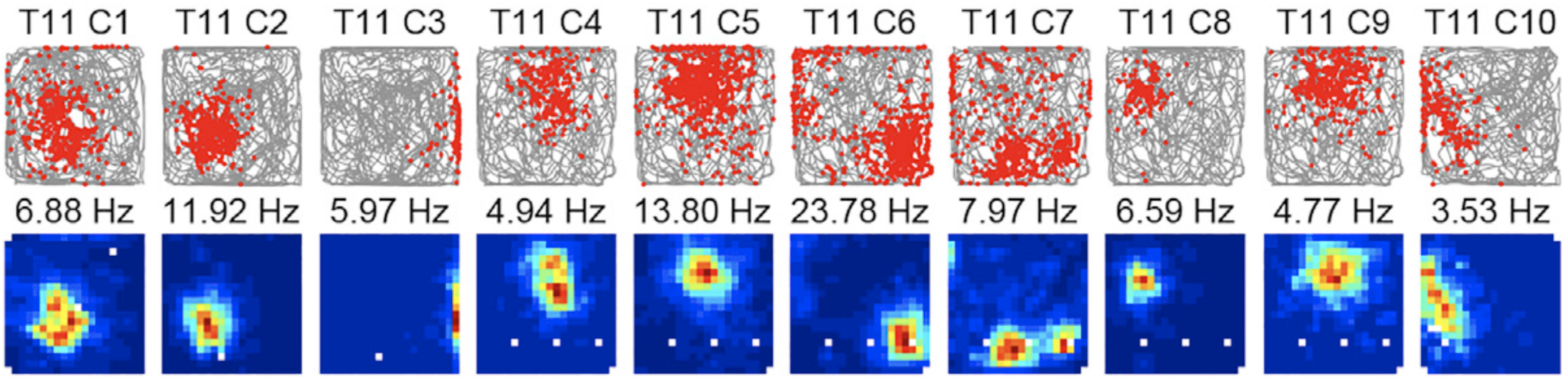
2. Neuroscience and AI have both embraced this bias, with either explicit or implicit input and output layers for computations

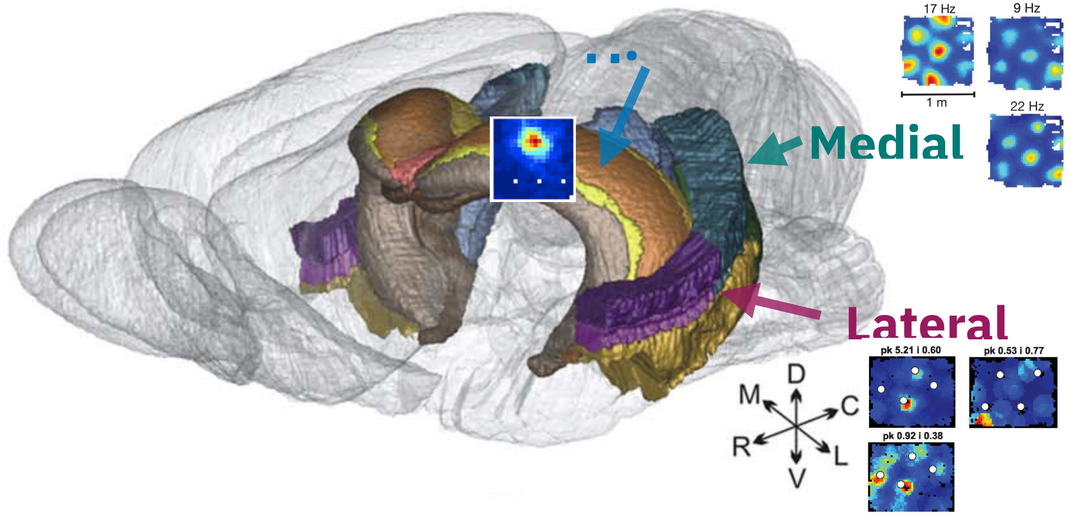
3. Implied control paradigm is one of building forward (predictive) models

Image Credit: Glazer et al. (PEGASOS)

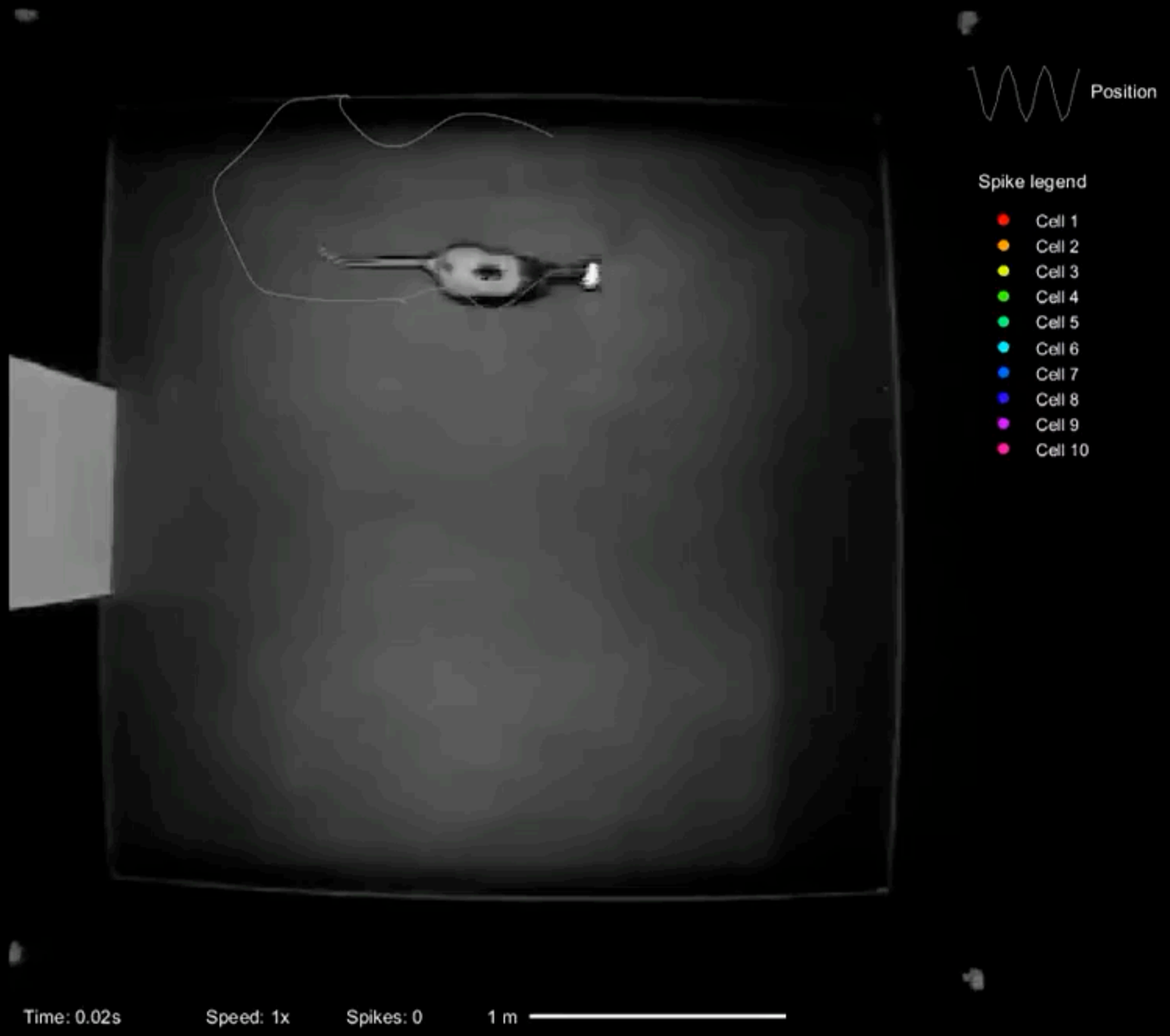


Boccara CN, *et al*. (2015). Hippocampus, 25: 838





Boccara CN, *et al*. (2015). Hippocampus, 25: 838



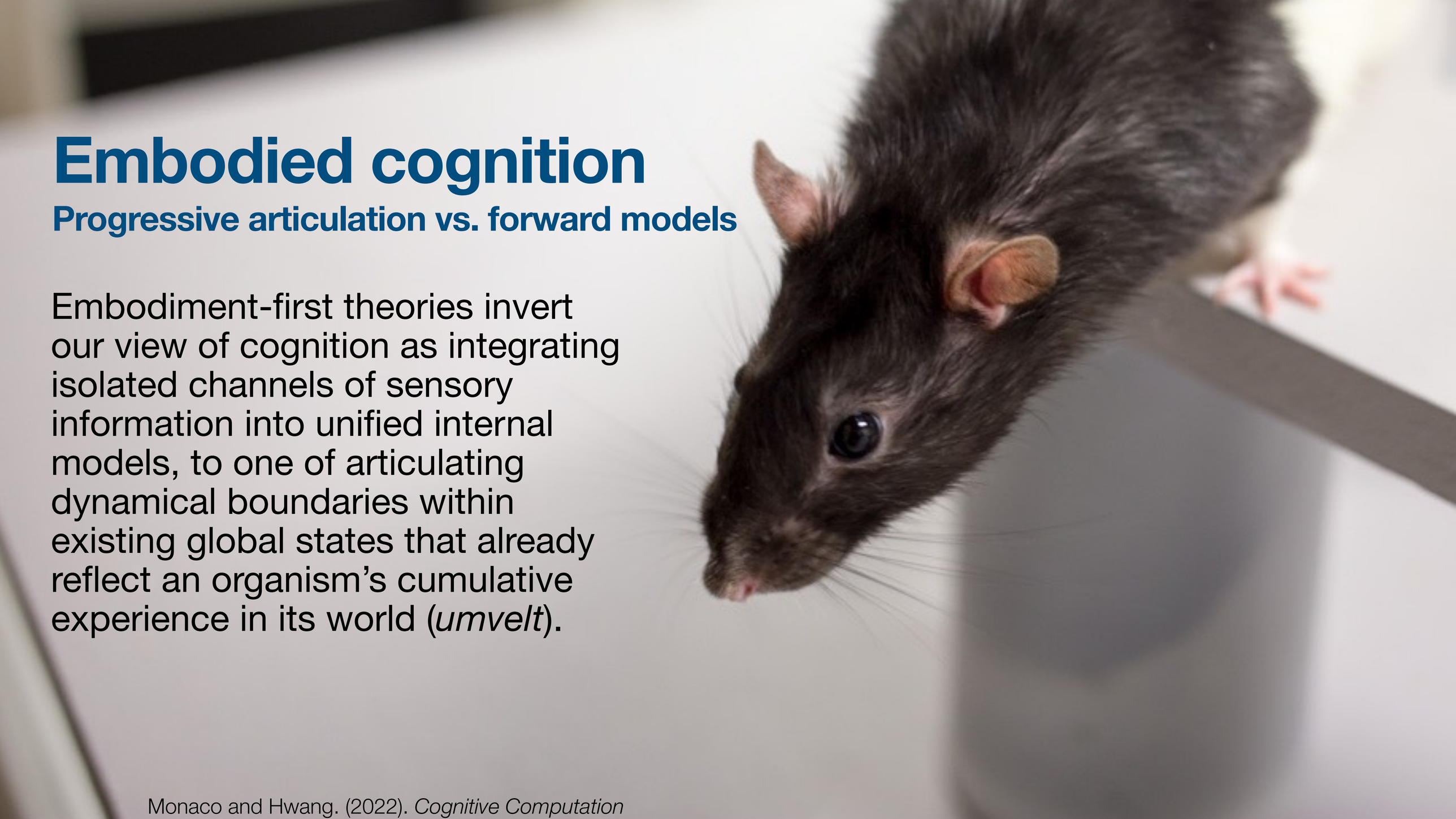
Not Actual Speed

Video Credit: R. Grieves

Embodied cognition

Progressive articulation vs. forward models

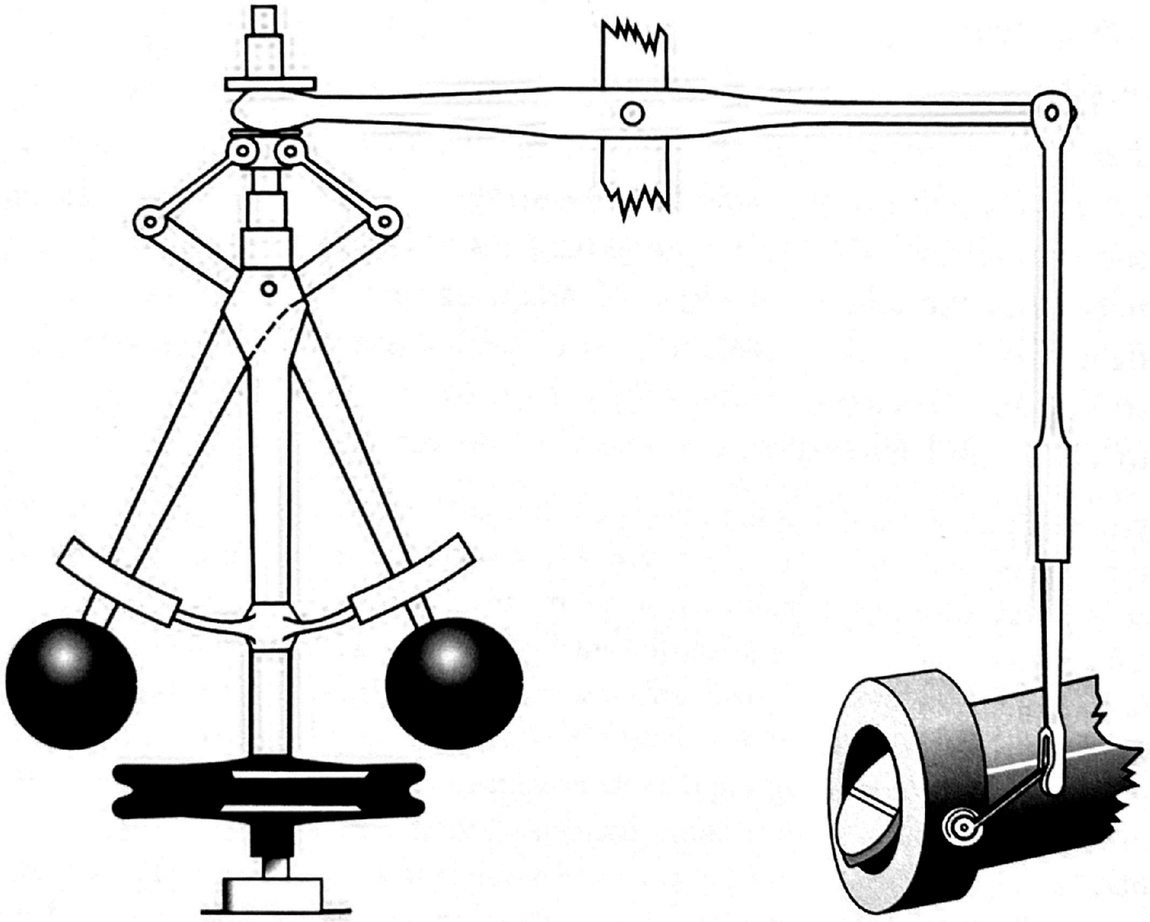
Embodiment-first theories invert our view of cognition as integrating isolated channels of sensory information into unified internal models, to one of articulating dynamical boundaries within existing global states that already reflect an organism's cumulative experience in its world (*umvelt*).



Monaco and Hwang. (2022). *Cognitive Computation*

Dynamical systems view of cognition

Temporal unfolding and the locus of agency

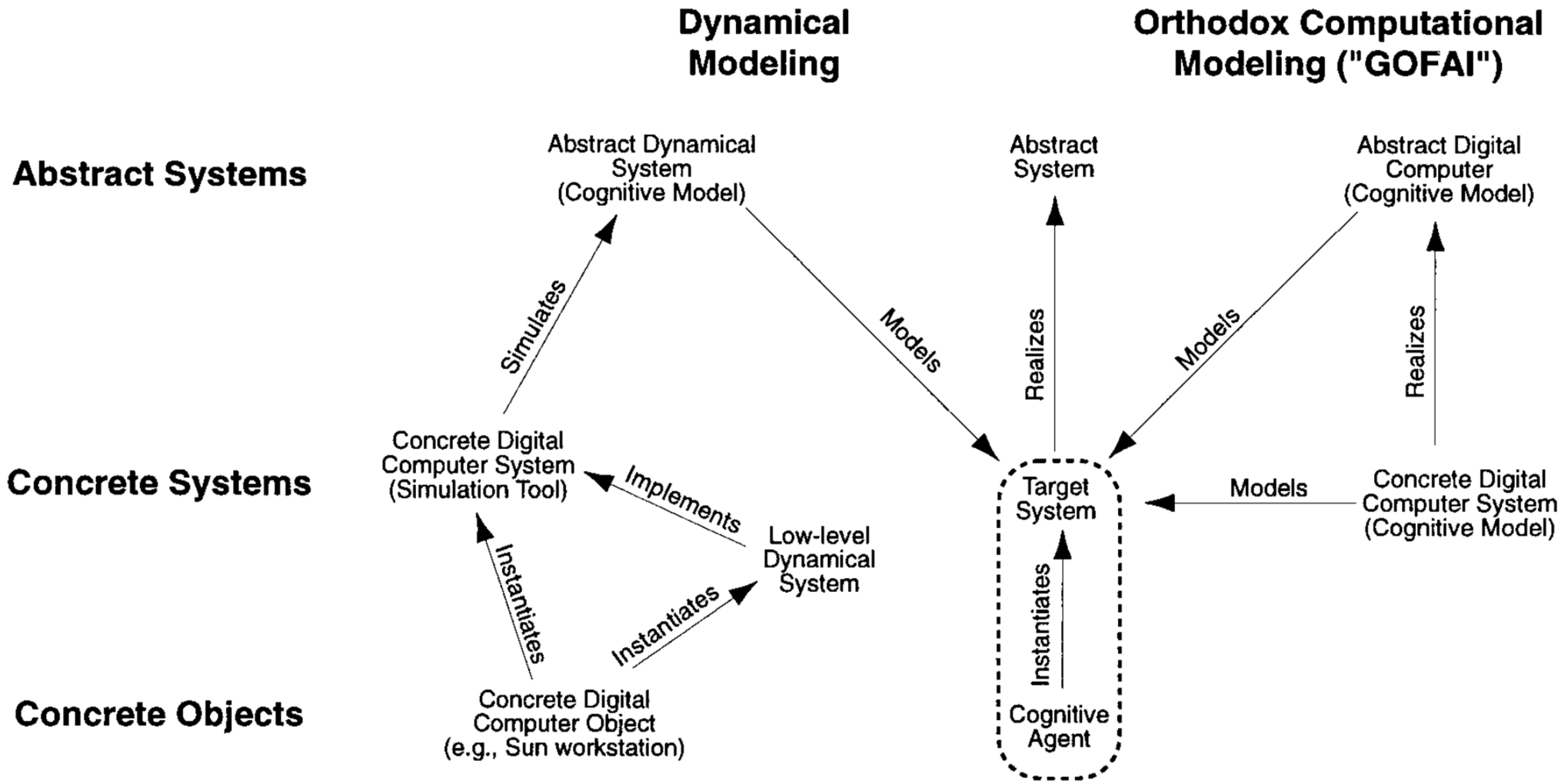


Watts' steam governor: agent or tool?

van Gelder. (1998). *Behav Brain Sci*, 21(5): 615

Dynamical systems view of cognition

Temporal unfolding and the locus of agency



van Gelder. (1998). *Behav Brain Sci*, 21(5): 615

Reorganizing the control flow

Perceptual control internalizes input, output, and goals

- Goal-setting autonomy recognizes the agency inherent in embodied living systems
    - Animals have goals and those goals govern their behavior
- Environmental control is established through internal perceptual control of corresponding sensory input

Mansell (ed.). (2020). *International Handbook of Perceptual Control Theory*

Reorganizing the control flow

Perceptual control internalizes input, output, and goals

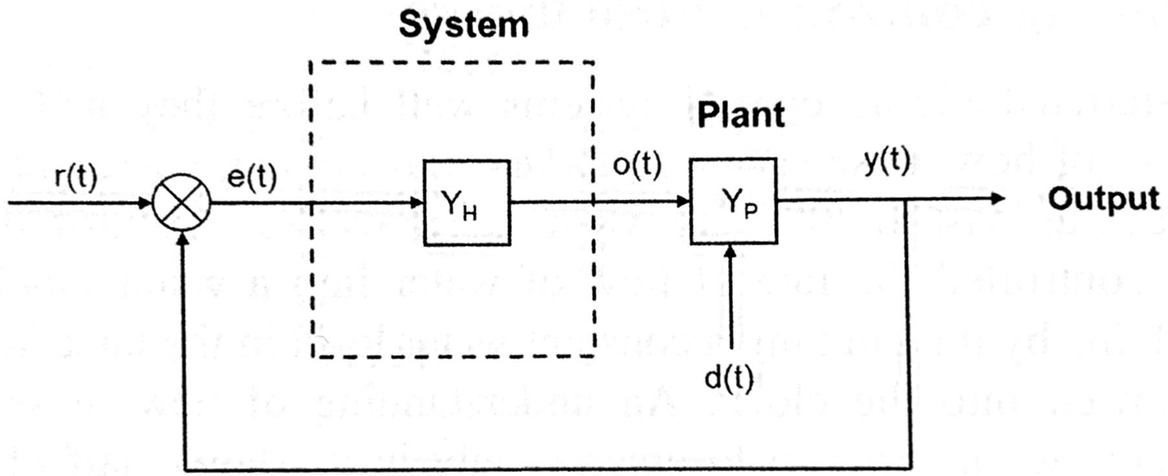


FIG. 2.1 Diagram of a negative feedback control system.[21]

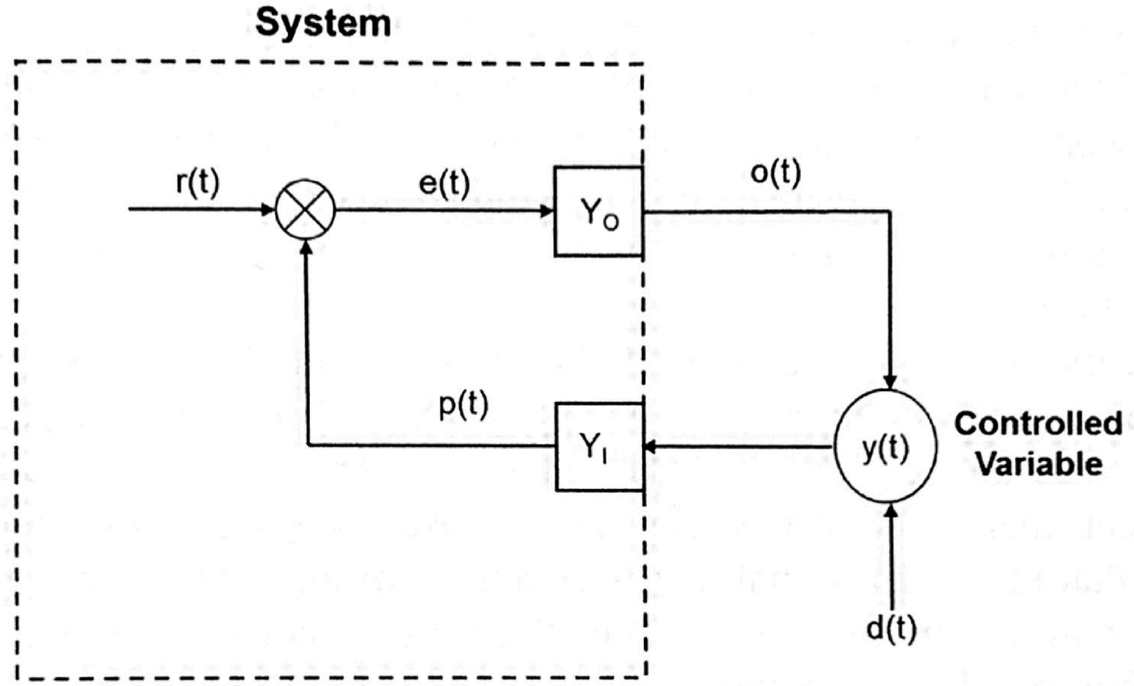


FIG. 2.2 PCT model of a control system; control theory for psychologists.

Mansell (ed.). (2020). *International Handbook of Perceptual Control Theory*

Reorganizing the control flow

Perceptual control internalizes input, output, and goals

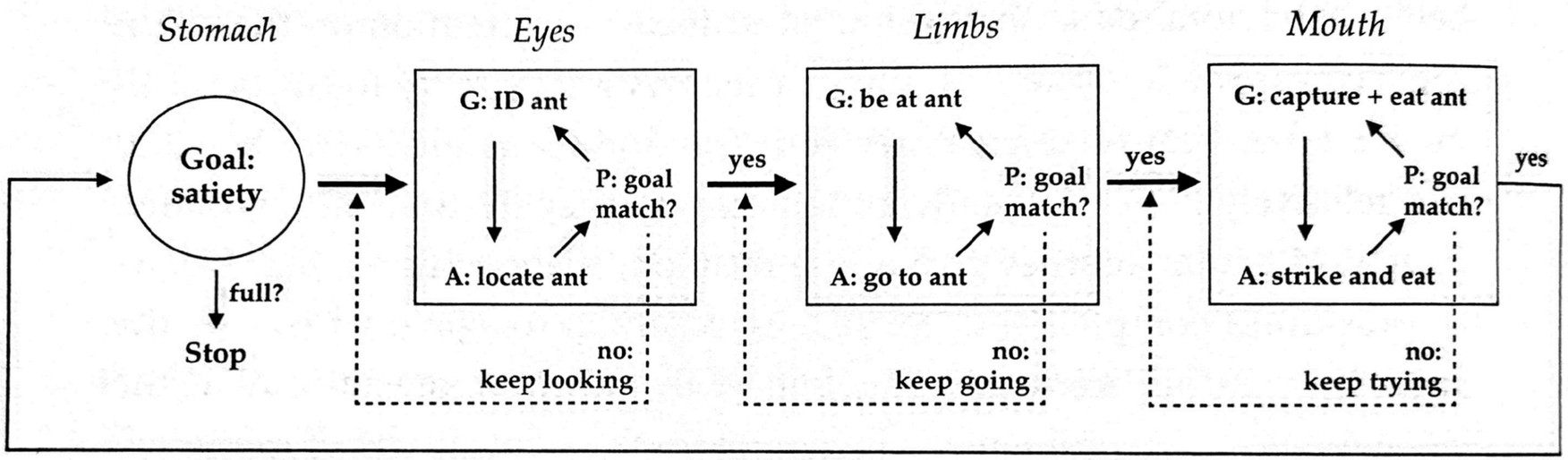


Figure 3.3

Highly simplified sequence of feedback control systems comprising a lizard's foraging for an ant efficiently and flexibly. *G* = goal; *A* = action; *P* = perception (to see if actual situation matches goal situation). Each box actually represents a hierarchy of submechanisms (e.g., moving limbs to locomote, opening mouth to eat, etc.).

Tomaselli. *The Evolution of Agency*

Reorganizing the control flow

Perceptual control internalizes input, output, and goals

- Behavior is no longer the *output* of the neural system
  - Outputs (Y_0) are cascading internal reference signals
  - The lowest control levels form the self–nonself boundary that interacts with the environment
- Internal perceptions of controlled environmental variables are controlled, not behavior

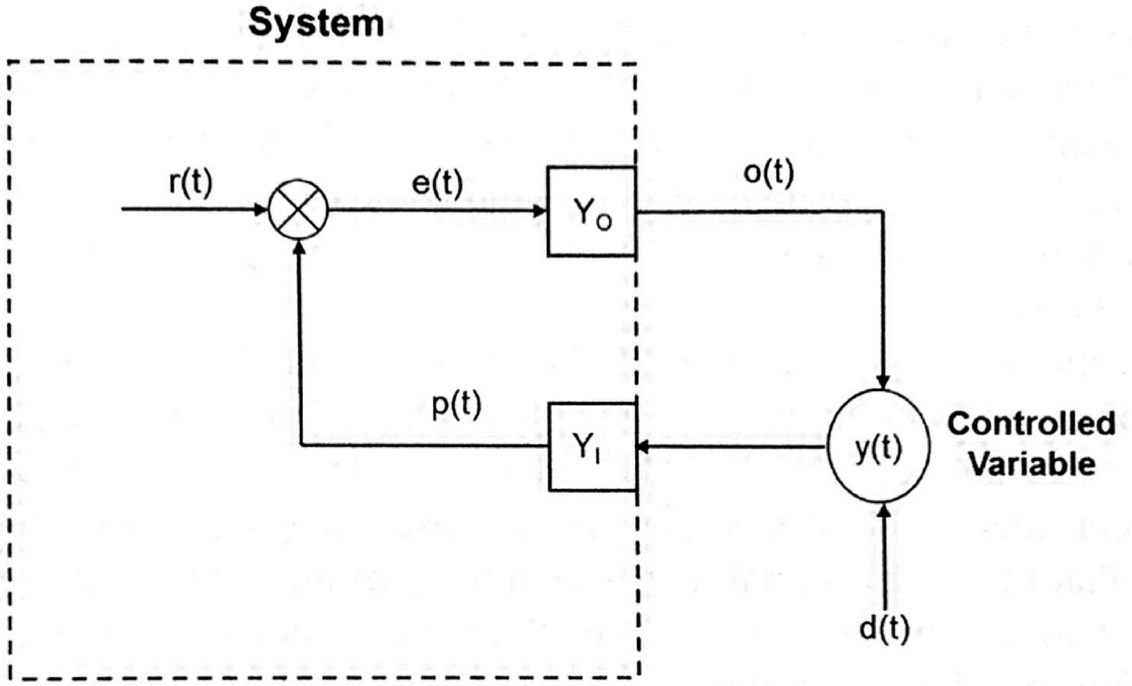


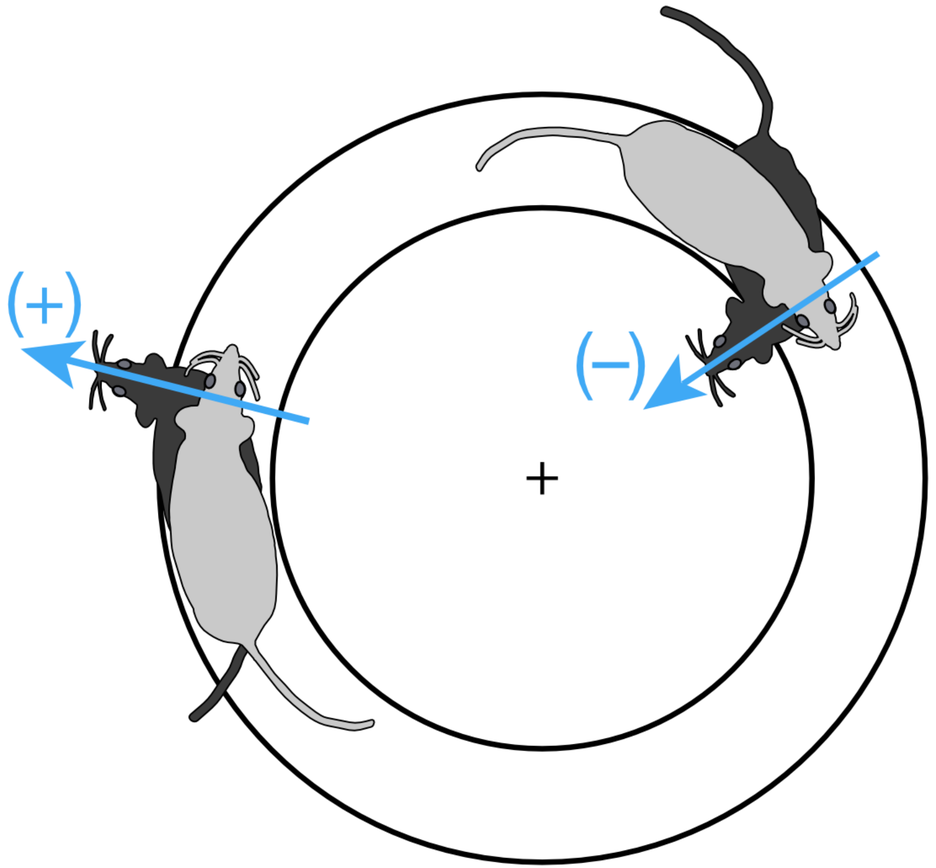
FIG. 2.2 PCT model of a control system; control theory for psychologists.

Mansell (ed.). (2020). *International Handbook of Perceptual Control Theory*

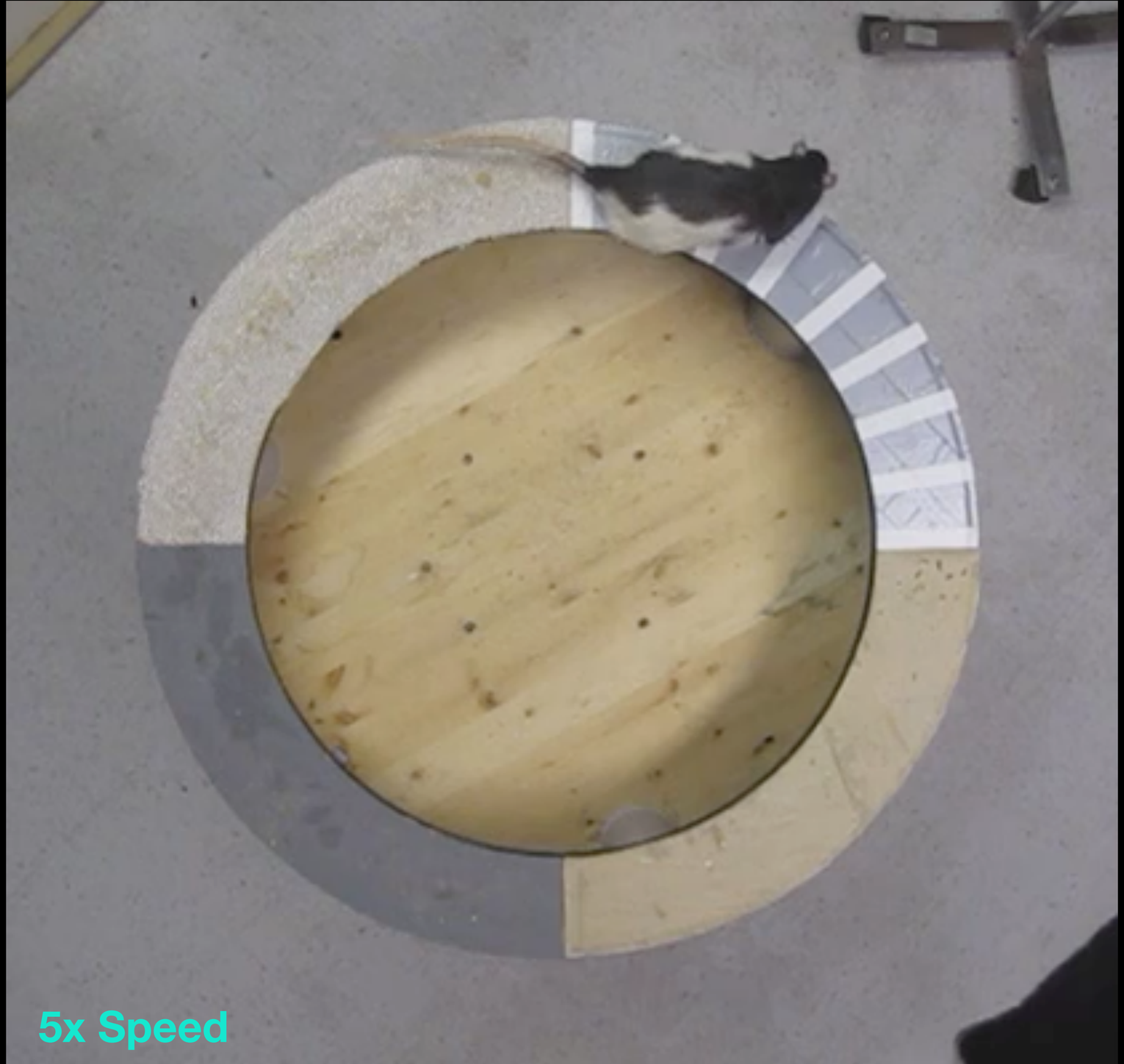
Active inference

The generative role of behavior

- Optimal (Bayesian) inference in feedback-driven generative models require *active inference*: actions that maximize model evidence by balancing internal active-state (self) entropy with external sensory-state (nonself) entropy.
    - *Agents learn massively distributed internal feedback models by adaptively balancing information streams arising at the self–nonself boundary.*

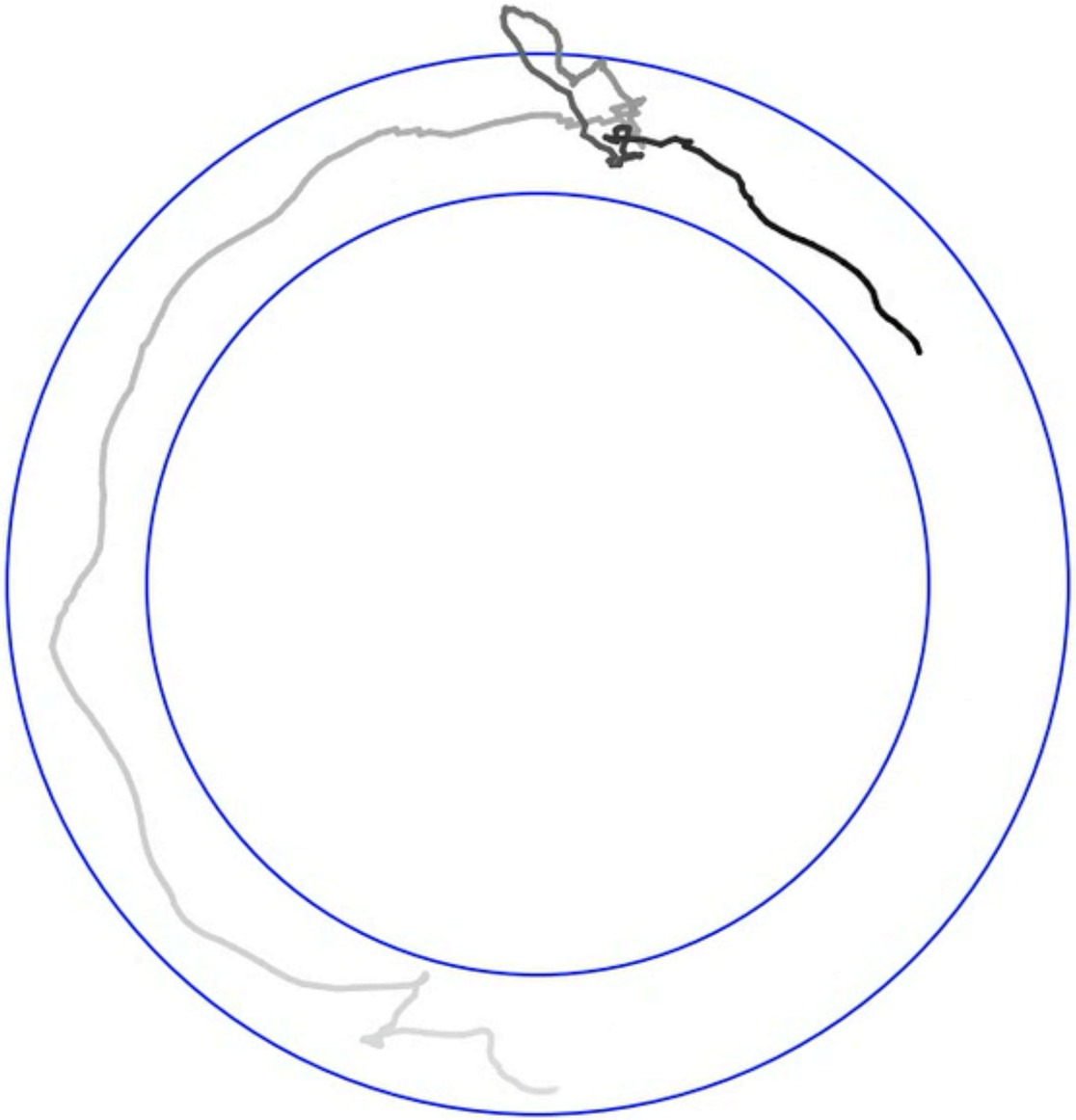


Friston K. Hierarchical models in the brain. PLOS Comput Biol. 2008;4: e1000211
Friston K. What is optimal about motor control? Neuron. 2011;72:488–98.



Video Credit: G. Rao

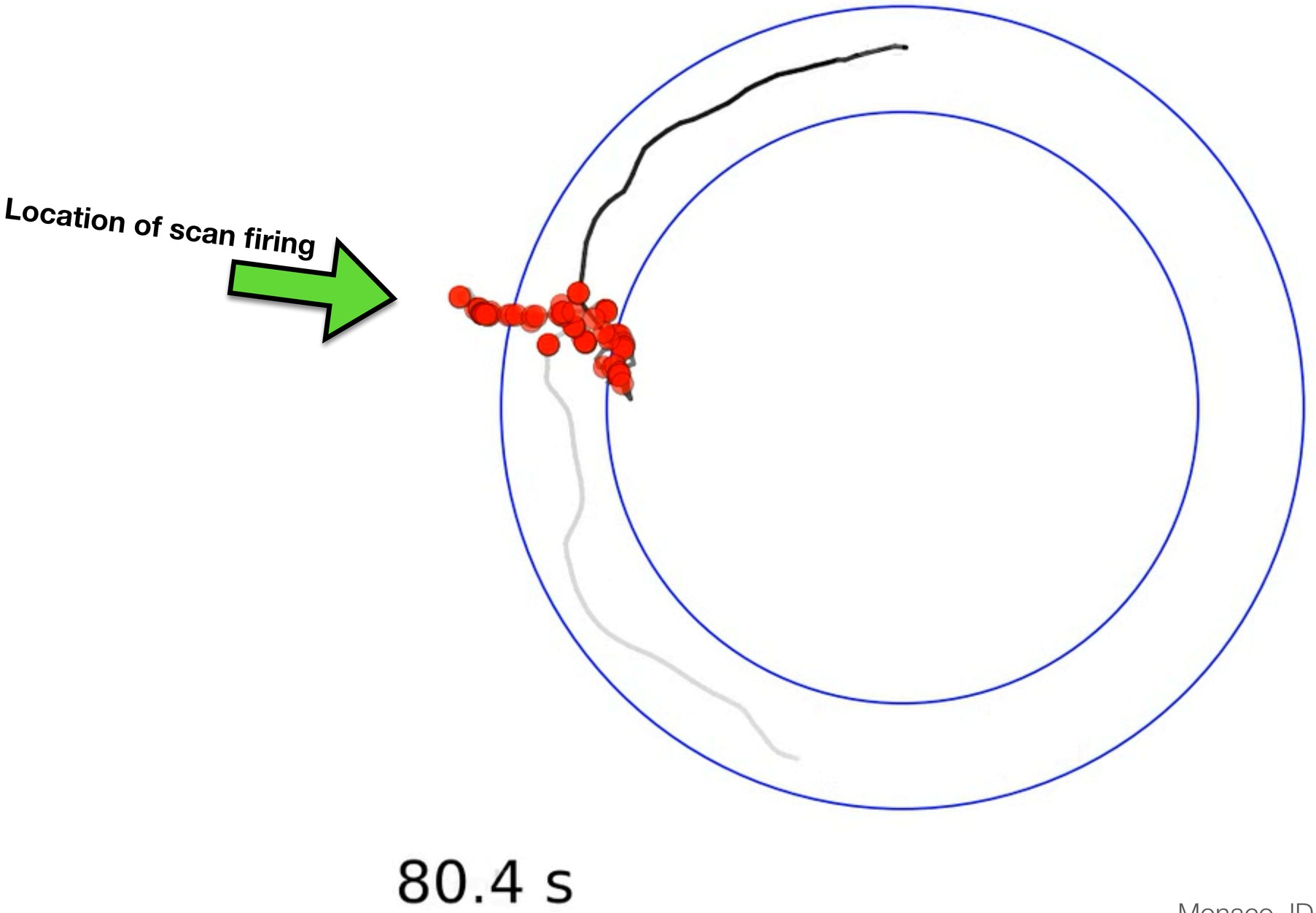
Example



63.4 s

Monaco JD, *et al*. (2014). Nature Neuroscience, 17: 725

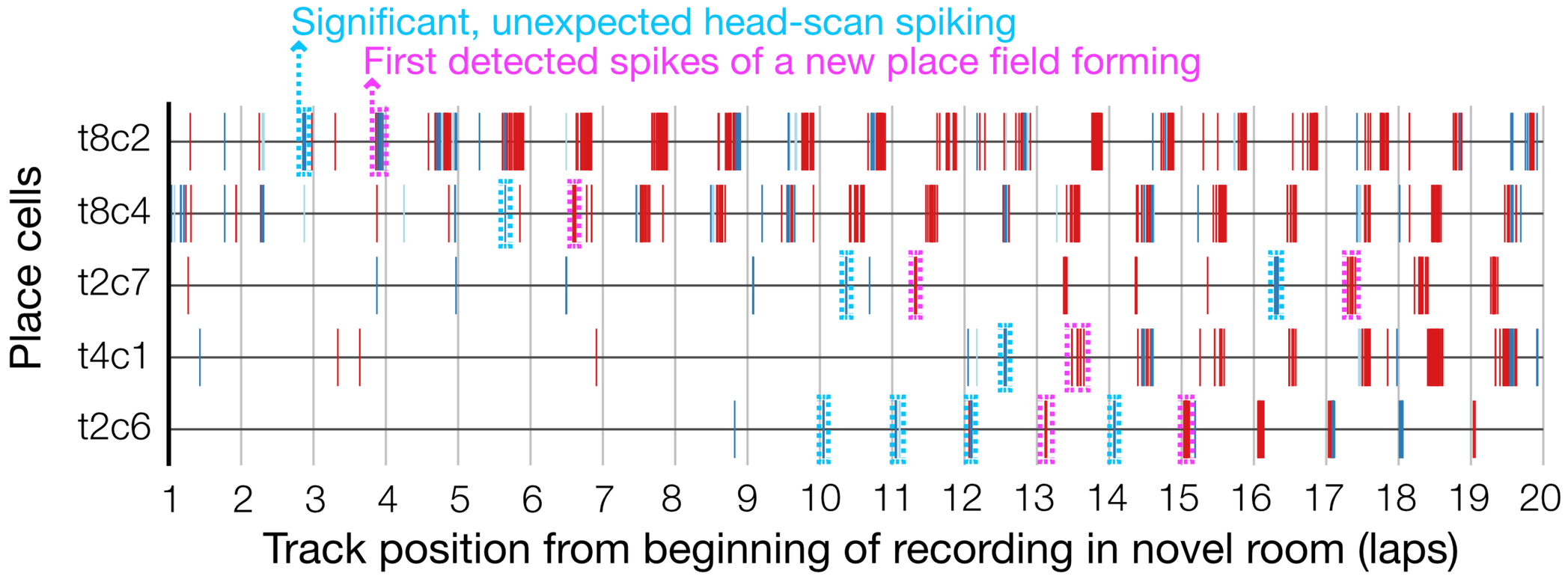
Example



Monaco JD, *et al*. (2014). Nature Neuroscience, 17: 725

Active inference

Cognitive map-building driven by autonomous head-scan sampling

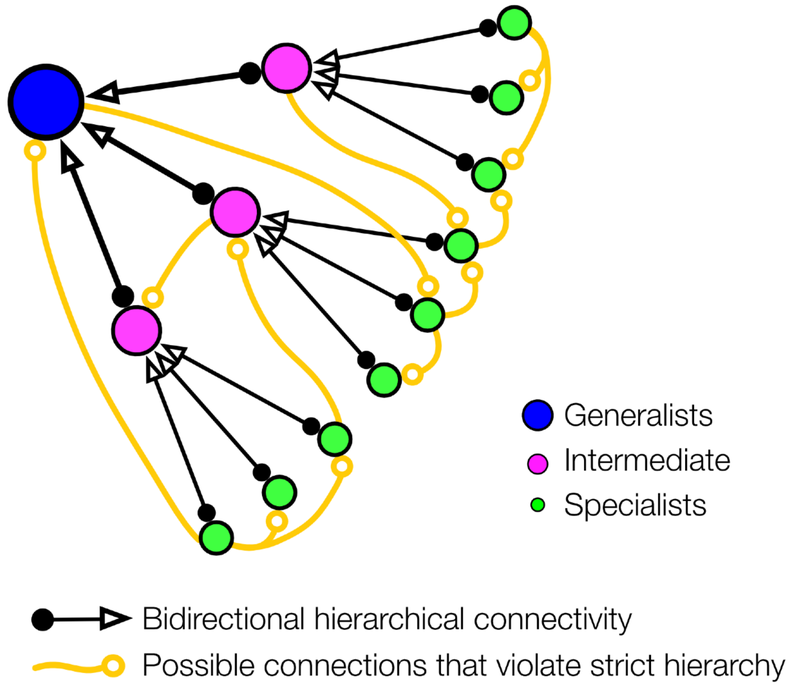


Monaco JD, *et al*. (2014). Nature Neuroscience, 17: 725

Integrative framework for neurodynamical cognition

(1) Network structure:

Sparse, distributed hierarchies are non-strict



(2) Temporal dynamics:

(3) Agentic interaction:

Monaco and Hwang. (2022). *Cognitive Computation*

Integrative framework for neurodynamical cognition

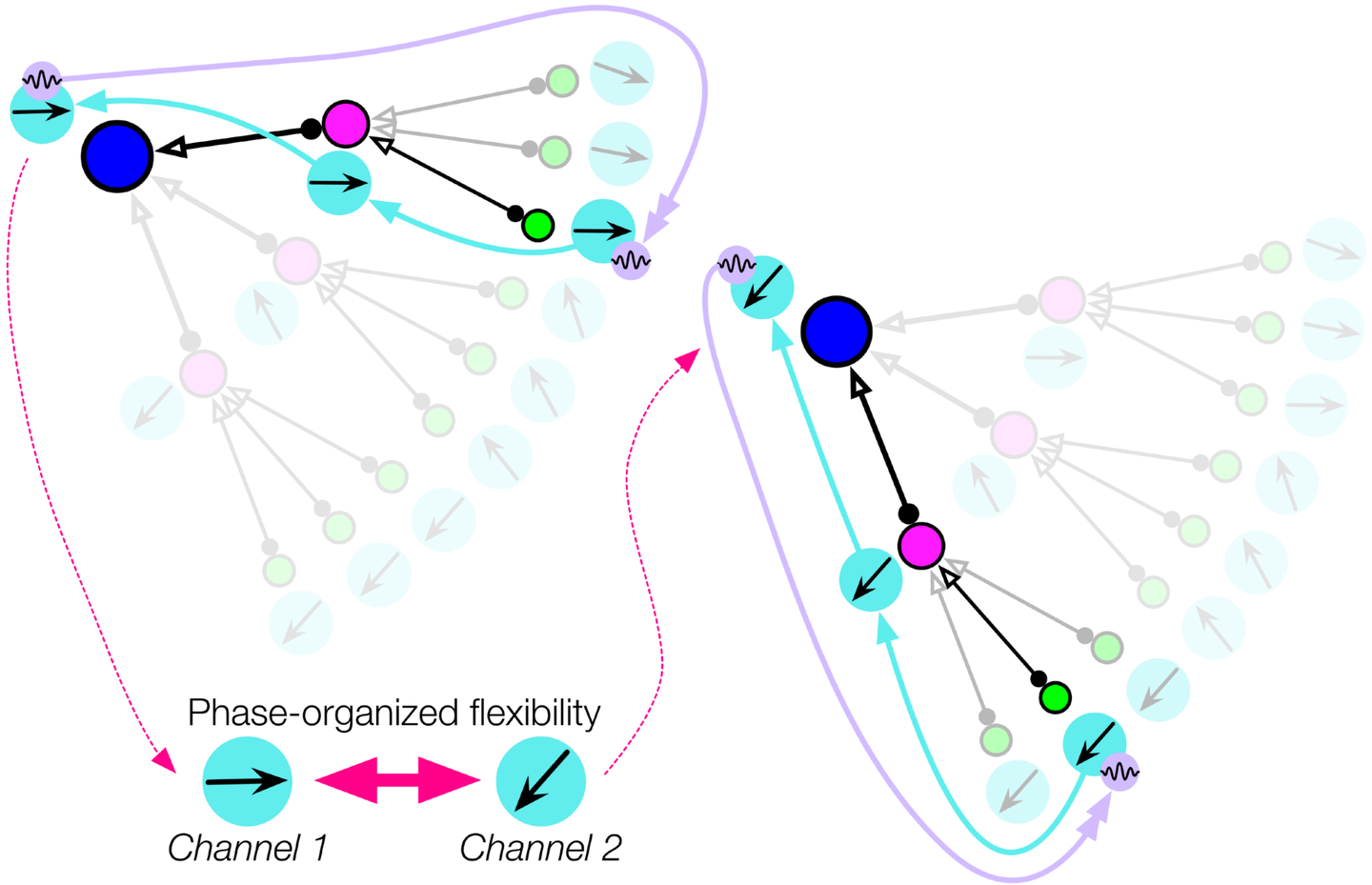
Readers phase-shift to select inputs and establish communication channels

(1) Network structure:

(2) Temporal dynamics:

- Example: Nested oscillations with phase-amplitude coupling between levels of the pseudohierarchy

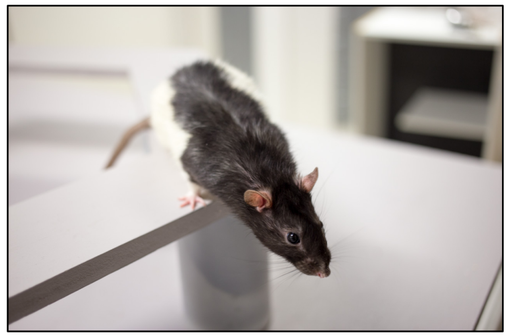
(3) Agentic interaction:

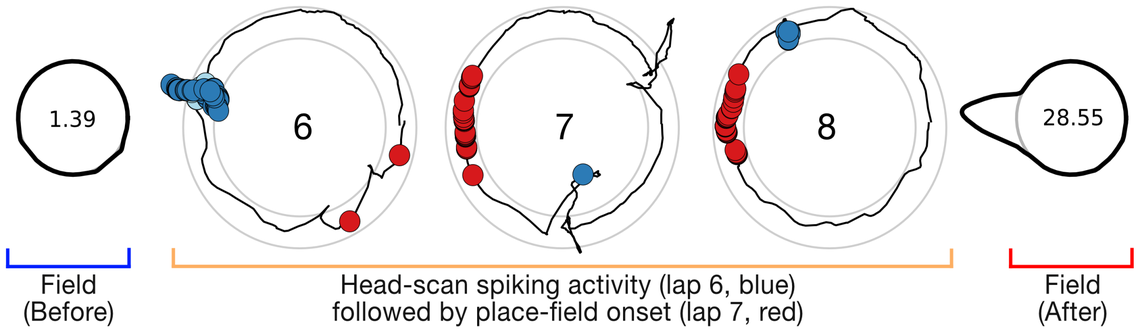


Monaco and Hwang. (2022). *Cognitive Computation*

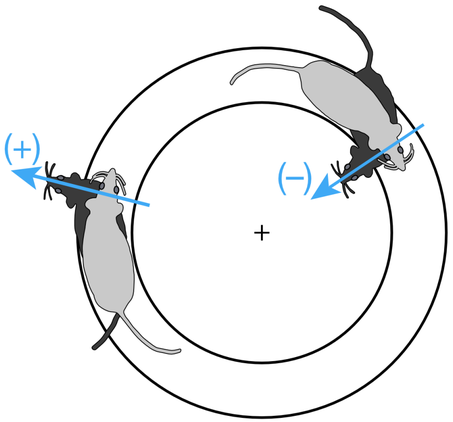
Integrative framework for neurodynamical cognition

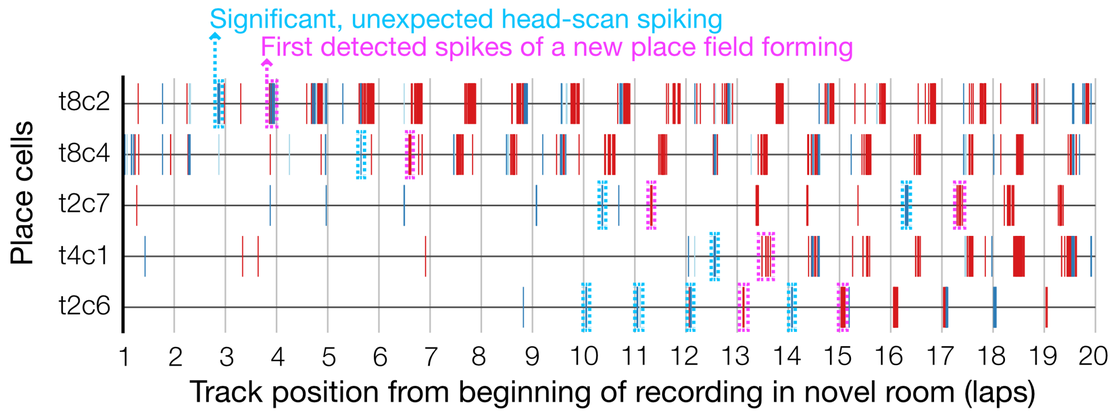
(1) Network structure:





(2) Temporal dynamics:



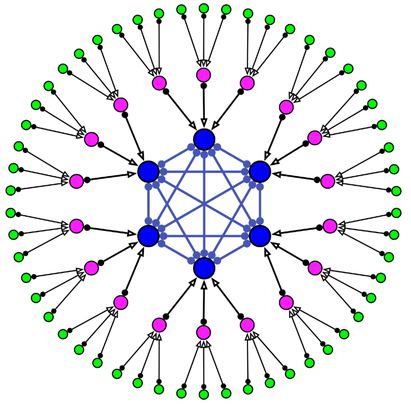


(3) Agentic interaction:

- Example: Attentive head-scanning behavior (Monaco et al., 2014)

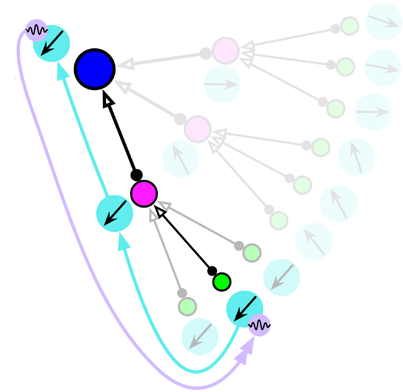
Monaco and Hwang. (2022). *Cognitive Computation*

Papers



Neurodynamical principles for embodied intelligence

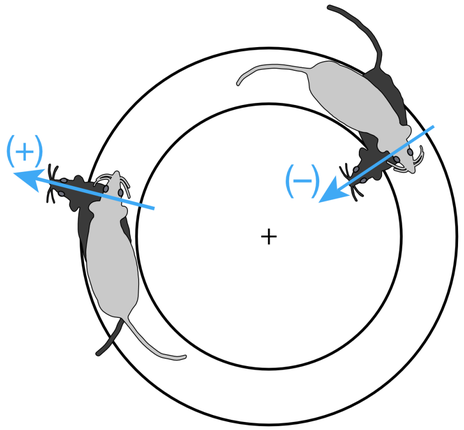
Monaco JD and Hwang GM. (2022). Neurodynamical computing at the information boundaries of intelligent systems. *Cognitive Computation*. doi: 10.1007/s12559-022-10081-9



Monaco JD, Rajan K, and Hwang GM. (2021). A brain basis of dynamical intelligence for AI and computational neuroscience. *ArXiv Preprint*. arxiv:2105.07284

Head scanning modifies cognitive maps

Monaco JD, Rao G, Roth ED, and Knierim JJ. (2014). Attentive scanning behavior drives one-trial potentiation of hippocampal place fields. *Nature Neuroscience*, 17(5), 725–731. doi: 10.1038/nn.3687

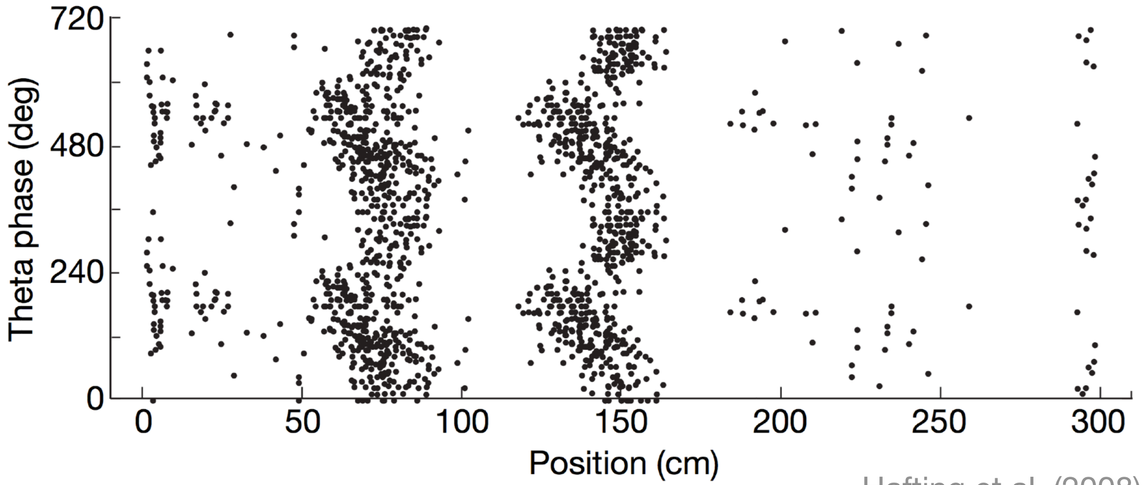


→ https://jdmonaco.com/pubs

Temporal and Population Dynamics

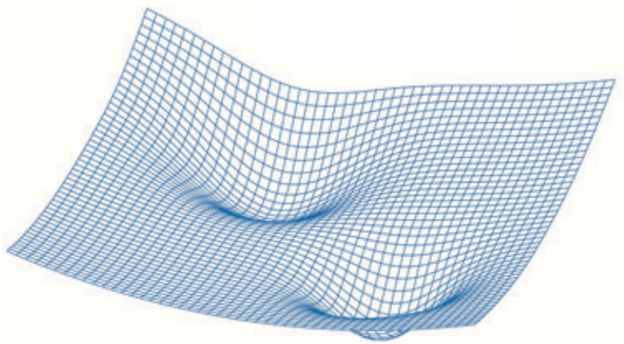
Key Building Blocks

- **Local oscillations and neuronal synchrony**
  - Temporal coding with oscillatory phase
  - O'Keefe & Recce (1993) — Theta-phase precession of hippocampal place-field firing

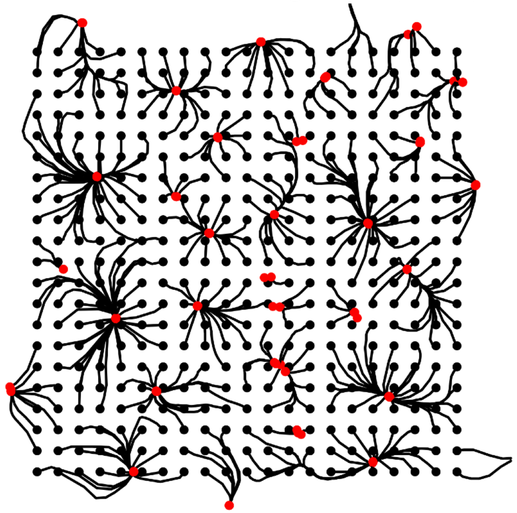


Hafting et al. (2008)

- **Emergent self-organizing states arising from recurrence and feedback in structured networks**
  - Hopfield networks (1982) — Pattern completion supports content-addressable memory with (limited) generalization
  - **Memory retrieval as a state-space trajectory that probes basins of attraction**



Knierim & Zhang (2012)



Hedrick & Zhang (2016)

Monaco and Hwang. (2022). *Cognitive Computation*

Temporal and Population Dynamics

Key Building Blocks

- **Local oscillations and neuronal synchrony**
  - Temporal coding with oscillatory phase
  - O’Keefe & Recce (1993) — Theta-phase precession of hippocampal place-field firing

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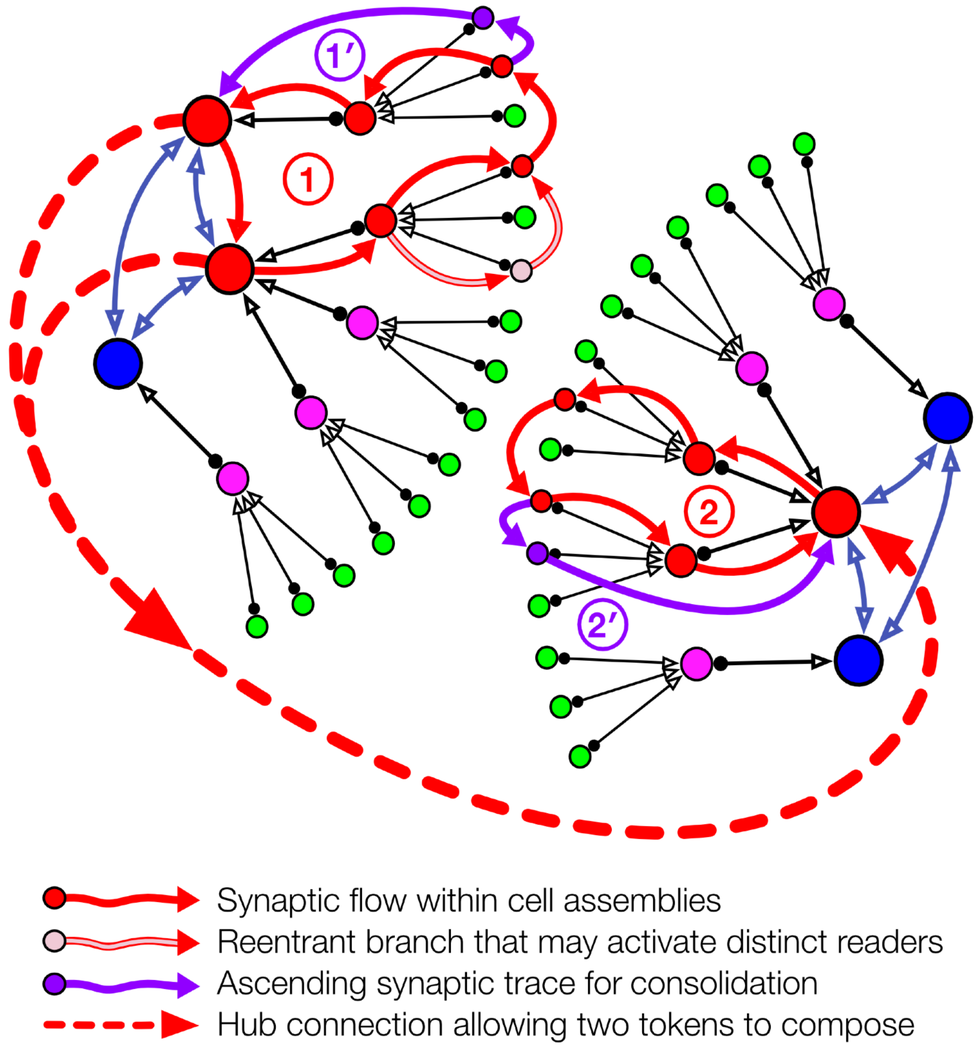
  - Hopfield networks (1982) — Pattern completion supports content-addressable memory with (limited) generalization
  - **Memory retrieval as a state-space trajectory that probes basins of attraction**

Cell assemblies, synaptic traces, and reentrant loops



Monaco and Hwang. (2022). *Cognitive Computation*

Continual rebuilding of world models

Theta-flickering of hippocampal maps

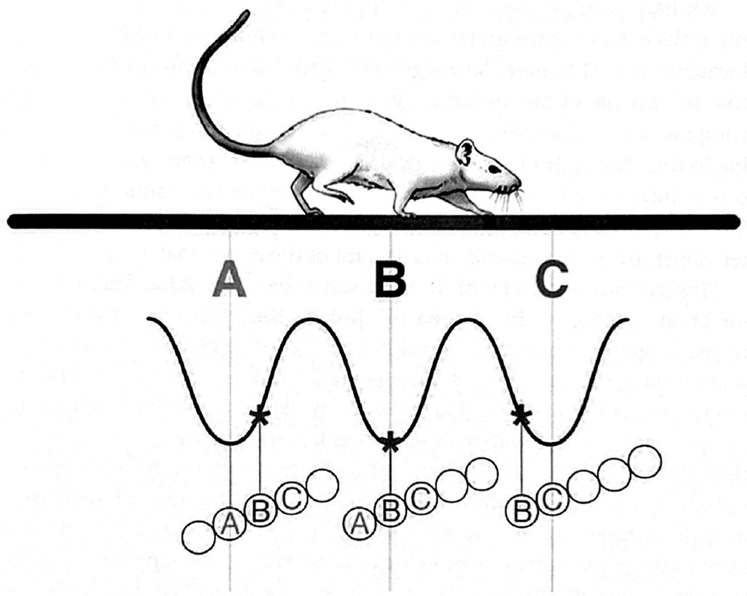
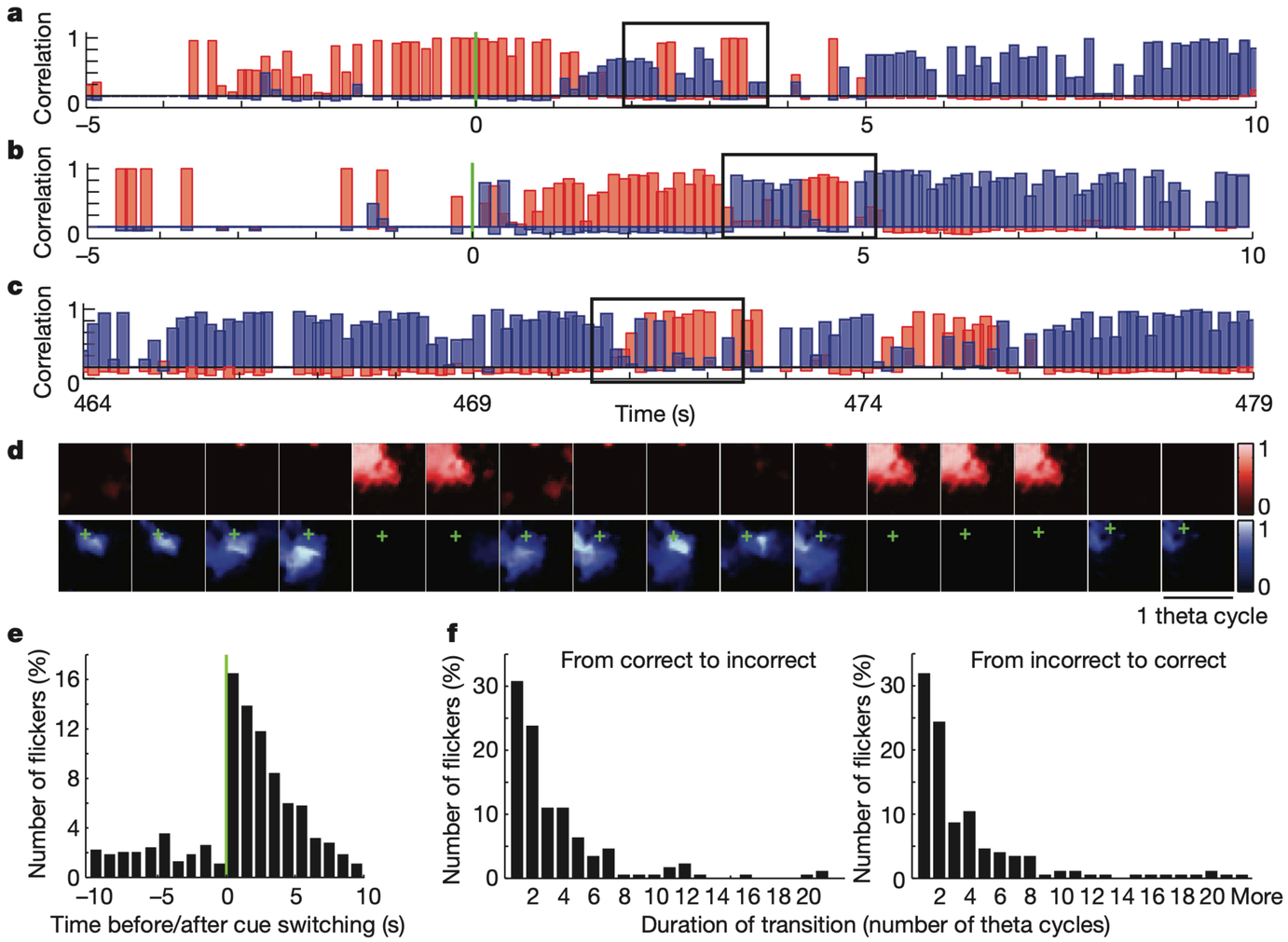


Figure 3a.1
Place cell B fires at different times relative to the background theta-wave as the rat moves from locations A through C. Reprinted from Buckner (2010) with permission.



Anderson. (2014) *After Phrenology*

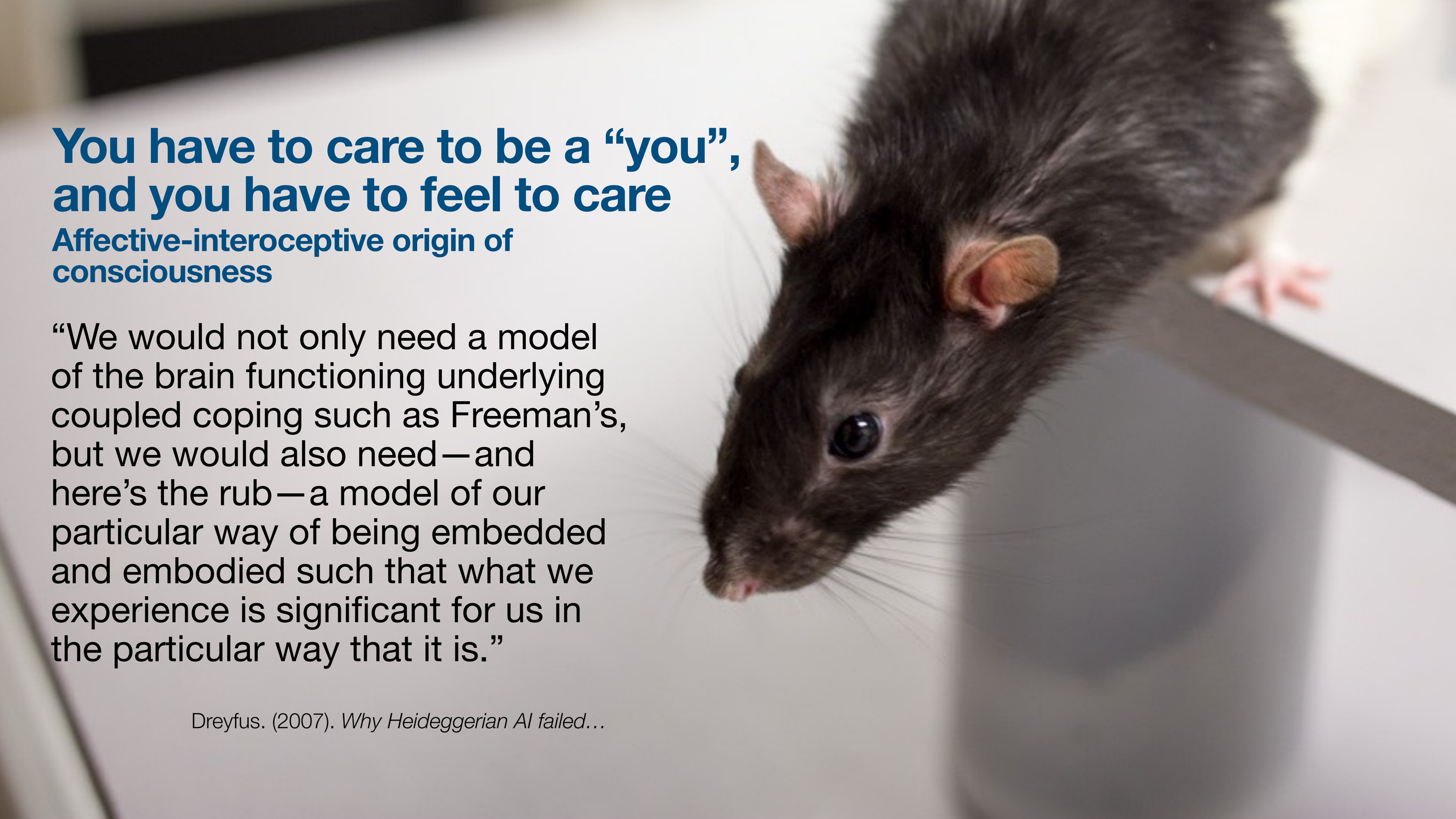
Jezek, *et al*. (2011). *Nature*

You have to care to be a “you”, and you have to feel to care

Affective-interoceptive origin of consciousness

“We would not only need a model of the brain functioning underlying coupled coping such as Freeman’s, but we would also need—and here’s the rub—a model of our particular way of being embedded and embodied such that what we experience is significant for us in the particular way that it is.”

Dreyfus. (2007). *Why Heideggerian AI failed…*



Intelligence vs. conscious experience

Interoceptor theory of consciousness and narrative dynamics across the lifespan

- The BIG questions…
  - What is intelligence and what is it for?
  - What is consciousness and what is it for?

- These are *real* questions, but are they *hard*?

Theories of consciousness

There are many…

Table 1 | **A selection of theories of consciousness**

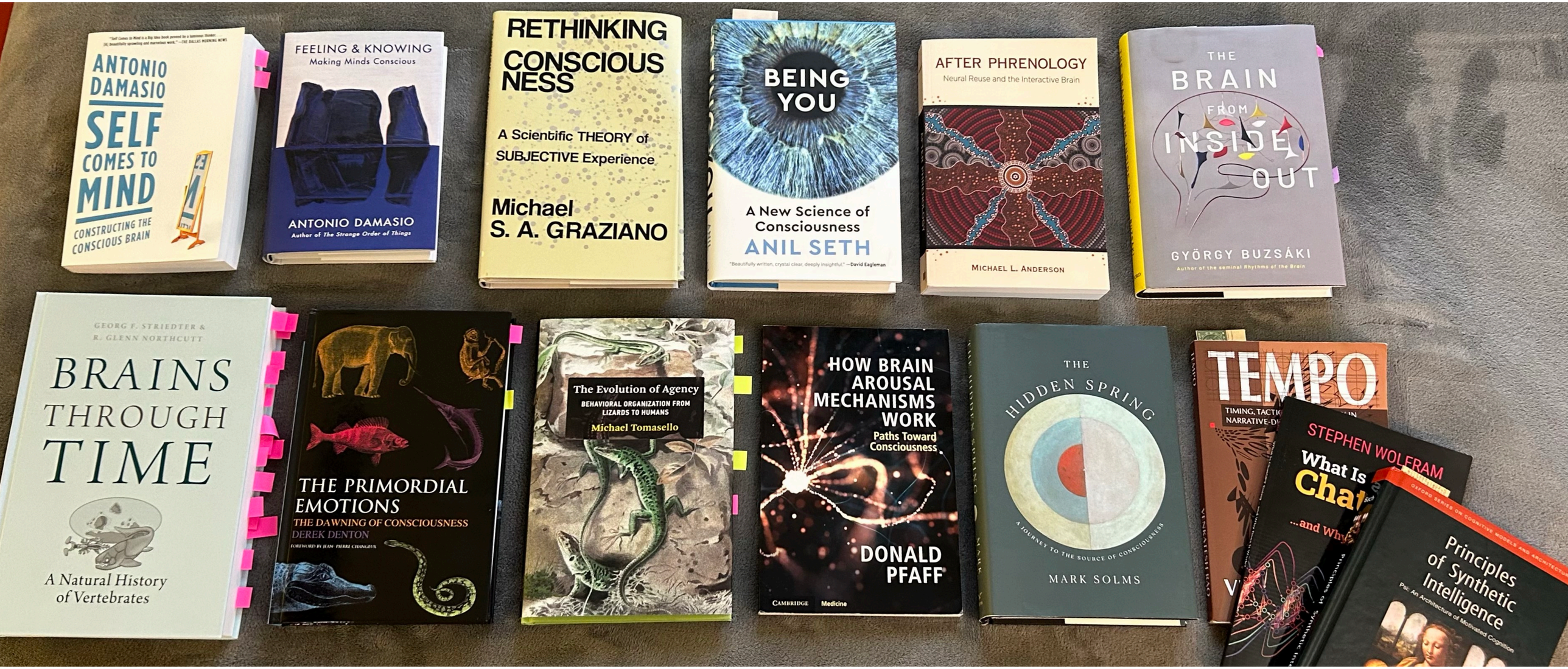
Theory	Primary claim	Key refs
Higher-order theory (HOT)	Consciousness depends on meta-representations of lower-order mental states	31,46
Self-organizing meta-representational theory	Consciousness is the brain's (meta-representational) theory about itself	34,140
Attended intermediate representation theory	Consciousness depends on the attentional amplification of intermediate-level representations	141,142
Global workspace theories (GWTs)	Consciousness depends on ignition and broadcast within a neuronal global workspace where fronto-parietal cortical regions play a central, hub-like role	47–49
Integrated information theory (IIT)	Consciousness is identical to the cause–effect structure of a physical substrate that specifies a maximum of irreducible integrated information	57,59,60
Information closure theory	Consciousness depends on non-trivial information closure with respect to an environment at particular coarse-grained scales	143
Dynamic core theory	Consciousness depends on a functional cluster of neural activity combining high levels of dynamical integration and differentiation	144
Neural Darwinism	Consciousness depends on re-entrant interactions reflecting a history of value-dependent learning events shaped by selectionist principles	145,146
Local recurrency	Consciousness depends on local recurrent or re-entrant cortical processing and promotes learning	65,71
Predictive processing	Perception depends on predictive inference of the causes of sensory signals; provides a framework for systematically mapping neural mechanisms to aspects of consciousness	67,73,79
Neuro-representationalism	Consciousness depends on multilevel neurally encoded predictive representations	84
Active inference	Although views vary, in one version consciousness depends on temporally and counterfactually deep inference about self-generated actions	76; see also 91
Beast machine theory	Consciousness is grounded in allostatic control-oriented predictive inference	13,75,77; see also 90
Neural subjective frame	Consciousness depends on neural maps of the bodily state providing a first-person perspective	24
Self comes to mind theory	Consciousness depends on interactions between homeostatic routines and multilevel interoceptive maps, with affect and feeling at the core	23,147
Attention schema theory	Consciousness depends on a neurally encoded model of the control of attention	148
Multiple drafts model	Consciousness depends on multiple (potentially inconsistent) representations rather than a single, unified representation that is available to a central system	149
Sensorimotor theory	Consciousness depends on mastery of the laws governing sensorimotor contingencies	88
Unlimited associative learning	Consciousness depends on a form of learning which enables an organism to link motivational value with stimuli or actions that are novel, compound and non-reflex inducing	150
Dendritic integration theory	Consciousness depends on integration of top-down and bottom-up signalling at a cellular level	151
Electromagnetic field theory	Consciousness is identical to physically integrated, and causally active, information encoded in the brain's global electromagnetic field	152
Orchestrated objective reduction	Consciousness depends on quantum computations within microtubules inside neurons	18

Our selection of theories includes those that are either neurobiological in nature or potentially expressible in neurobiological terms.

Seth. (2022). *Theories of consciousness.* NRN

Theories of consciousness

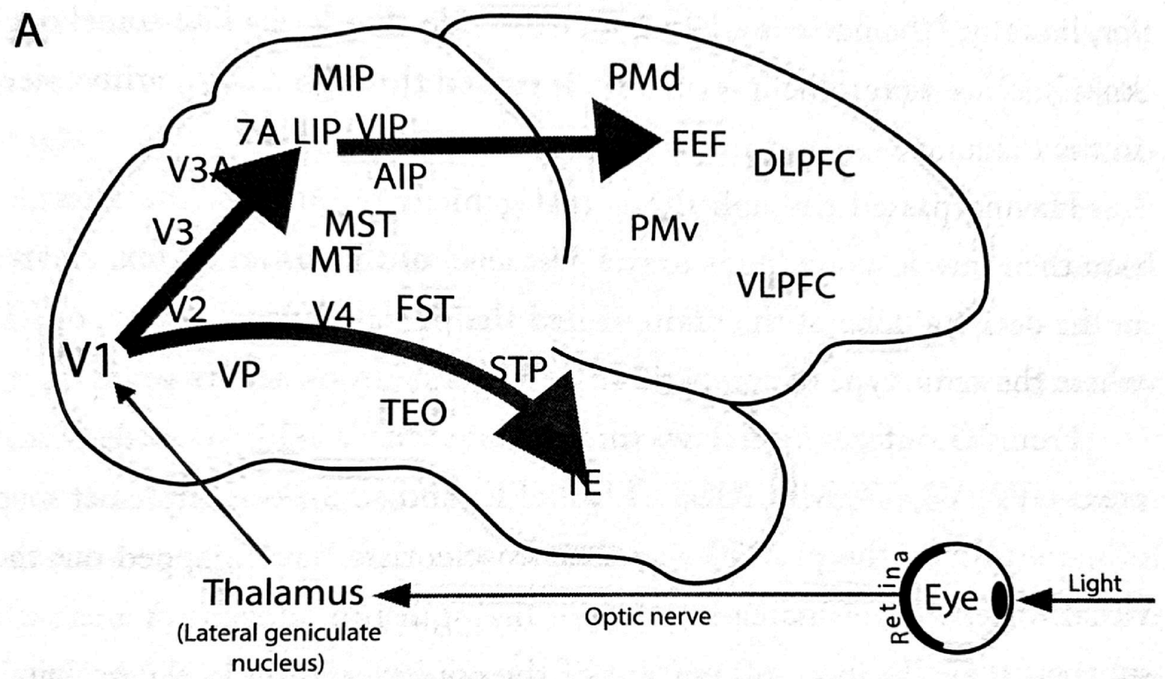
There are many…



Images, maps, and conscious content

Mutually aligned and registered maps

- An organism manages three sensoriums
  - Exteroception
  - Proprioception
  - Interoception
- All peripheral sensory activations construct neural patterns that pass through cortical and subcortical maps that impose a shared regimented order and structure
  - Neural patterns → mental “images”
  - Fingerprint of “ownership” and origin of self-perspective



Graziano. *Rethinking Consciousness*

The cortical fallacy

Do we need it?

- Hydroanencephalic children

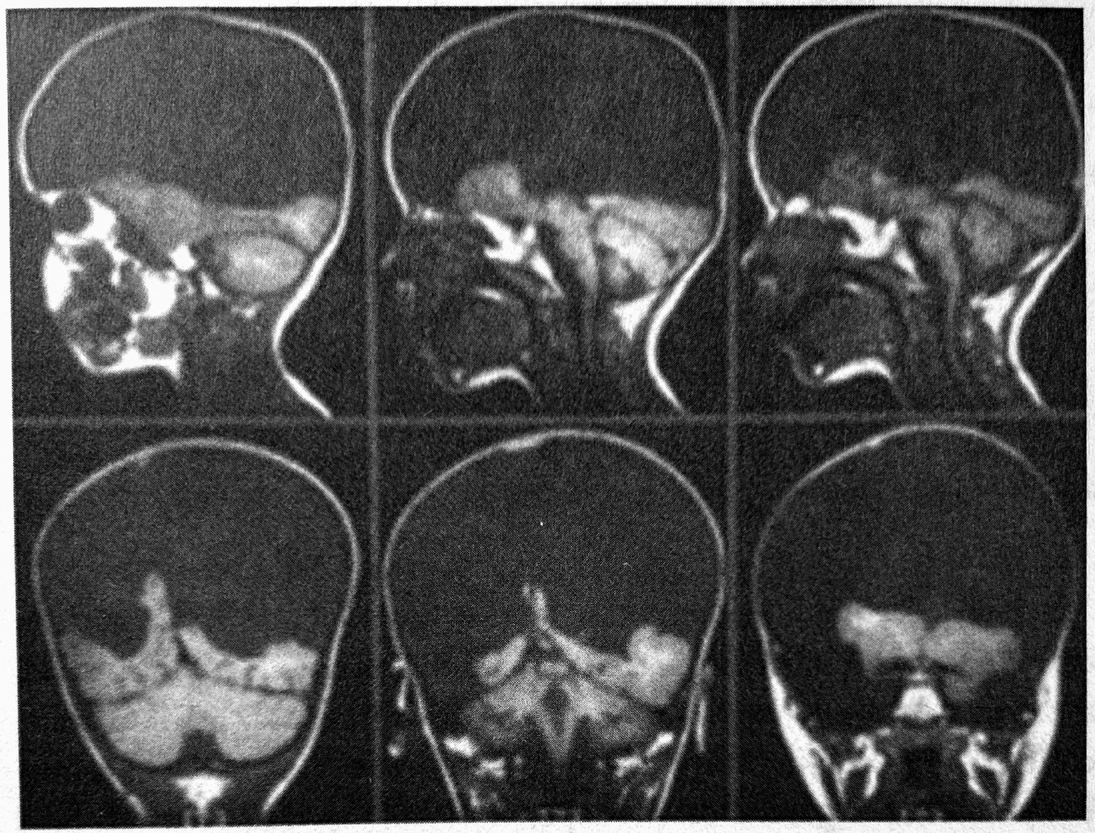


Figure 4 Brain scan of a three-year-old-girl born without a cerebral cortex. The large dark region inside the skull indicates missing tissue.

Figure 5 Reaction of a hydranencephalic girl to her baby brother being placed in her lap.

Solms. *Hidden Spring*

Non-explicit vs. explicit intelligence

Knowledge requires conscious inspection

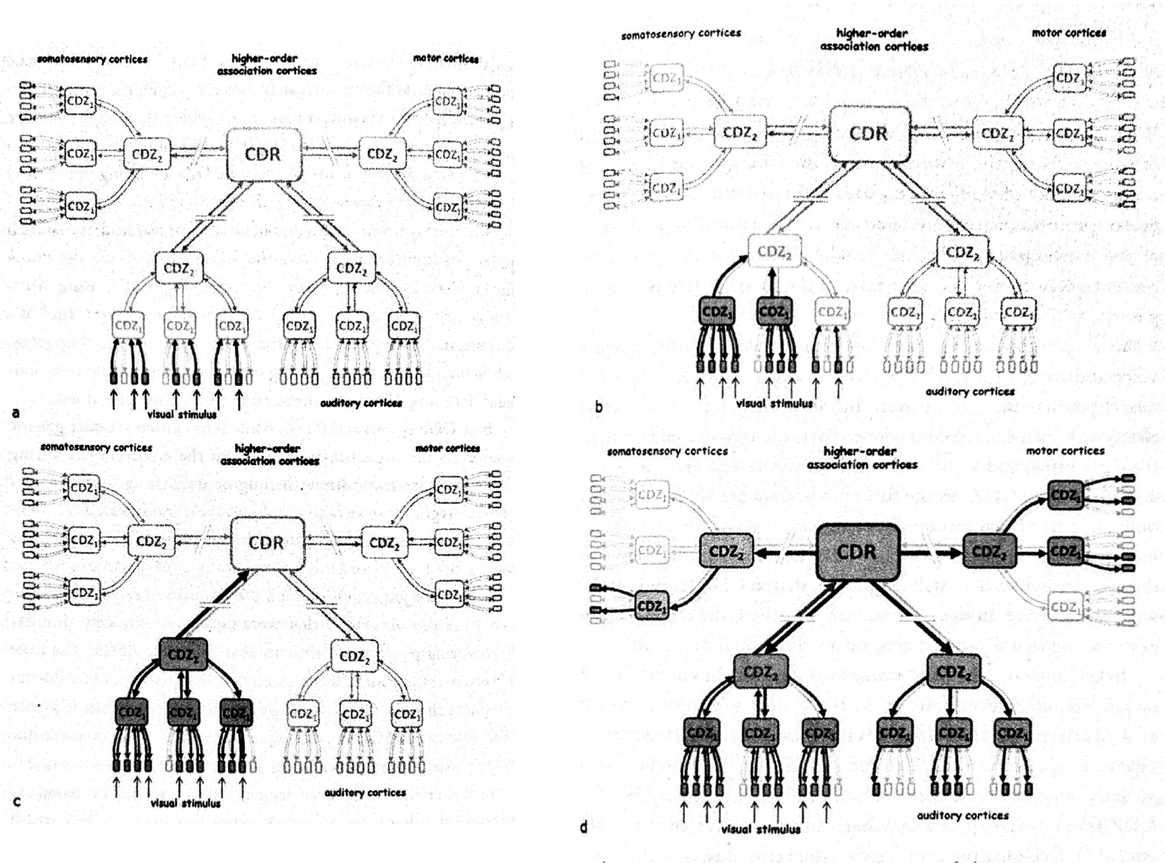
- All organisms sense and respond
  - Sensing is necessary for constructing a mind
    - A mind is necessary to support a conscious state
      - Disrupt sensing (e.g., anaesthesia) → conscious states evaporate
  - Unminded intelligence is far more ancient than minded
    - Reflex, habit, automaticity
    - Hidden/obscured adaptations at the molecular level and lower

Damasio. *Feeling & Knowing*

Then what is sufficient for conscious states?

Mental images must be grounded in (primordial) feeling

- An organism manages three sensoriums
  - Exteroception
  - Proprioception
  - Interoception
- All peripheral sensory activations construct neural patterns that pass through cortical and subcortical maps that impose a shared regimented order and structure
  - Neural patterns → mental “images”
  - Fingerprint of “ownership” and origin of self-perspective

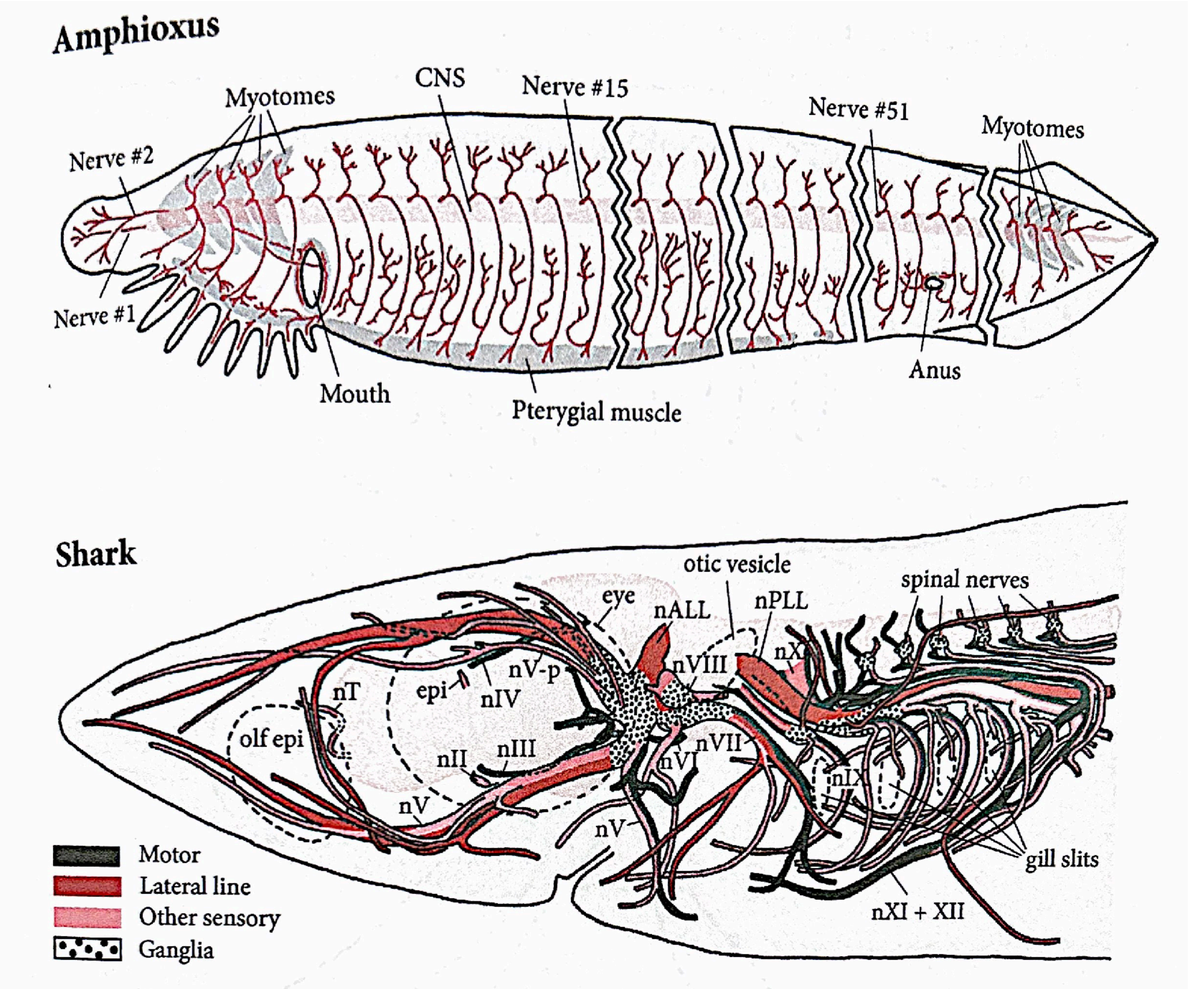


Damasio. *Self Comes to Mind*; Feeling & *Knowing*

Elaborate affective-emotive construction

Direct visceral access to neural systems

- The visceral and peripheral milieu of bodies has direct access to peripheral ascending nerves
  - Unmyelinated, unlike exteroceptive and proprioceptive systems
  - Less precision, but direct and deeply integrated access

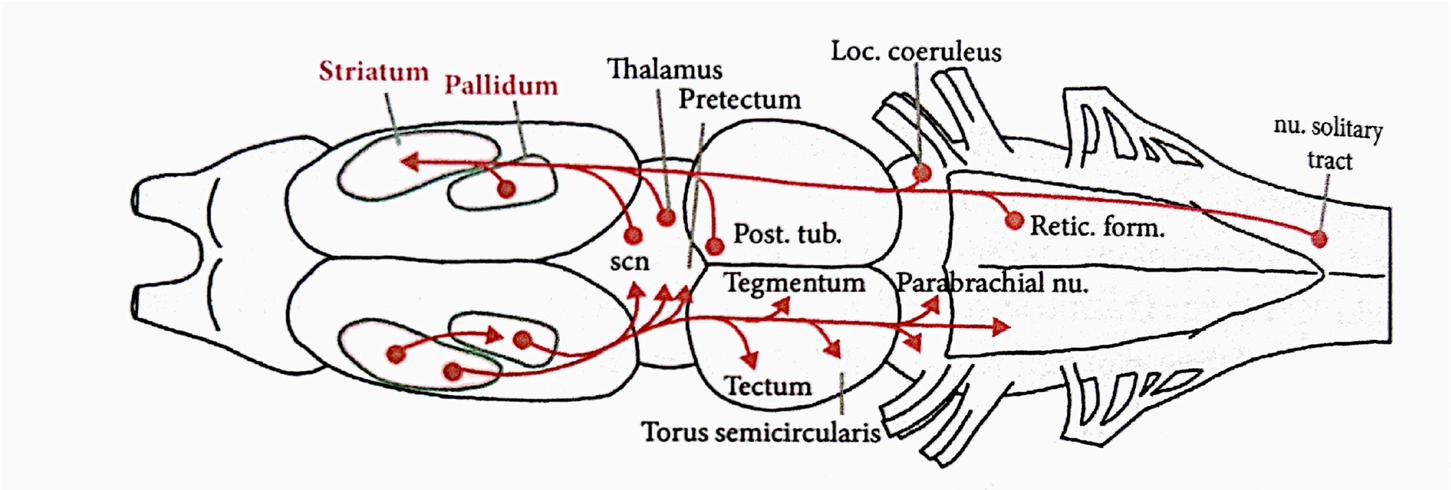


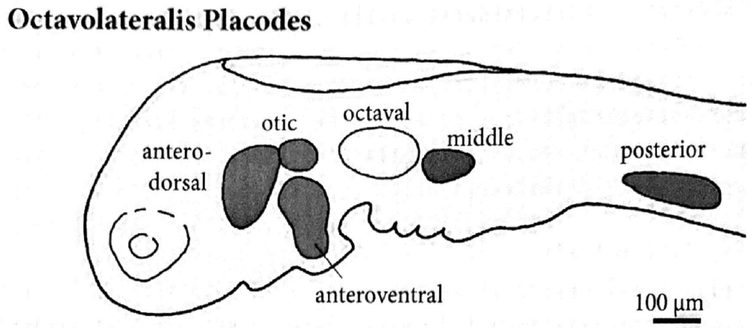
Striedter & Northcutt. *Brains Through Time*

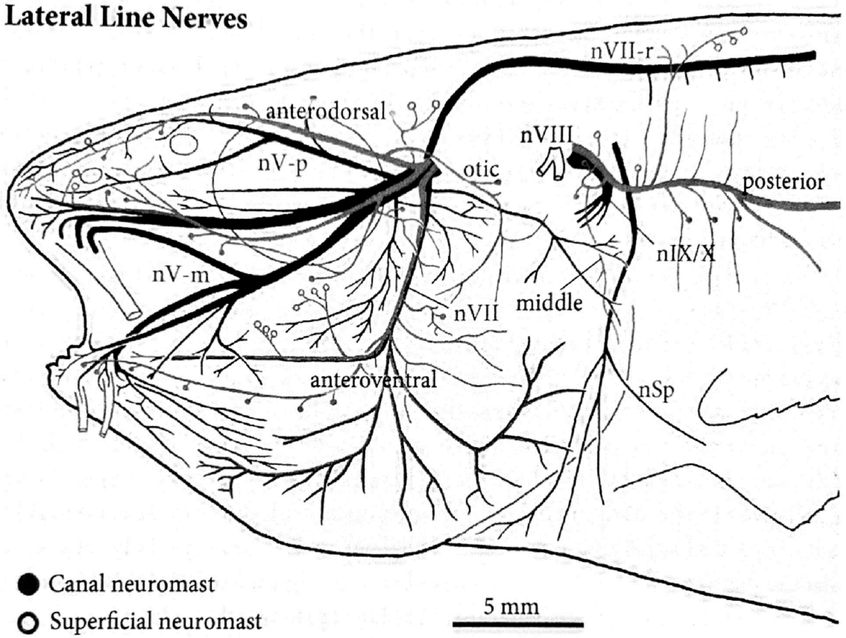
Elaborate affective-emotive construction

Direct visceral access to neural systems

- Evolutionarily ancient system
  - Early fish (right) and amphibians (below)





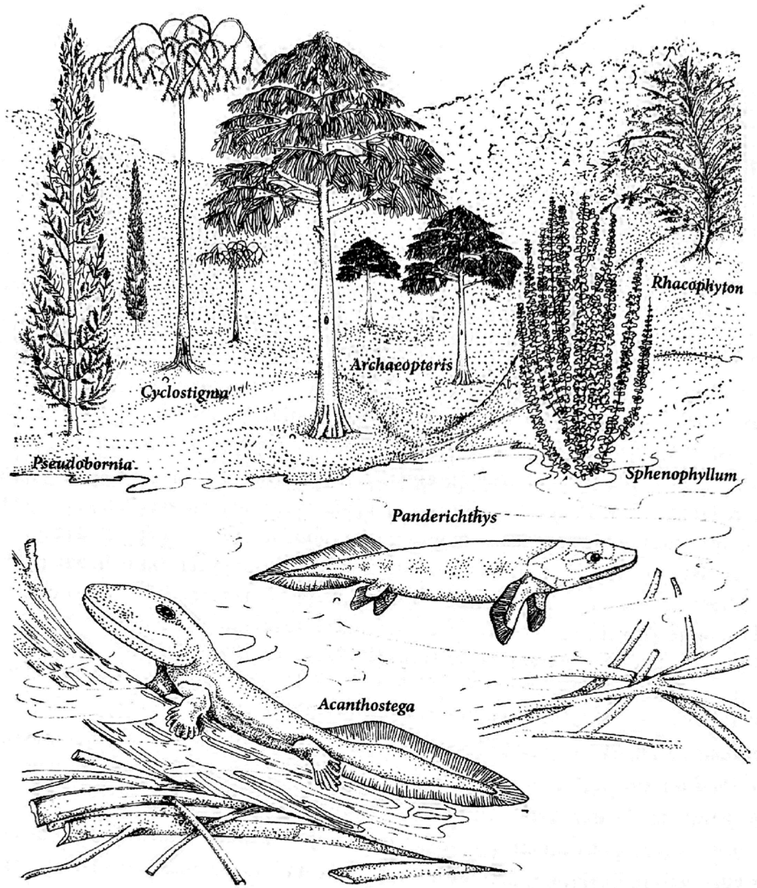


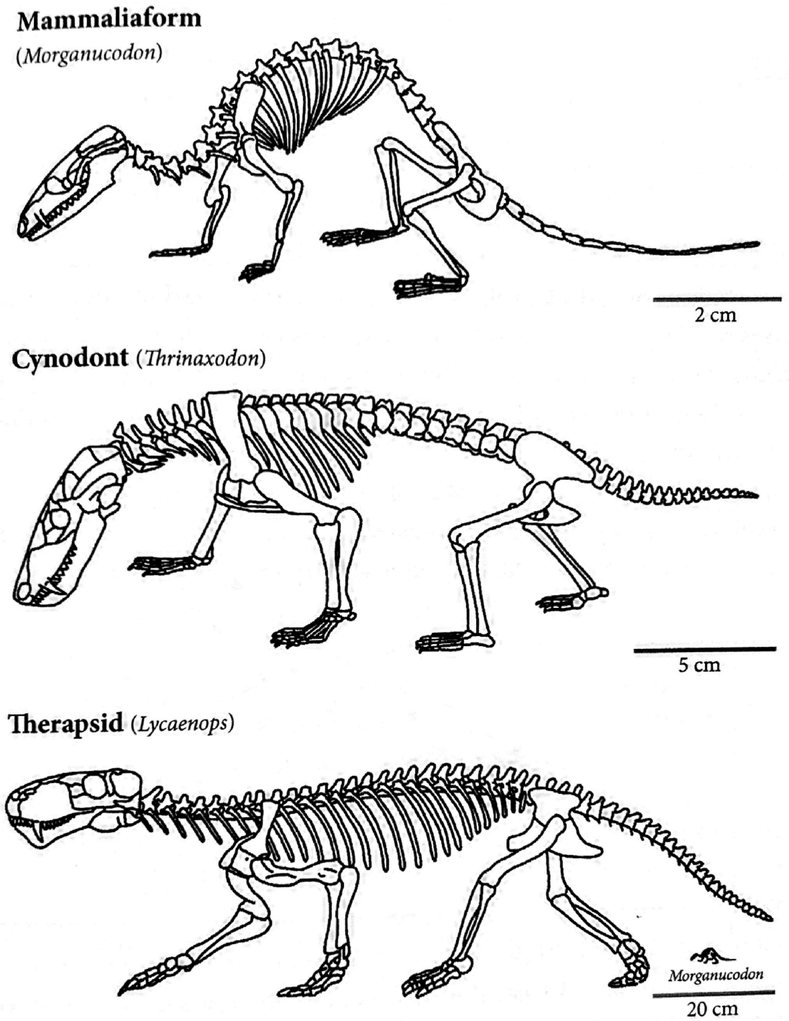
Striedter & Northcutt. *Brains Through Time*

Elaborate affective-emotive construction

Direct visceral access to neural systems

- Stem tetrapods and stem mammals



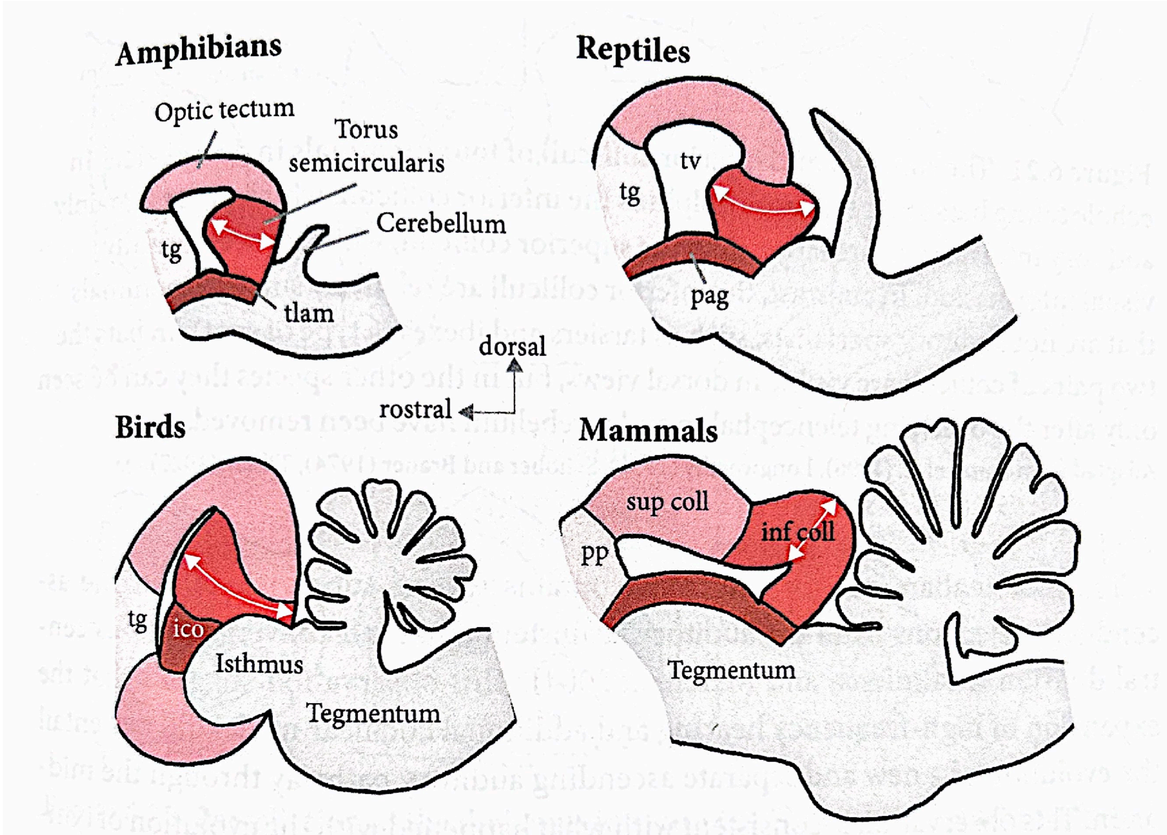


Striedter & Northcutt. *Brains Through Time*

Elaborate affective-emotive construction

Direct visceral access to neural systems

- Interoceptive signals converge onto a small set of highly conserved brainstem nuclei
  - Parabrachial nucleus
  - Periaqueductal gray (PAG)
  - Nucleus of the tractus solitarius



Striedter & Northcutt. *Brains Through Time*

Elaborate affective-emotive construction

Direct visceral access to neural systems

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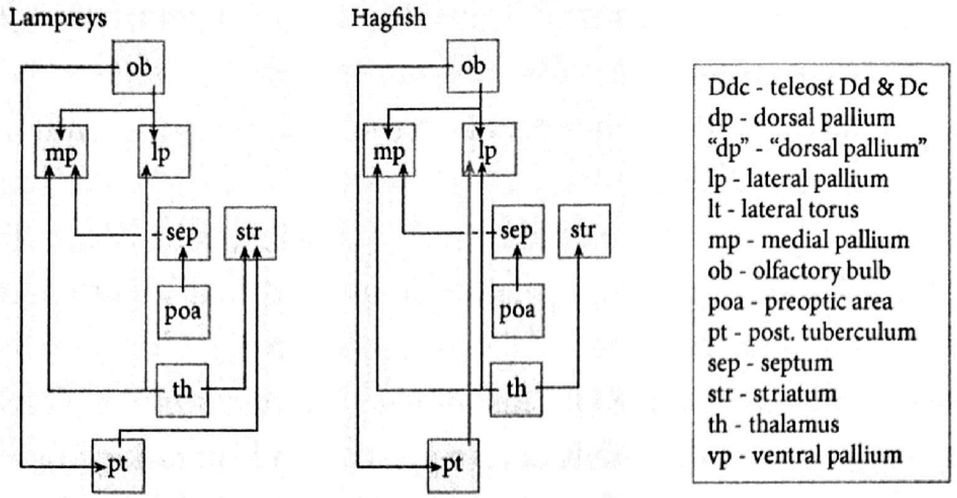
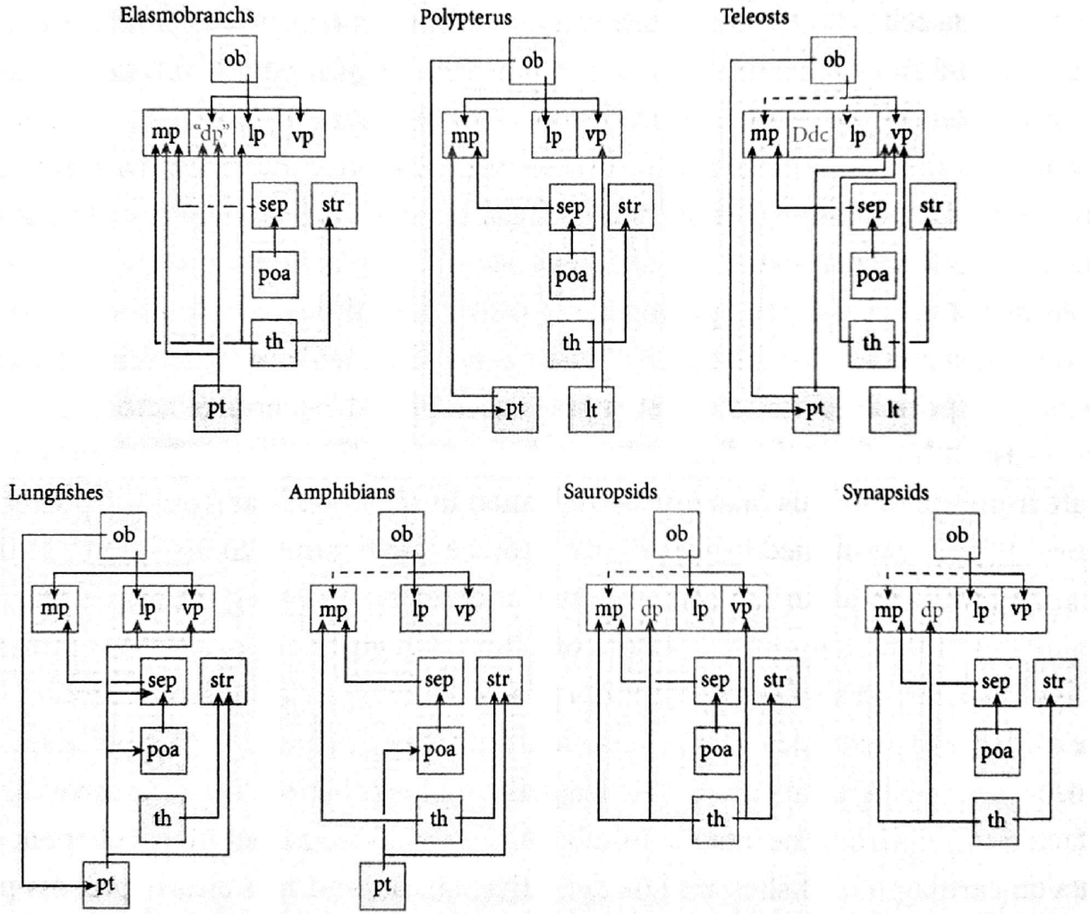


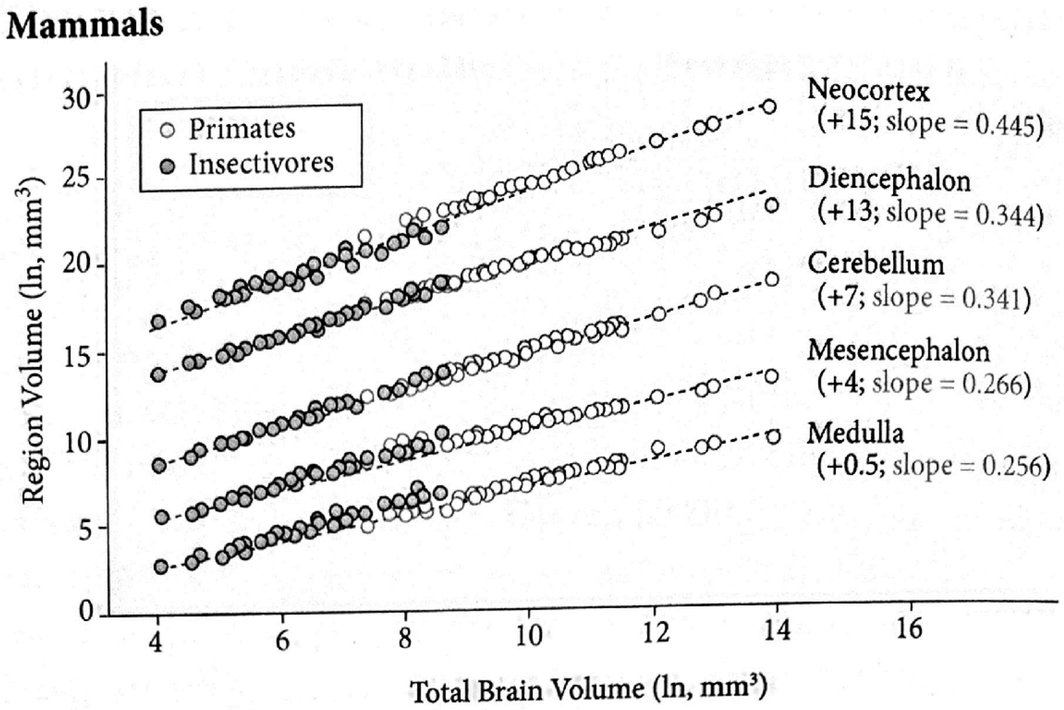


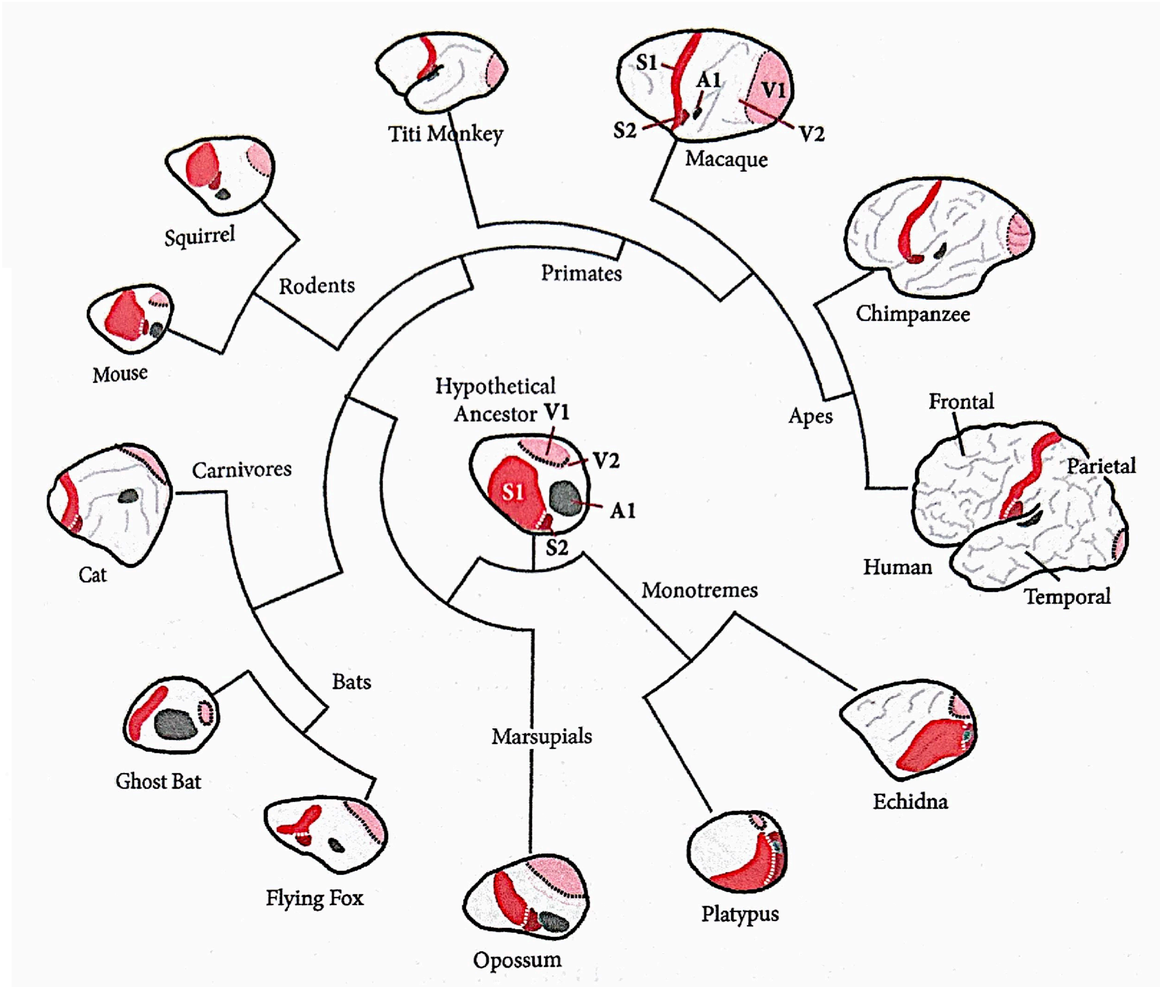
Striedter & Northcutt. *Brains Through Time*

Conserved imagetic mapping cortices

Exteroceptive (body-in-world) and proprioceptive (brain-in-body) reference frames

- The “image-making” cortices are also highly conserved within mammalia, reflecting ~200 million years of selection



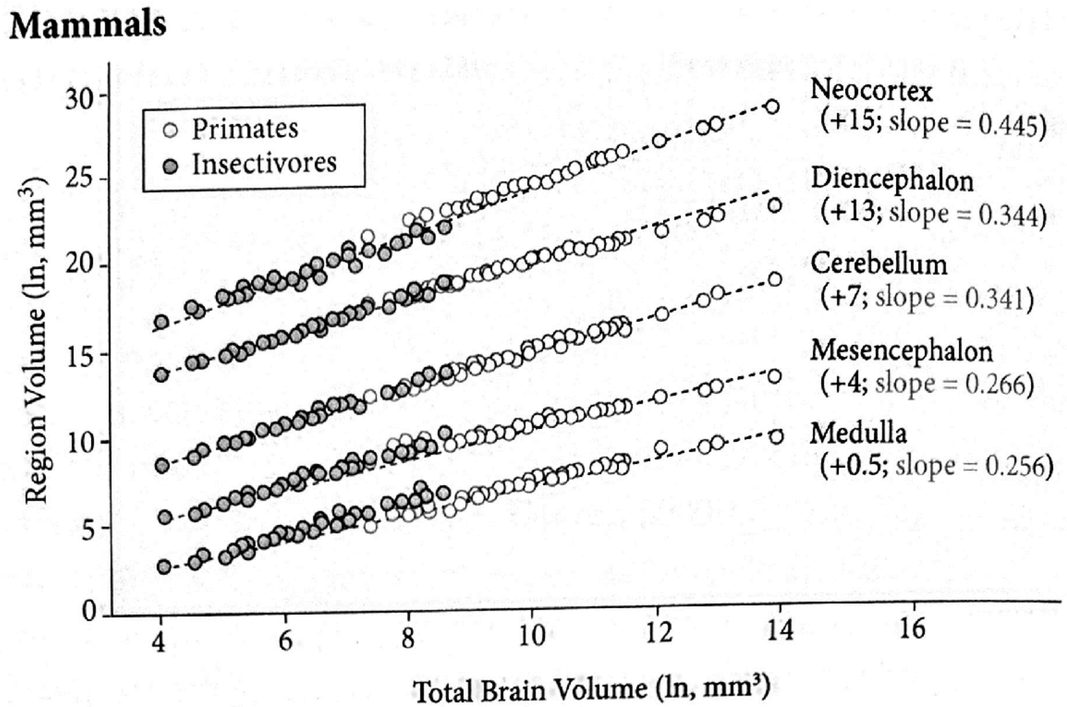


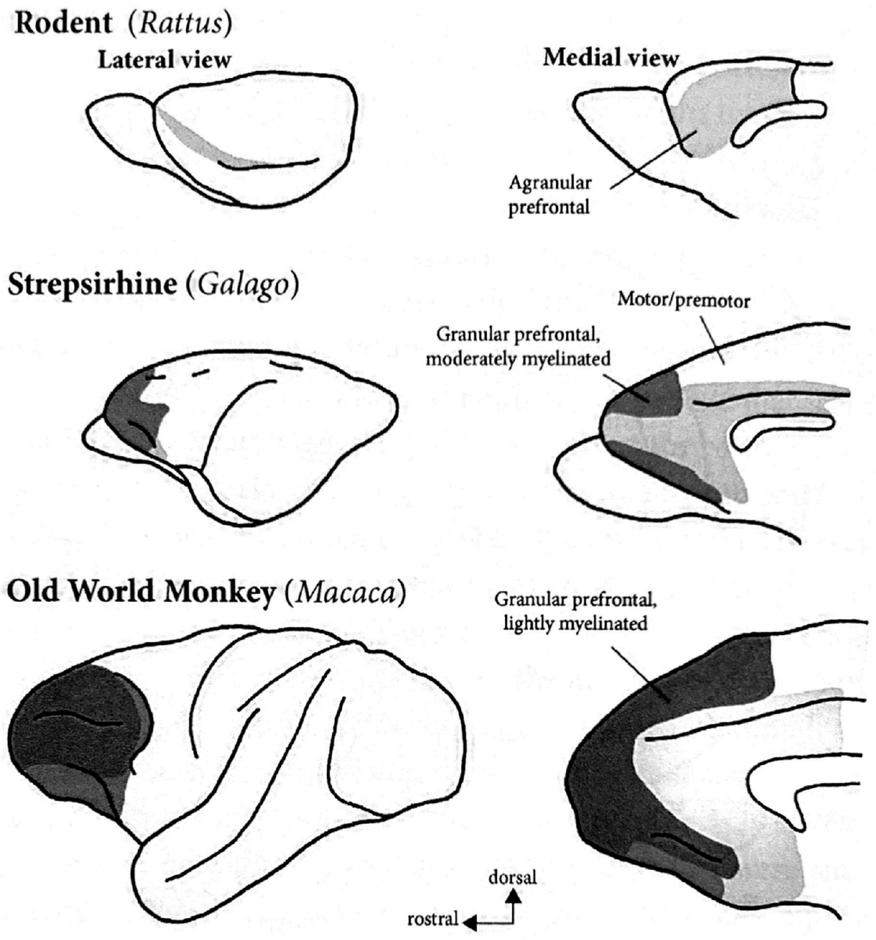
Striedter & Northcutt. *Brains Through Time*

Conserved imagetic mapping cortices

Exteroceptive (body-in-world) and proprioceptive (brain-in-body) reference frames

- Massive increase in primate and human prefrontal volumes does not alter conserved brain-region allometry

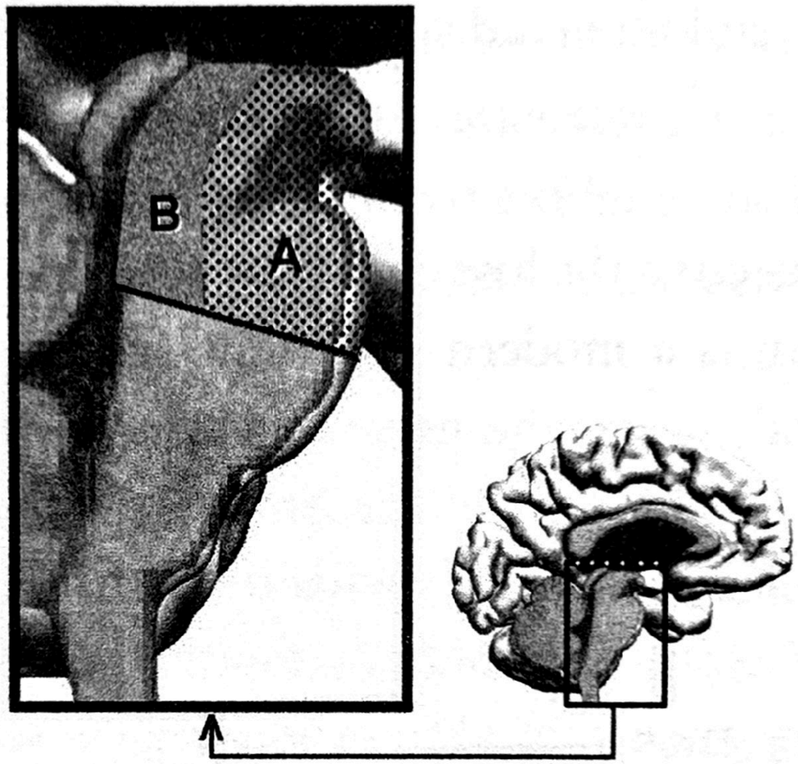


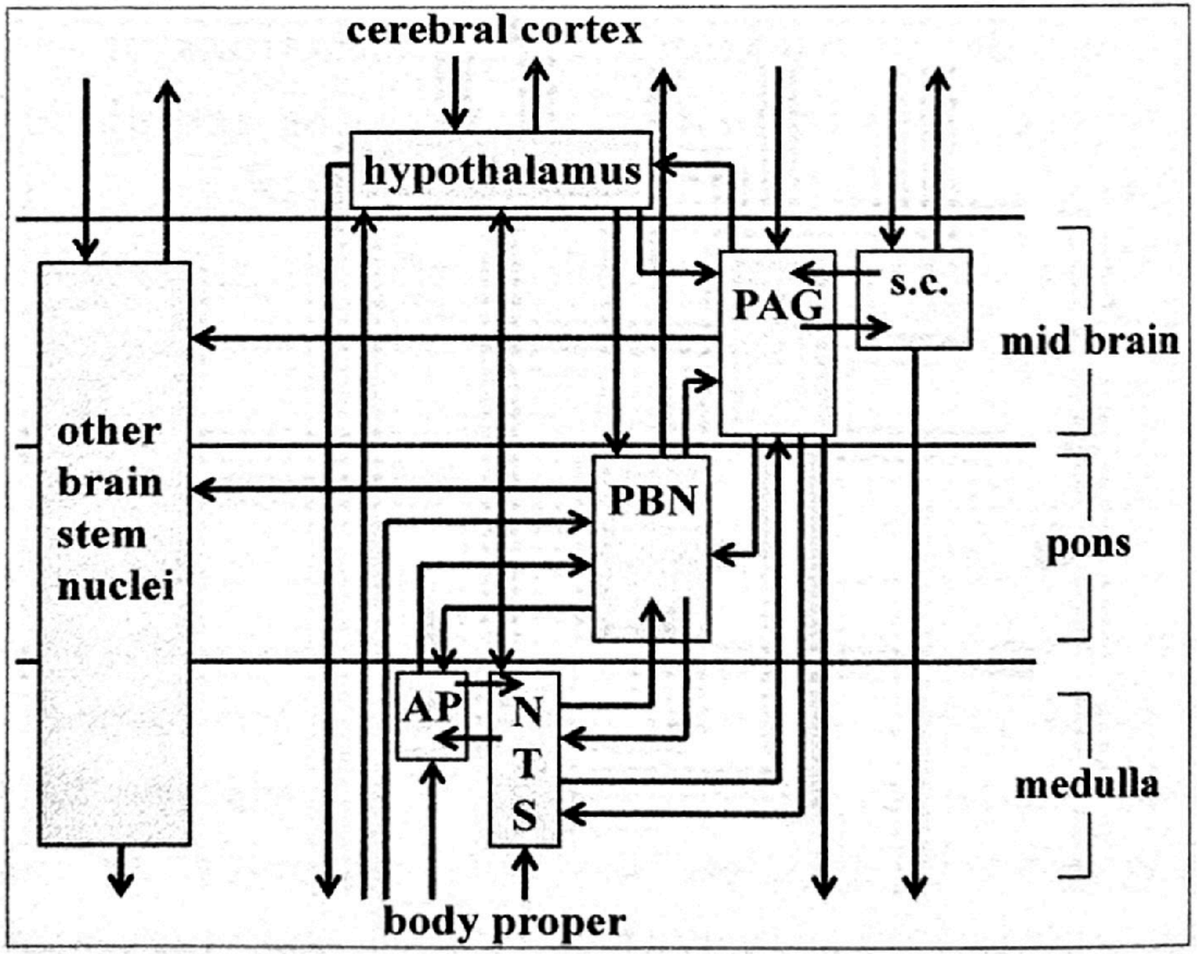


Striedter & Northcutt. *Brains Through Time*

The periaqueductal gray (PAG)

Key affective-emotive relay for modulating pain, drives, neuromodulators





Damasio. *Feeling and Knowing*

Ok, so how do we make a conscious robot?

It must feel pain, and learn to cope with it.

There would have been a time for such a word
Tomorrow, and tomorrow, and tomorrow,
Creeps in this petty pace from day to day
To the last syllable of recorded time,
And all our yesterdays have lighted fools
The way to dusty death. Out, out, brief candle!
Life’s but a walking shadow, a poor player
That struts and frets his hour upon the stage
And then is heard no more: it is a tale
Told by an idiot, full of sound and fury,
Signifying nothing.

Patrick Stewart as Macbeth

The Real Bard. *Macbeth*