Neurodynamical computing at the information boundaries of intelligent systems

APS/DBIO Neurodynamical Models of Cognition // March 8, 2023

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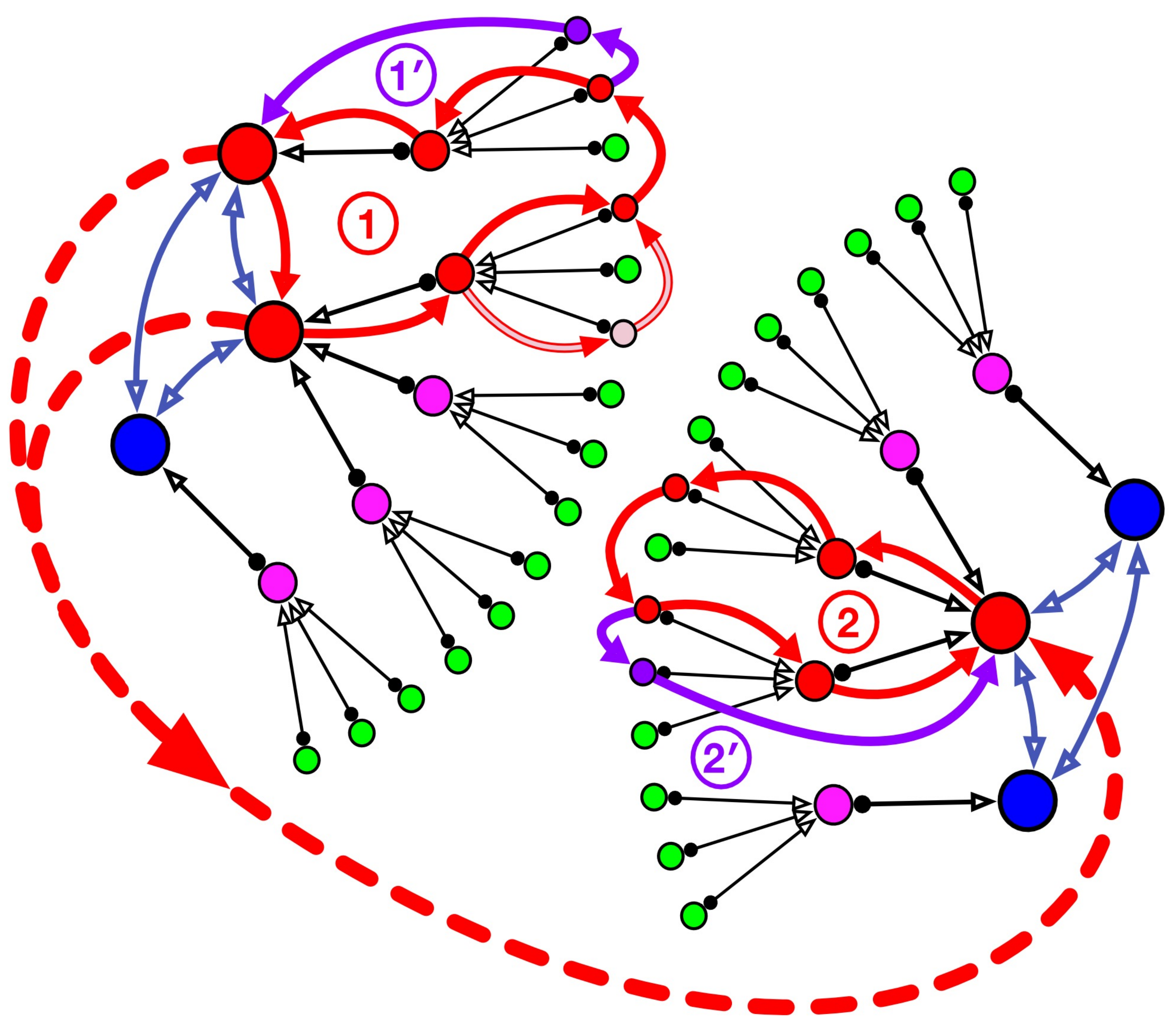
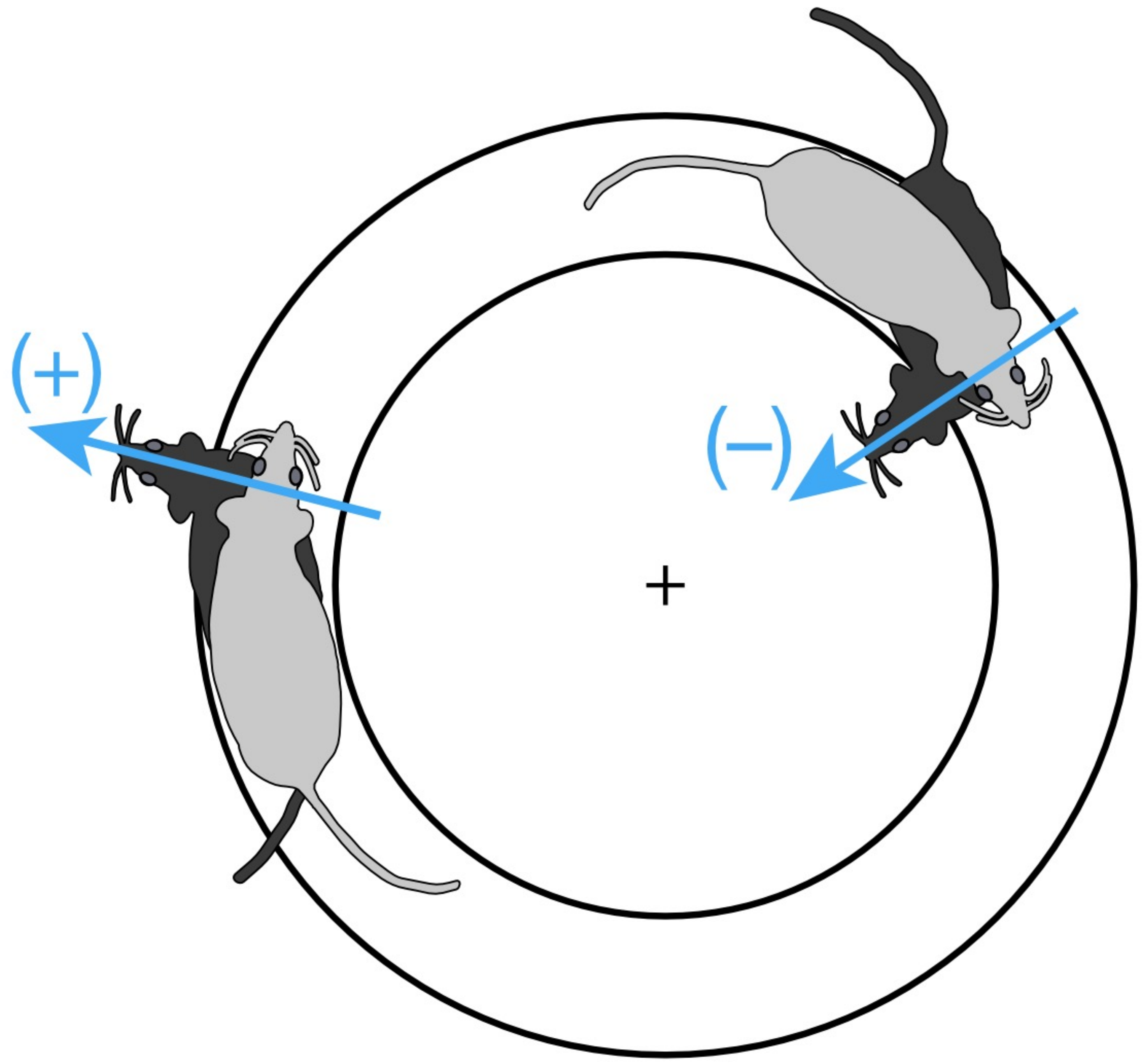
Outline

Toward a nonreductive dynamical neuroscience of 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

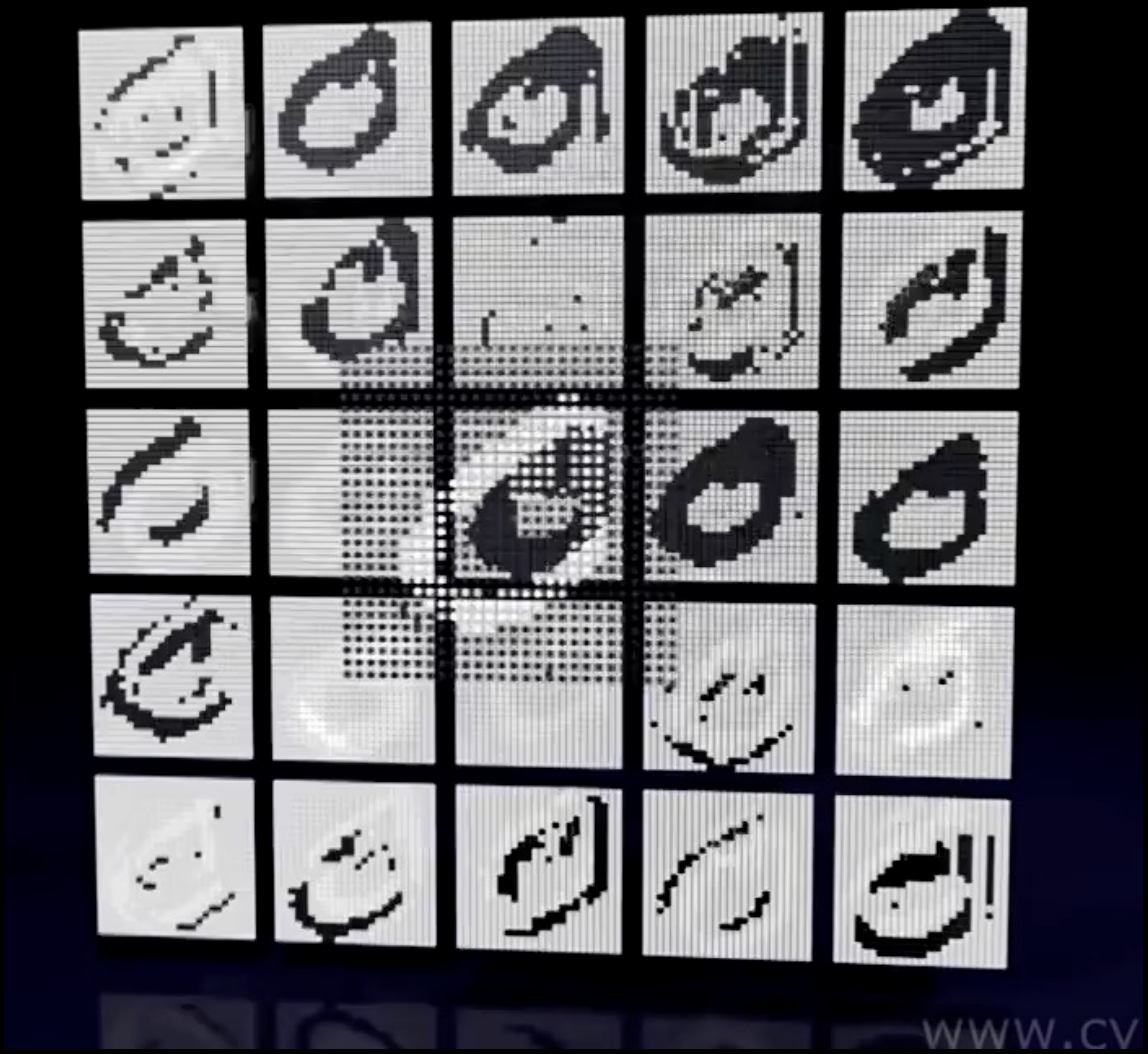


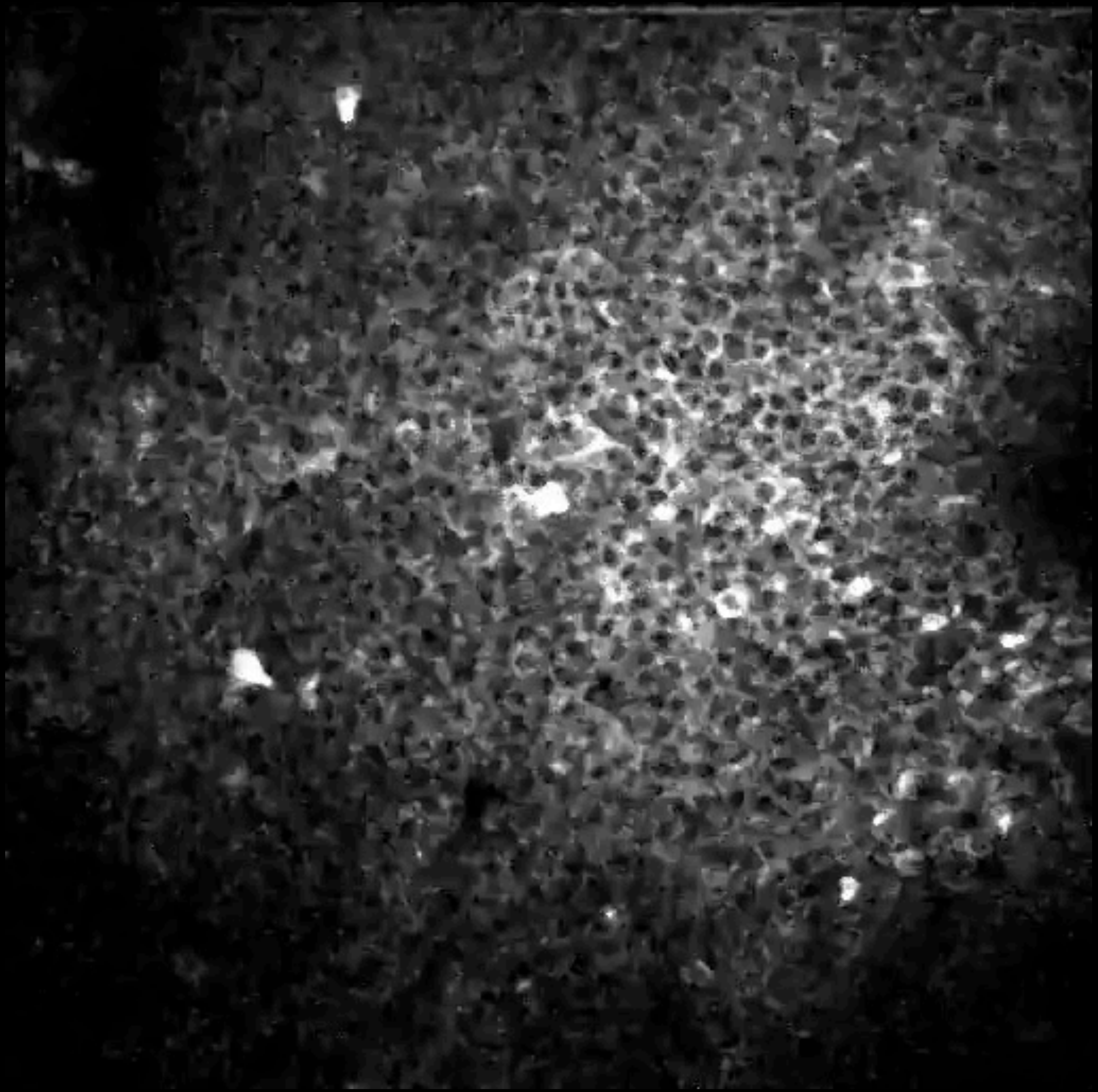


Three paths…

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

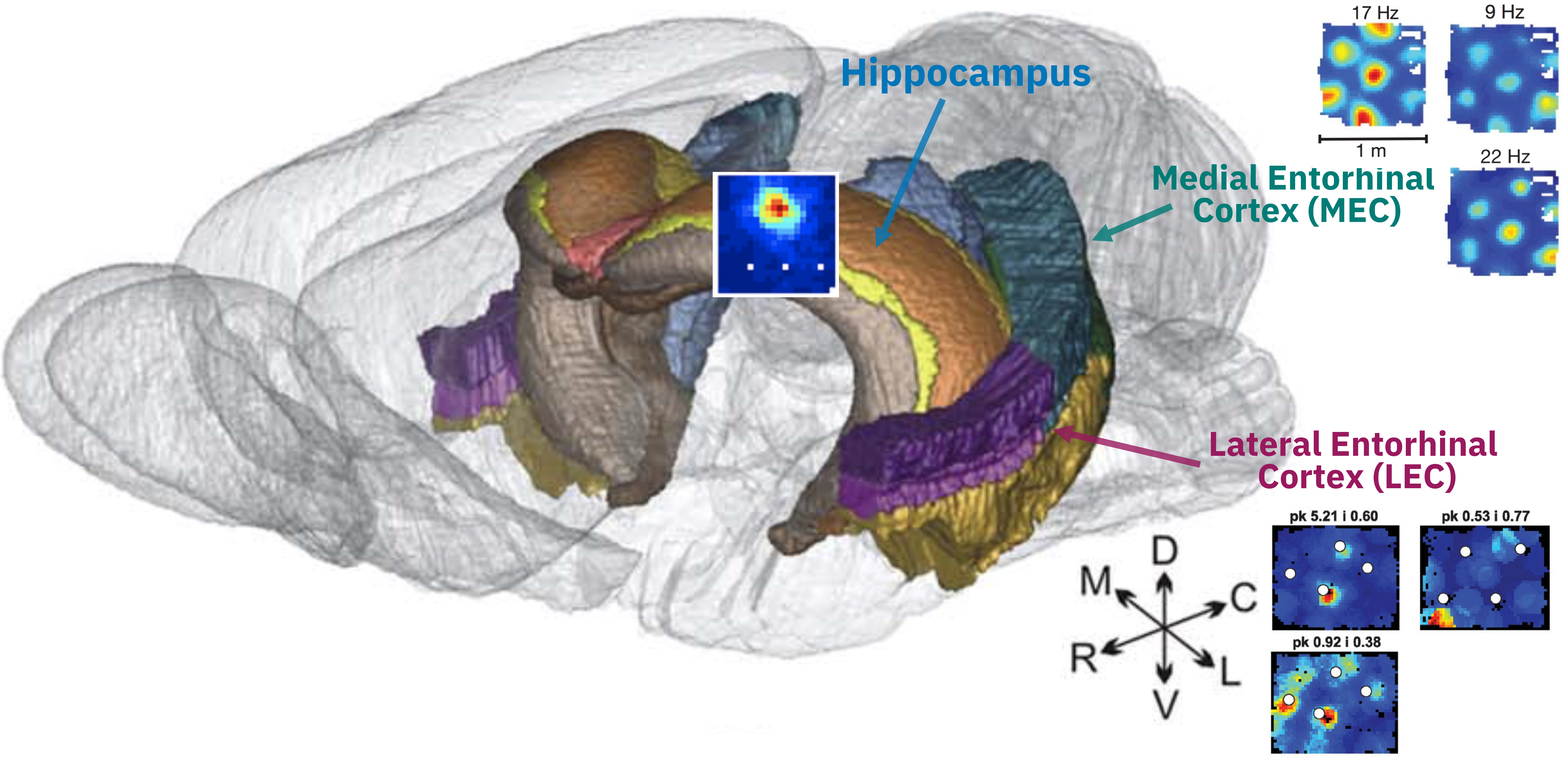
Inverting the input-output paradigm

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

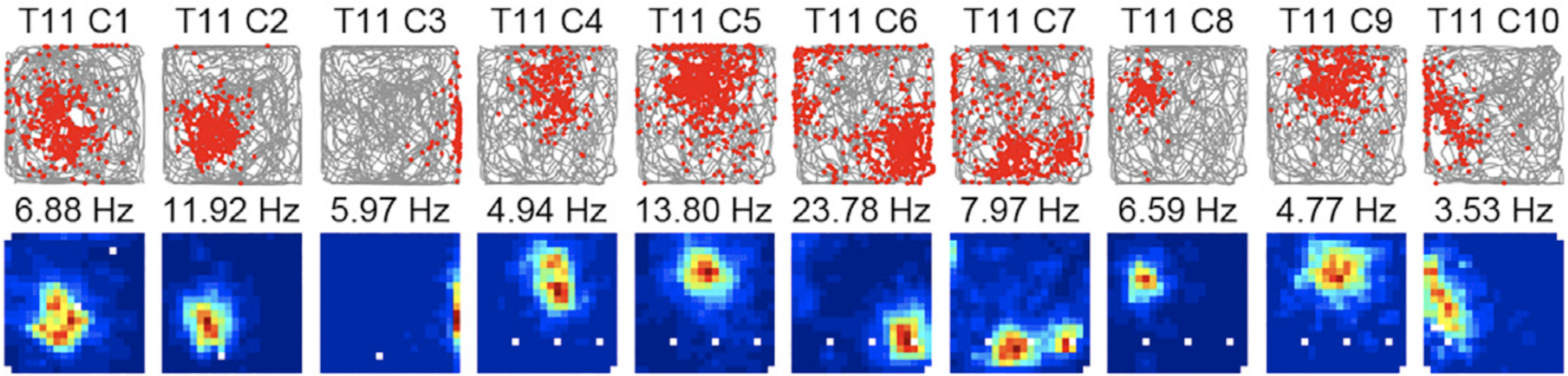
2. Neuroscience and AI have both embraced this bias, with either explicit or implicit input and output layers for computations

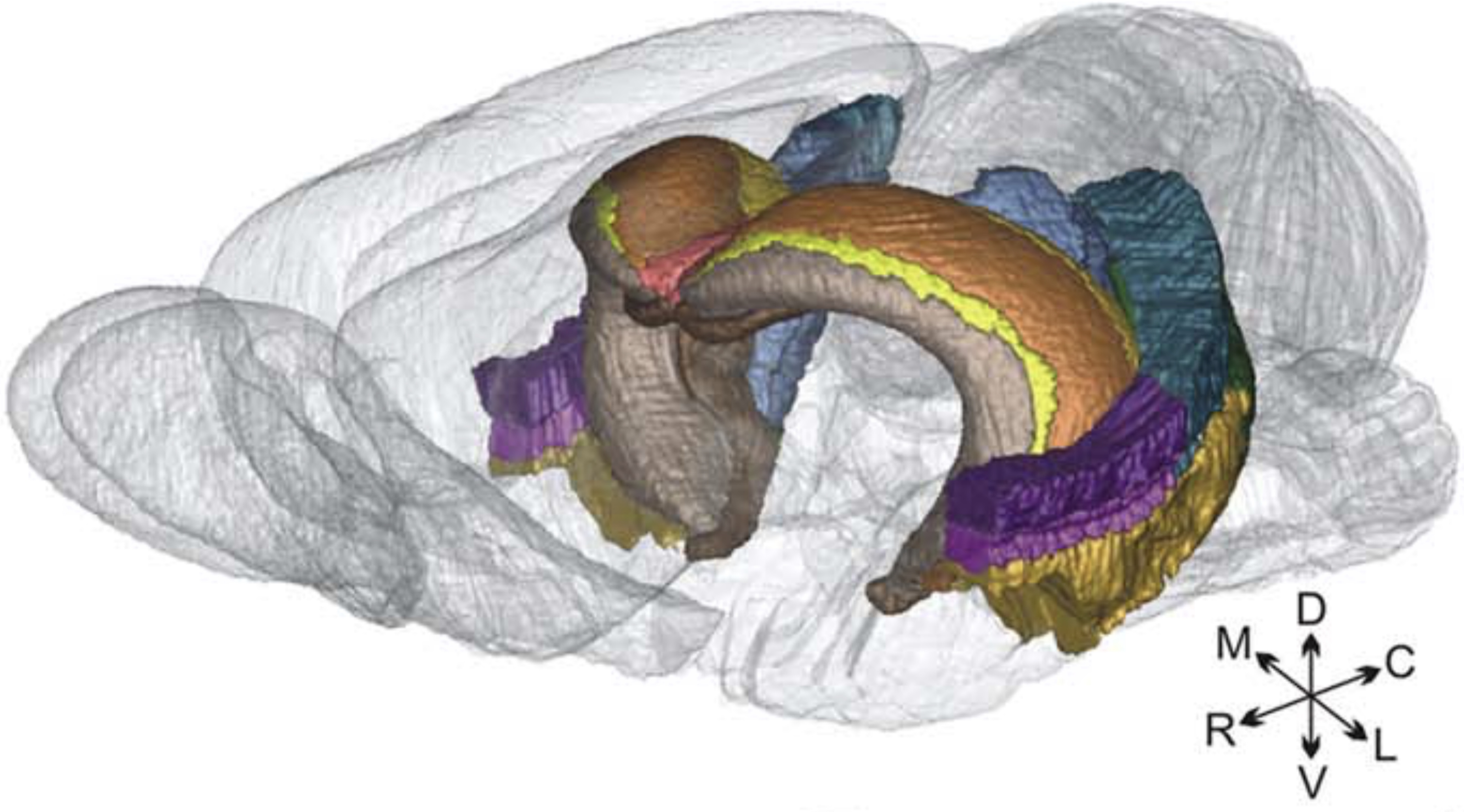
3. Implied control paradigm is one of building forward (predictive) models

Image Credit: Glazer et al. (PEGASOS)



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





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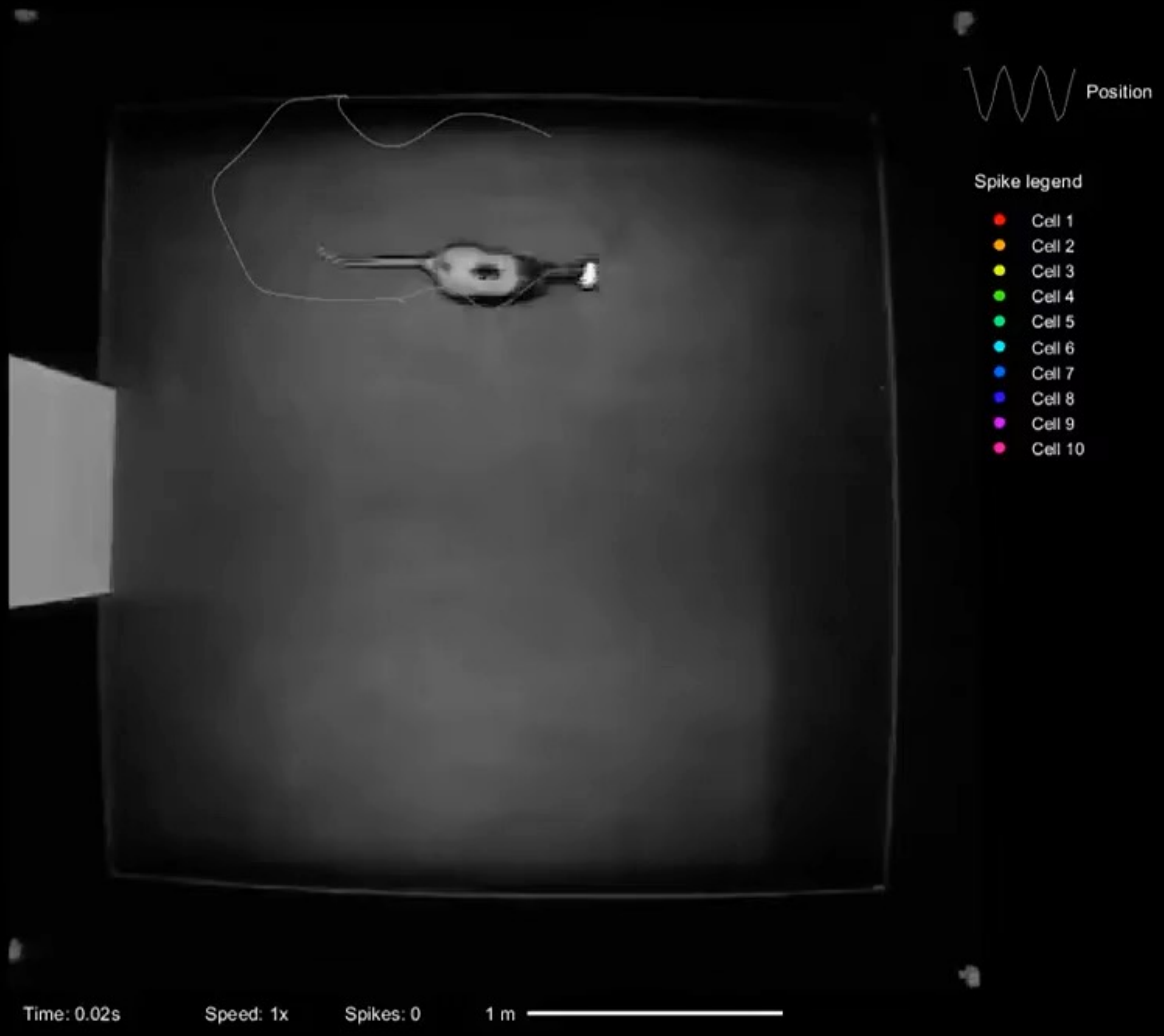


Not Actual Speed

Video Credit: R. Grieves

Embodied cognition

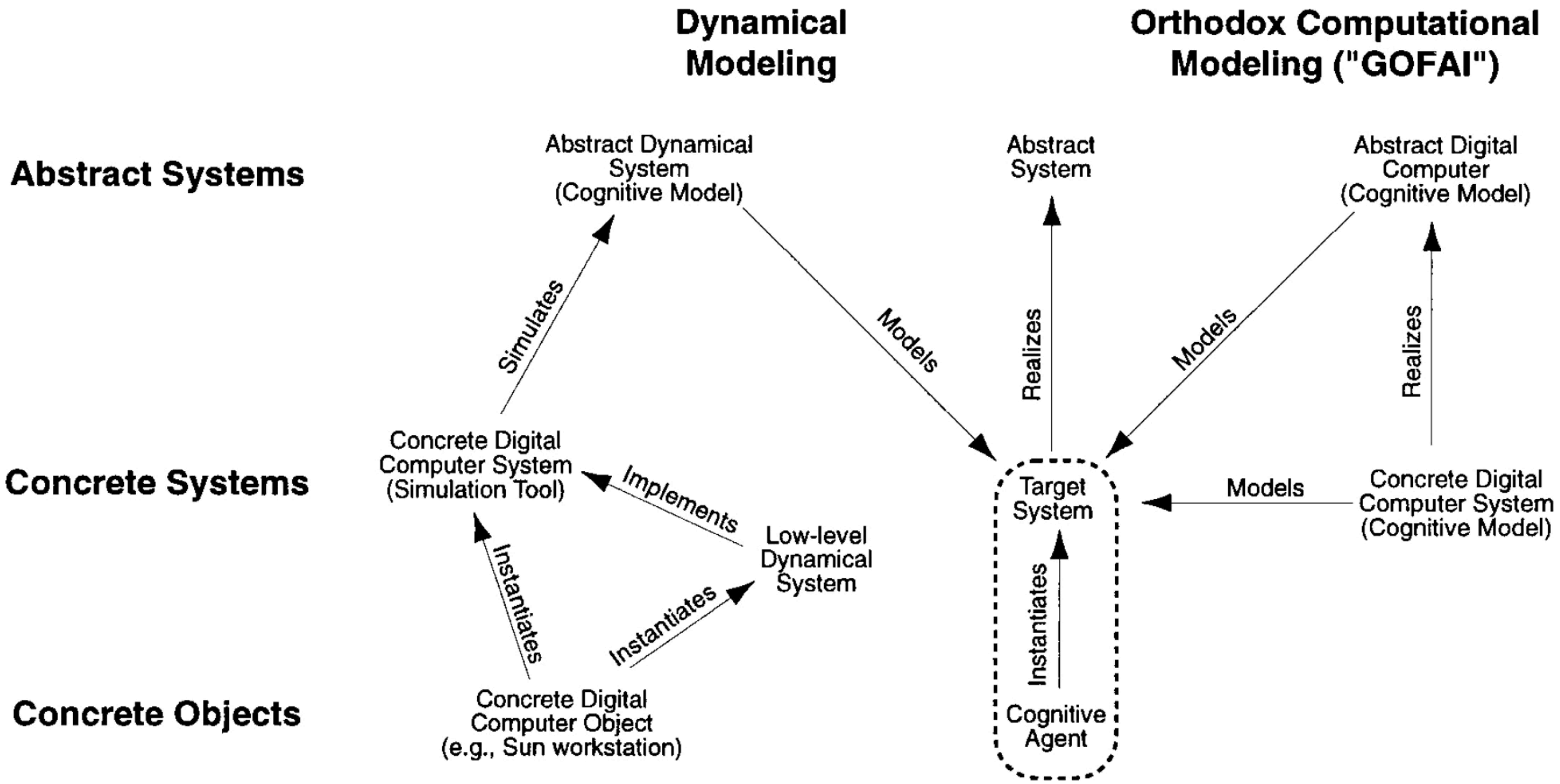
Progressive articulation vs. forward models

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



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

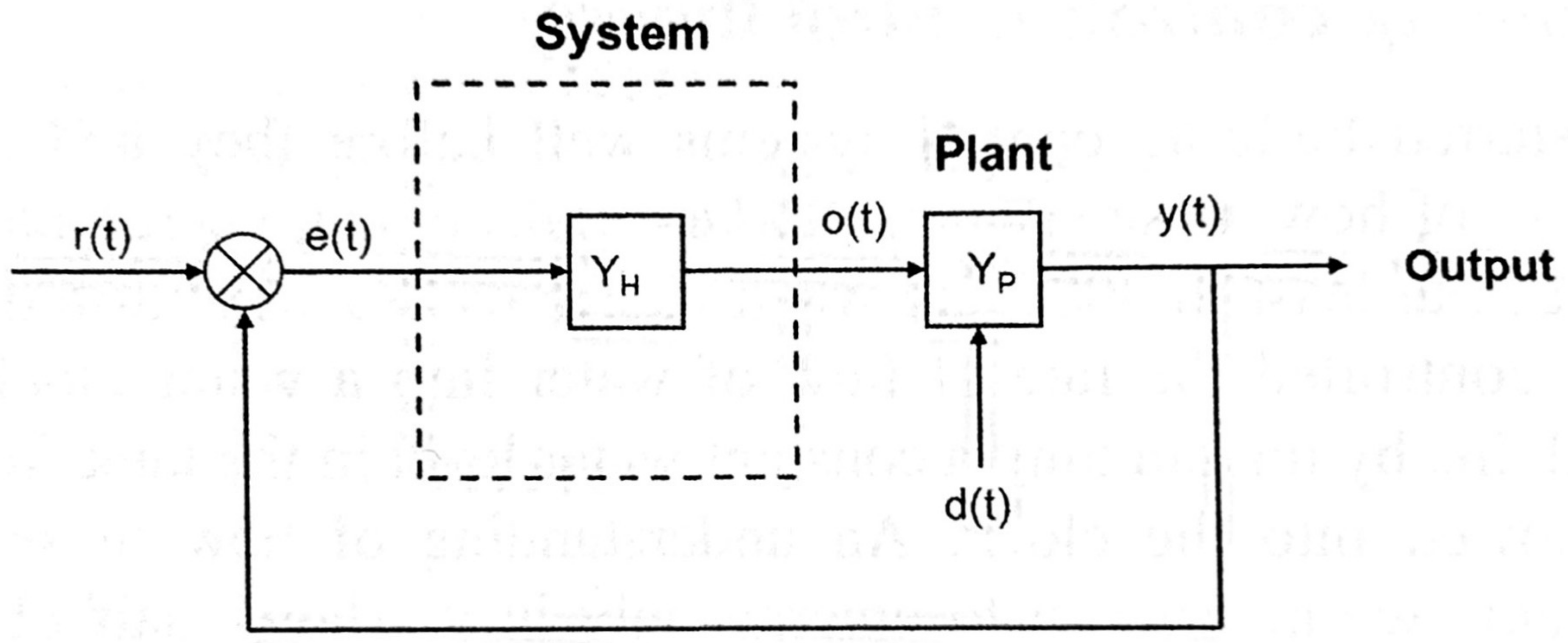


FIG. 2.1 Diagram of a negative feedback control system.[21]

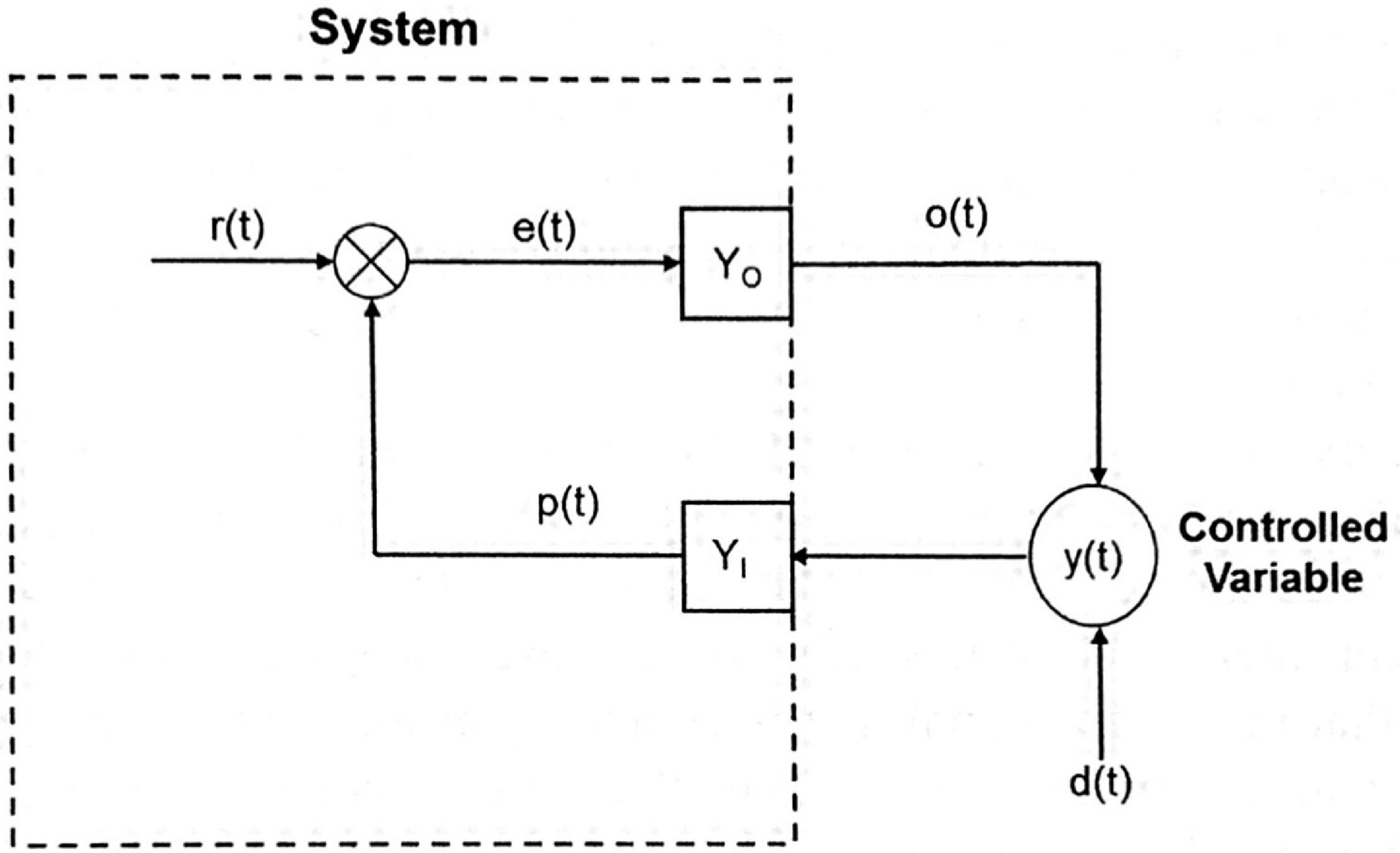


FIG. 2.2 PCT model of a control system; control theory for psychologists.

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

Reorganizing the control flow

Perceptual control internalizes input, output, and goals

- 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

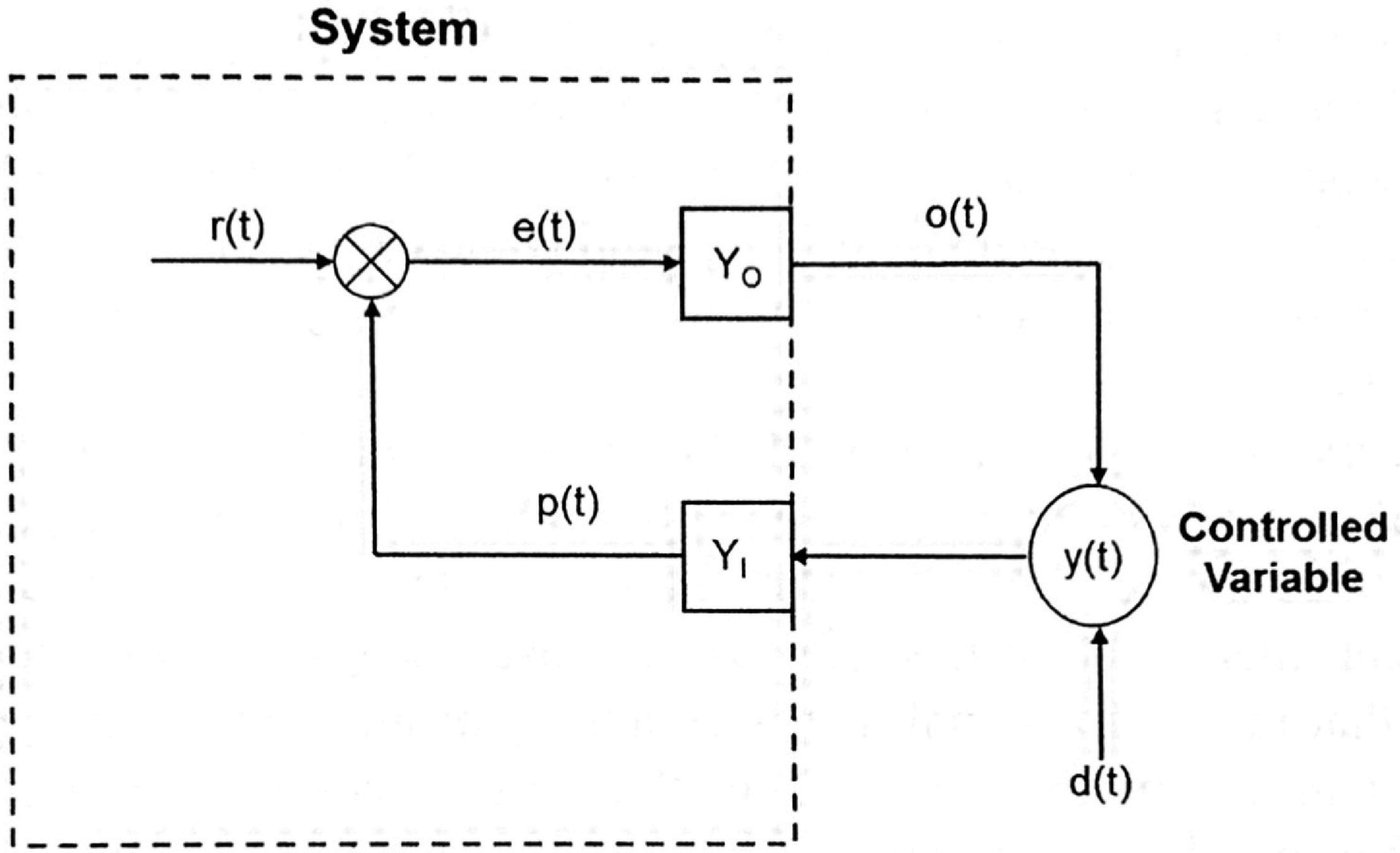


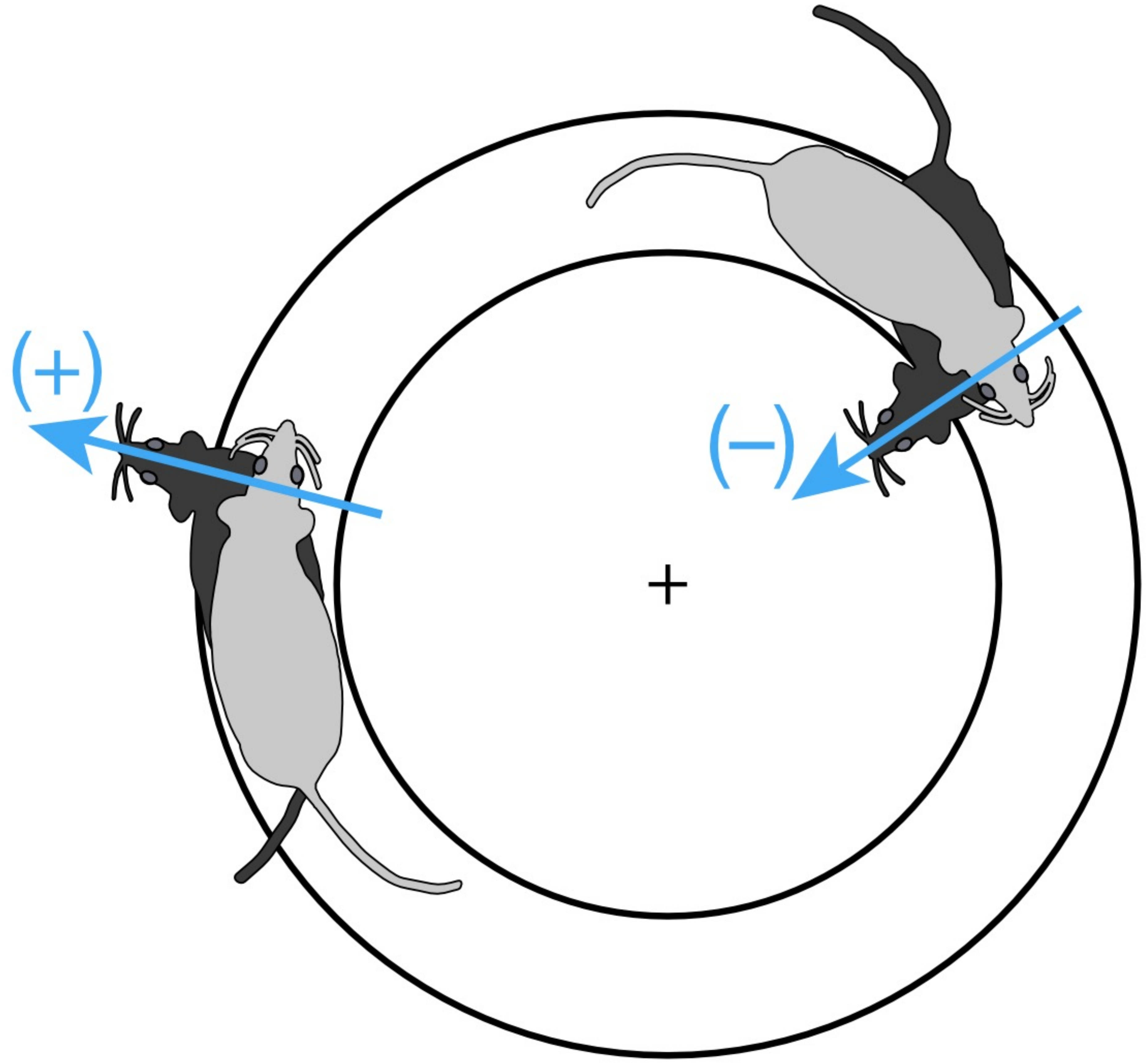
FIG. 2.2 PCT model of a control system; control theory for psychologists.

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

Active inference

The generative role of behavior

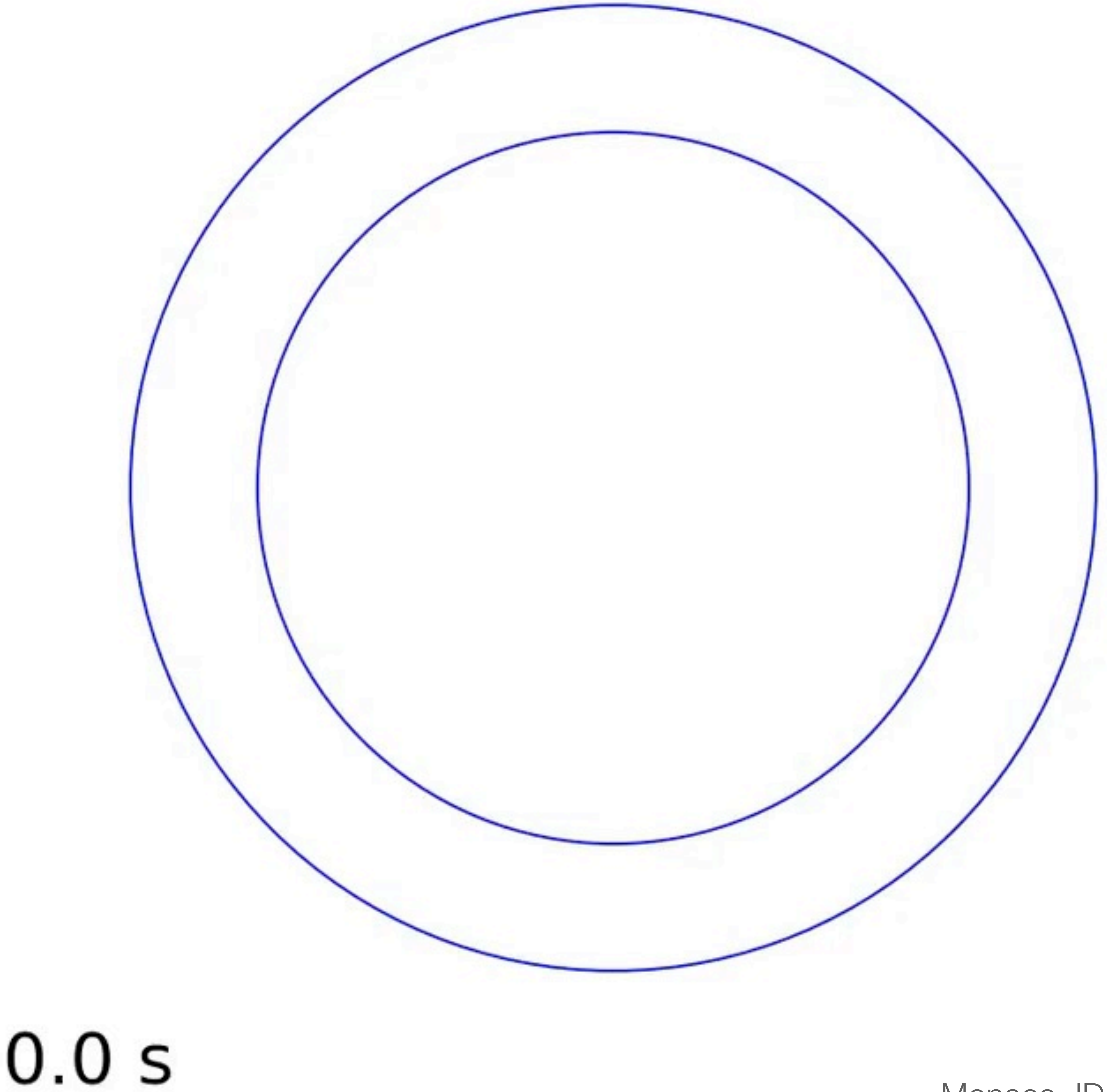
- Optimal (Bayesian) inference in feedback-driven generative models require *active inference*: actions that maximize model evidence by balancing internal active-state (self) entropy with external sensory-state (nonself) entropy.
    - *Agents learn massively distributed internal feedback models by adaptively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

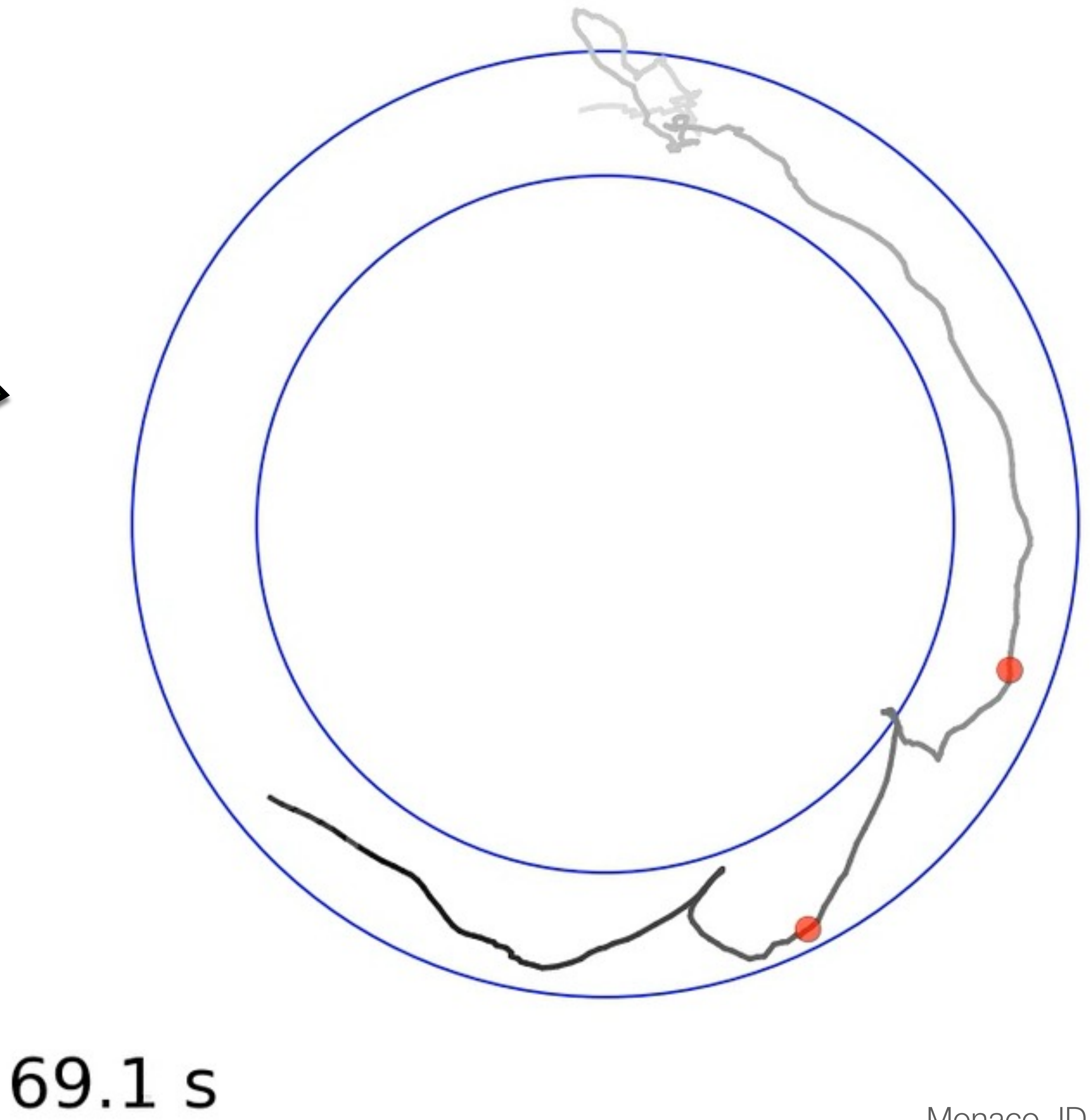
Example



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

Example

Location of scan firing



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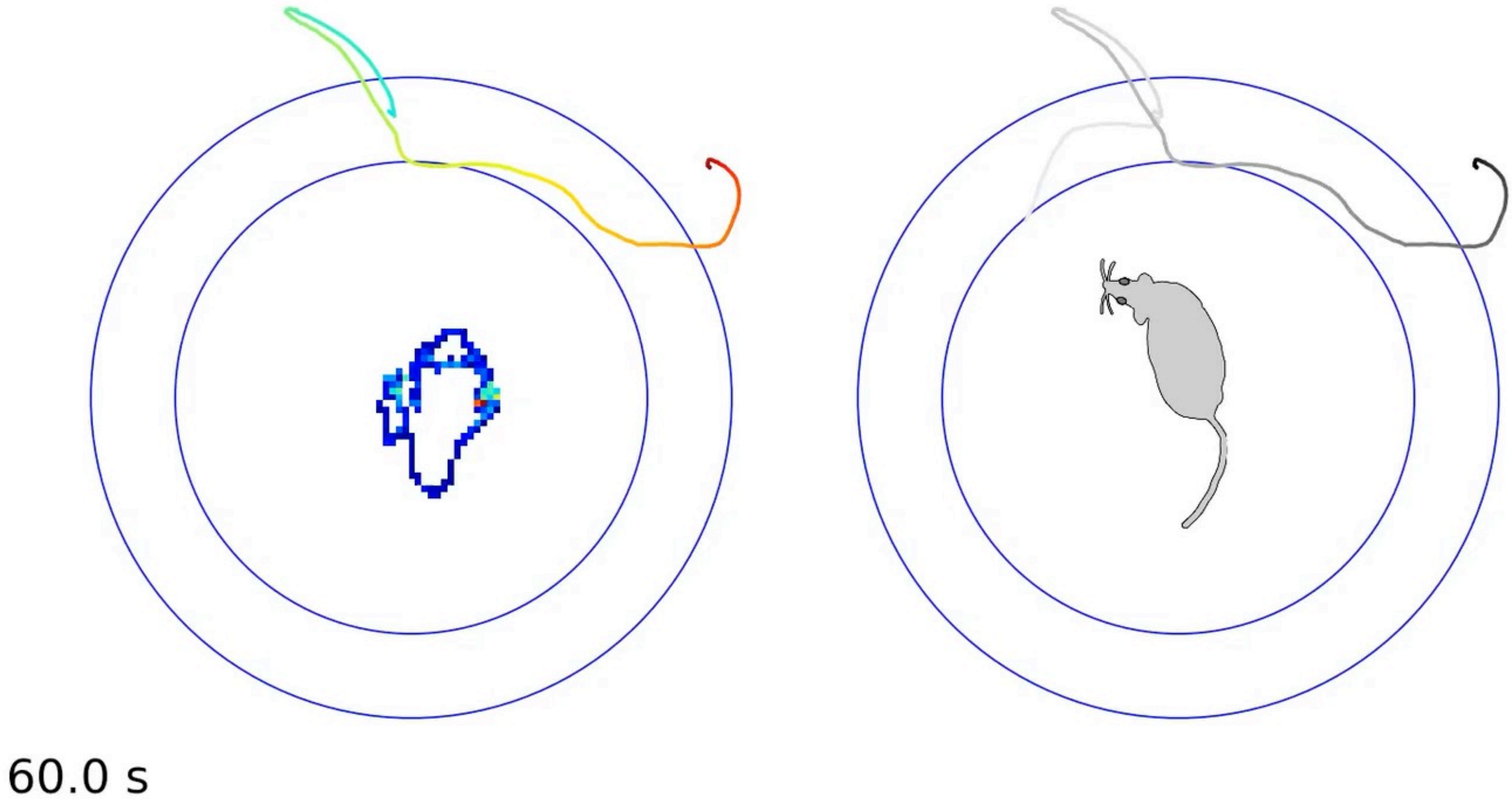
Quantifying Lateral Head-Scan Behaviors



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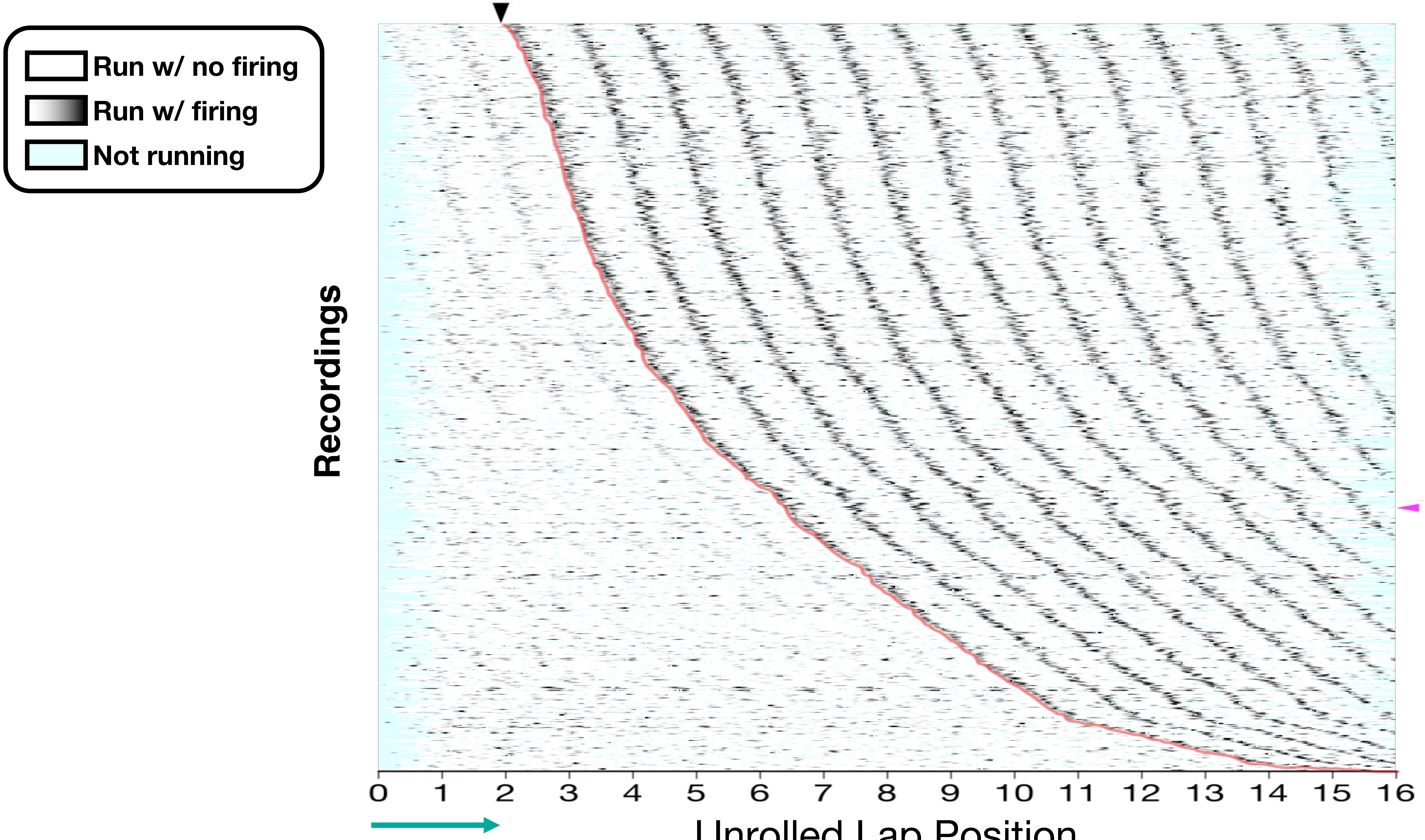
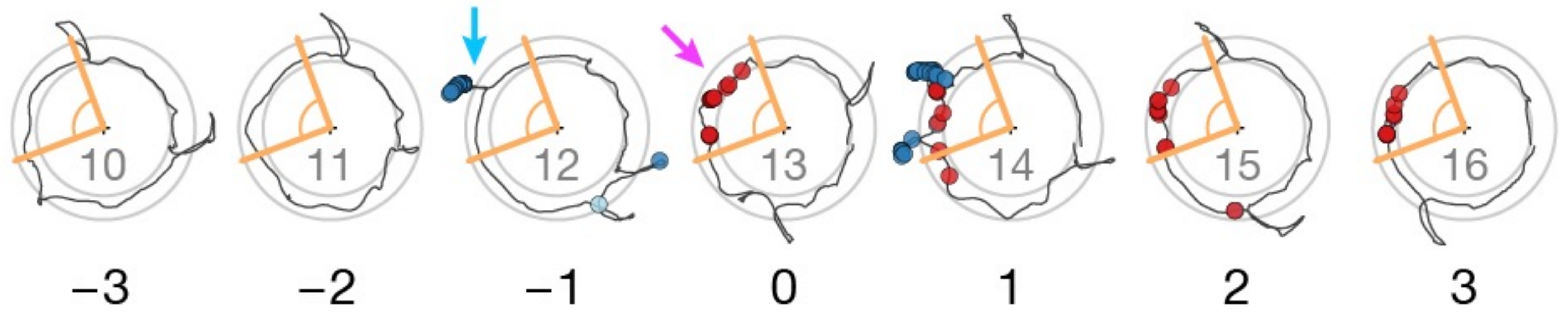
Place-Field Firing

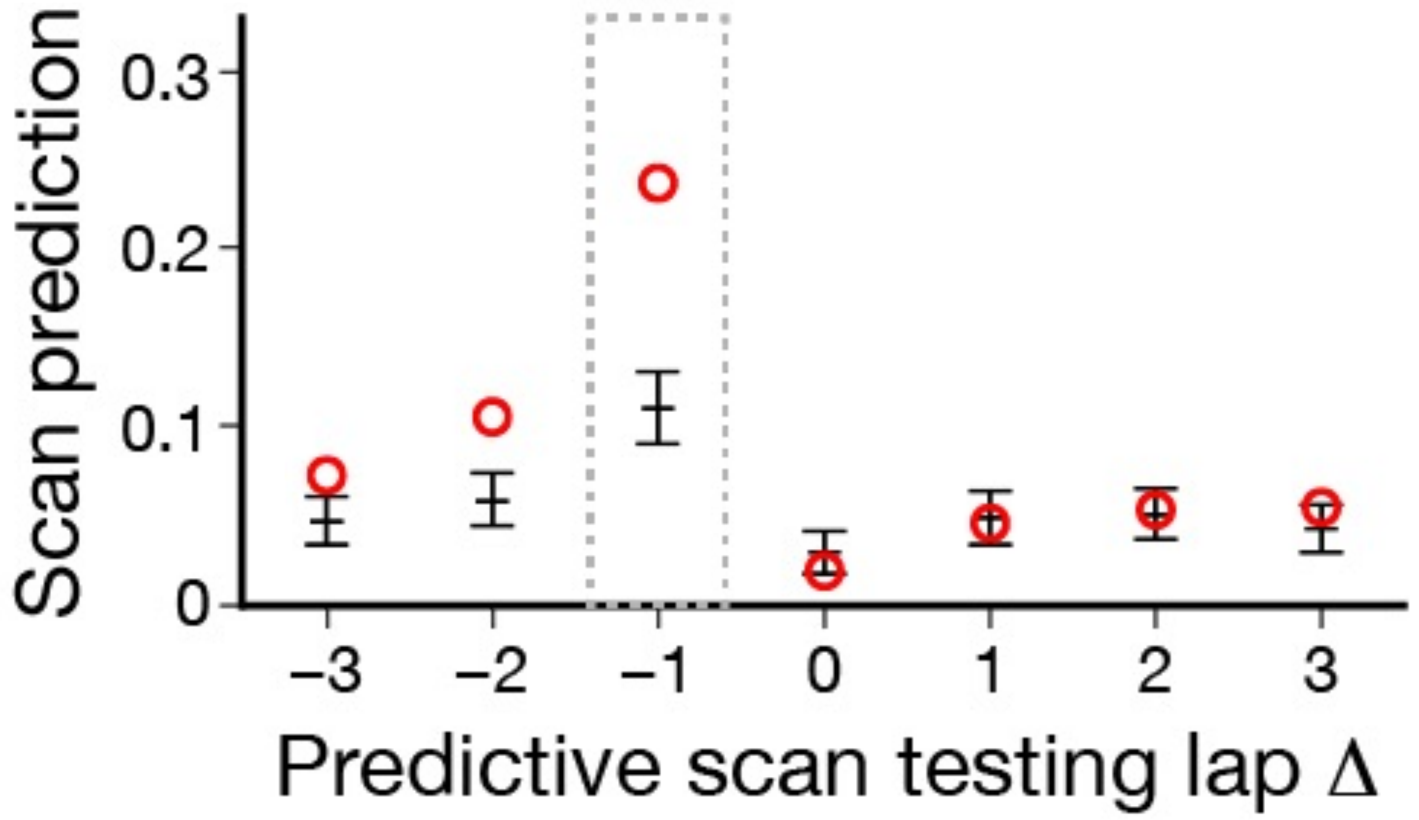


Monaco JD, *et al*. (2014). Nature Neuroscience, 17: 725

Significant Predictive Value: Scan Firing→Place-Field Event



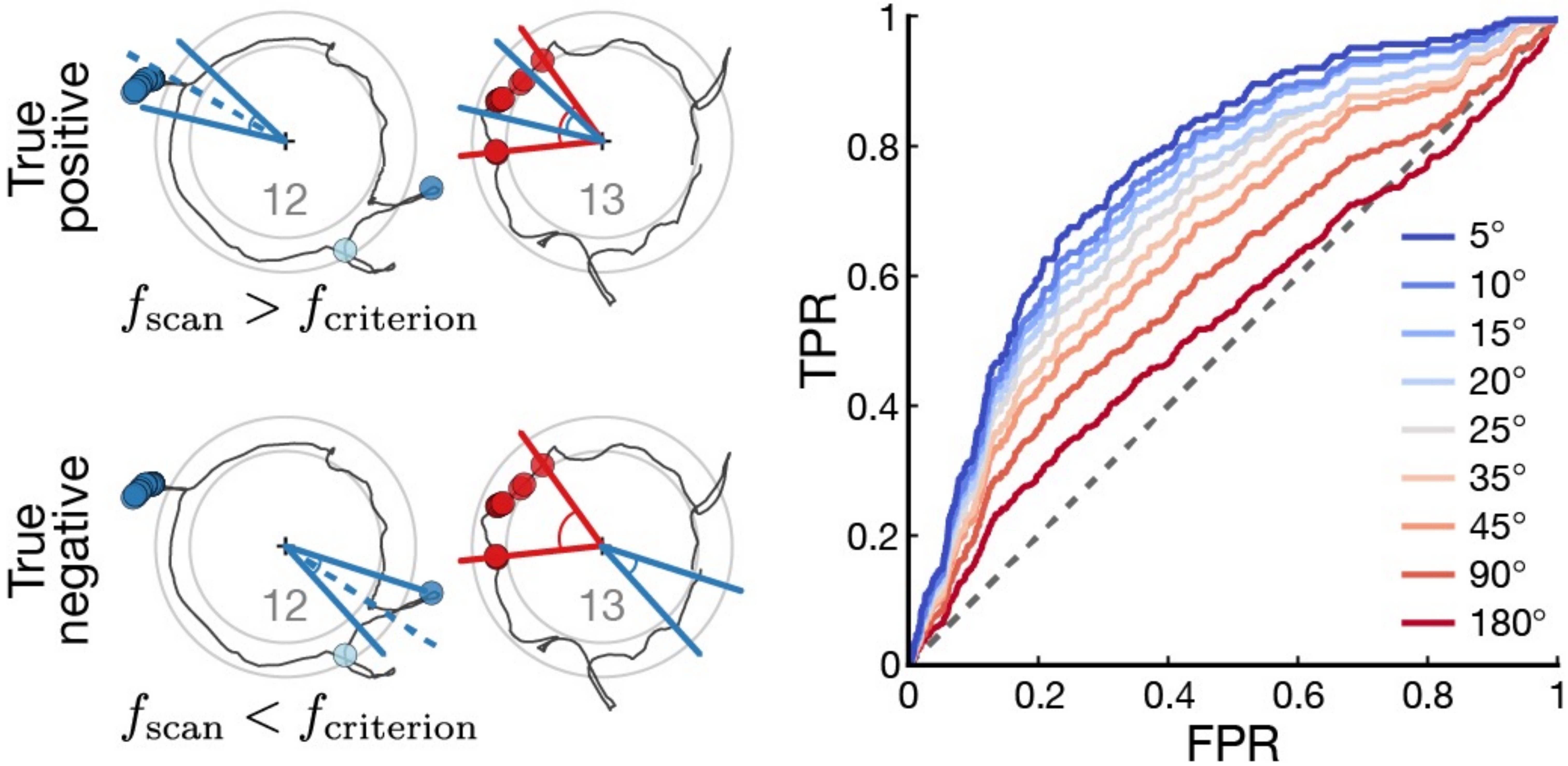
• **<u>Scan Predictive Value:</u>**
Fraction of criterion scan-firing events that fall within the track-angle bounds of a new or potentiated place field on the lap prior to the event (Δ=–1)



• **<u>Overall Result:</u>**
Computed over all criterion scan-firing events in all animals (n=36), subregions (CA3, CA1), experiments (novelty vs. double rotation), training days, and session number (up to 5).

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

ROC Analysis: Place-Field Event→Prior Co-Localized Head Scan

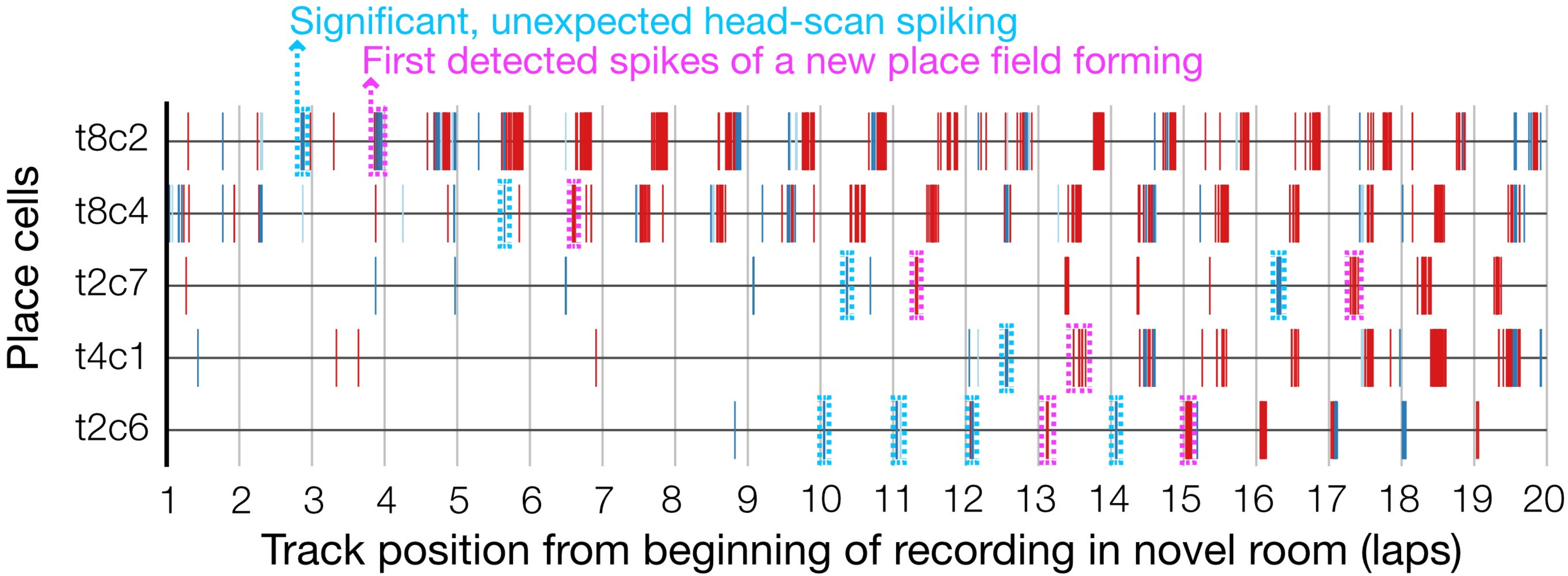


- **Abrupt place-field changes were diagnostically associated with significant high-firing head scans on the previous lap, with the association increasing to 75% AUC as the specificity of spatial co-localization approached ±5º**

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

Active inference

Cognitive map-building driven by autonomous head-scan sampling

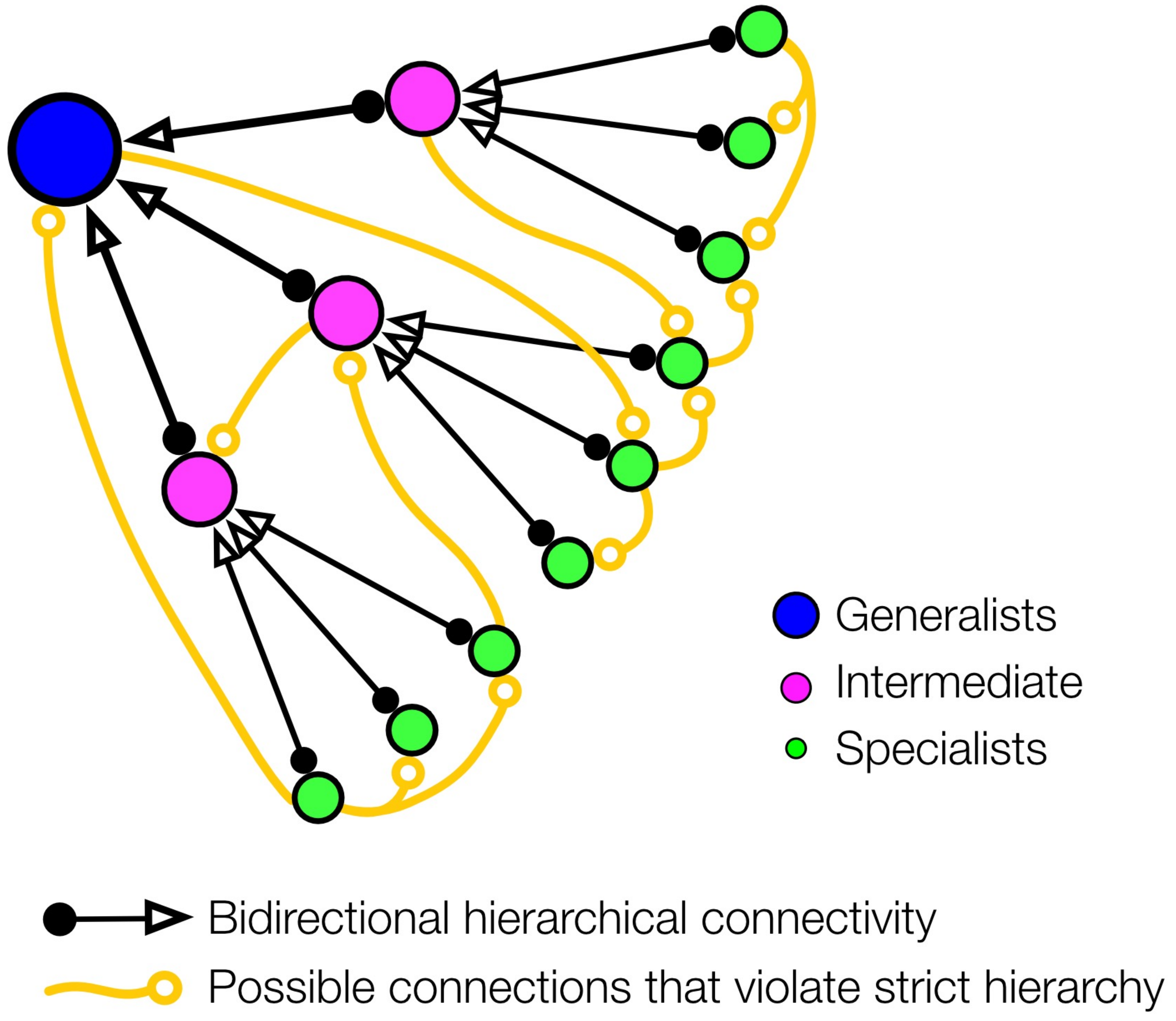


Monaco JD, *et al*. (2014). Nature Neuroscience, 17: 725

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*

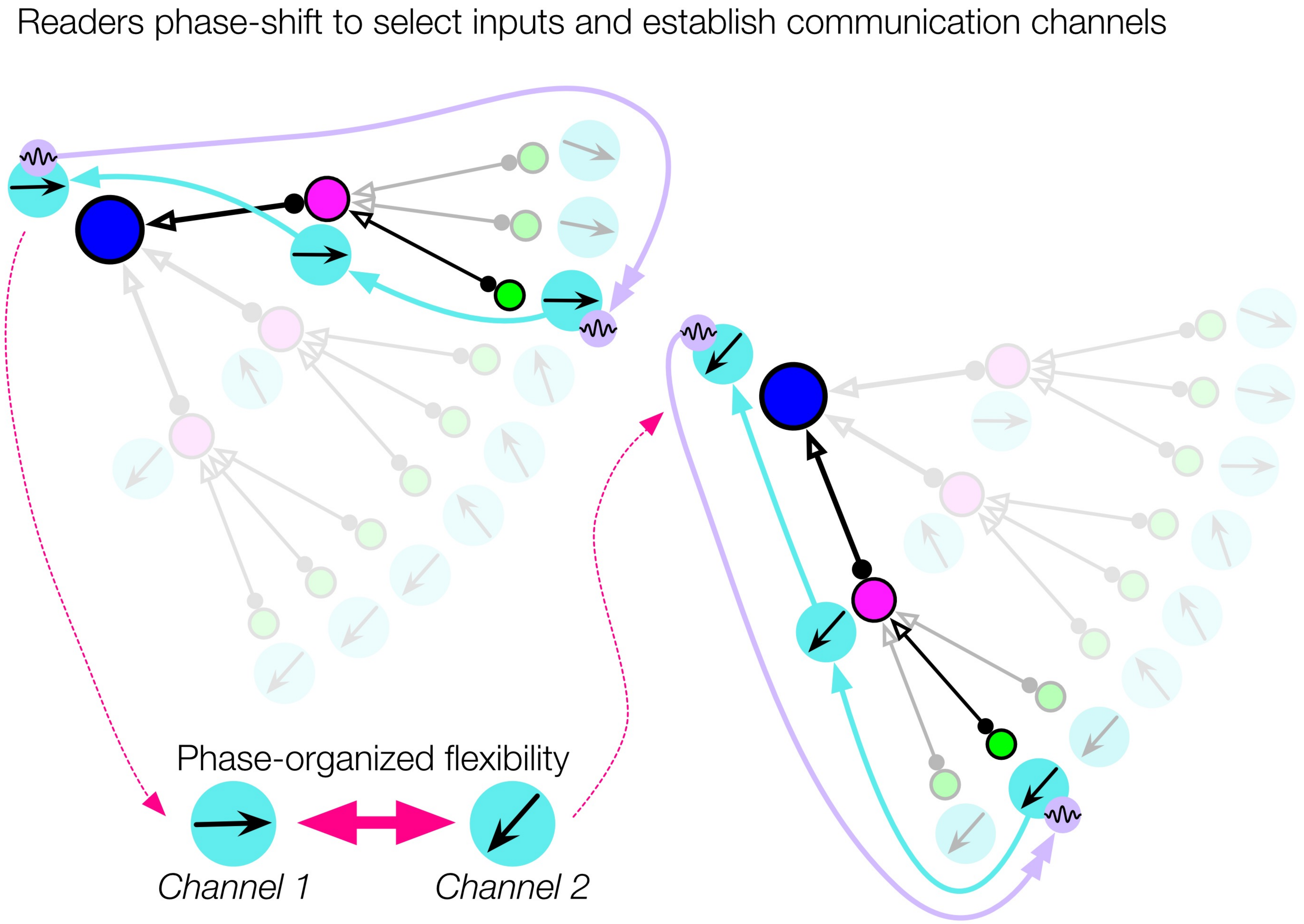
Integrative framework for neurodynamical cognition

(1) Network structure:

(2) Temporal dynamics:

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

(3) Agentic interaction:



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Integrative framework for neurodynamical cognition

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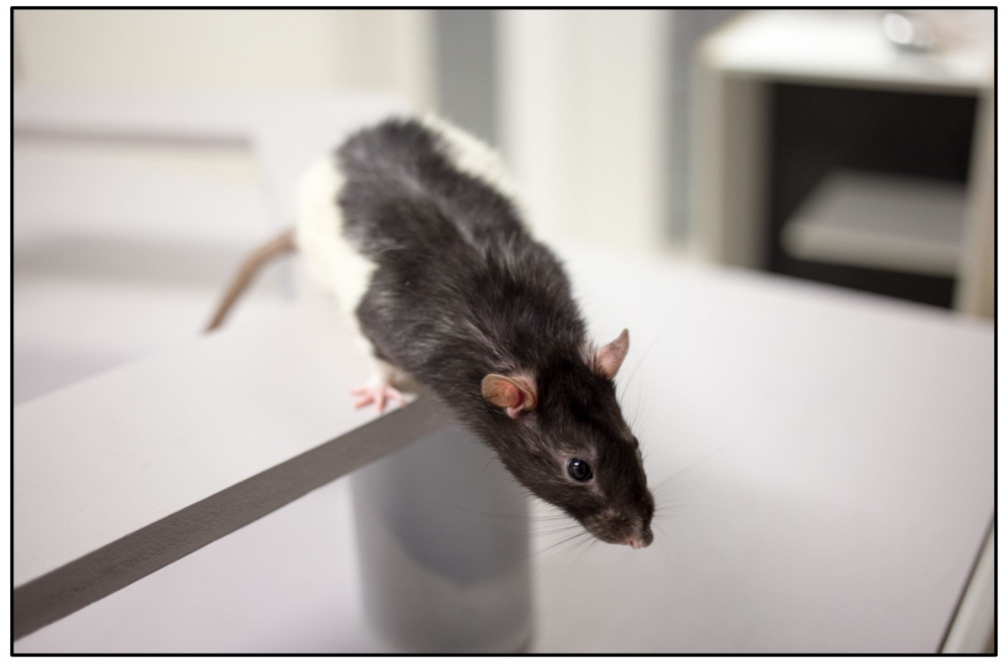

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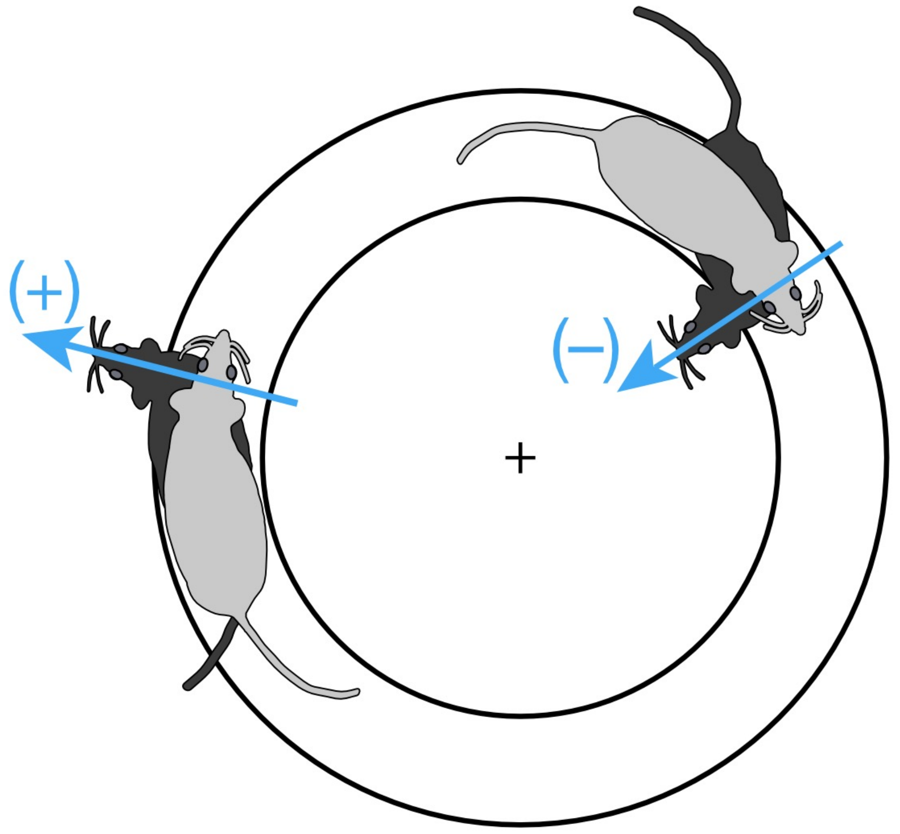
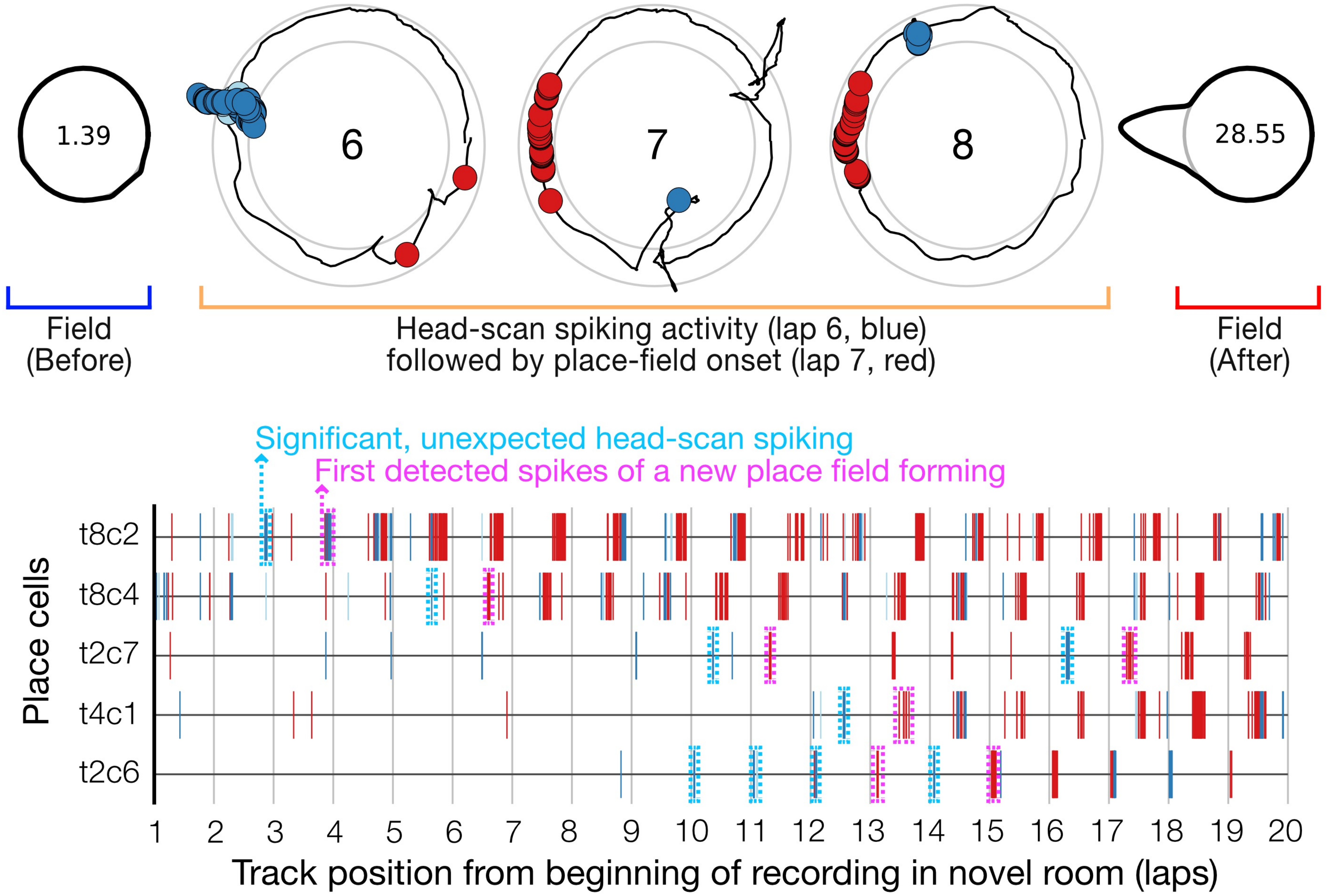


(3) Agentic interaction:

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



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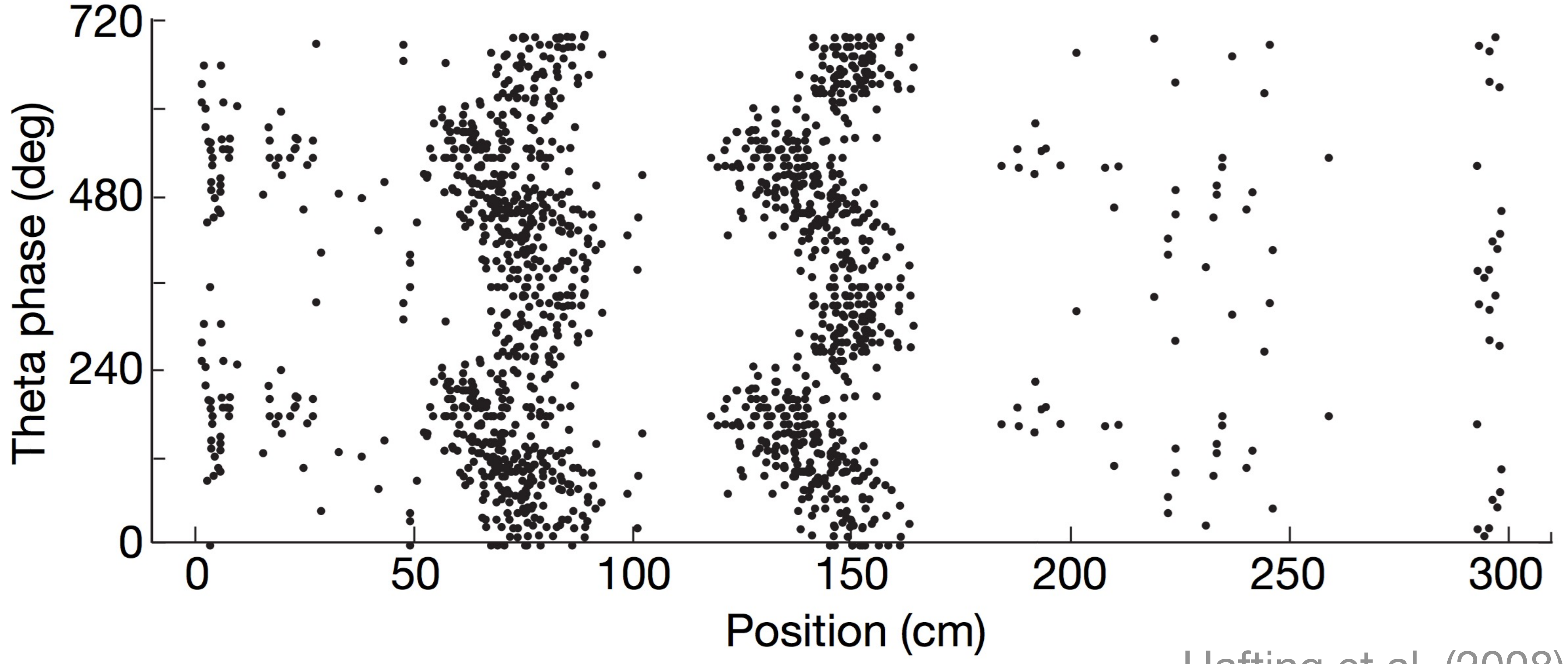
Temporal and Population Dynamics

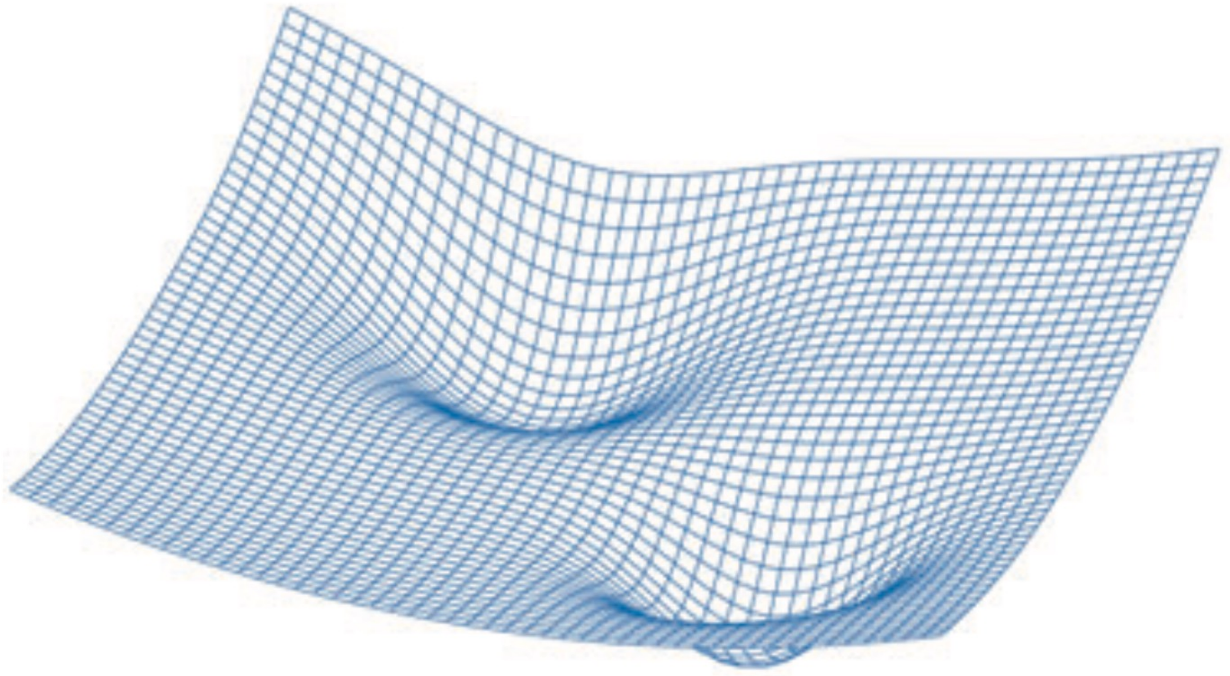
Key Building Blocks

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

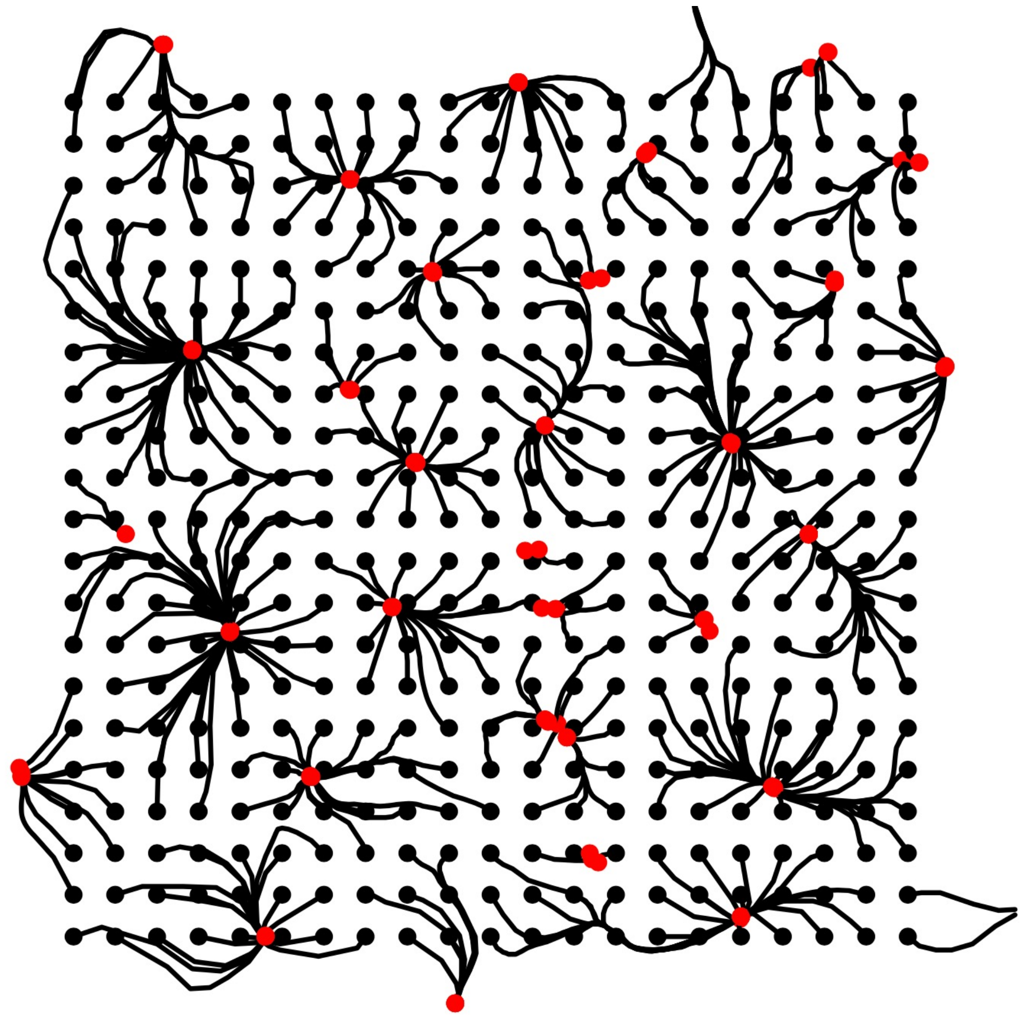


Hafting et al. (2008)

- **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*

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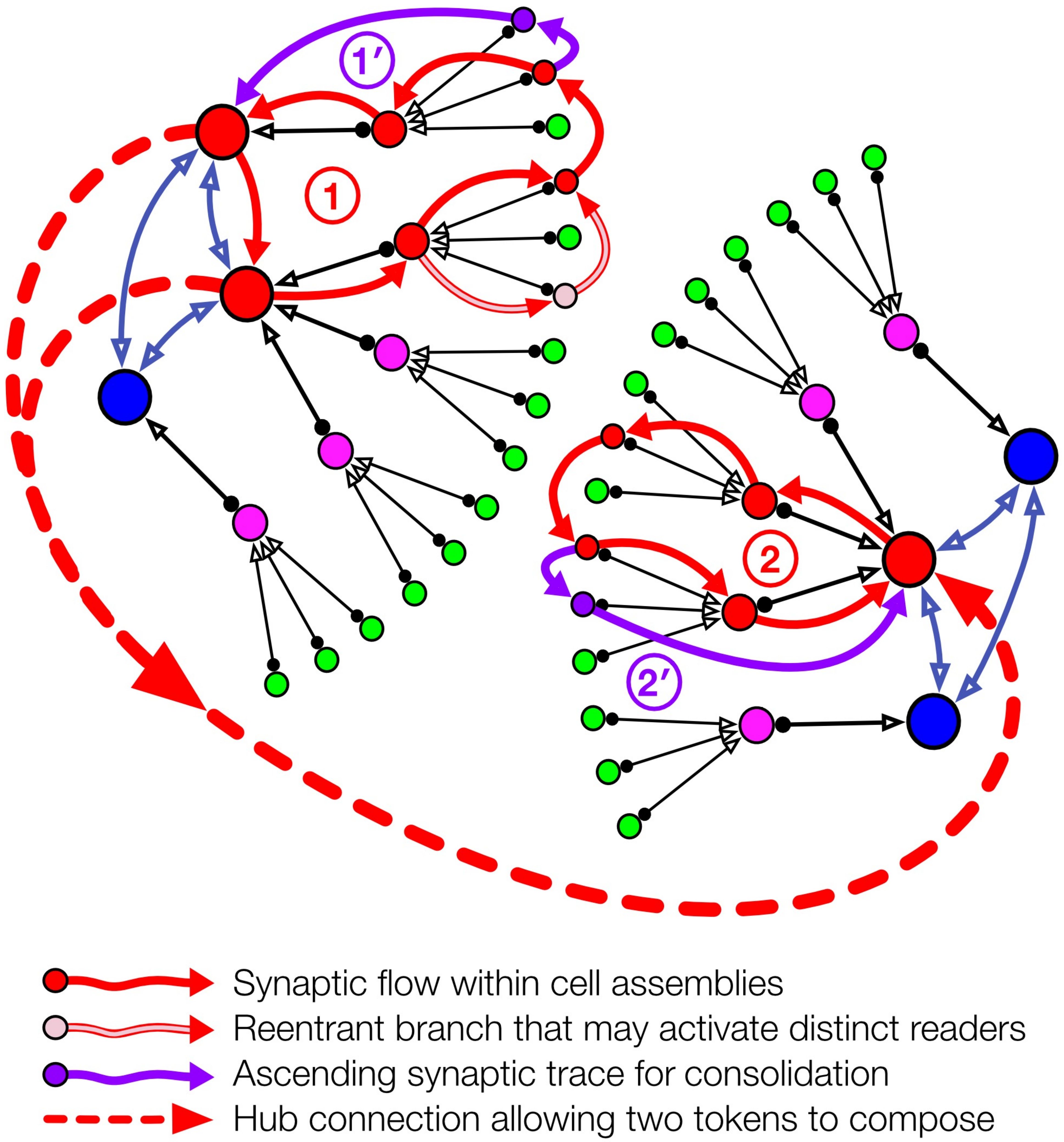
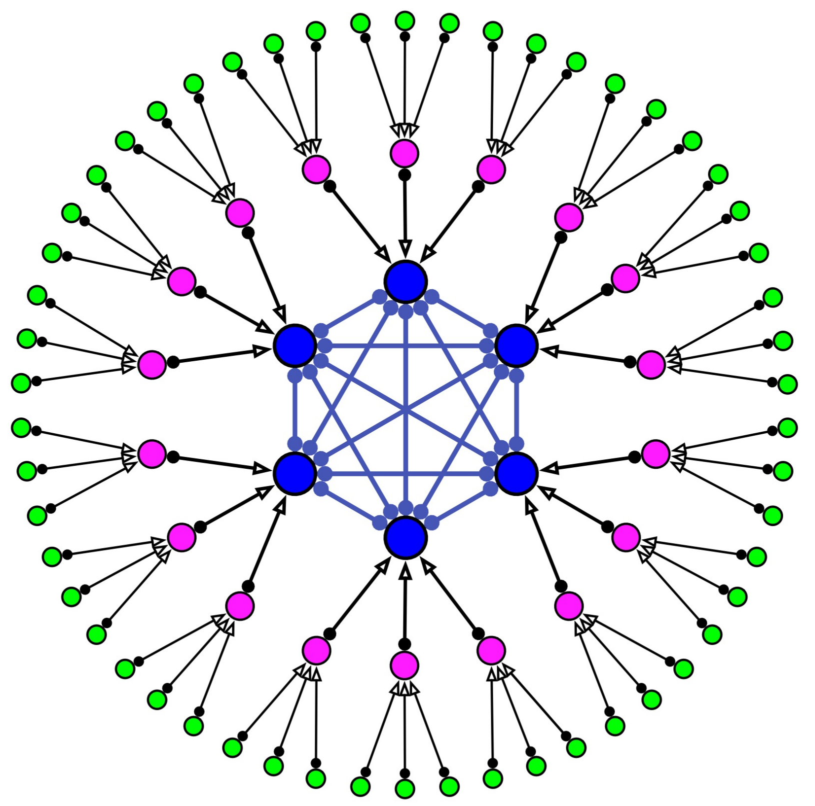
Cell assemblies, synaptic traces, and reentrant loops



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

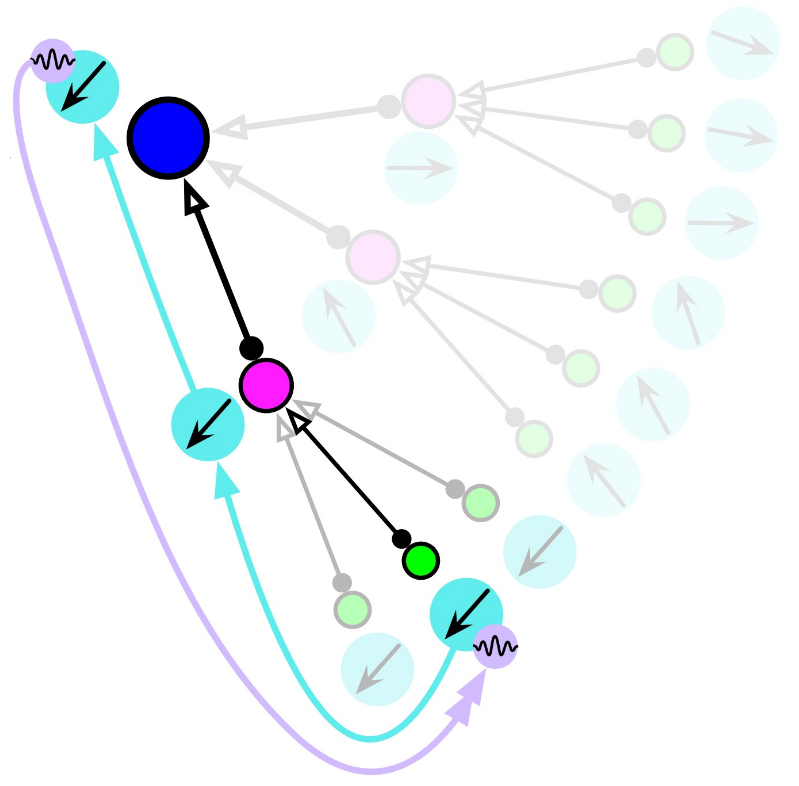
Papers

Neurodynamical principles for embodied intelligence



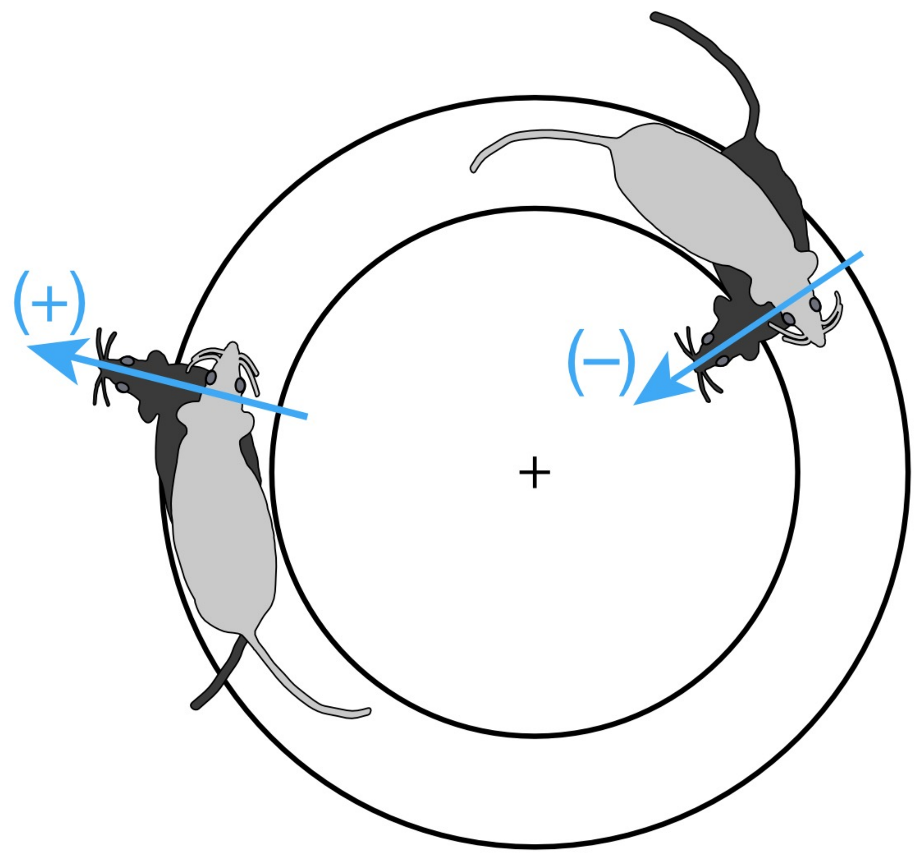
Monaco JD and Hwang GM. (2022). Neurodynamical computing at the information boundaries of intelligent systems. *Cognitive Computation*. doi: 10.1007/s12559-022-10081-9

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



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