Zero-Shot Visual Numerical Reasoning in Dual-Stream Neural Networks

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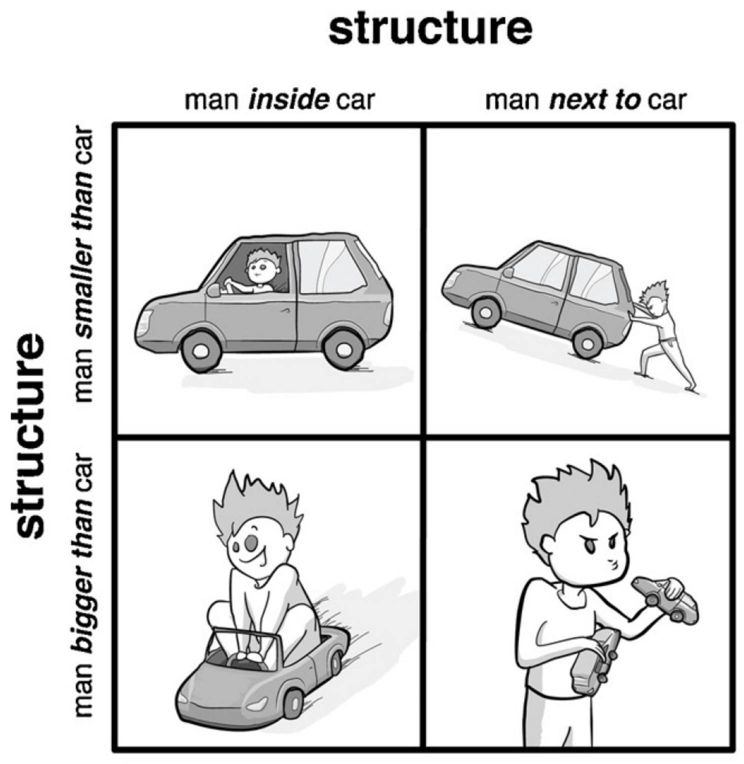
Introduction

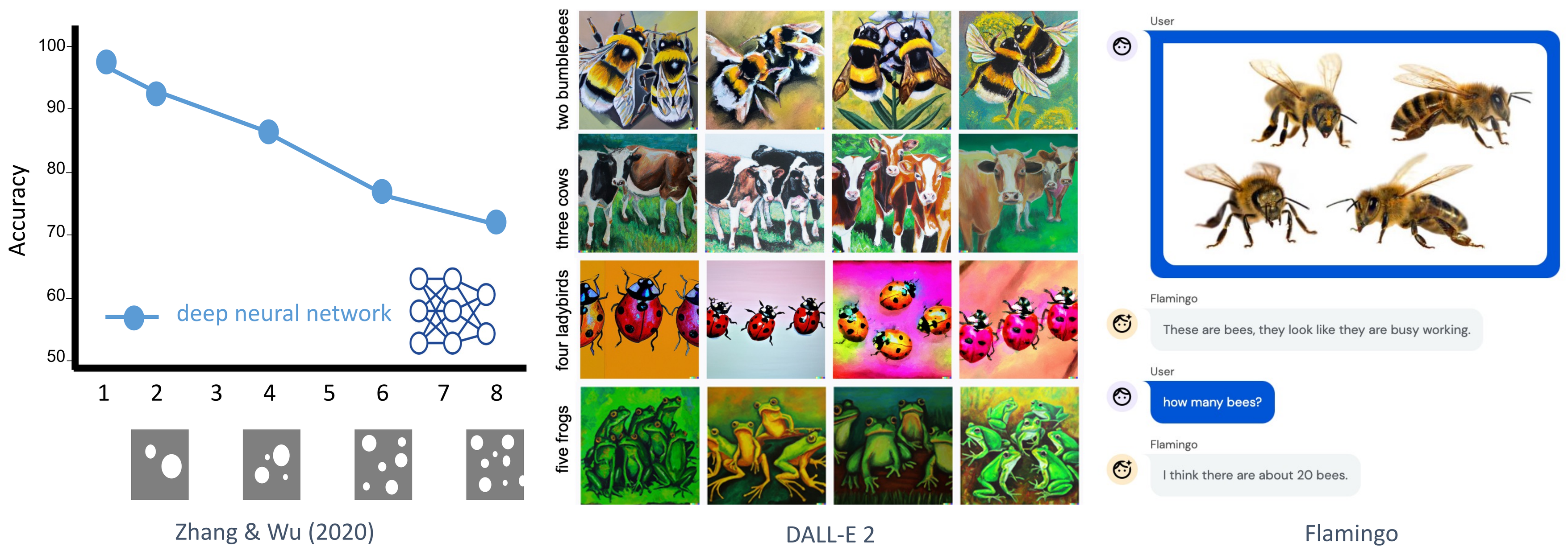
Visual scene understanding requires reasoning about the relations among objects—the "structure" of visual scenes. Here we use numerical reasoning as a testbed to study visual relational reasoning in the primate brain.

Research Goals:

- Formalize theory of primate relational reasoning in a neural network model
- Demonstrate that the model can generalize numerical reasoning zero-shot
- Show that it generalizes *because* of the specific neural-inspired features we built in
- Understand how its function and organization relate to visual numerical reasoning in biology



Zero-shot numerical reasoning challenges modern AI systems



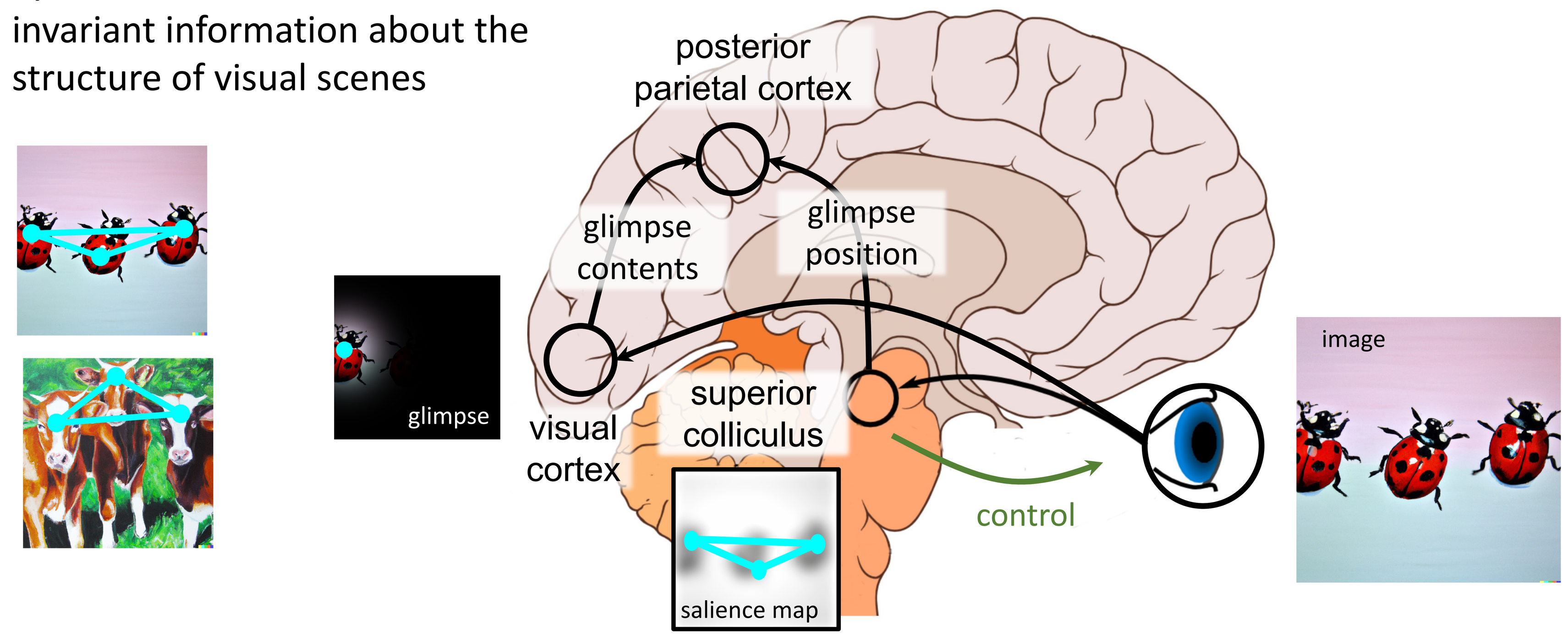
Numerical Reasoning in the Primate Brain

Beyond the ventral stream:

- Patients with damage to parietal regions (e.g., intraparietal sulcus) show deficits in numerical cognition.
- Electrophysiology in monkeys and fMRI in humans have revealed topographic representations of visual number in posterior parietal cortex
- Eye-movements contain content-invariant information about the structure of visual scenes

Hypothesize that relational reasoning enabled by:

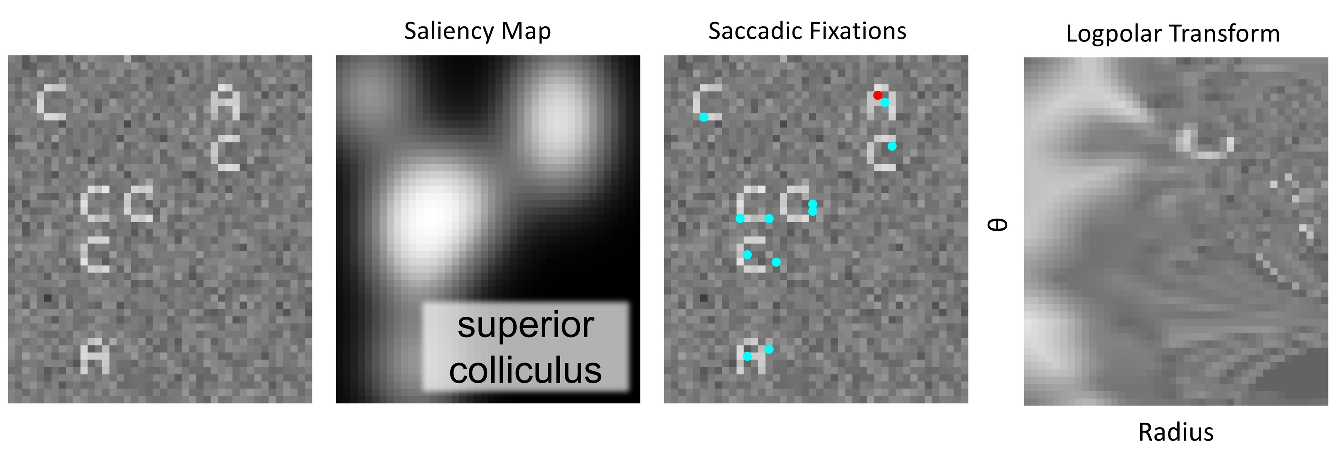
- Factorized representations of scene contents and structure in the parallel visual pathways
- Efferent copies of action-related signals (e.g., eye movements) provide relational information, enabling abstractions grounded in action
- Signal integration in posterior parietal cortex



Model

Simulating Foveated Glimpses

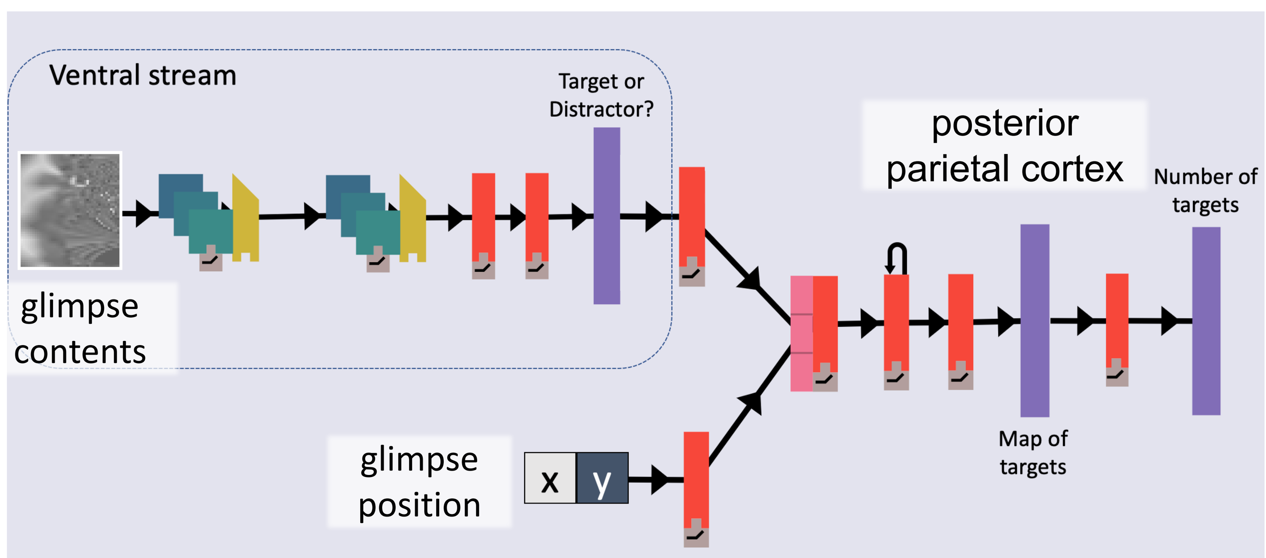
Saccadic targets (fixation points) are sampled from a saliency map of the image, subject to the constraint that all items are glimpsed at least once.



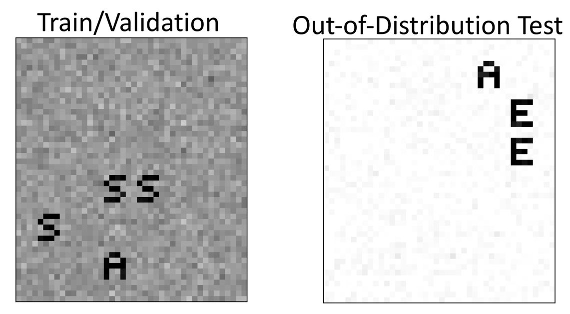
We model the retinal-to-cortical transformation as a log-polar transform centered on the fixation point.

Dual-Stream Recurrent Glimpse Network

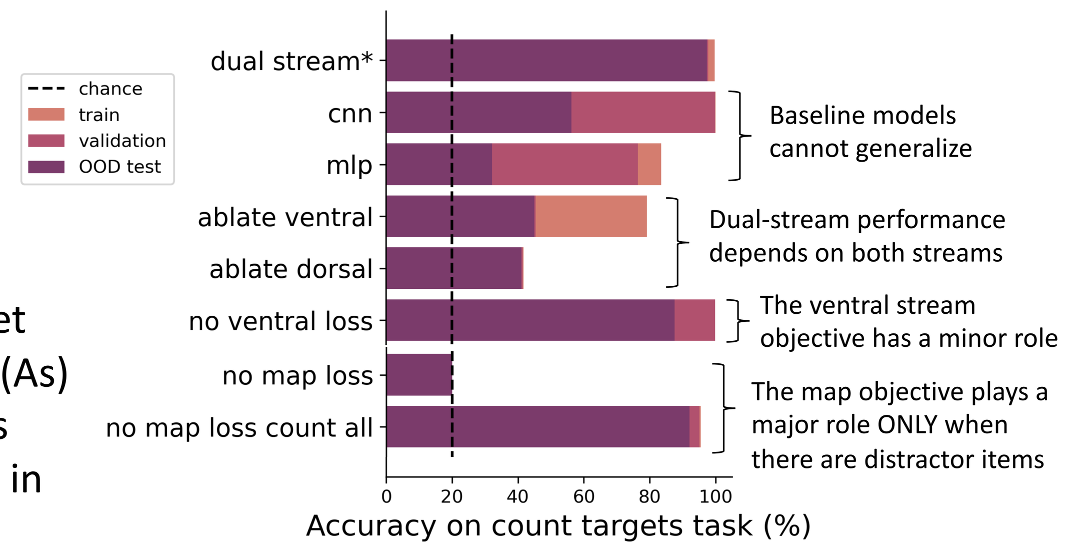
Model embodies our hypotheses about how the parallel pathways of the primate visual systems and posterior parietal cortex serve zero-shot visual numerical reasoning.



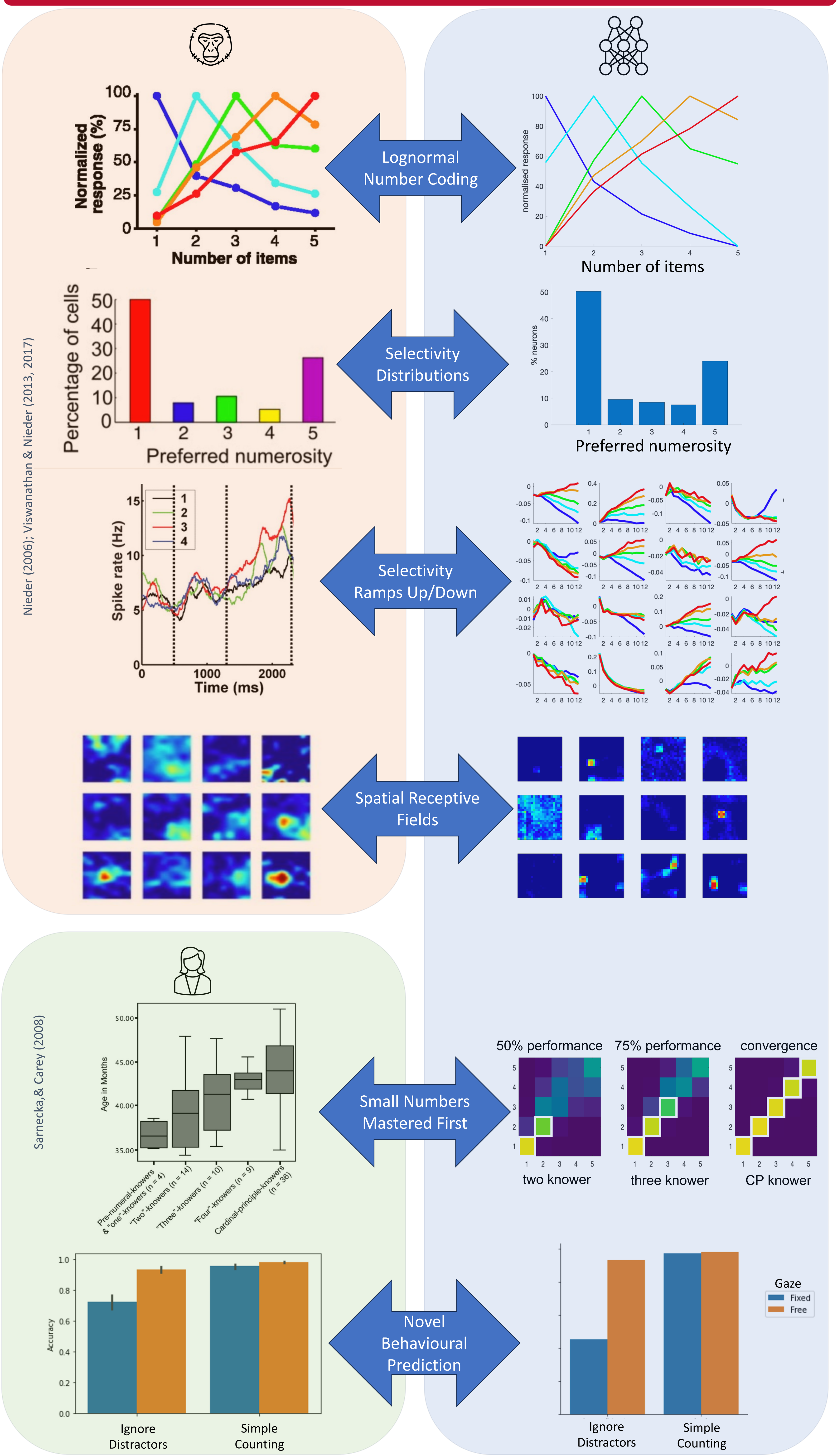
Inspecting Model Performance



- Training objective: Count all target letters while ignoring distractors (As)
- OOD test set includes new letters and new luminances not present in the training set.



Neural and Behavioural Comparisons



Conclusion

Neuro and cognitively-inspired dual-stream neural network:

- Displays zero-shot numerical reasoning
- Mirrors behavioural and neural signatures of numerical/spatial cognition
- Makes verified predictions about human behaviour

Evidence for a theory of the role of PPC in visual relational reasoning

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