

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

Jessica A.F. Thompson¹, Hannah Sheahan², Tsvetomira Dumbalska¹, Julian Sandbrink¹, Manuela Piazza³, Christopher Summerfield¹

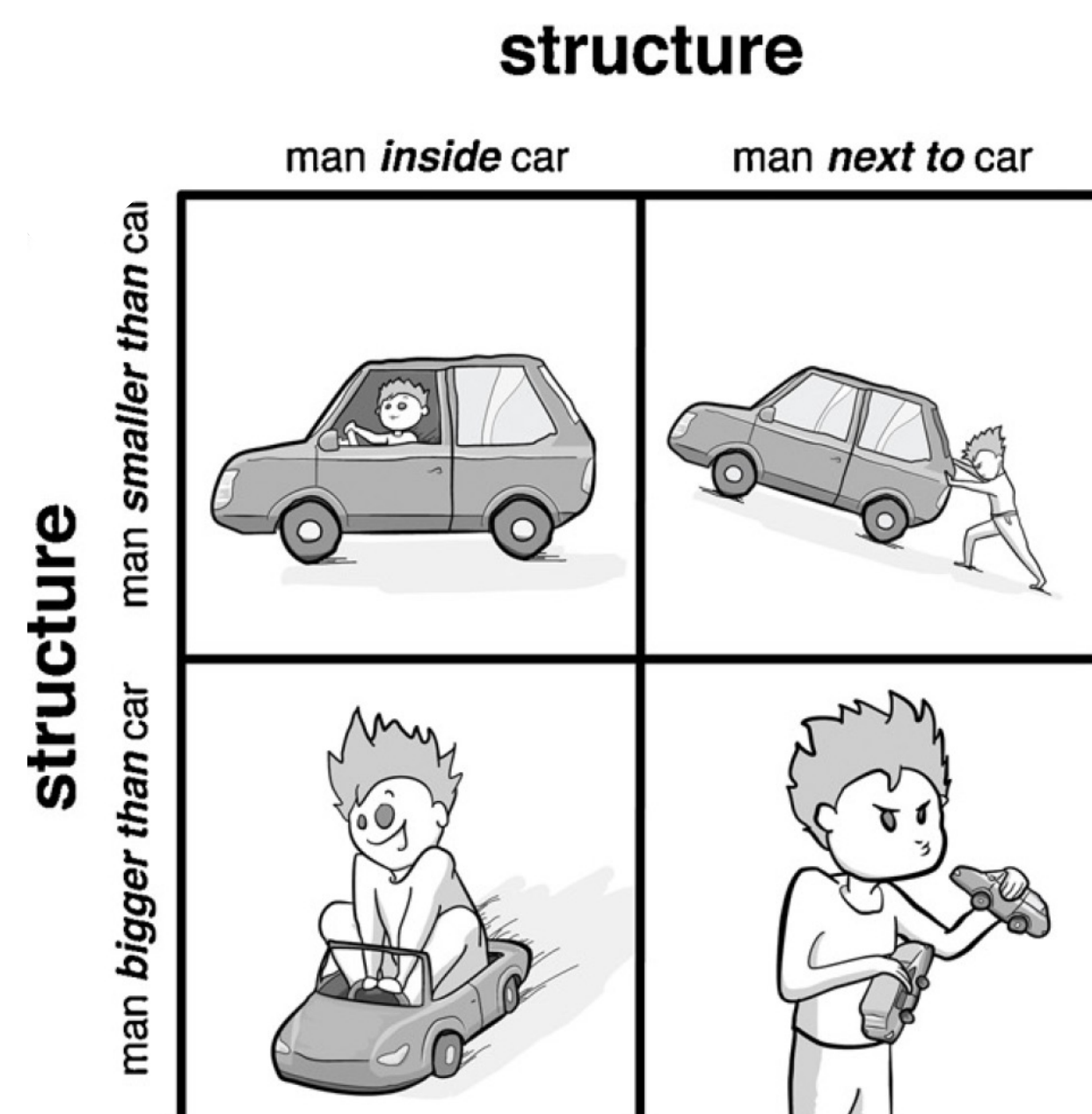
¹Department of Experimental Psychology, University of Oxford ²Google DeepMind, London, UK ³University of Trento, Trento, Italy

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



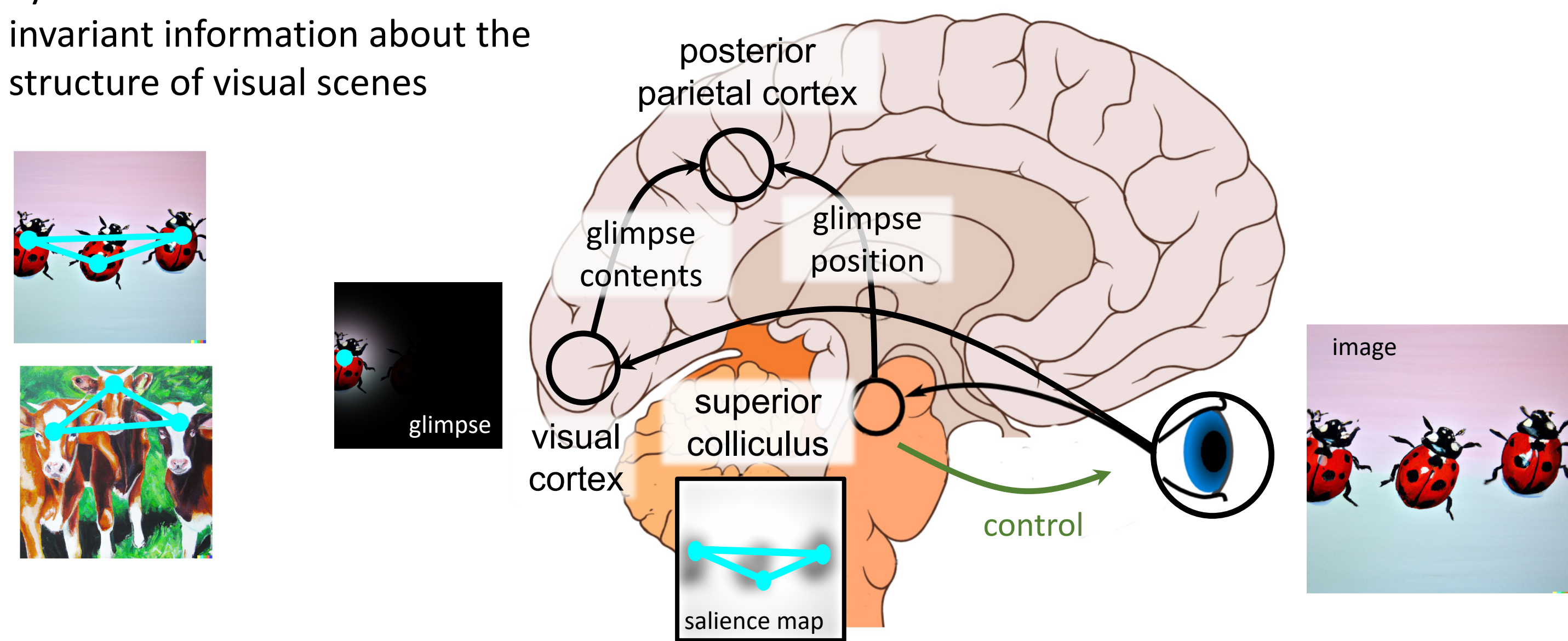
Numerical Reasoning in the Primate Brain

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:

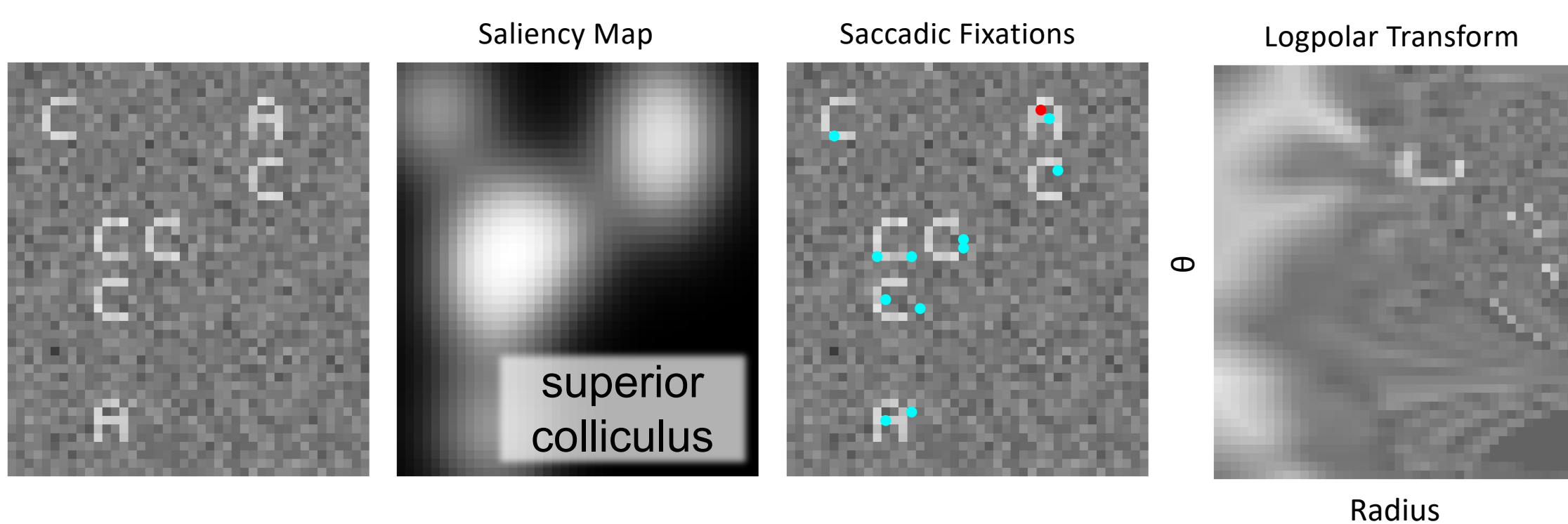
- Factorized representations of scene contents and structure in the parallel visual pathways
- Efferent copies of action-related signals (e.g., eye movements) provide relational information, enabling abstractions grounded in action
- Signal integration in posterior parietal cortex



Model

Simulating Foveated Glimpses

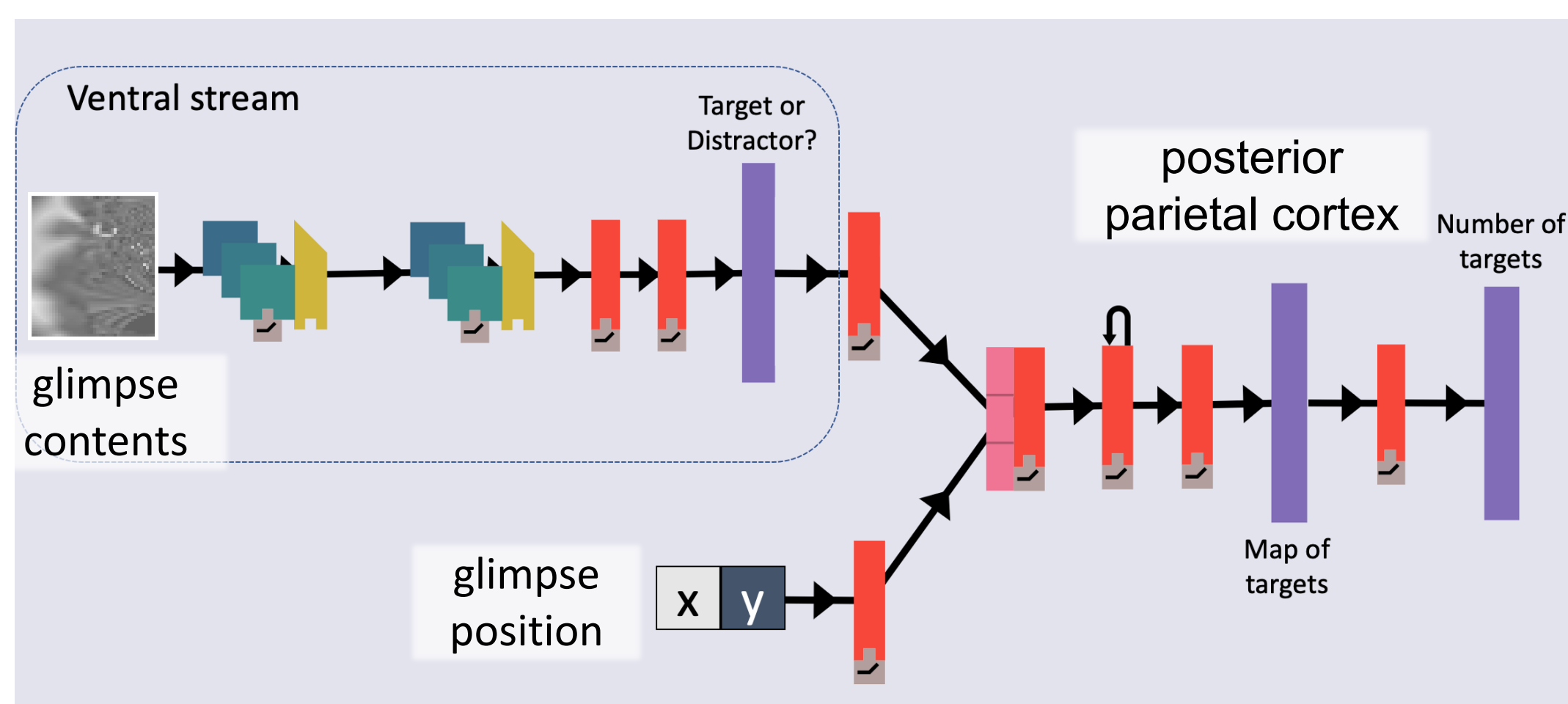
Saccadic targets (fixation points) are sampled from a saliency map of the image, subject to the constraint that all items are glimpsed at least once.



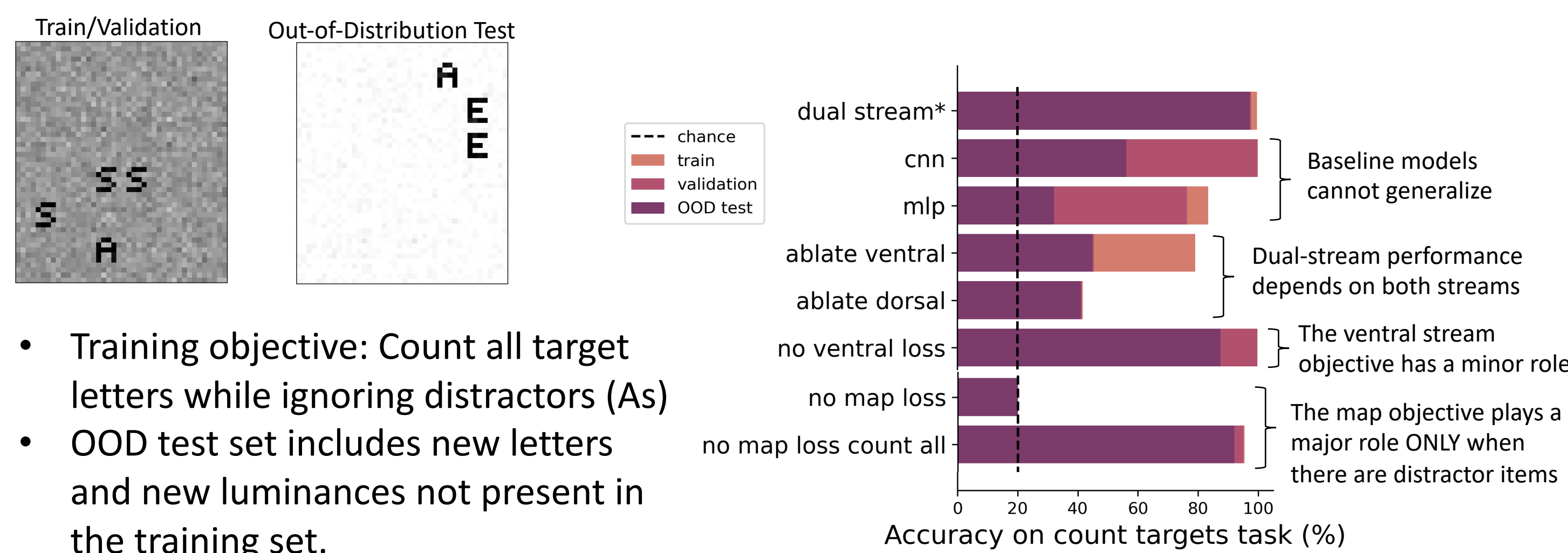
We model the retinal-to-cortical transformation as a log-polar transform centered on the fixation point.

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.

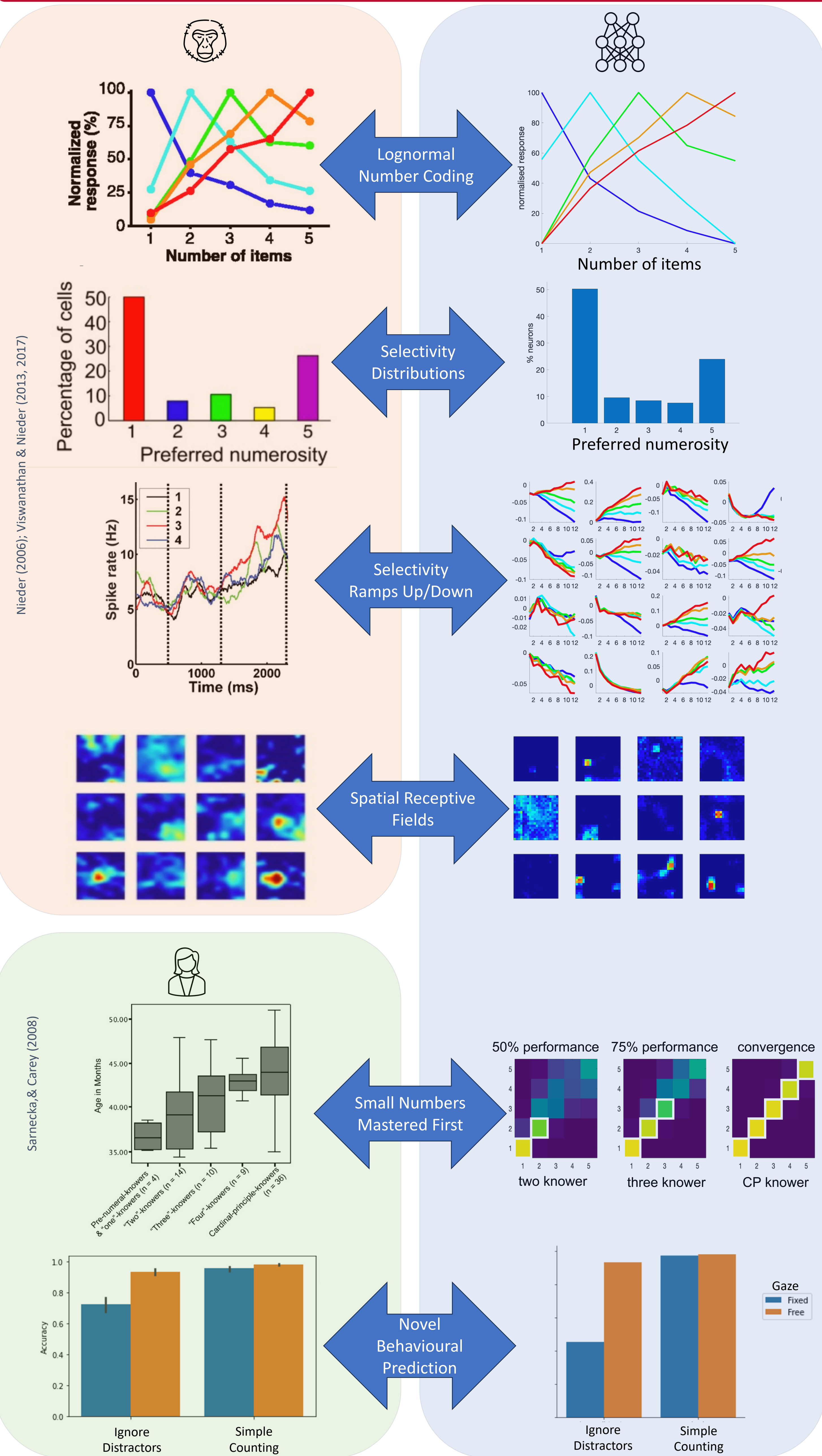


Inspecting Model Performance



- 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

References

- Summerfield, C., Luyckx, F., & Sheahan, H. (2020). Structure learning and the posterior parietal cortex. *Progress in Neurobiology*.
- Zhang, X., & Wu, X. (2020). On numerosity of deep neural networks. *Advances in Neural Information Processing Systems*.
- Viswanathan, P., & Nieder, A. (2017). Comparison of visual receptive fields in the dorsolateral prefrontal cortex and ventral intraparietal area in macaques. *European Journal of Neuroscience*.
- Viswanathan, P., & Nieder, A. (2013). Neuronal correlates of a visual “sense of number” in primate parietal and prefrontal cortices. *PNAS*.
- Nieder, A., Diester, I., & Tudusciuc, O. (2006). Temporal and spatial enumeration processes in the primate parietal cortex. *Neuroforum*.
- Sarnecka, B. W., & Carey, S. (2008). How counting represents number: What children must learn and when they learn it. *Cognition*.