A Resource Rational Perspective on Mental Imagery

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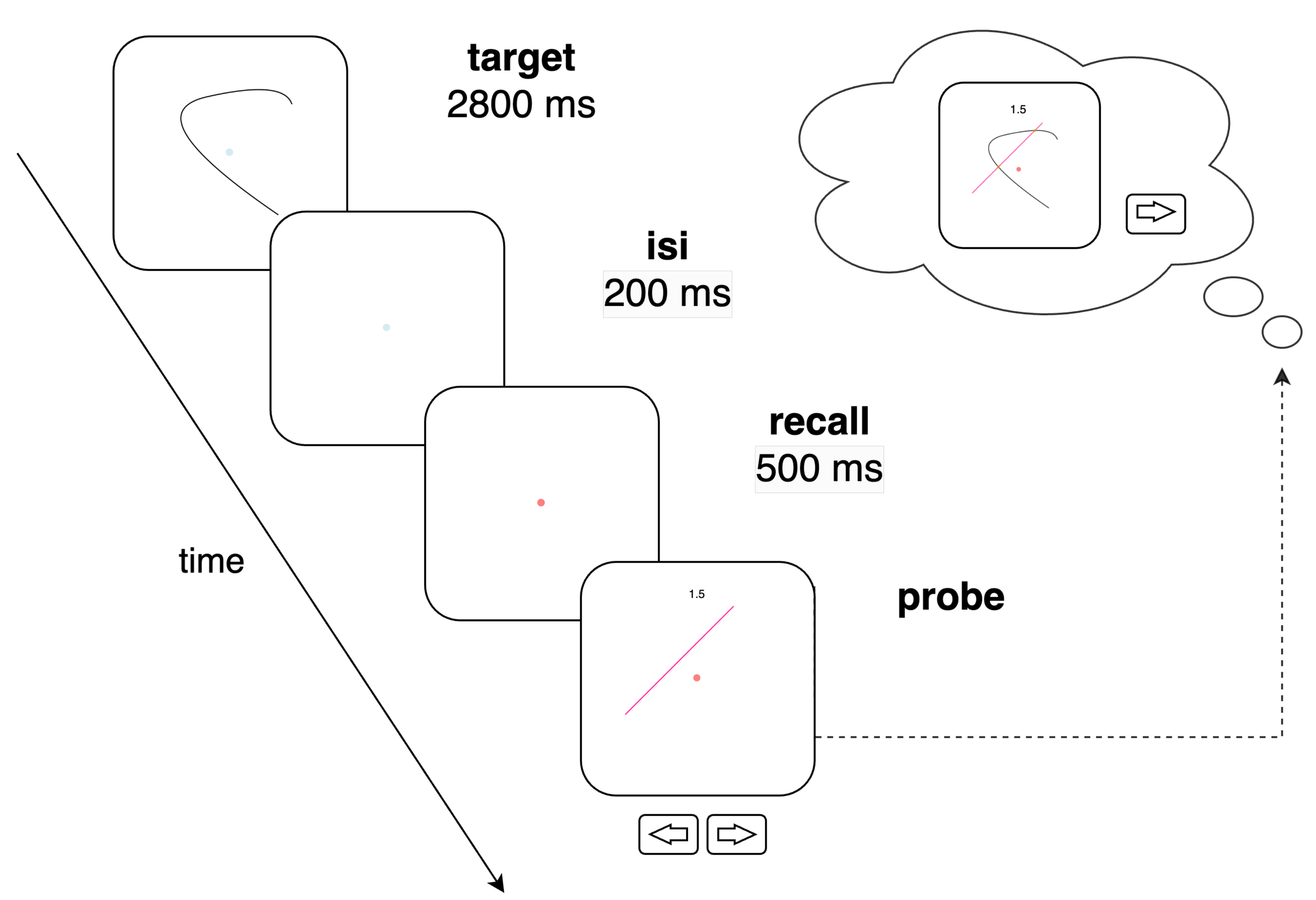
1. Introduction

- Intuition suggests that mental imagery is both **limited** (loses accuracy when the complexity of the imagined stimuli increases) and **stochastic** (can vary across repeated generations).
- In this work, we investigate the hypothesis that these properties jointly arise from capacity limitations on visual information processing.
- To do this, we developed a 2AFC psychophysical task where the subject must count the number of intersections between a seen and imagined curve – we then compute the average response accuracy, variance, and discriminability across a range of stimulus complexities.
- Motivated by the principle of resource rationality [1], we present a probabilistic model of mental imagery and demonstrate how the observed response statistics can be reproduced under information-theoretic capacity constraints.

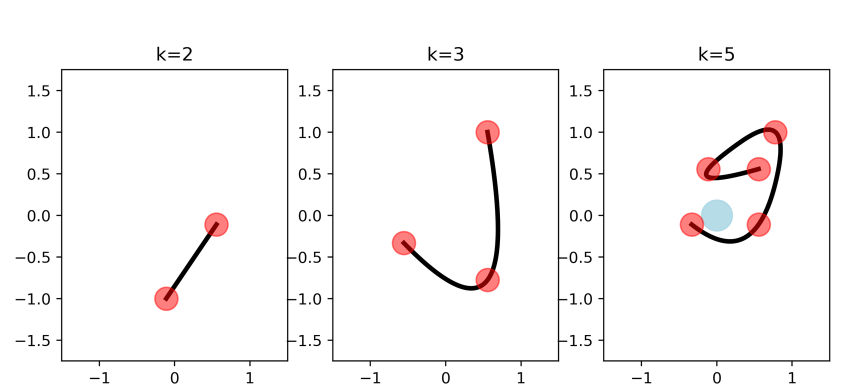
2.Task design



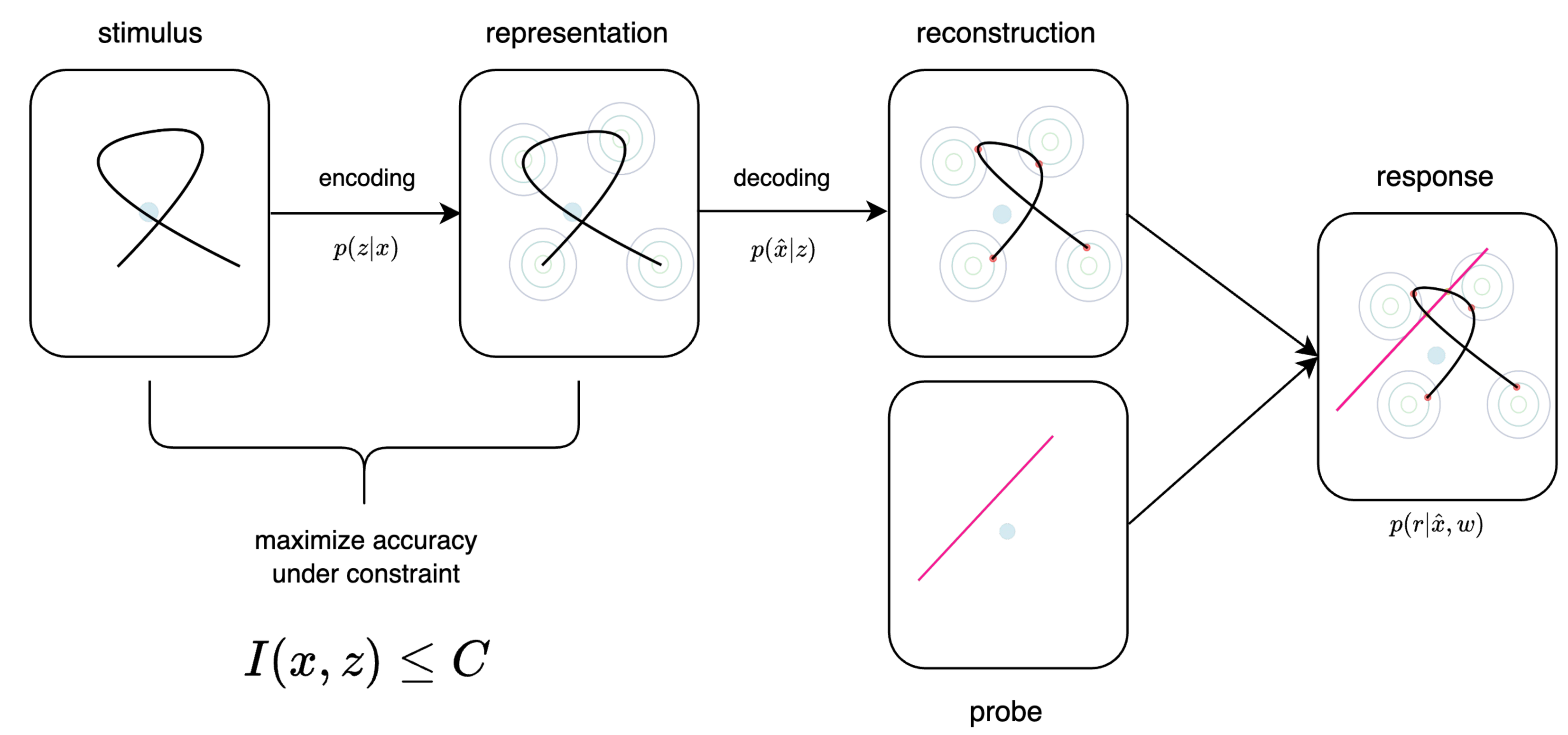
- The subject is first presented with a black 'target' curve, which they are to store in working memory.
- After a brief interval, a pink 'probe' curve is presented on the screen.
- The subject is then asked to imagine the memorized target curve overlaid on the probe curve, counting the number of times they intersect.
- If the number of inferred intersections is more than the number on the screen, the subject presses the right arrow key, otherwise, they press the left.

3. Stimulus design

- Target curves are generated by interpolating between sampled 'control' points.
- The 'complexity' of a stimulus is the number of control points used to generate the curve.



4. Capacity-limited model



5. Key prediction: covariance scales with complexity

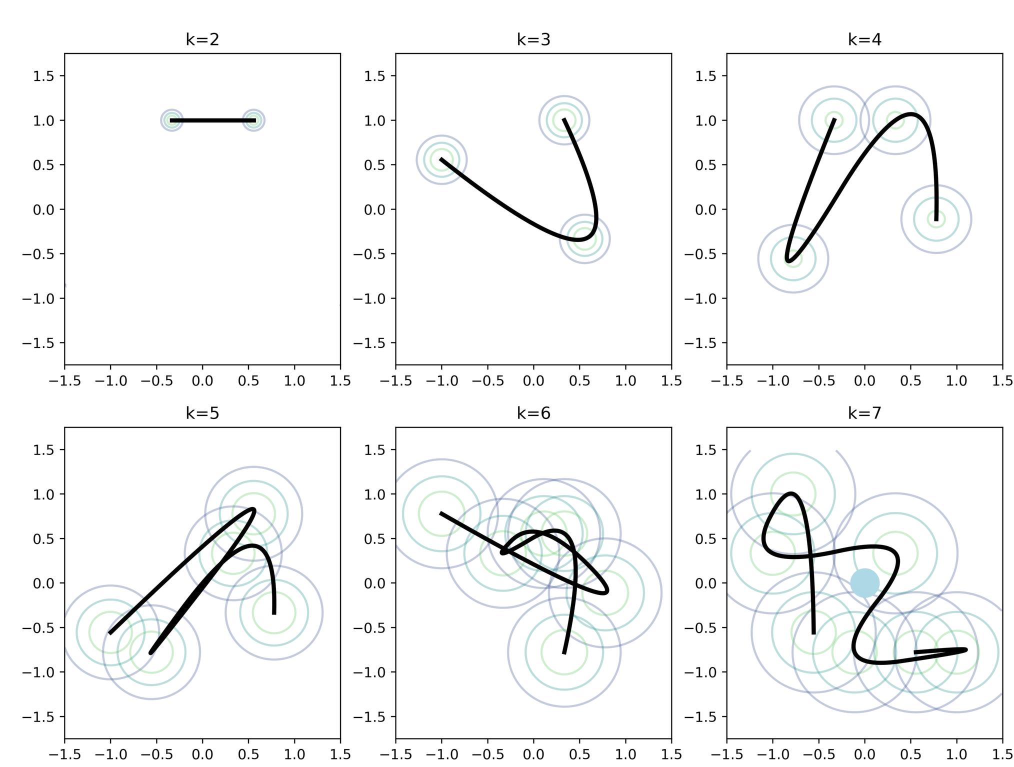
Assuming

- $p(z_i \mid x) = Gaussian(\mu, \alpha I_2)$
- $I(x,z) \leq C$

$$\alpha \geq \sqrt{exp[2(\lambda - \frac{C}{k} - ln2\pi - 1)]}$$

Where:

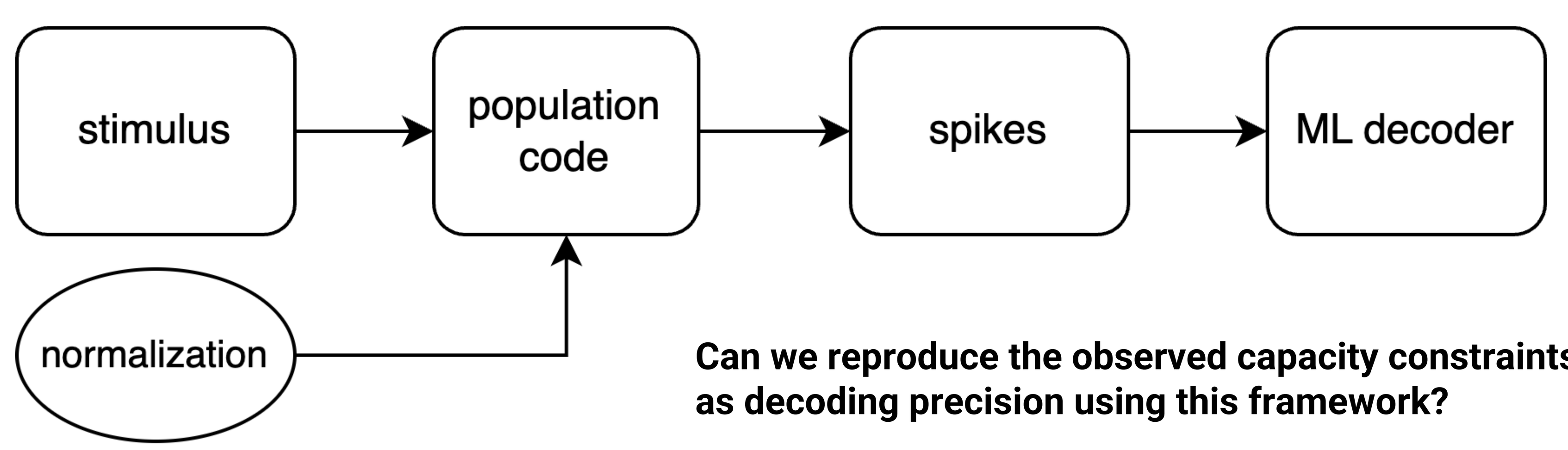
- $\lambda = h(z)$
- k is the number of 'control points'



7. Abstract circuit model

How could these capacity limitations emerge neurally?

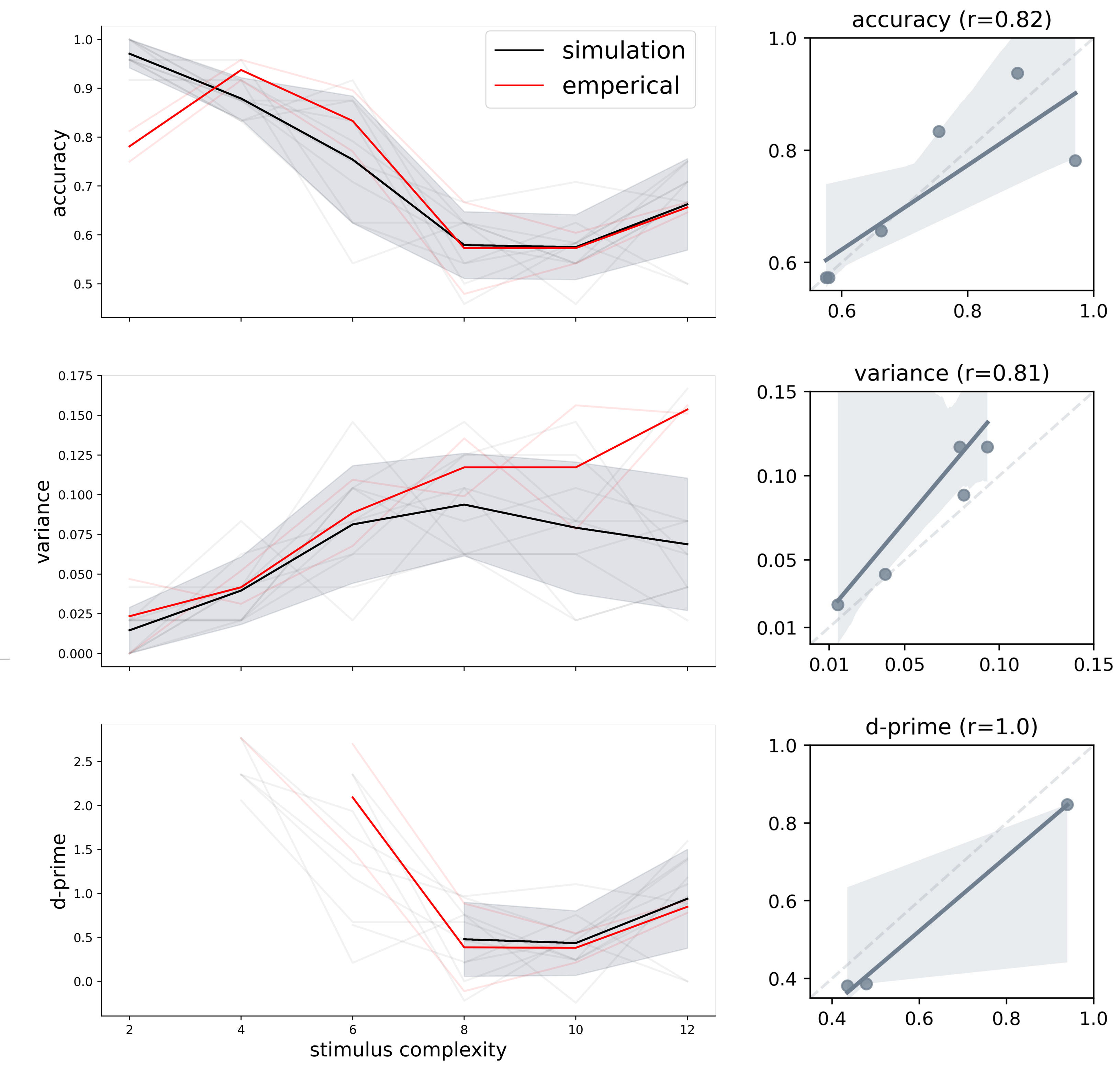
- Shared resource models of visual working memory provide a promising foundation, as they predict a similar decrease in representational precision as more stimuli are encoded into memory [2].
- These models can be instantiated through population codes where capacity limitations arise through the process of **normalization**, an important neural computation observed at several stages of sensory processing [3].



Can we reproduce the observed capacity constraints as decoding precision using this framework?

6. Results

(Channel capacity determined via grid search)



8. Conclusion

- In this work, we developed a psychophysical task where the subject must detect intersections between seen and imagined curves.
- We find that response accuracy and discriminability decrease with stimuli complexity, with a corresponding increase in response variance.
- We demonstrate these statistics can be reproduced through a probabilistic model of mental imagery under information-theoretic capacity constraints.
- Lastly, we introduce an abstract circuit model to inspire future work and suggest normalization as a candidate mechanism for understanding the neural basis of the observed capacity constraints.
- Ultimately, we consider this approach as an initial step towards a unified account of mental imagery and visual working memory through the lens of resource rationality – i.e., the rational allocation of limited cognitive resources.

References

[1] Bhui, R., Lai, L., & Gershman, S. J. (2021). Resource-rational decision making. *Current Opinion in Behavioral Sciences*, *41*, 15-21.

[2] Bays, P. M. (2015). Spikes not slots: noise in neural populations limits working memory. *Trends in cognitive sciences*, *19*(8), 431-438.

[3] Carandini, M., & Heeger, D. J. (2012). Normalization as a canonical neural computation. *Nature reviews neuroscience*, *13*(1), 51-62.