Efficient Allocation of Working Memory Resource for Utility Maximization in Humans and Recurrent Neural Networks

NEURAL INFORMATION PROCESSING SYSTEMS

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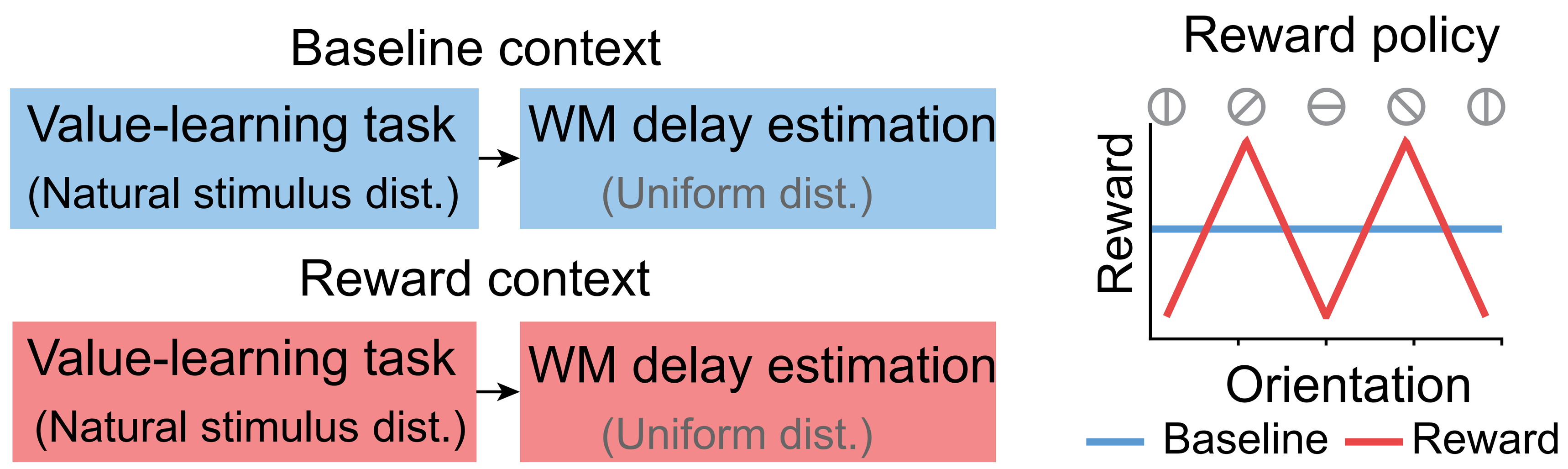
Background

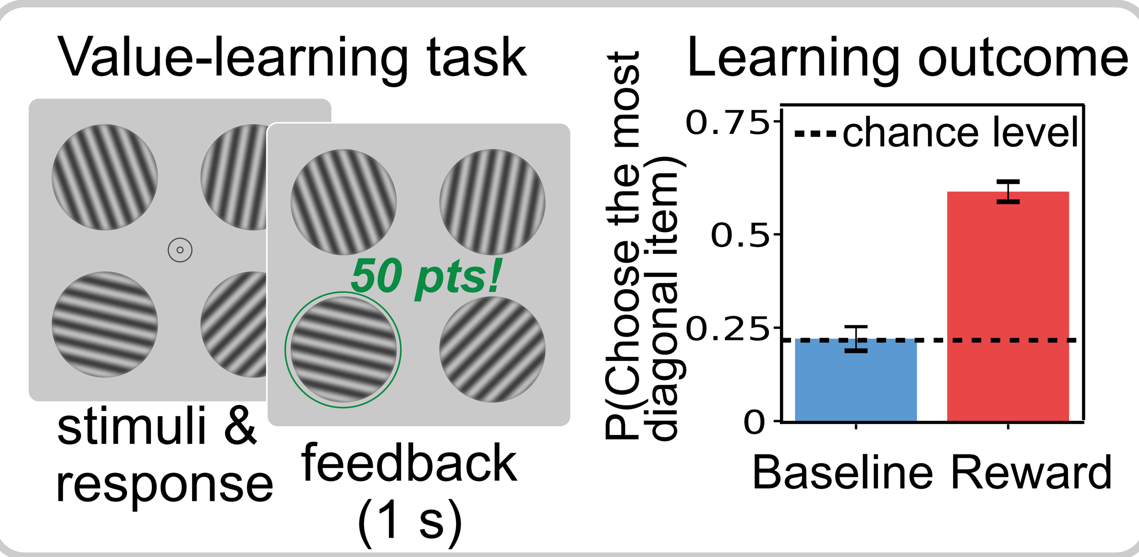
- Working memory (WM) resource is high limited [1,2]. However, the effect of reward incentives alone on WM resource allocation is mixed [3-5].
- In perception, resource distribution appears to be optimized with respect to natural stimulus distribution and cost functions [6-9].

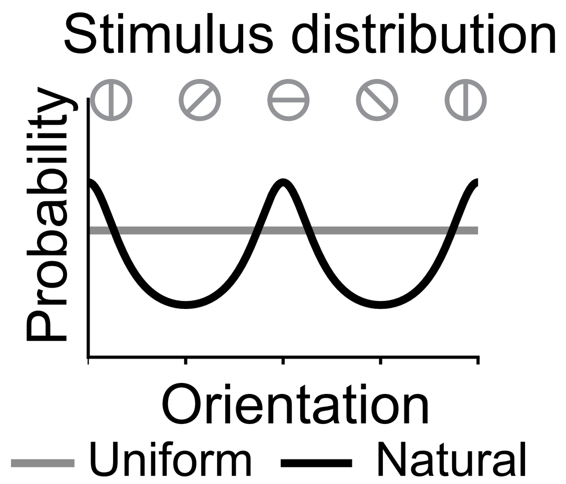
Whether WM resource is allocated effciently to maximize reward?

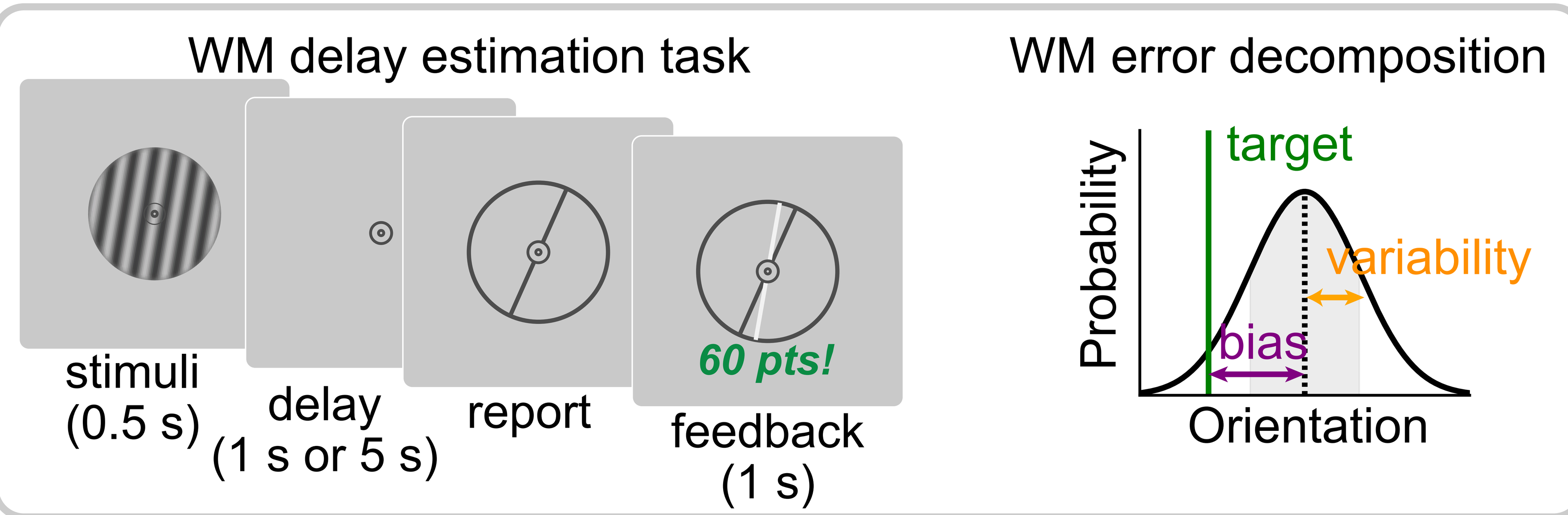
Procedure

- On each day (context), a value-learning task was followed by a WM delay estimation task (N=14). The contexts were counterbalanced.







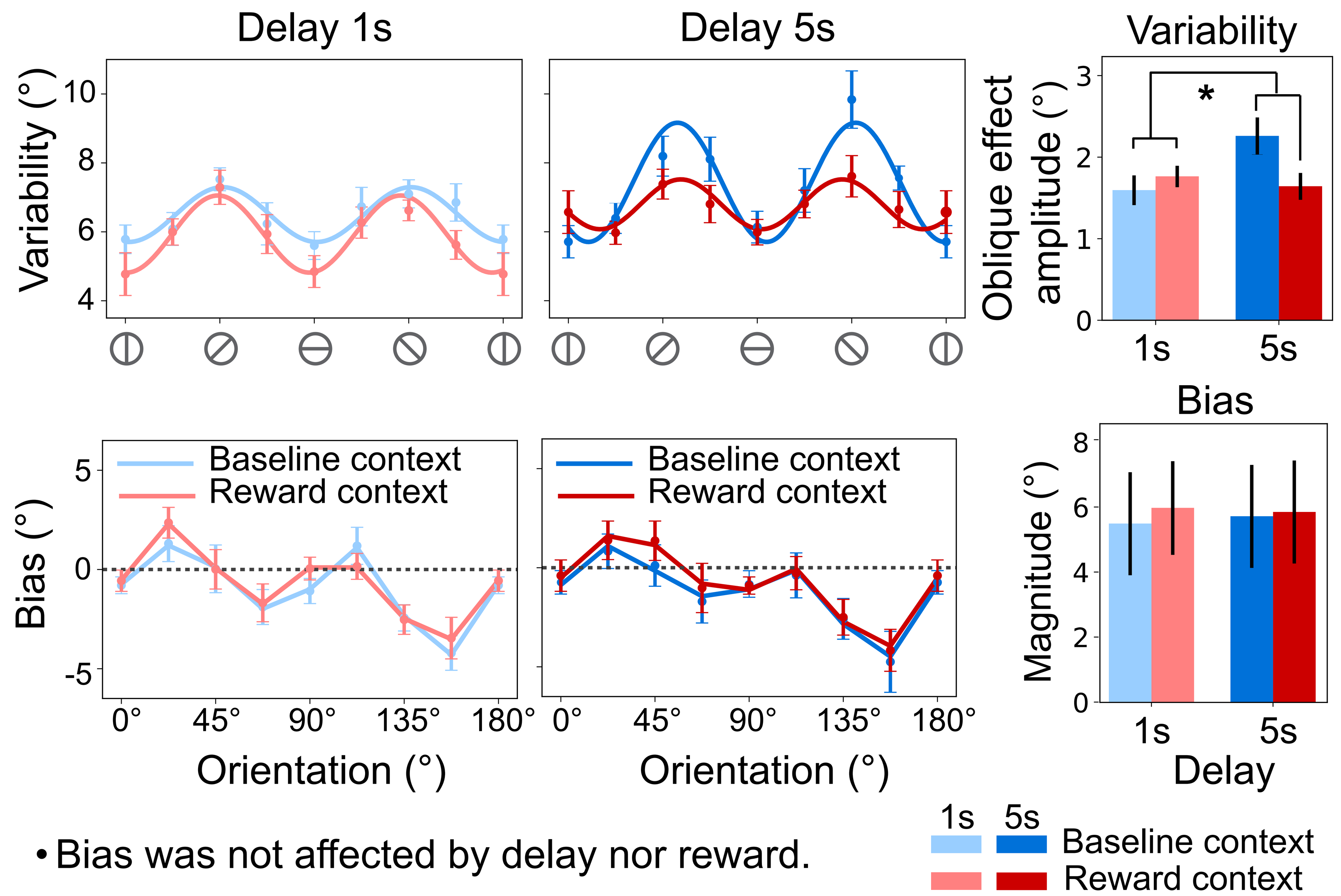


Takeaways

- Humans and RNNs efficiently allocate the WM resource based on prior stimulus distribution and reward.
- We extended efficient coding theory to the time domain and reformulated the objective, offering a normative account of how WM resource is allocated over time to maximize expected utility.

Reward stablizes human WM representations

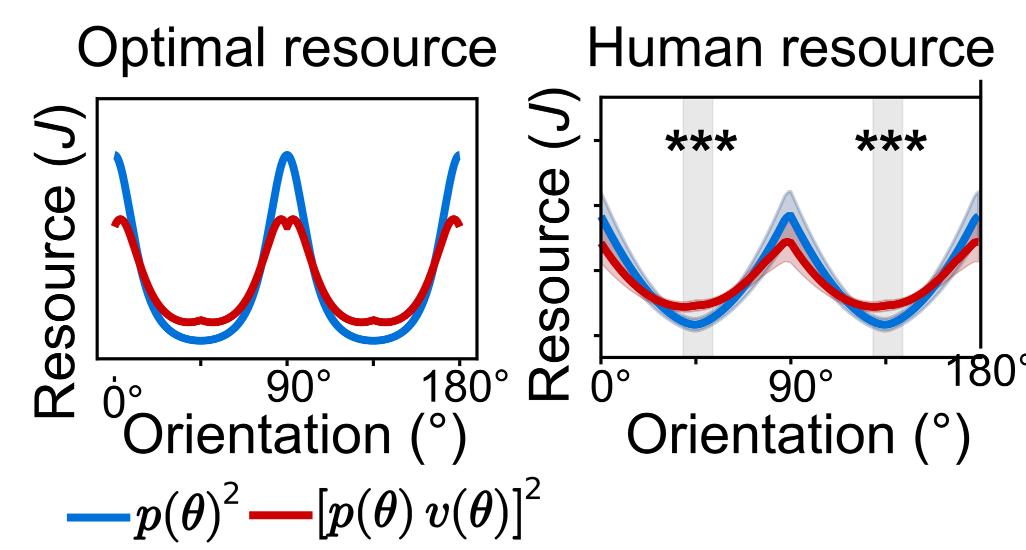
- Variability was affected by delay and reward (a 2-way interaction, $p < .05$).
  - Delay = 1s: Frequent (cardinal) orientations are maintained better.
  - Delay = 5s: High-reward (diagonal) stimuli are maintained better compared to the baseline.



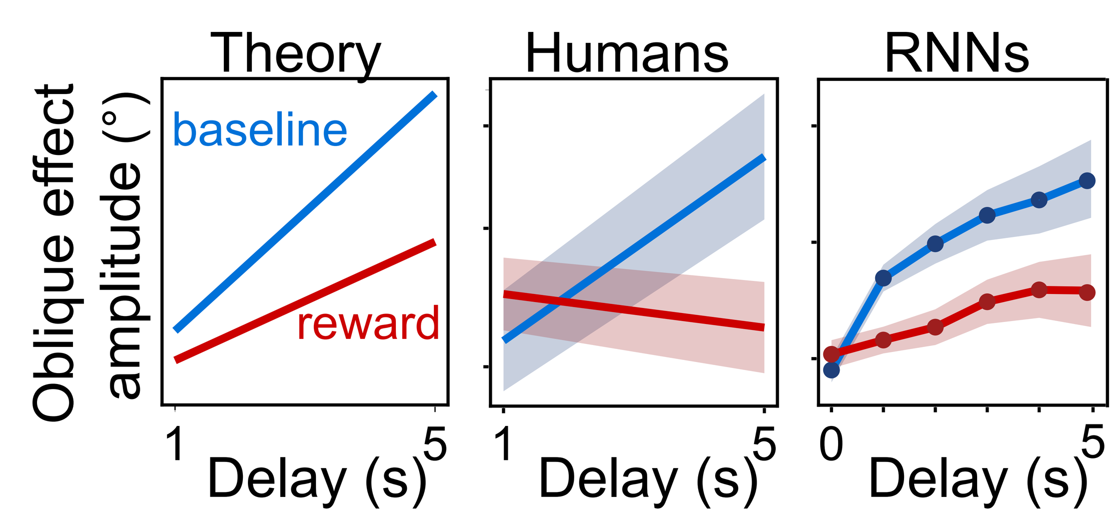
- Bias was not affected by delay nor reward.

Efficient coding for utility maximization in WM

- We extended previous efficient coding theory by shifting the objective from error minimization [6-9] to reward maximization, and updated the optimal resource allocation solution:
  $J_{\mathrm{opt}} \propto p(\theta)^q \rightarrow J_{\mathrm{opt}} \propto [p(\theta)\,v(\theta)]^q$



- After incorporating the time domain, we found that the optimal solution is stable across time.



References

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[4] Brissenden et al (2023). JEP: General.
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[6] Wei and Stocker (2015). Nature Neuroscience.
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[8] Morais and Pillow (2018). Advances in NIPS.
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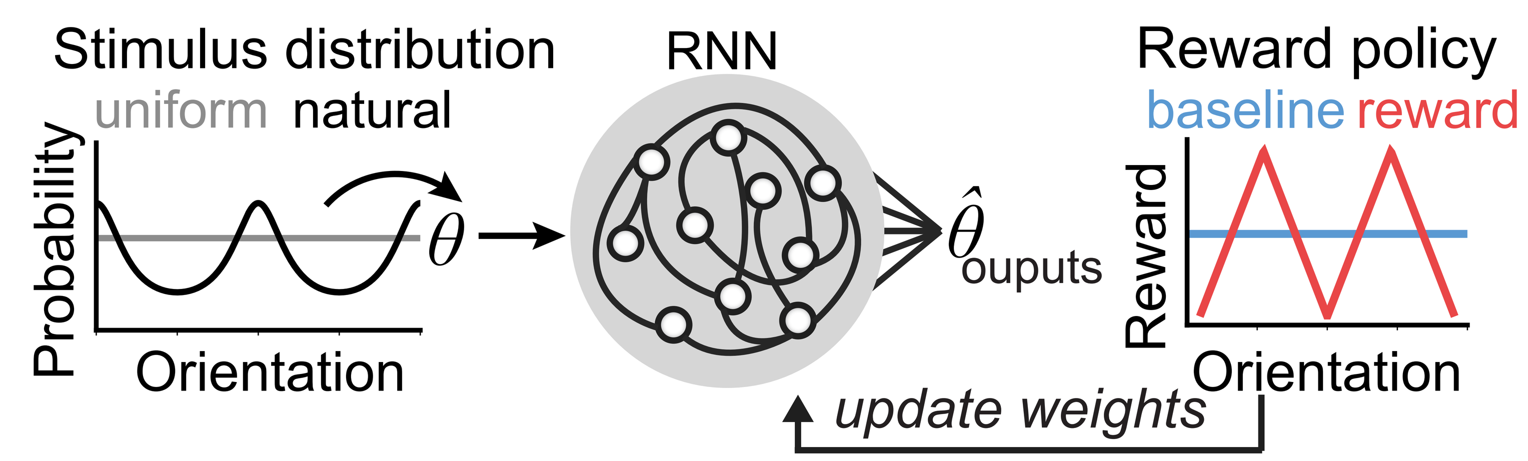
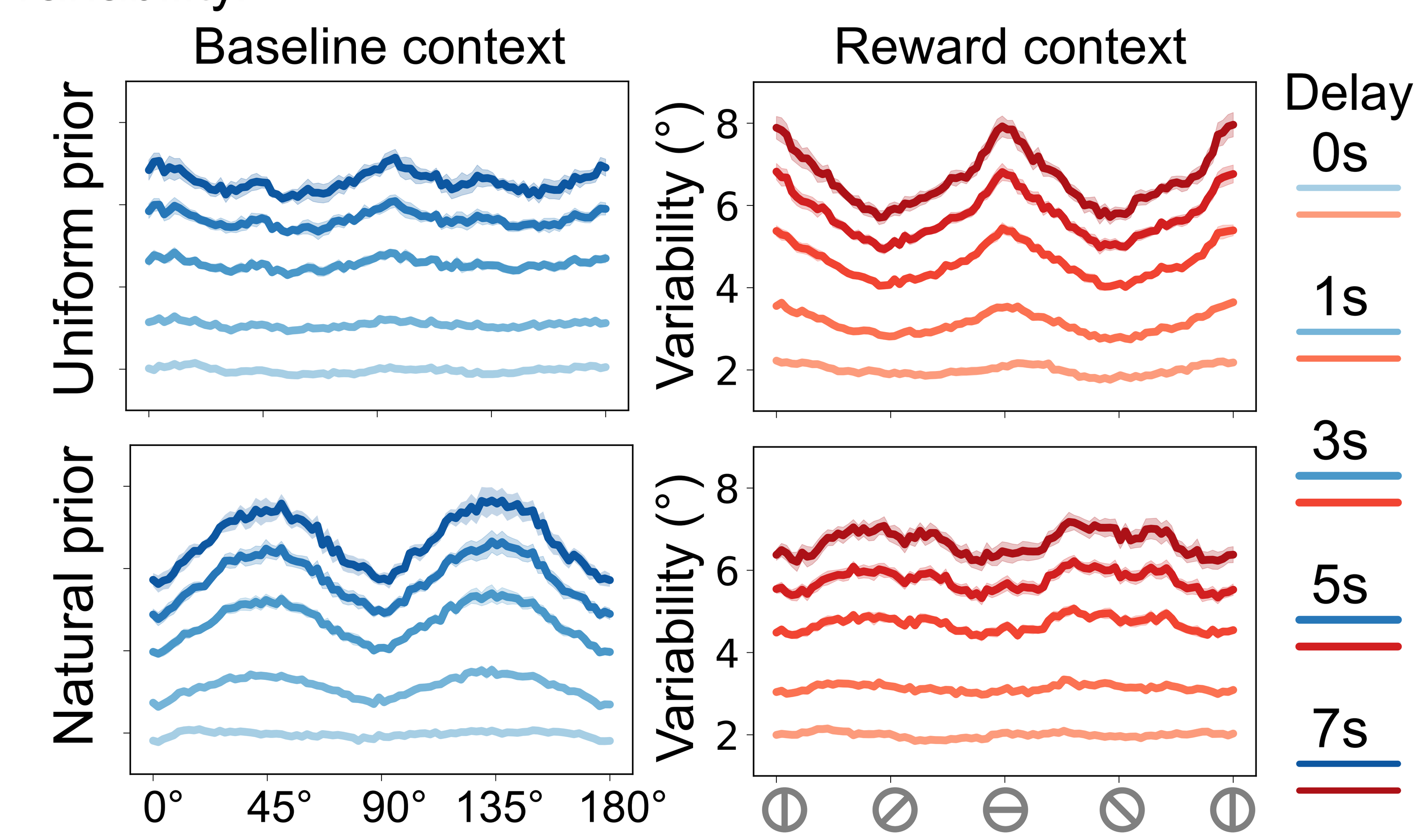
Joint effect of prior and reward on WM in RNNs

RNNs were trained in a 2x2 design:

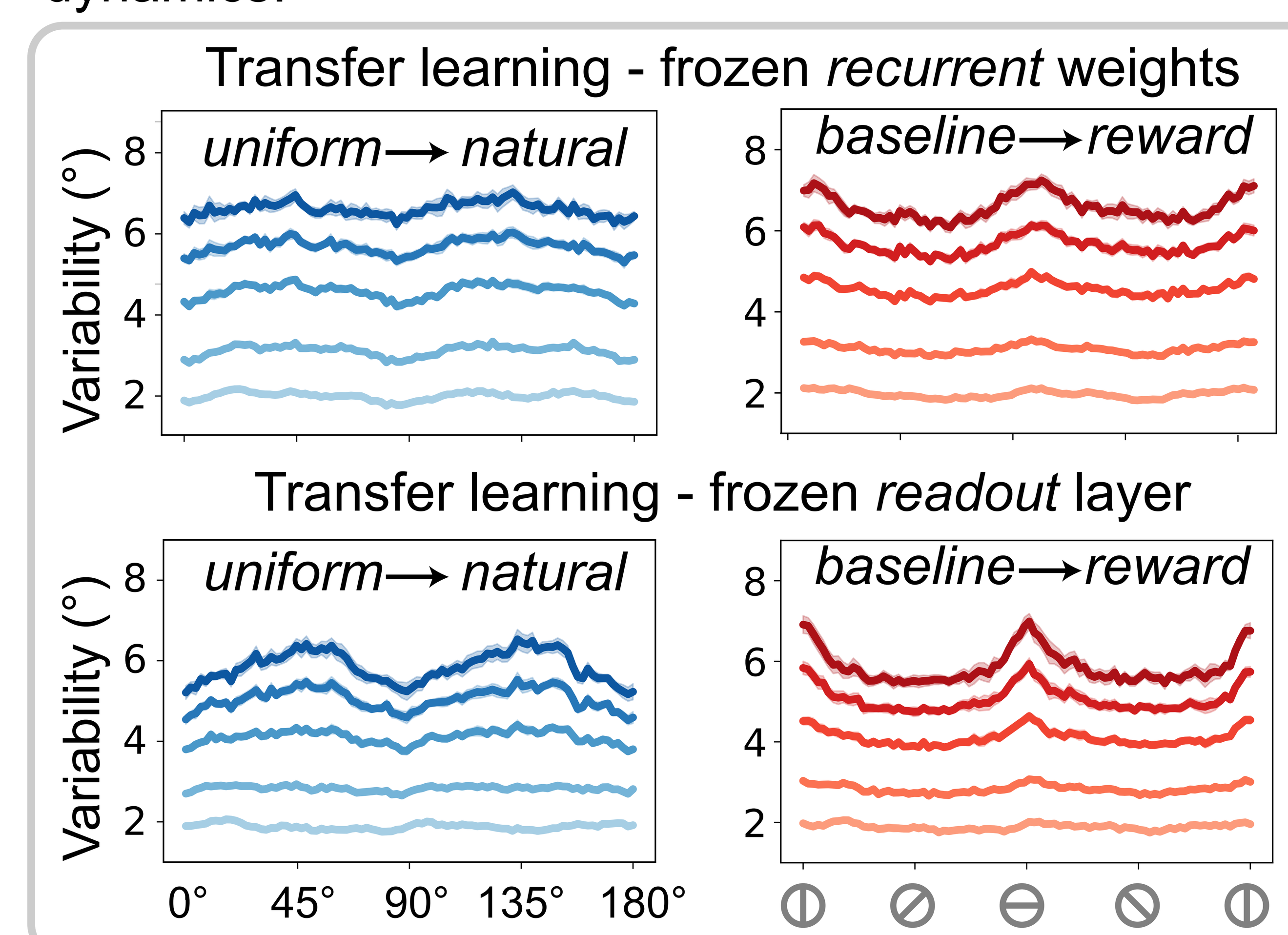
- Training stimulus distribution (uniform or natural dist.);
- Loss function (minimize error or maximize reward).



- Both prior and reward improved WM by reducing its variability.



- The effect of prior and reward was carried in recurrent dynamics.



- The results were robust with RNN sizes, initilizations, and can be generalized to untrained delays.