Uncertainty-based arbitration between incremental and episodic control over decisions

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Background

**How does reward uncertainty modulate the use of multiple memory systems?**

- Value-based decisions are typically thought to depend on average value, constructed incrementally over many experiences with an option.

- Decisions can also be based on a single episode.[1,2,3,4] If both incremental and one-shot value are available, it is unclear which should be prioritized.

- Uncertainty may play an important role. Artificial agents benefit from single experiences when there is high uncertainty about average estimates.[5,6,7]

Goal | To experimentally track the effect of uncertainty on the use of one-shot memory vs. memory for incrementally learned value.

Methods

Decision Making Task

- 80 participants ages 18-35 were recruited from Mechanical Turk.

- Participants chose between two card decks, one with higher expected value than the other. This expected value reversed periodically.[4]

- Each card within a deck also had a trial-unique object on it. Objects could be repeated once and were always worth the same amount.

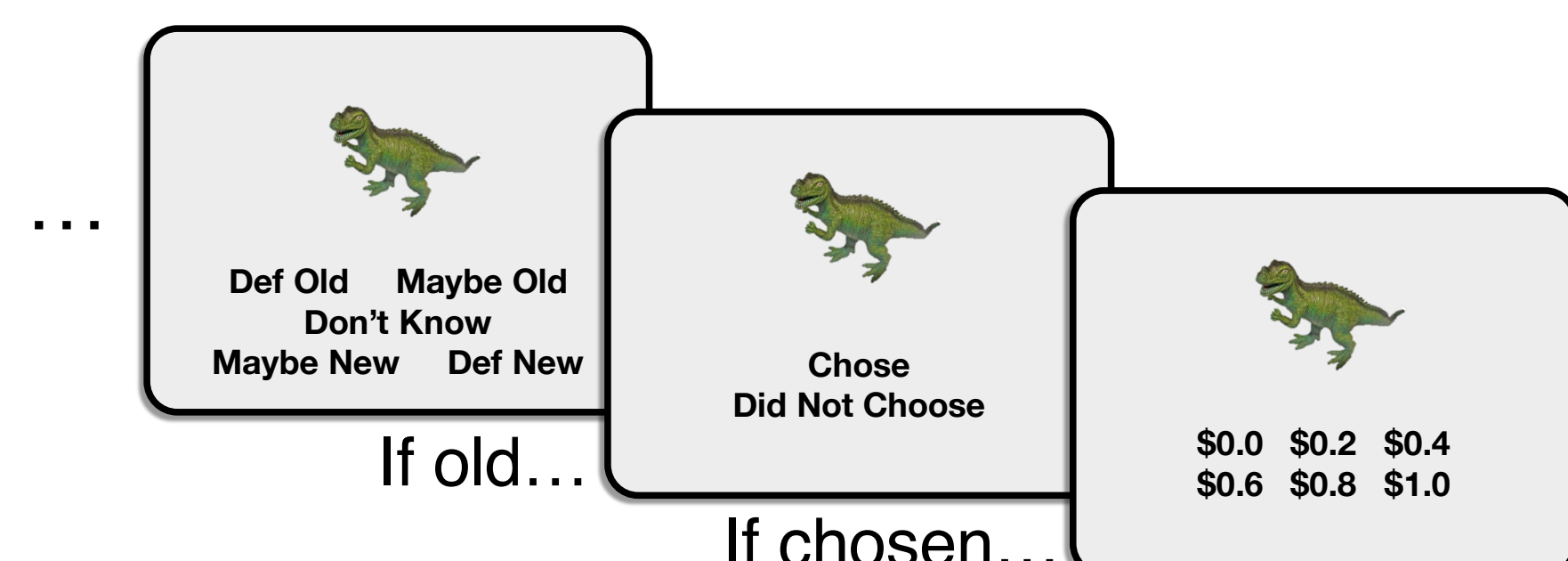Choice: 1.5s (Lab) 3.0s (Online)   Outcome: 1.5s   ITI: Jitter 0.5-2s
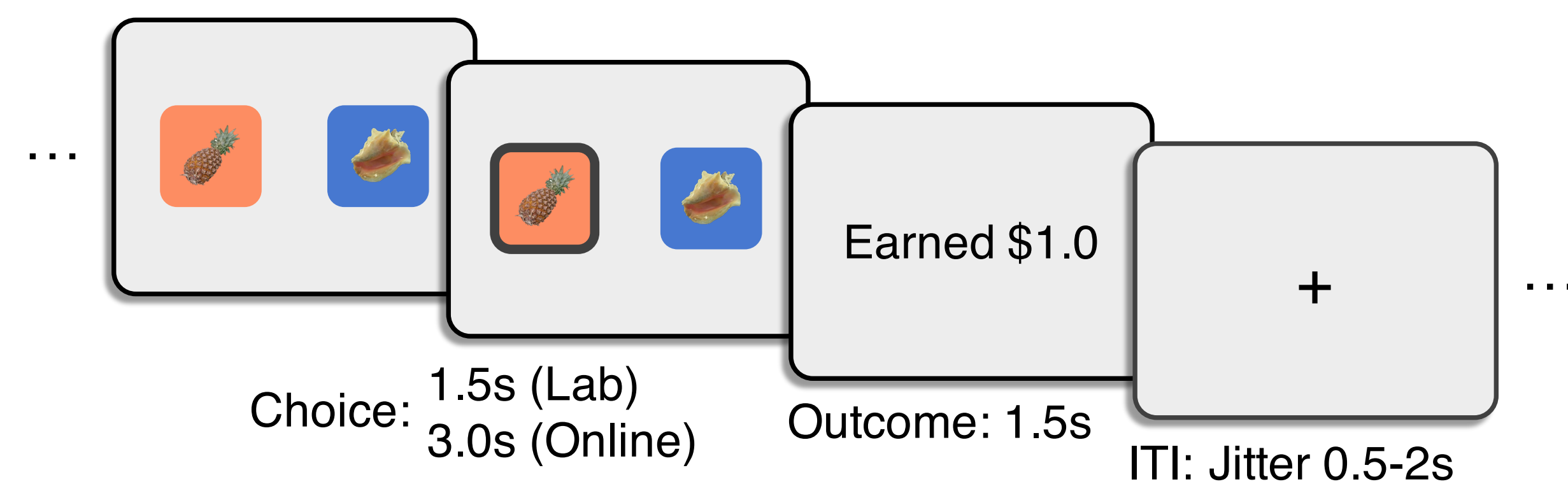
Manipulating Uncertainty

- Choices were made in two environments (counterbalanced within subjects) that differed in their rate of deck reversals.
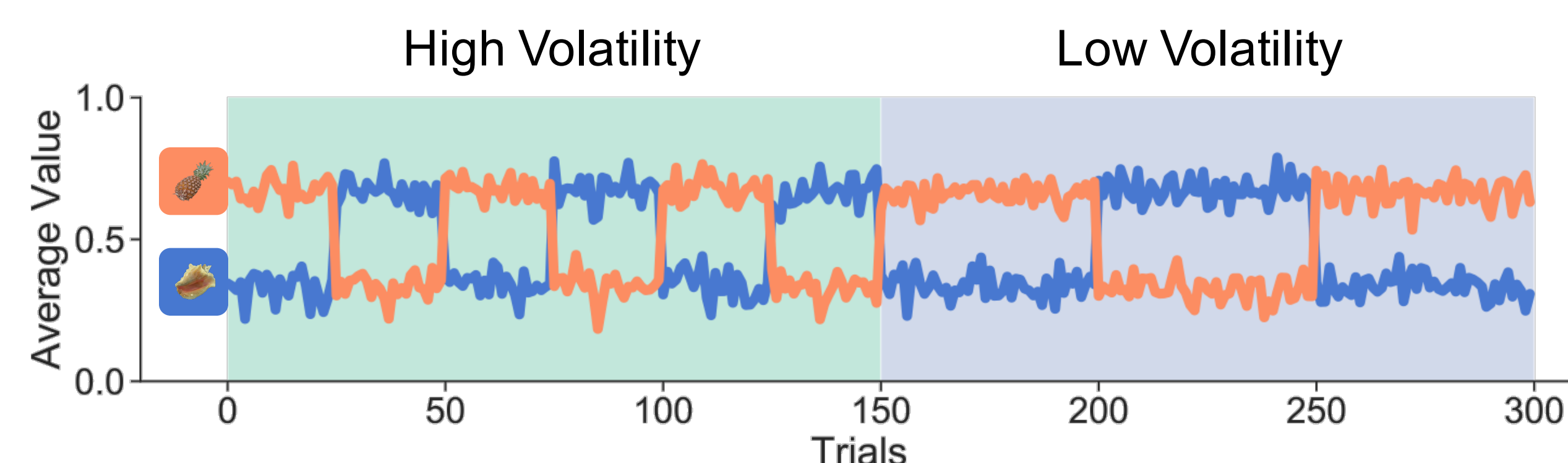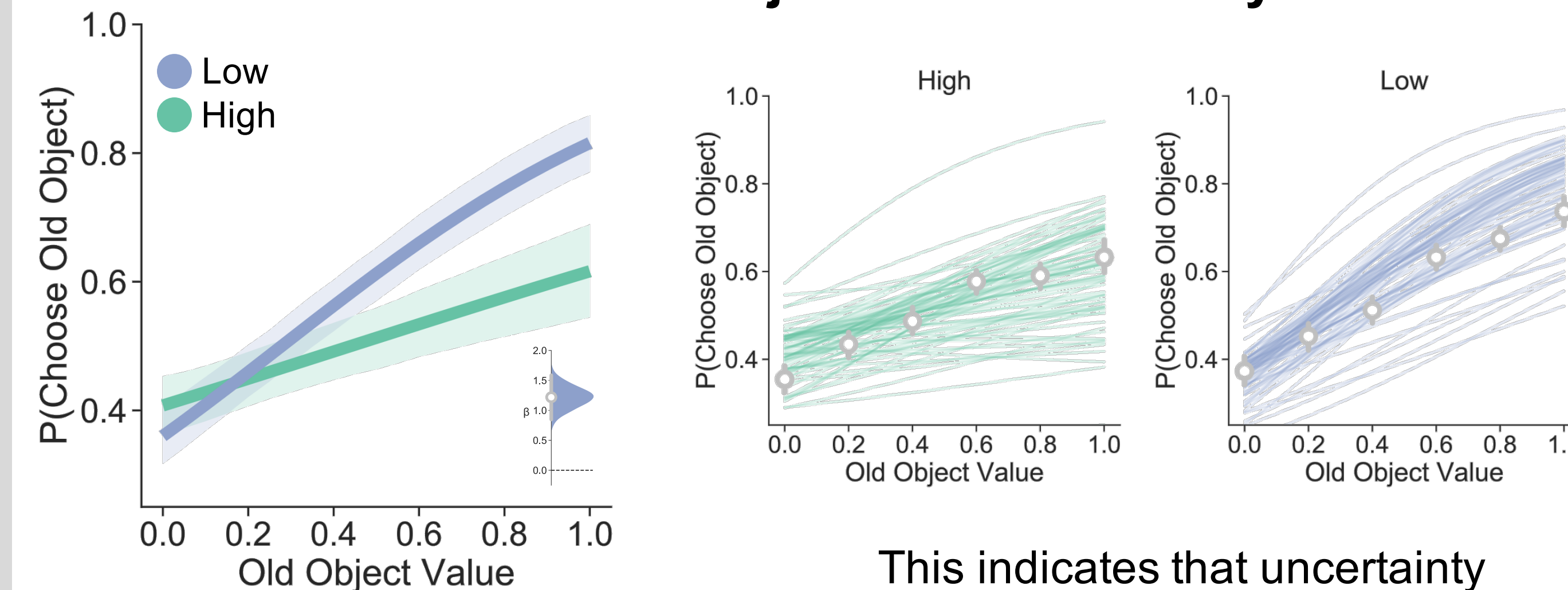

Surprise Memory Test

- Following the decision making task, participants were asked about their memory for a subset of objects.
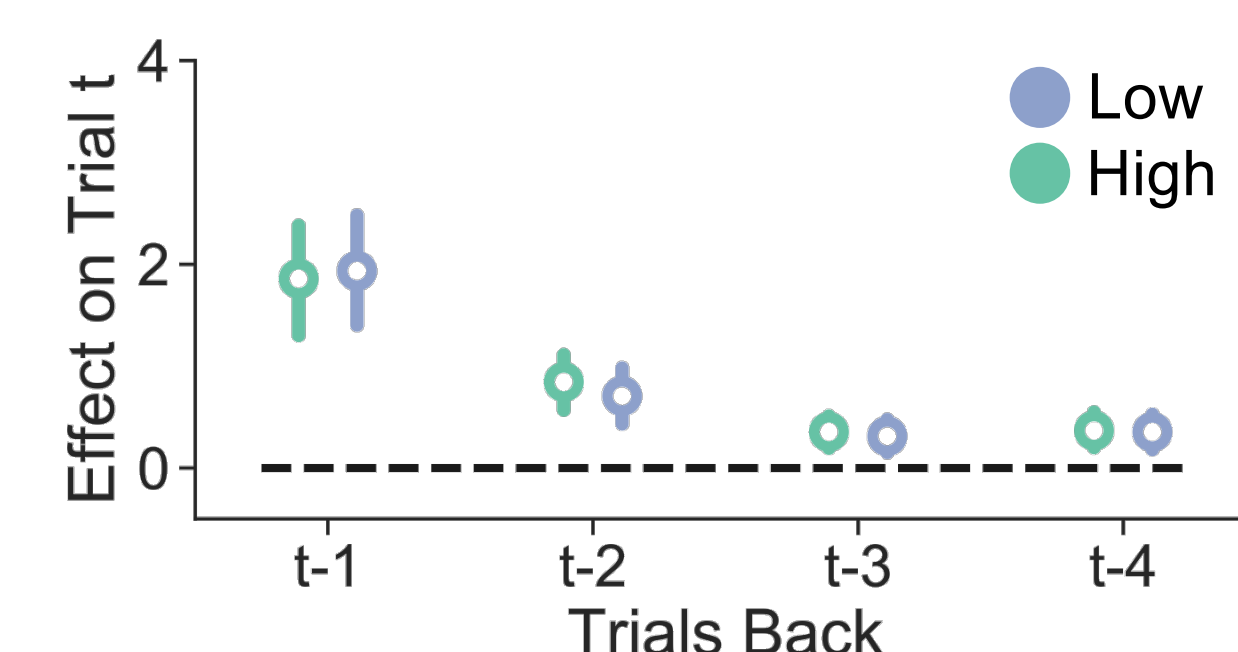

If old…   If chosen…

How does uncertainty affect which type of memory is used for decisions?

Greater use of old objects when volatility is low

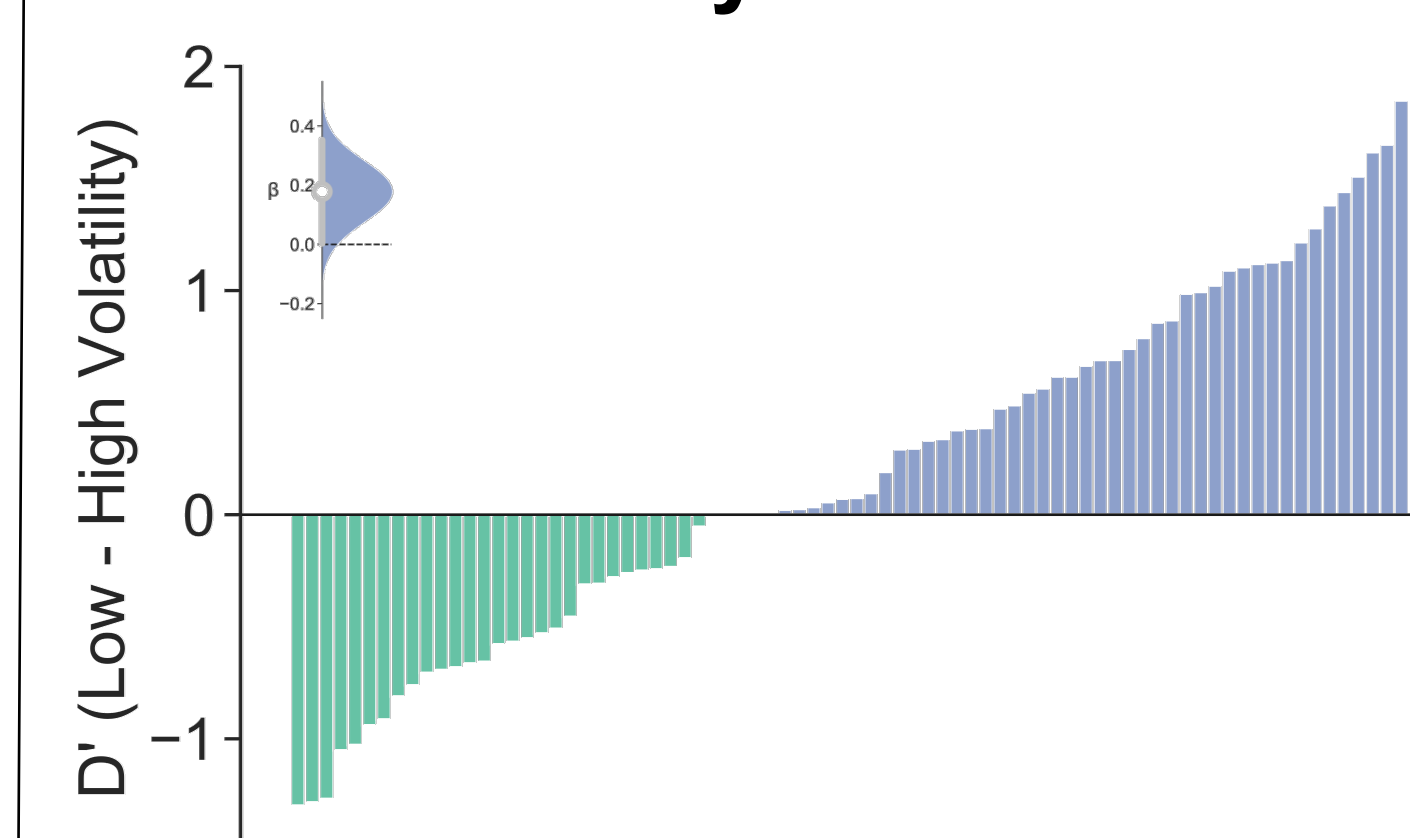This indicates that uncertainty decreases the use of one-shot memory.

$$Old\ Chosen \sim Old\ Object\ Value * Environment + (Old\ Object\ Value * Environment \mid Subject)$$

Equal use of deck value in both environments

This indicates that uncertainty leaves incremental memory intact.

$$Left\ Chosen_t \sim \sum_{n=1}^{4} (Outcome_{t-n} : Left\ Chosen_{t-n}) * Environment + [(Outcome_{t-n} : Left\ Chosen_{t-n}) * Environment \mid Subject]$$

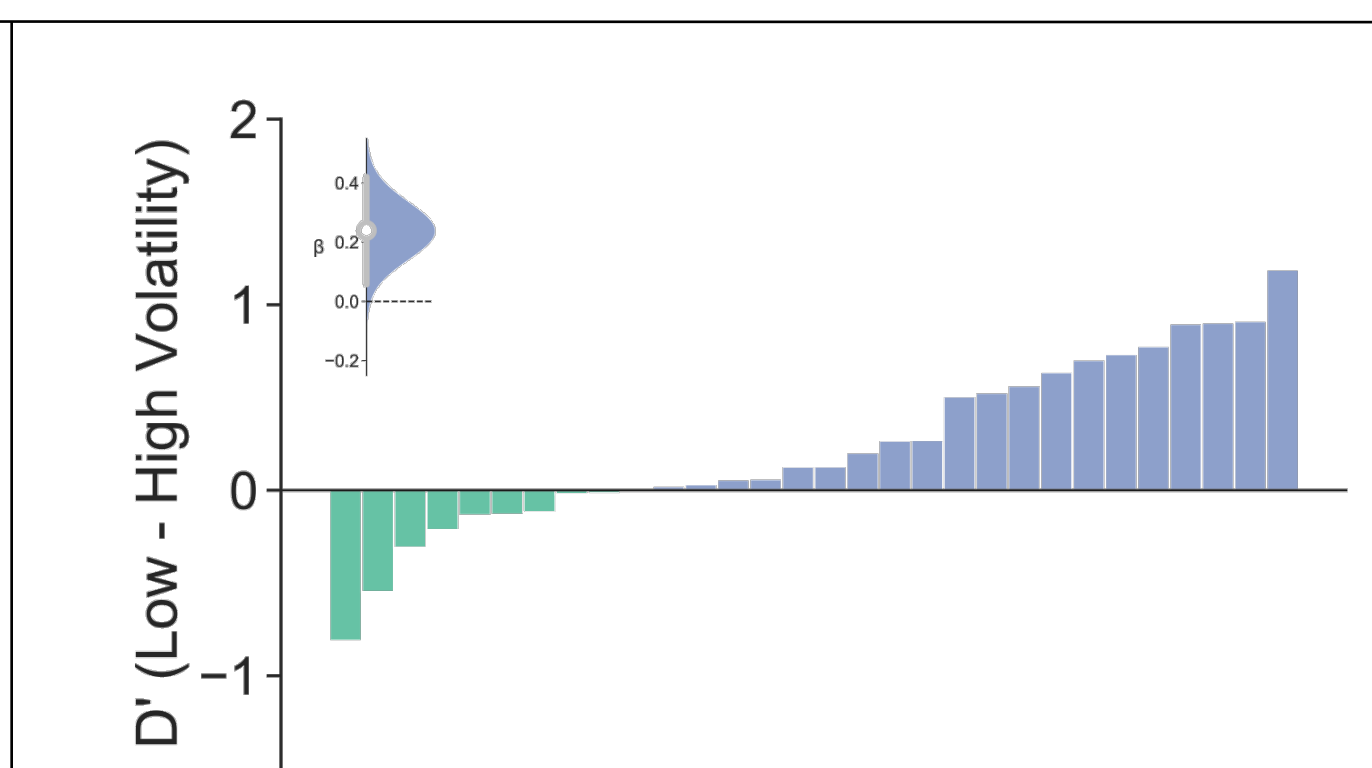### Better memory for objects from low volatility environment
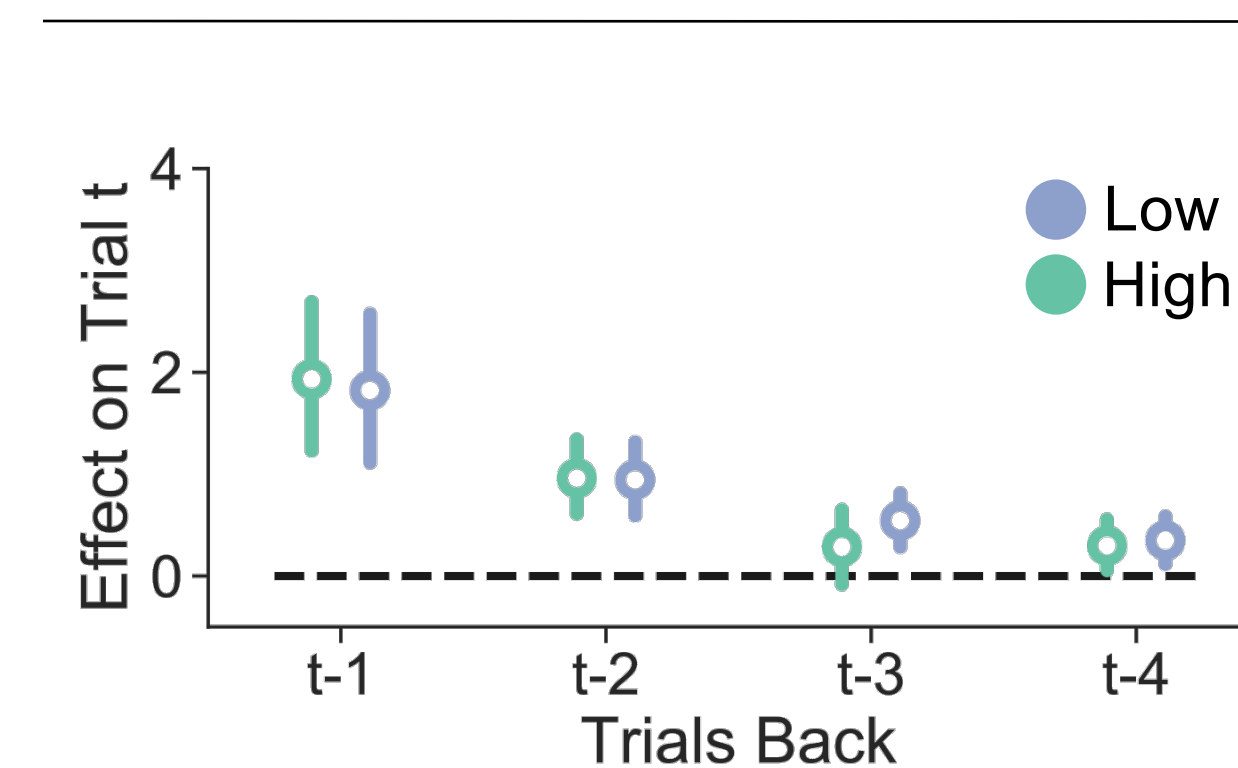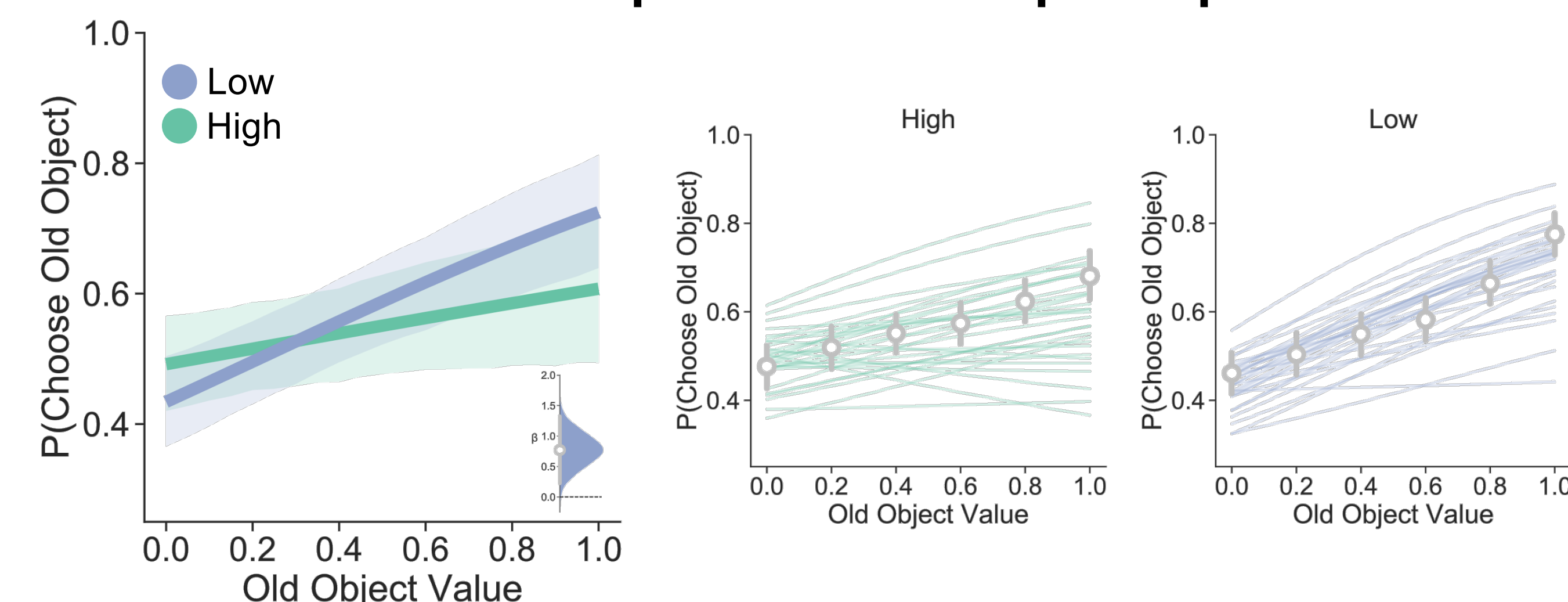

This indicates that uncertainty reduces subsequent one-shot memory.

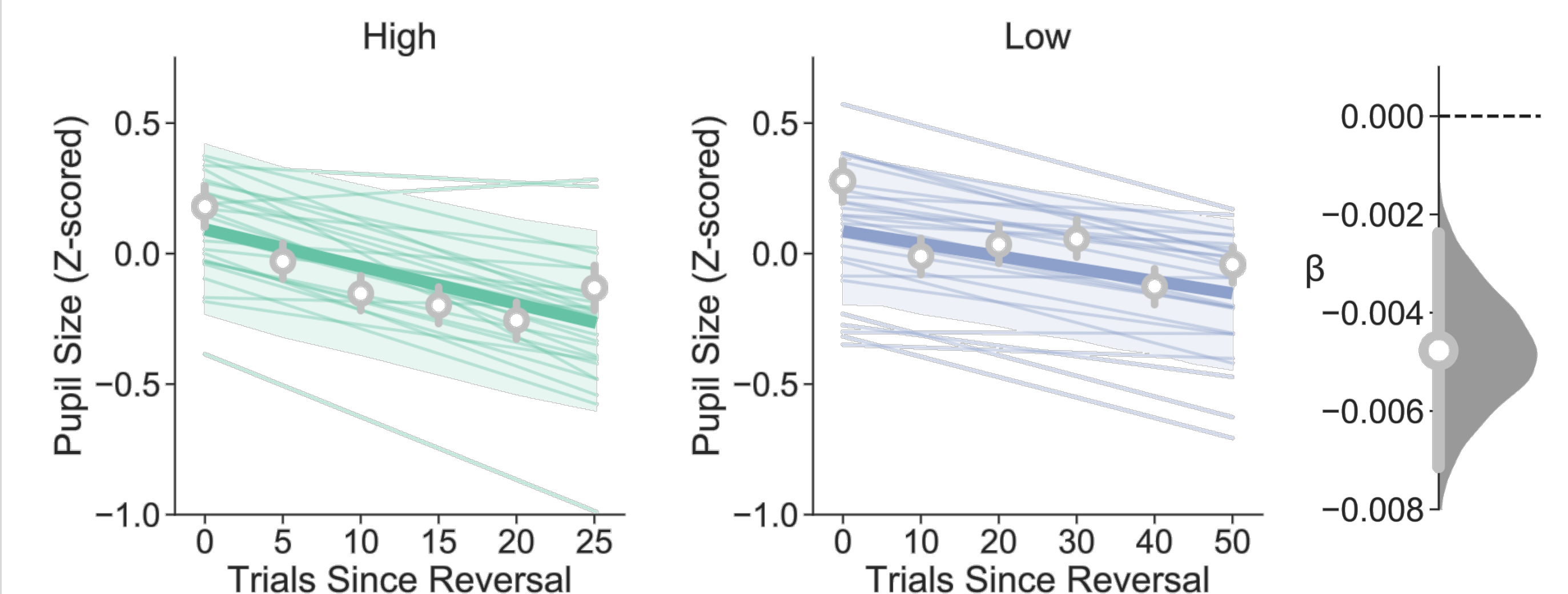## Do these effects replicate in a separate, lab-based sample?

- 30 participants ages 18-35 completed the decision making task in the lab while we recorded their pupil diameter.

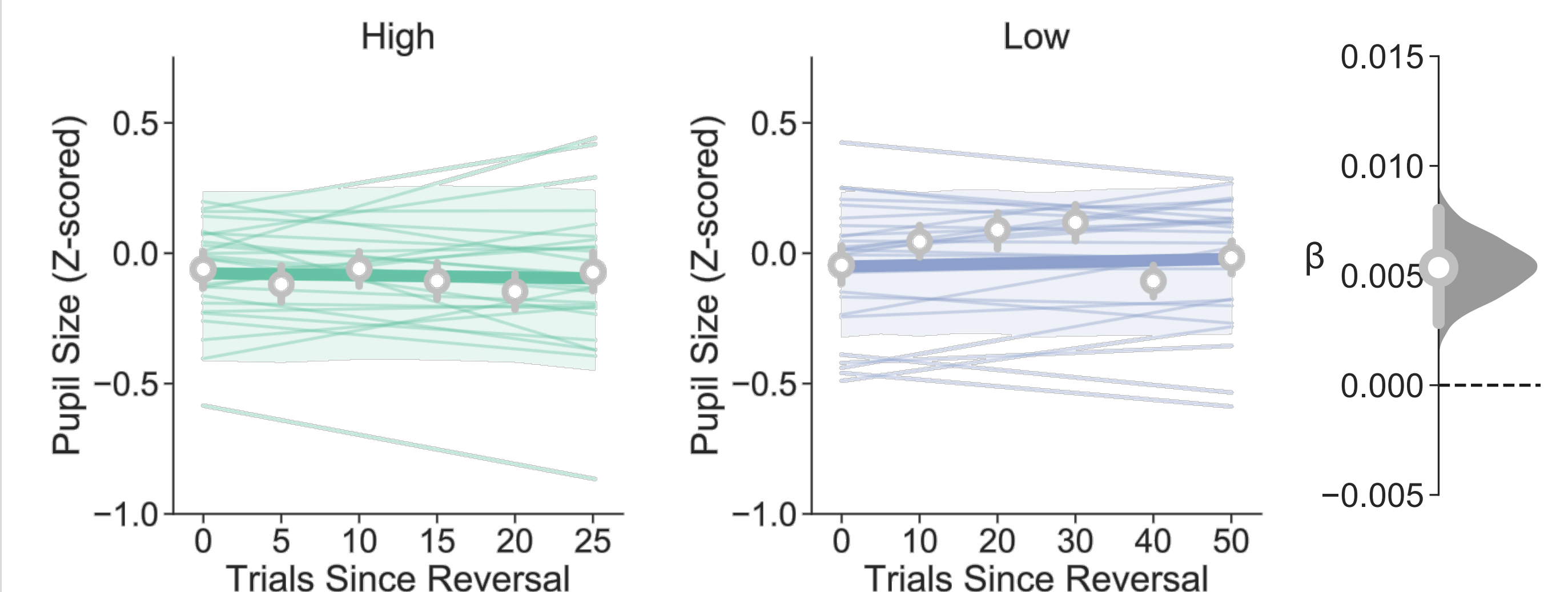### All effects replicate with lab participants

Does uncertainty modulate pupil dilation during decision making?

Pupil diameter is largest following a reversal

This indicates that greater pupil diameter may reflect uncertainty.

Reversals do not predict pupil size when an object is old

This indicates that pupil diameter may also reflect object recognition.

$$Pupil\ Size \sim Trial\ Number + Trials\ Since\ Reversal * Environment * Old\ Object + (Trial\ Number + Trials\ Since\ Reversal * Environment * Old\ Object \mid Subject)$$

Conclusions

Take Home | Environmental uncertainty decreases use of one-shot value and reduces subsequent memory but leaves incremental value intact.

- Pupil dilation is related to change-induced uncertainty and may help to differentiate between the use of multiple memory systems. This tradeoff between systems may be regulated by noradrenergic arousal systems.[8]

- Future work will probe the role of uncertainty in modulating hippocampal and striatal BOLD activity during this task.

References & Acknowledgements

[1]Bornstein, A. et al. (2017) *Nature Communications* 8:15958
[2]Bakkour, A. et al. (2019) *eLife* 8:e46080
[3]Shadlen, M. & Shohamy, D. (2016) *Neuron* 90(5), 927-939
[4]Duncan, K., Semmler, A., Shohamy, D. (2019) *Journal of Cognitive Neuroscience* 31(10), 1455-1467
[5]Lengyel, M. & Dayan, P. (2008) *Advances in Neural Information Processing Systems* 20:889–896
[6]Blundell, C. et al. (2016) *arXiv:1606.04460*
[7]Santoro, A., Frankland, P.W., & Richards, B.A. (2016) *Journal of Neuroscience* 36(48), 12228–12242
[8]Nassar, M. et al. (2012) *Nature Neuroscience* 15(7), 1040-1046