Precision-weighted evidence integration predicts time-varying influence of memory on perceptual decisions

Poster GitHub

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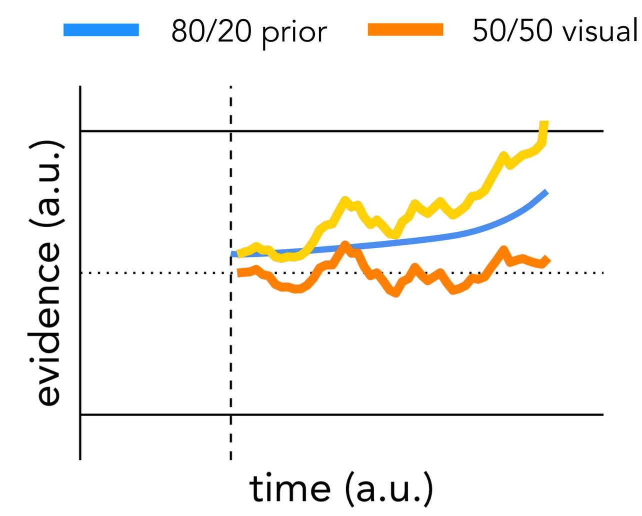
Motivation

How are expectations integrated with sensory evidence during decision making under uncertainty?

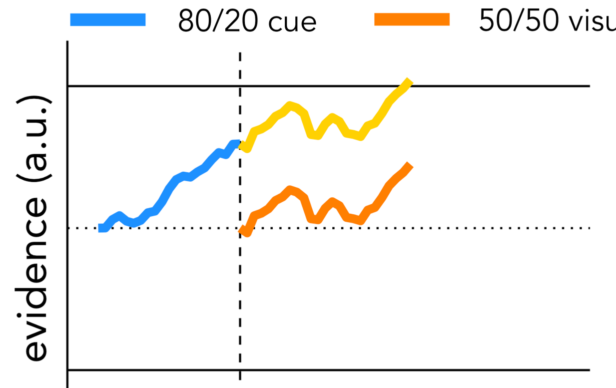
Two different studies found **time-varying** effects of expectations (the *prior*) on perceptual evidence accumulation:

Late effect: slow mixing of prior over time

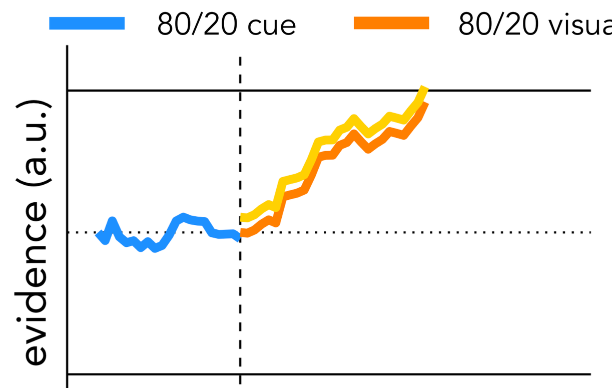


Prior expectations are incorporated according to a dynamic additive bias that increases with decision time (Hanks et al., 2011)

Early effects: adaptive memory sampling



Memory evidence is sampled more strongly during pre-stimulus period when upcoming visual evidence is anticipated to have low reliability (Bornstein et al., 2018)



Memory sampling is attenuated when visual evidence is anticipated to have high reliability (Bornstein et al., 2018)

We propose *dynamic*, *relative* reliability-weighted integration as a unifying explanation.

Precision-weighted multi-source sequential sampling model

The simulated agents treat each evidence source *s* as reflecting an independent probability of observing target *X*:

$$p(x_s) \sim Beta(\alpha_s, \beta_s)$$

where $s = \{memory, vision\}$

At each timepoint *t*, evidence samples *o* are drawn from a Bernoulli distribution with reliability θ and additive Gaussian noise:

$$o_{s_t} \sim Bernoulli(\theta) + \mathrm{Normal}(0,1)$$

Memory samples are drawn at ¼ the rate of visual samples to approximate the ratio of theta oscillations (~8Hz) to visual sample presentation rate (30Hz).

Each sample updates the probability of observing target *X*:

$$p(x_s)_t \sim \begin{cases} Beta(\alpha_{s_{t-1}}+1,\ \beta_{s_{t-1}}) & if\, o_{s_t} > 0 \\ Beta(\alpha_{s_{t-1}},\ \beta_{s_{t-1}}+1) & if\, o_{s_t} < 0 \end{cases}$$

The precision of each evidence stream is computed as the inverse variance of the updated Beta distribution:

$$precision_{s_t} = \left[\frac{\alpha_{s_t}\beta_{s_t}}{(\alpha_{s_t}+\beta_{s_t})^2(\alpha_{s_t}+\beta_{s_t}+1)}\right]^{-1}$$

The weight placed on each sample at each timepoint is computed as the *relative* precision of each stream at that timepoint:

$$w_{mem_t} = \frac{precision_{mem_t}}{precision_{mem_t} + precision_{viz_t}}$$

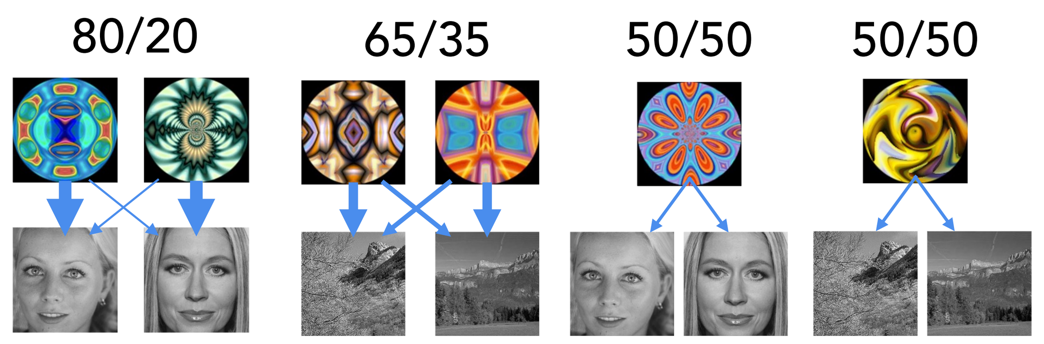
$$w_{viz_t} = \frac{precision_{viz_t}}{precision_{mem_t} + precision_{viz_t}}$$

The decision variable is a weighted sum of samples from each evidence stream:

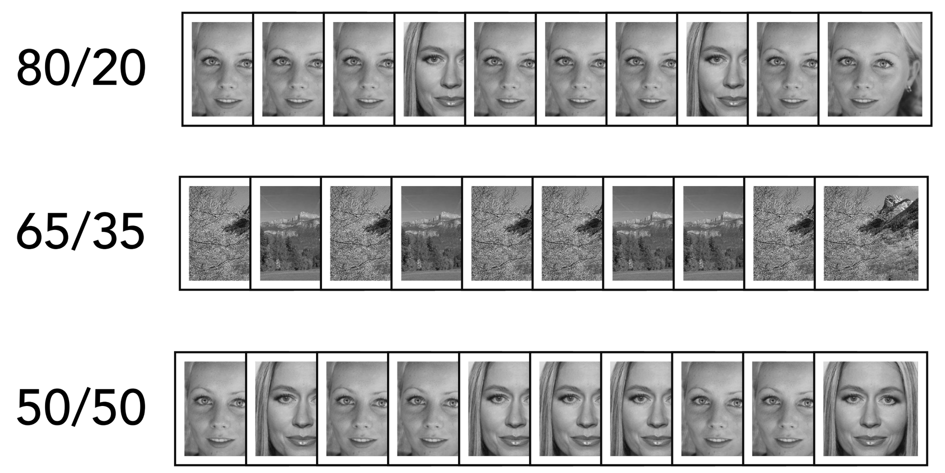
$$DV_t = DV_{t-1} + o_{mem_t} w_{mem_t} + o_{viz_t} w_{viz_t}$$

Task design

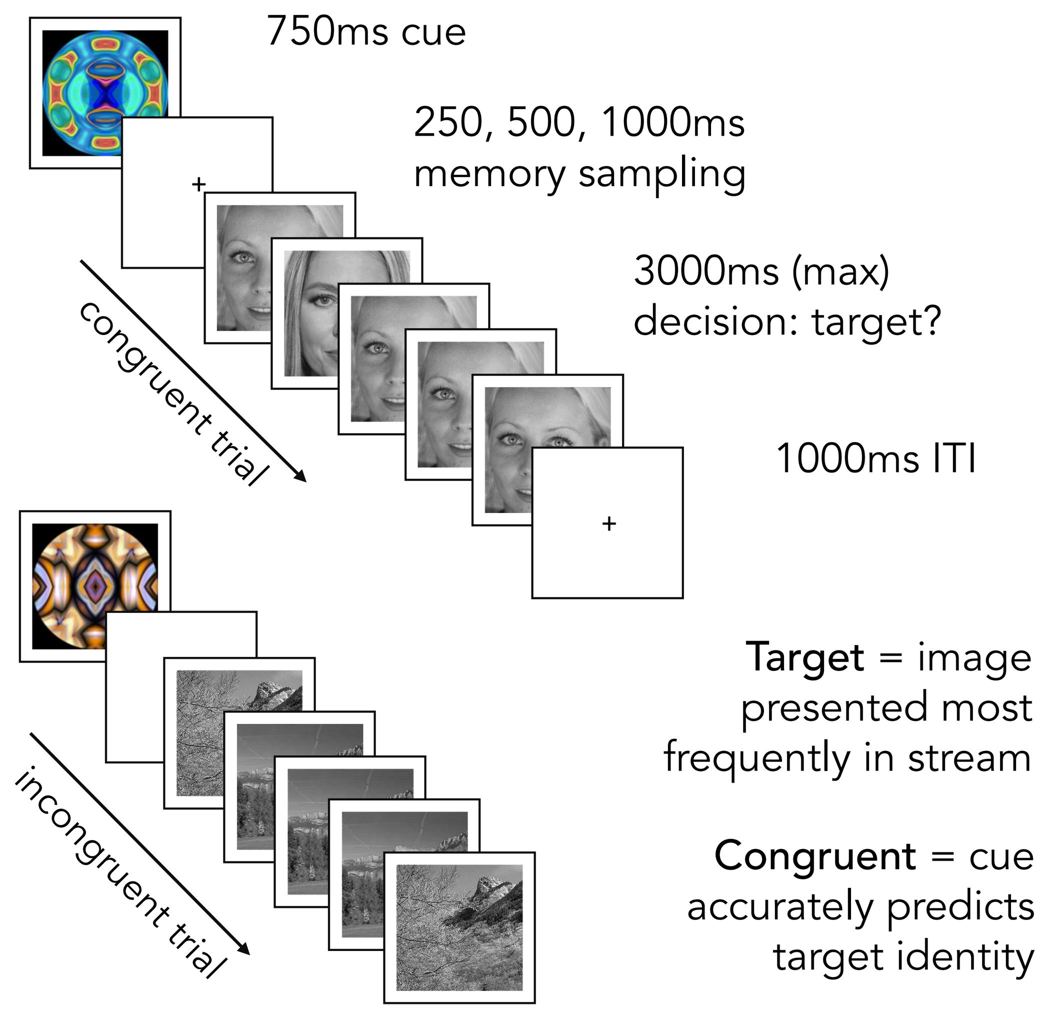
Learned prior target probabilities



Visual coherence: proportion of frames containing target image



Cued perceptual inference

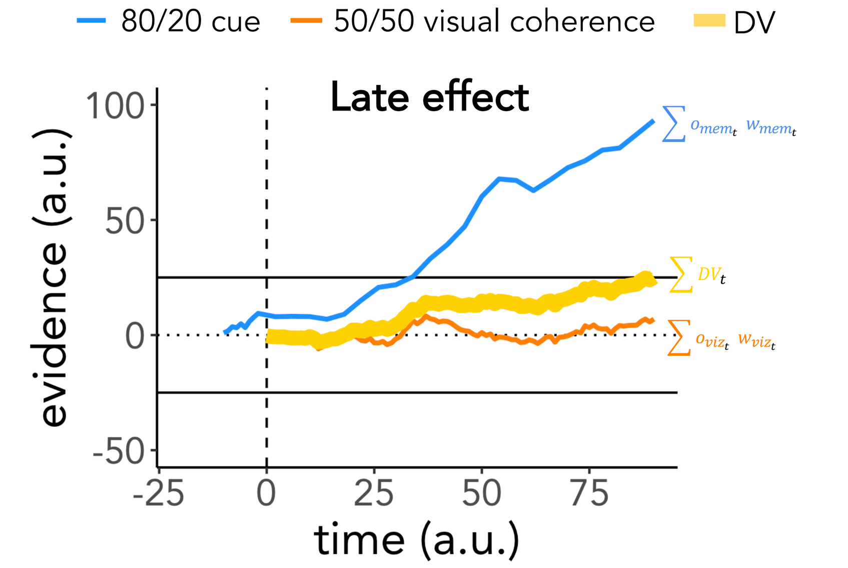


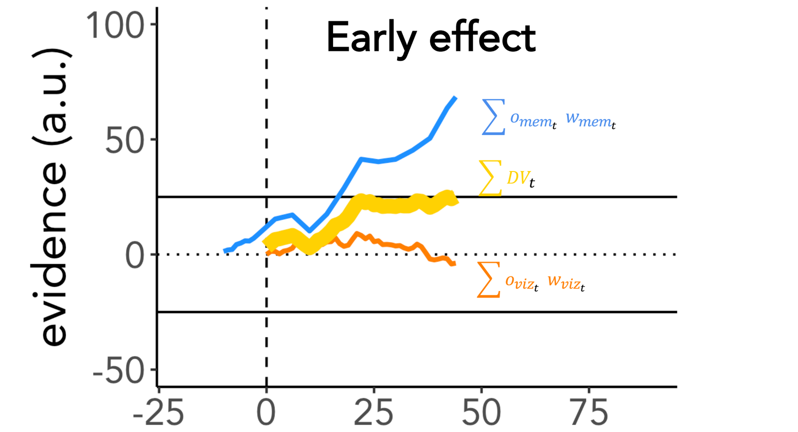
Target = image presented most frequently in stream

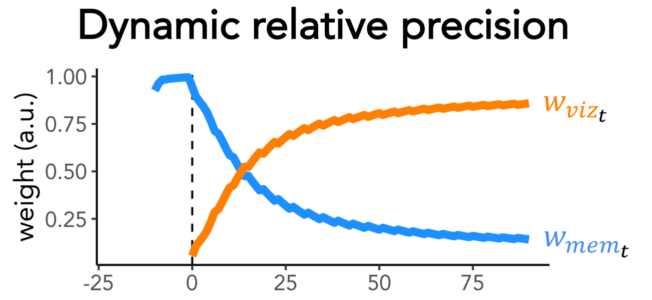
Congruent = cue accurately predicts target identity

Simulation results and predictions

Dynamic precision weighting captures late and early effects of prior on DV

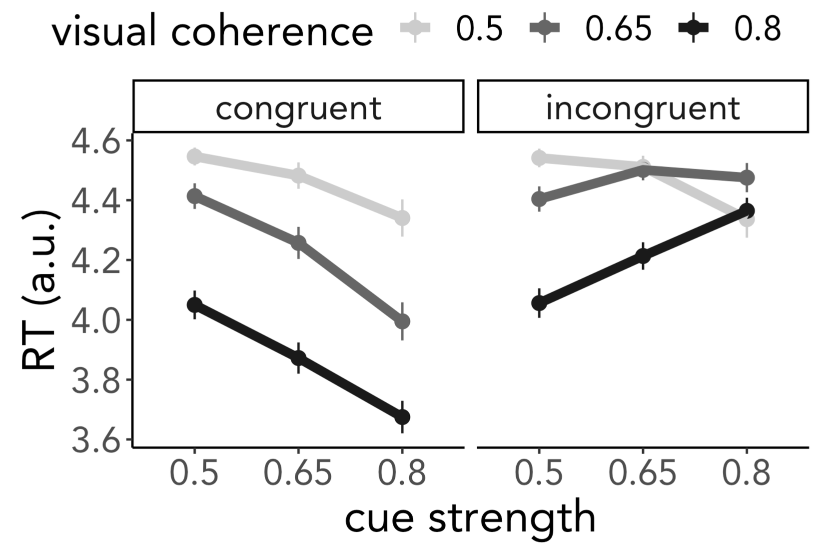


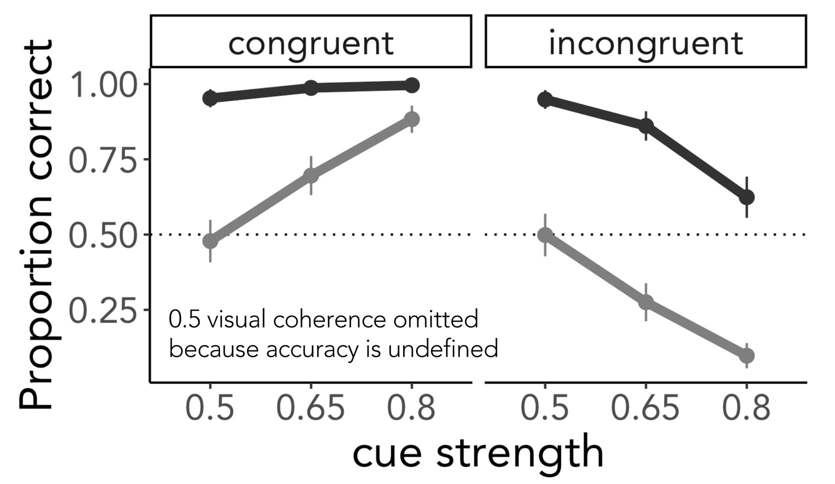




Ideal observer predictions with 25 trials/cell

n=50, error bars = +/- 1 SEM





Stronger memory associations result in faster and more accurate decisions for congruent visual evidence, while slowing responses and impairing accuracy for incongruent visual evidence (all $\beta > 0.04$, all $p < .001$).

Future directions

- Collect behavioral and EEG data to test model predictions.
- Investigate how *subjective* confidence in each evidence stream modulates their integration.

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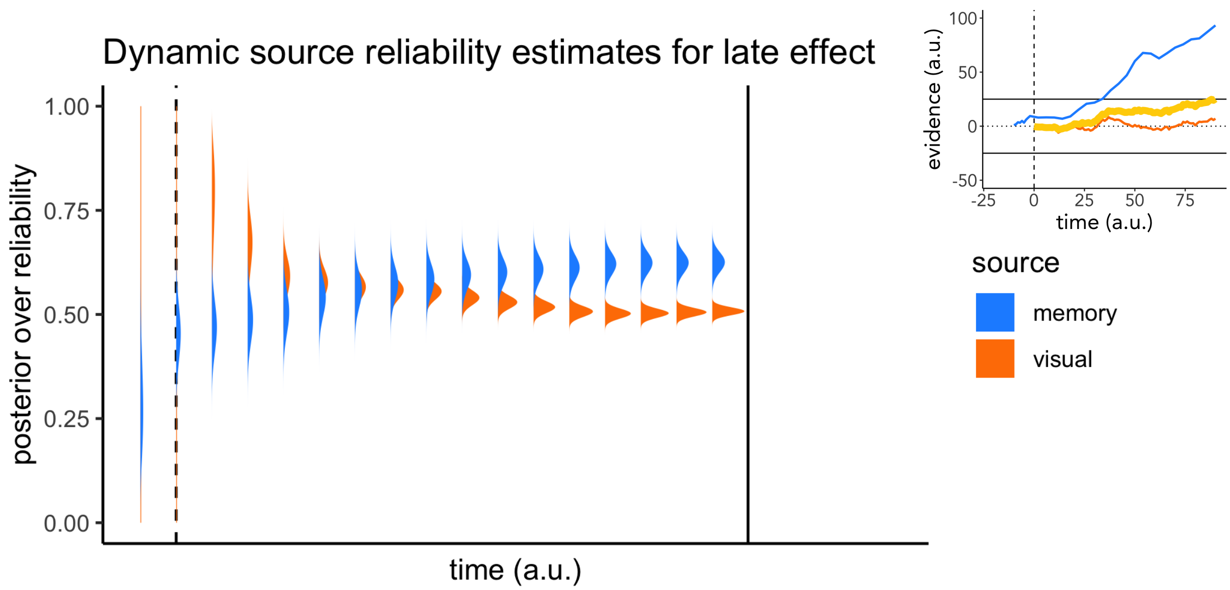
References:

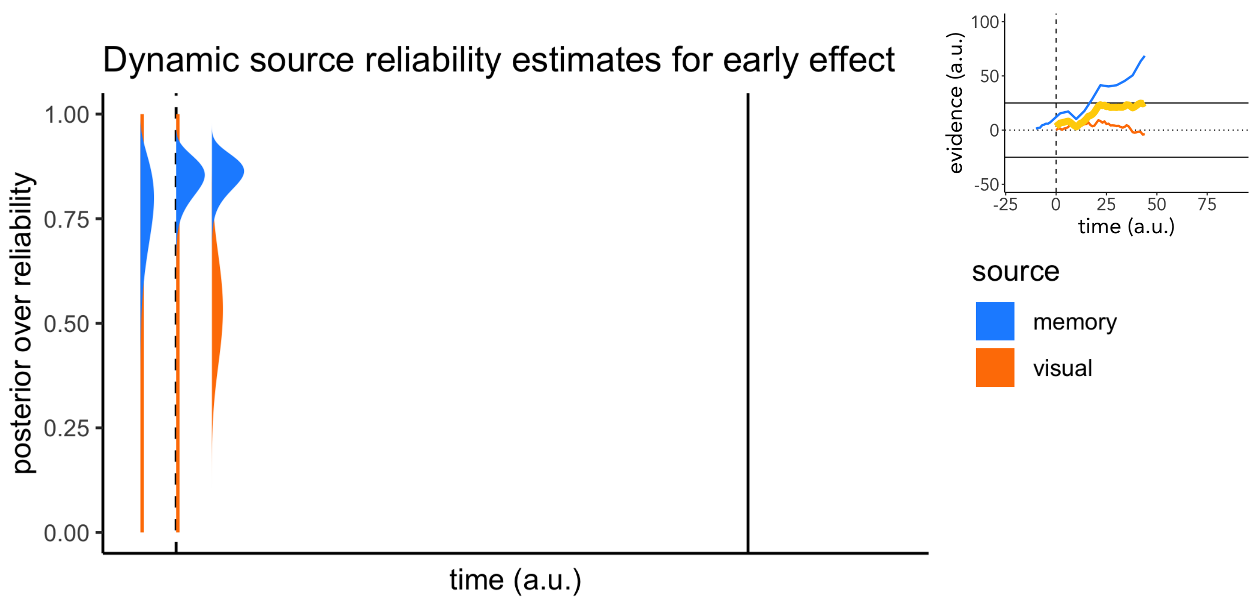
Hanks, T. D., Mazurek, M. E., Kiani, R., Hopp, E., & Shadlen, M. N. (2011). Elapsed decision time affects the weighting of prior probability in a perceptual decision task. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 31(17), 6339–6352.

Bornstein, A. M., Aly, M., Feng, S. F., Turk-Browne, N. B., Norman, K. A., & Cohen, J. D. (2018). Perceptual decisions result from the continuous accumulation of memory and sensory evidence. In *bioRxiv*. *bioRxiv*. https://doi.org/10.1101/186817

Supplemental materials

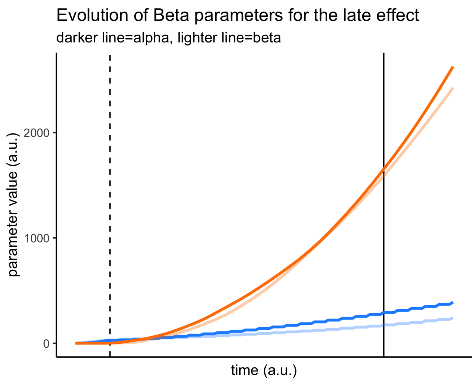
Posterior distributions over source reliability estimated over the course of sampling in a single trial

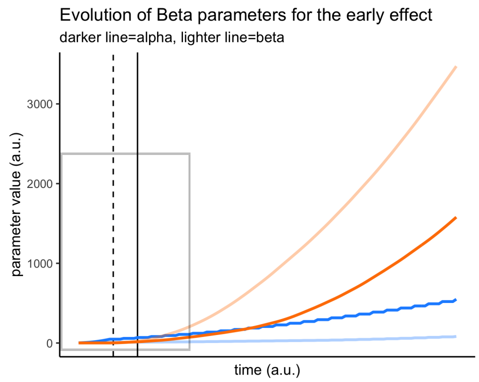


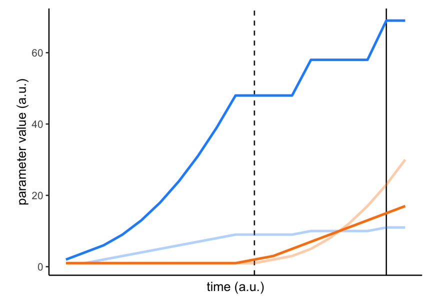


Supplemental materials

Evolution of alpha & beta parameters over the course of sampling in a single trial

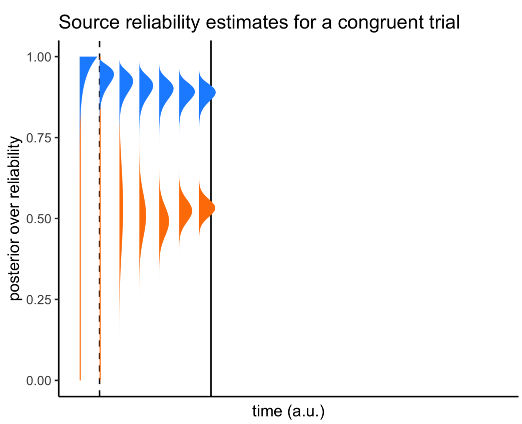


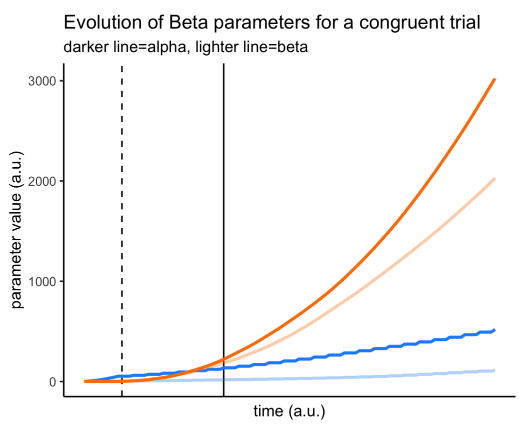


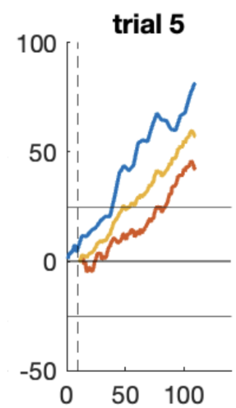


Posterior plots & parameter evolution for 0.8 cue, 0.65 coh

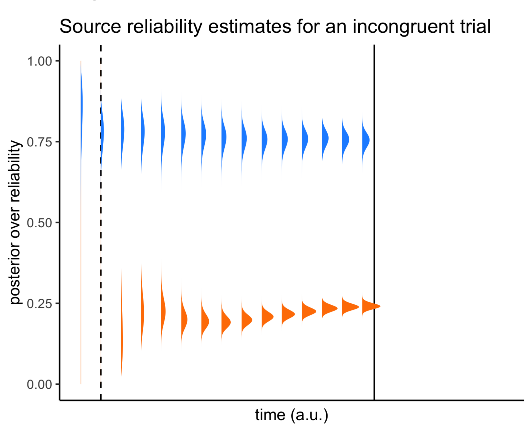
congruent

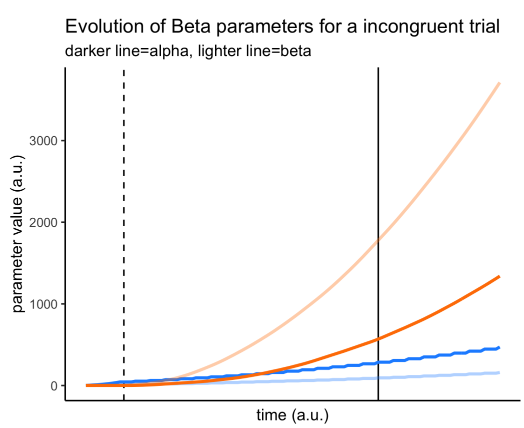


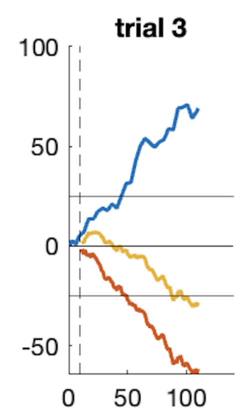




incongruent

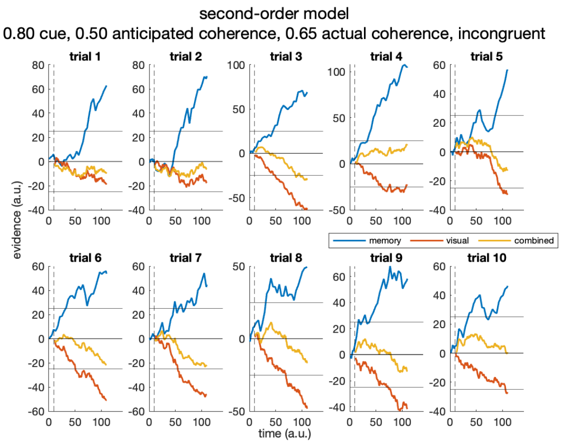


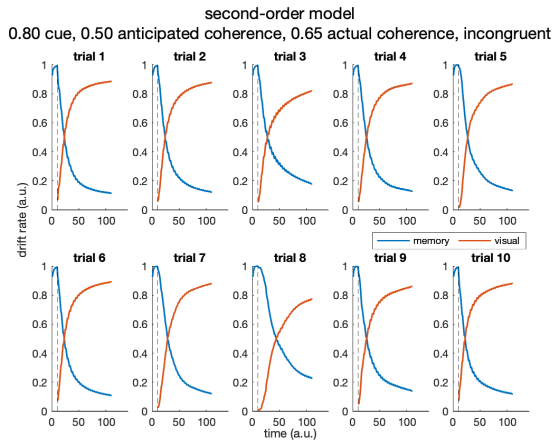




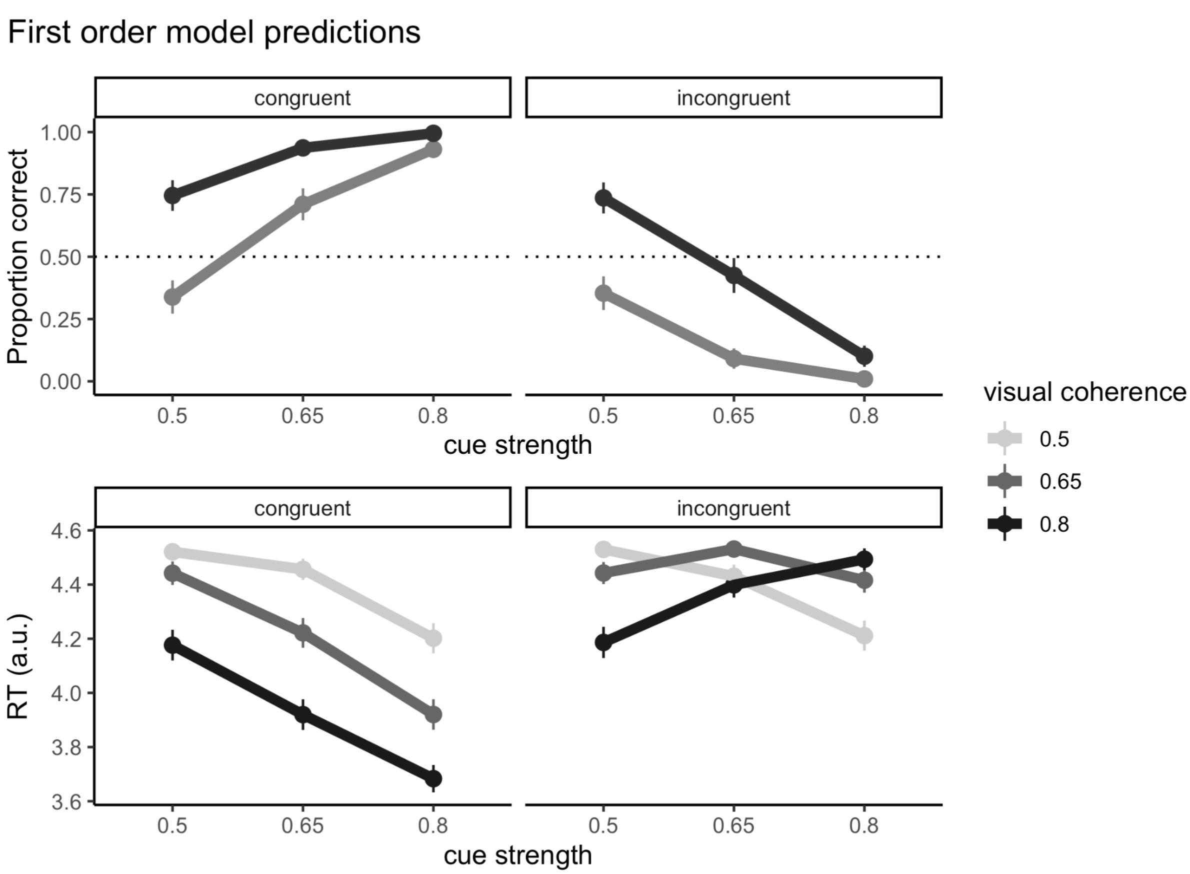
Supplemental materials

Example incongruent trials





First-order model: precision computed as inverse Shannon entropy of each evidence stream at each timestep

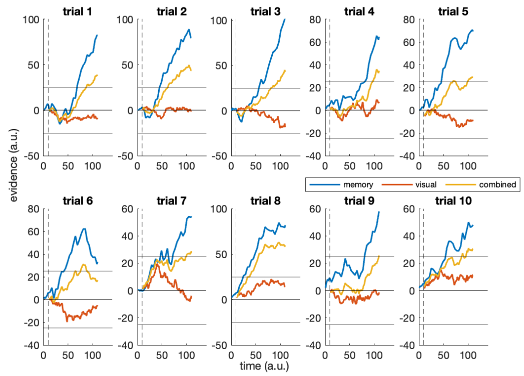


Supplemental materials

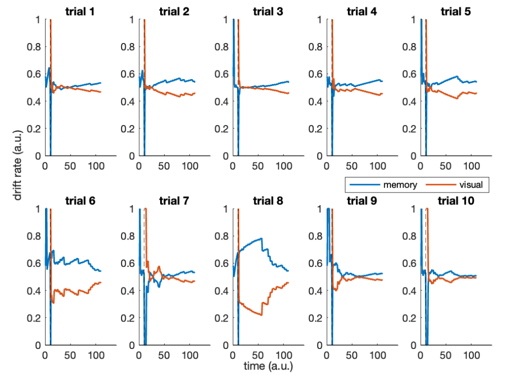
Example traces & drifts

0.8 cue, 0.5 coh (parallel to second-order plots on poster)

first-order model
0.80 cue, 0.50 anticipated coherence, 0.50 actual coherence, incongruent

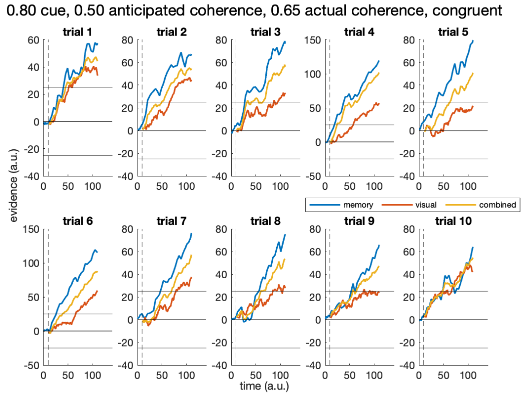


first-order model
0.80 cue, 0.50 anticipated coherence, 0.50 actual coherence, incongruent

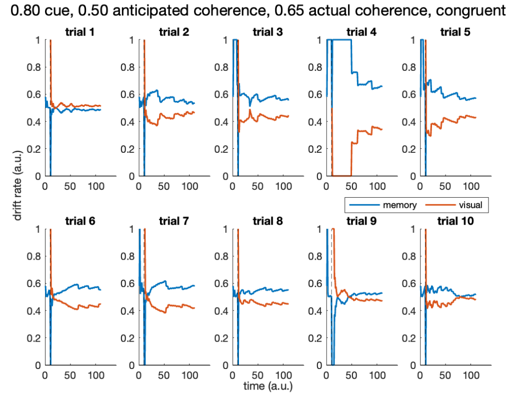


0.8 cue, 0.65 coh, congruent

first-order model
0.80 cue, 0.50 anticipated coherence, 0.65 actual coherence, congruent

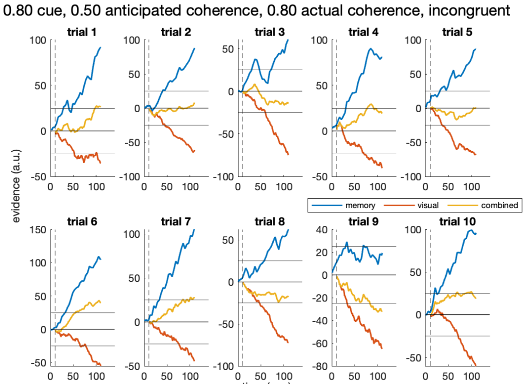


first-order model
0.80 cue, 0.50 anticipated coherence, 0.65 actual coherence, congruent



0.8 cue, 0.8 coh, incongruent

first-order model
0.80 cue, 0.50 anticipated coherence, 0.80 actual coherence, incongruent



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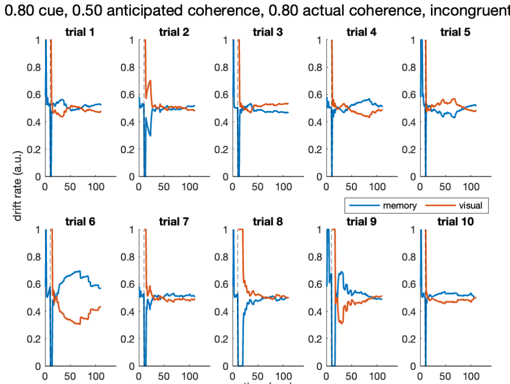
0.80 cue, 0.50 anticipated coherence, 0.80 actual coherence, incongruent



Supplemental materials

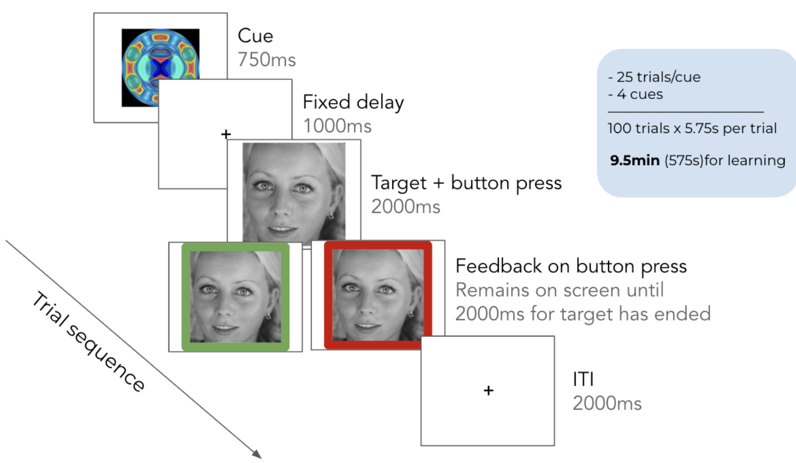
Design slides

Response training & cue learning

Response training

1. Targets are shown sequentially (twice) and participants make a self-paced key press
2. Targets are shuffled and participants have 2000ms to make a button press. If they are correct, they get visual feedback (green border around photo). If they are not, the photo remains on screen until the correct button is pressed (at which point the green feedback is given). Each photo is presented 10 times.
    a. If participants get the same photo wrong ≥2 times, they have to start the whole training phase over

Sequence learning



Supplemental materials

Unimodal confidence trials