Probing adaptive decision-making under uncertainty using extended Hidden Markov Models

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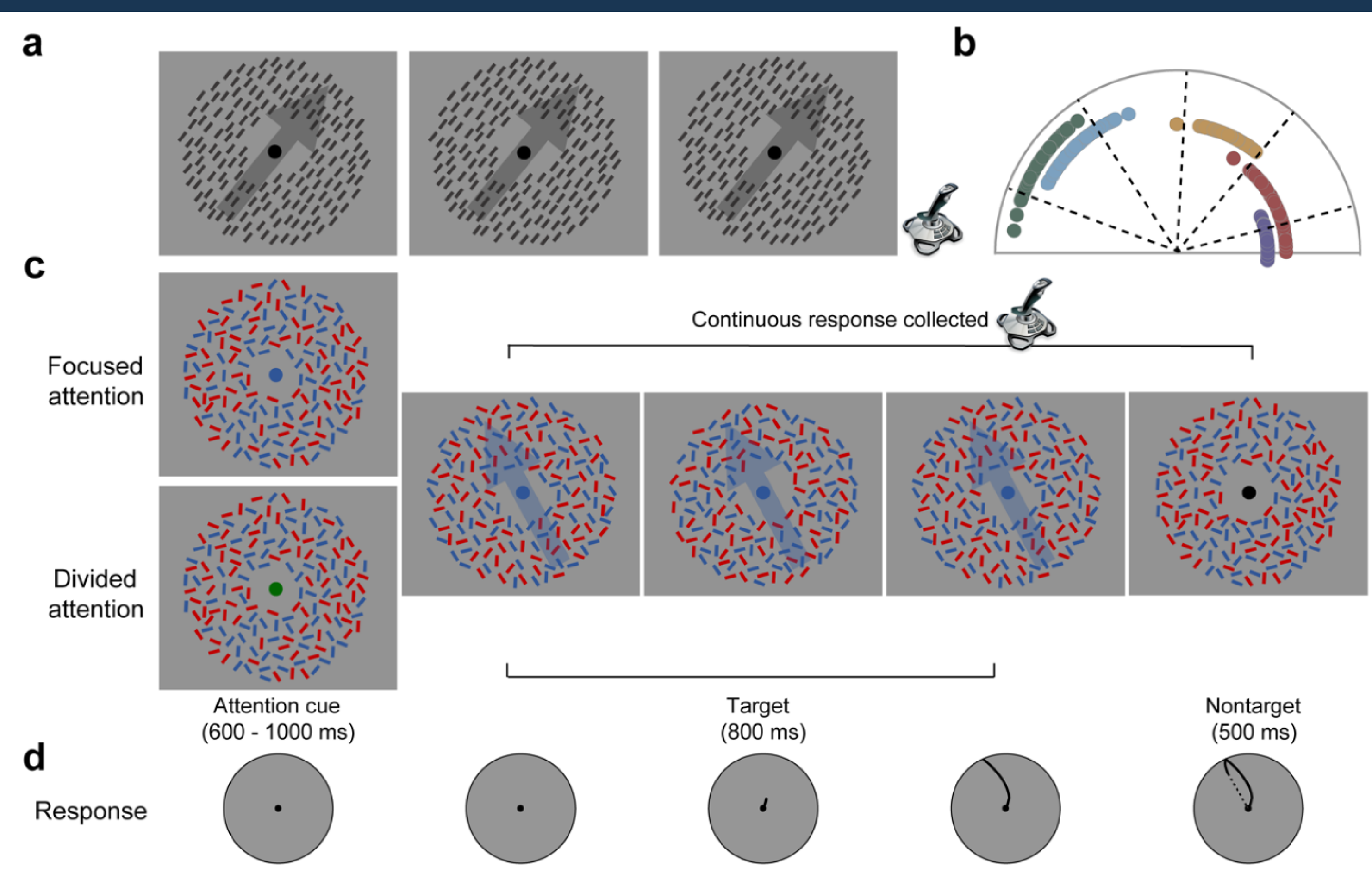
Abstract

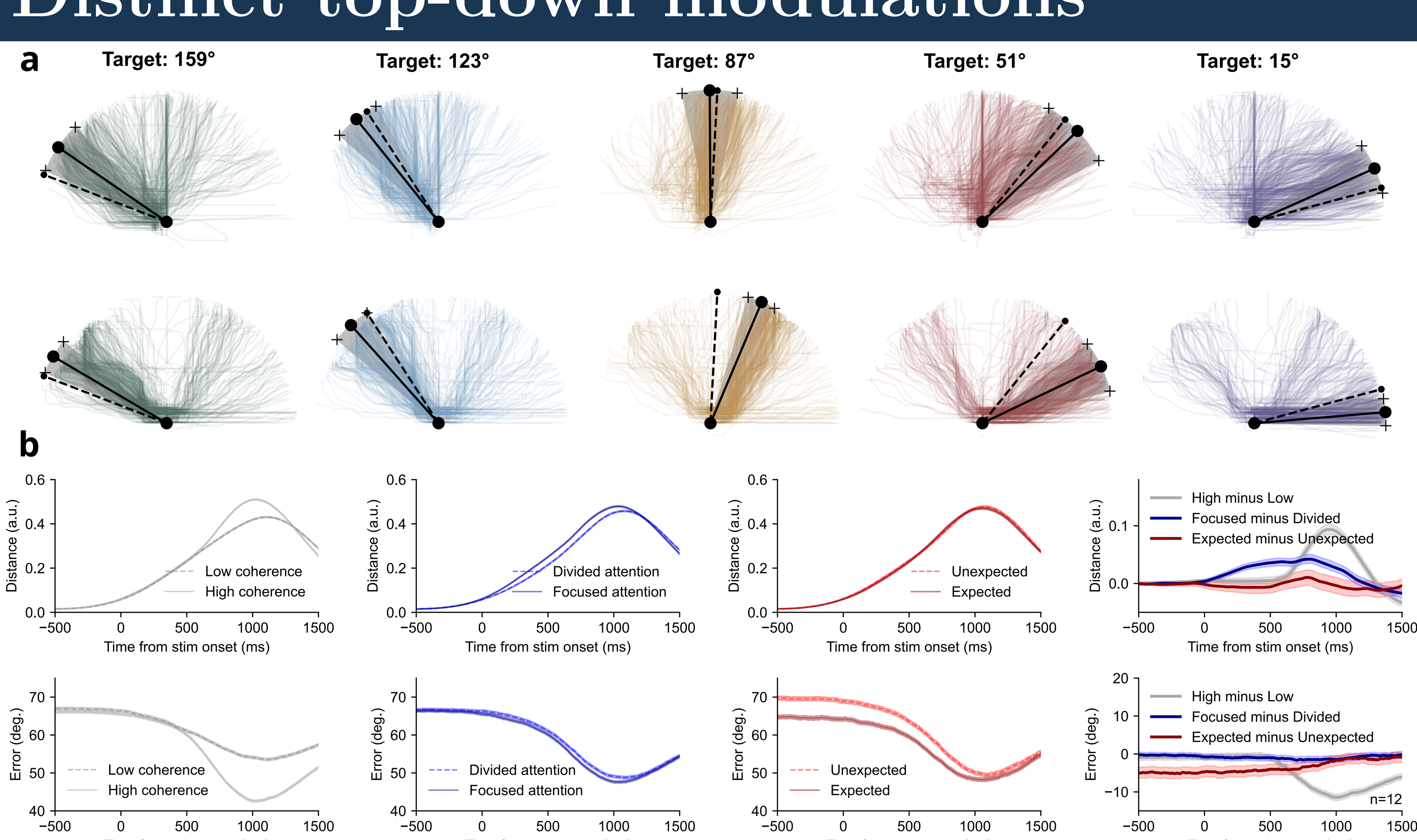
Decision-making under uncertainty challenges both biological and artificial systems. Past work shows that humans leverage top-down (e.g., selective attention and prior expectation) and bottom-up signals (stimulus strength) to optimize decisions, however the interplay of these factors remain poorly understood. We devised a cognitive task that orthogonally manipulated these factors and revealed latent cognitive states that shape decision dynamics using state-space modeling and Hidden Markov Models (HMMs). We found that attention and stimulus strength accelerated early sensory processing, while expectation biased motor responses.

Experimental setup



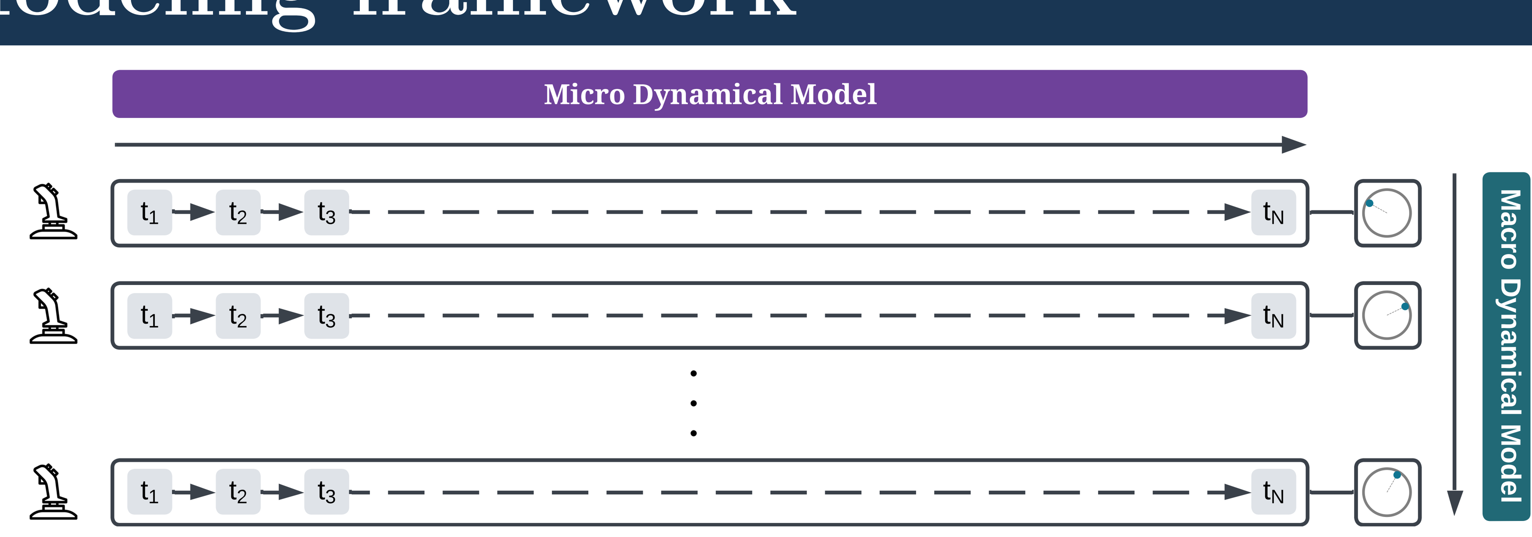
(a) Calibration block: Participants viewed flickering black bars and reported the coherent orientation using a 360° flight simulator joystick. **(b)** Stimulus space: Five evenly spaced target orientations were presented; sample responses (solid circles) illustrate the response distributions. **(c)** Main task: Each trial began with a fixation (400–800 ms) followed by an attention cue (600–1000 ms) indicating the target bar color—red/blue for focused attention and green for divided attention. In addition, prior expectation was manipulated by biasing the probability of one target orientation within a block, and stimulus strength was varied using two coherence levels (low and high). **(d)** Example response trajectory.

Distinct top-down modulations



(a) Two example participants' response trajectory distributions. **(b)** Effects of coherence, attention, and expectation on response error and response trajectory from stimulus onset.

Modeling framework



Twelve participants performed 4 sessions (6 blocks of 120 trials each). We modeled the timesteps within each trial using a Gaussian Hidden Markov Models (HMMs) to capture trial-level micro dynamics. Next, we modeled blocks of trials with circular Input-Output Hidden Markov Models (IO-HMMs) to characterize the macro dynamics and external dependencies (current stimulus, previous stimulus, and previous response).

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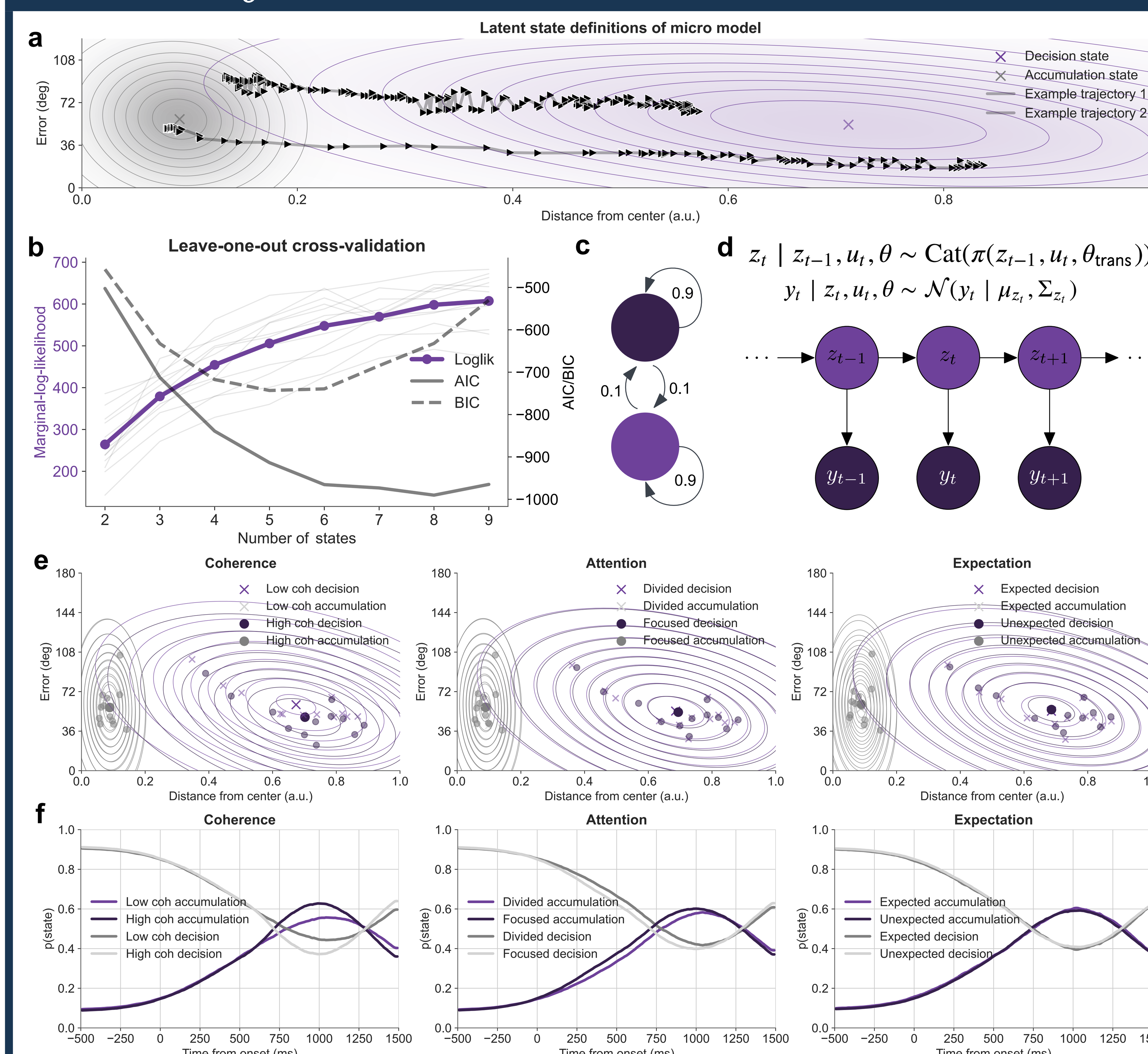
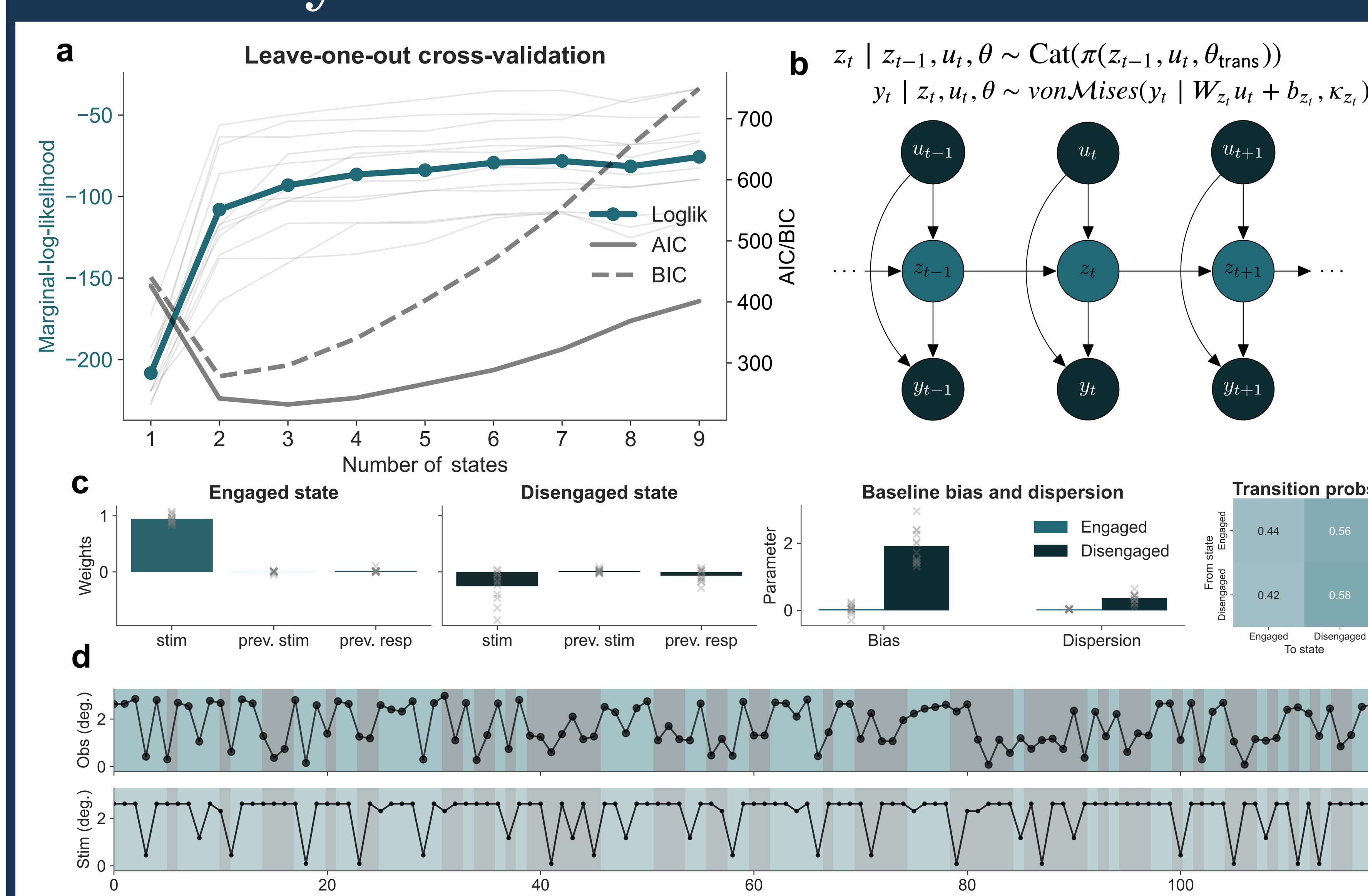
Micro dynamics with Gaussian HMM



Our Gaussian HMM analysis at the micro scale revealed two latent states: an accumulation state and a decision state. While prior expectation did not change the overall proportion of time spent in each state, it notably influenced the state definitions, especially by modulating the characteristics of the accumulation state. In contrast, we found that the effects of attention and coherence emerged only after stimulus onset. Specifically, attention influenced the state occupancy proportions after stimulus onset without altering the accumulation state. Coherence also impacted occupancy post-stimulus, with a substantially larger impact on the decision state dynamics.

Macro dynamics with circular IO-HMM



At the macro scale, our circular IO-HMM analysis revealed two distinct latent states: an engaged state and a disengaged state. The engaged state is characterized by active stimulus processing and heightened sensitivity to external inputs, whereas the disengaged state shows a greater reliance on task-driven internal bias.

Conclusions & Acknowledgements

Our modeling framework decouples attention and expectation, revealing distinct contributions to decision-making. The micro and macro analyses show distinct roles for selective attention and prior expectation. These results advance our understanding of human probabilistic reasoning.

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This research was supported by a Center of Excellence grant from the Air Force Office of Scientific Research (grant FA9550-22-1-0337)