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The Secret Bayesian Life of Ring Attractor Networks

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Efficient navigation requires animals to track their position, velocity and heading direction (HD). Some animals' behavior suggests that they also track uncertainties about these navigational variables, and make strategic use of these uncertainties, in line with a Bayesian computation. Ring-attractor networks have been proposed to estimate and track these navigational variables, for instance in the HD system of the fruit fly Drosophila. However, such networks are not designed to incorporate a notion of uncertainty, and therefore seem unsuited to implement dynamic Bayesian inference. Here, we close this gap by showing that specifically tuned ring-attractor networks can track both a HD estimate and its associated uncertainty, thereby approximating a circular Kalman filter. We identified the network motifs required to integrate angular velocity observations, e.g., through self-initiated turns, and absolute HD observations, e.g., visual landmark inputs, according to their respective reliabilities, and show that these network motifs are present in the connectome of the Drosophila HD system. Specifically, our network encodes uncertainty in the amplitude of a localized bump of neural activity, thereby generalizing standard ring attractor models. In contrast to such standard attractors, however, proper Bayesian inference requires the network dynamics to operate in a regime away from the attractor state. More generally, we show that near-Bayesian integration is inherent in generic ring attractor networks, and that their amplitude dynamics can account for close-to-optimal reliability weighting of external evidence for a wide range of network parameters. This only holds, however, if their connection strengths allow the network to sufficiently deviate from the attractor state. Overall, our work offers a novel interpretation of ring attractor networks as implementing dynamic Bayesian integrators. We further provide a principled theoretical foundation for the suggestion that the Drosophila HD system may implement Bayesian HD tracking via ring attractor dynamics.

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