Reward-modulated learning of population-encoded vectors for insect-like navigation in embodied agents

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Many insects exhibit robust and efficient visual-based navigation in complex environments [1]. Specifically, behavioral studies on ants and bees showed that they are guided by orientation vectors based on a process called path integration. This process allows them to estimate their current location by integrating cues from odometry and a sun-based compass. While it is mainly applied to return back to the nest, it also guides learning of so-called vector memories for subsequent foraging [2, 3]. Vector memories can be anchored globally to the nest or locally to landmarks. Recent neurophysiological studies revealed that the central complex, an insect neuropil, contains neural representations of compass [4] and odometric cues [5]. However, it is still unclear, how these representations are involved in path integration and vector memories, and how they produce goal-directed navigation. Computational modeling has been powerful in testing hypotheses about the underlying neural substrates and their generated behavior, and to predict further experimental data. Previous models [6, 7] sufficiently produced insect-like vector navigation, but they neglected biologically plausible explanations about underlying neural mechanisms that could generate this behavior.

We present here a novel computational model of neural mechanisms in closed-loop control for vector navigation in embodied agents. It consists of a path integration mechanism, reward-modulated learning of global and local vectors, random search, and action selection. The path integration mechanism computes a vectorial representation of the agent's current location. The vector is encoded in the activity pattern of circular arrays, where the angle is population-coded and the distance is rate-coded. We apply a reward-modulated learning rule for global and local vector memories, which associates the local food reward with the path integration state. A motor output is computed based on the combination of vector memories and random exploration. We show that the modeled neural mechanisms enable robust homing and localization in a simulated agent, even in the presence of external sensory noise. The proposed learning rules produce goal-directed navigation and route formation under realistic conditions. This provides an explanation for, how view-based navigational strategies are guided by path integration. As such, the model is the first to link behavioral observations to their possible underlying neural substrates in insect vector navigation.

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