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On the origin of systematic errors in a simple navigation task

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One of the simplest tasks in navigation is homing: returning to the point of origin after an excursion. If no positional information is given, e.g., in the dark, path integration is used for homing by various species, including ants and humans, to estimate traveled distance from self-motion cues. In desert ants, a systematic undershoot in homing performance, which increased with outbound distance, was contributed to the inherent leakiness of the ant's path integrator [1]. Previous studies on locomotor homing in blindfolded humans [2,3] similarly showed decreasing homing gain for increasing outbound distance, but the amount of error for a particular distance varied among studies. In contrast to the prediction of leaky integration, the gain-distance relation appeared to depend on the range of distances employed with gains larger than unity for short distances and smaller for long distances.

We first verified that this observation still holds for farther distances not yet tested (up to 250 m). Next, we showed that for a similar path integration task – blindfolded goal-directed locomotion – the gain-distance dependence did not hold as would be expected from a leaky path integrator. After thus having excluded the hypothesis that the gain-distance dependence was caused by leaky integration, we developed a new theory: homing distance is determined by Bayesian inference based on prior expectation and current measurement of outbound distance. Comparison of our homing data with that of the previous studies revealed that the dependence of homing distance on outbound distance follows a classical power law relation [4]: a linear slope in double-log representation.

We show that the power-law dependence is compatible with distance representation and Bayesian inference on an internal logarithmic scale, thus unifying two classical psychophysical theories, the Weber-Fechner law and Steven's law [4], with Bayesian inference. Furthermore, our theory provides a reason for the observed range effect and the "central tendency." Notably, a recent study showed the validity of Weber's law for locomotor path integration [5].

To answer the question of how the prior is determined – from cues such as the size of the experimental room or online during the experiment – we performed yet another experiment: two groups of subjects were tested with the same set of distances, but in reverse order. We found that the performance strongly depended on order of presentation, and that this dependence could be explained by Bayesian estimation of the prior implemented as discrete Kalman filter. In summary, we propose a three-stage mechanism for homing in humans: 1) representation of walked distance is affected by amplitude-dependent noise, 2) homing distance is determined by Bayesian integration of the actual distance estimate and prior expectation and 3) the distance prior is estimated online during the experiment by optimal Bayesian inference.

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