The head-direction system shows systematic parallax error

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Abstract

Spatial navigation relies on the head-direction (HD) system, which integrates angular head velocity (AHV) to track orientation. Since integration accumulates drift, visual landmarks provide corrective cues. However, whether the HD system accounts for the apparent shifts in proximal objects' position when viewed from different angles (parallax) remains unclear.

We analyzed postsubicular HD cell activity in mice navigating with a single visual cue. We discovered systematic parallax bias in decoded HD, indicating the HD system misinterprets the cue's position depending on viewing angle. The observed error was smaller than predicted by a pure vision model, which can be explained by combining AHV integration with simple visual anchoring.

Notably, each animal exhibited a unique anchoring angle — the direction at which the cue was associated with HD — suggesting the HD system maintains a possibly learned and stable mapping between cue angle from visual input (bearing) and HD. These results show that the HD system, at least in simplified environments, does not perform explicit parallax correction but may attenuate errors passively through AHV integration and simple anchoring to multiple cues. This highlights a fundamental trade-off in neural coding between computational efficiency and positional accuracy, with implications for biological and artificial navigation systems.

Introduction

Head-direction (HD) cells, discovered in postsubiculum (Rank, 1984), thalamus (Taube, Muller, & Ranck, 1990a), and other areas, encode the animal's orientation in allocentric coordinates, serving as an internal neural compass. These cells integrate angular head velocity (AHV) from vestibular, proprioceptive, and optic flow signals through a continuous attractor ring network (Skaggs, Knierim, Kudrimoti, & McNaughton, 1994; Zhang, 1996), but require recalibration through visual landmarks to prevent drift accumulation (McNaughton, Chen, & Markus, 1991; McNaughton, Battaglia, Jensen, Moser, & Moser, 2006).

Visual landmarks anchor the HD system to stable reference points (Taube, Muller, & Ranck, 1990b; Goodridge, Dudchenko, Worboys, Golob, & Taube, 1998). However, whether the HD system performs simple egocentric anchoring based on retinal cue location or complex computations involving position-dependent parallax error correction remains unclear. As systematic parallax-induced errors in HD cells have not been shown in neural data so far, current models of the HD system use position-based correction mechanisms instead of relying on simple cue anchoring to map from egocentric viewing angles to allocentric orientation (Bicanski & Burgess, 2016).

Here, we provide, to our knowledge, the first systematic experimental evidence of parallax effects in the HD system. The existence of parallax effects indicates that the HD system might not rely on position-dependent corrections but uses AHV integration and multiple cues instead to attenuate parallax errors. Weighting the cues' influence based on their distance might be an additional strategy to avoid parallax errors (Zugaro, Berthoz, & Wiener, 2001; Knierim & Hamilton, 2011).

Methods and Results

Experimental Data and HD Decoding

We analyzed publicly available neural recordings from the postsubiculum of six mice (Duszkiewicz et al., 2024). Mice explored a 30 cm diameter circular platform within a dark 90 x 90 cm square arena. A single LED cue was positioned at one of the walls. In addition to the neural recordings, the dataset provided the tracked HD and position of the animals. Using Bayesian decoding, we obtained the estimated HD based on the recorded HD neurons' spiking activity.

Parallax Error Estimation

To estimate the expected parallax effect, we computed the HD estimate assuming simple egocentric visual cue anchoring:

$$\alpha_{\text{vis}}(t) = \gamma_{\text{anchor}} + \phi_{\text{cue}}(t), \tag{1}$$

where γ_{anchor} is the anchoring angle and ϕ_{cue} is the egocentric viewing angle. As visualized in Fig. 1A-C, the fixed anchoring angle results in a position-dependent decoding error β_{vis}:

$$\beta_{\text{vis}}(t) = \gamma_{\text{anchor}} - \theta_{\text{cue}}(t), \tag{2}$$

where θ_{cue} is the allocentric angle of the vector from the animal to the cue (see Fig. 1 A,B). To investigate a possible

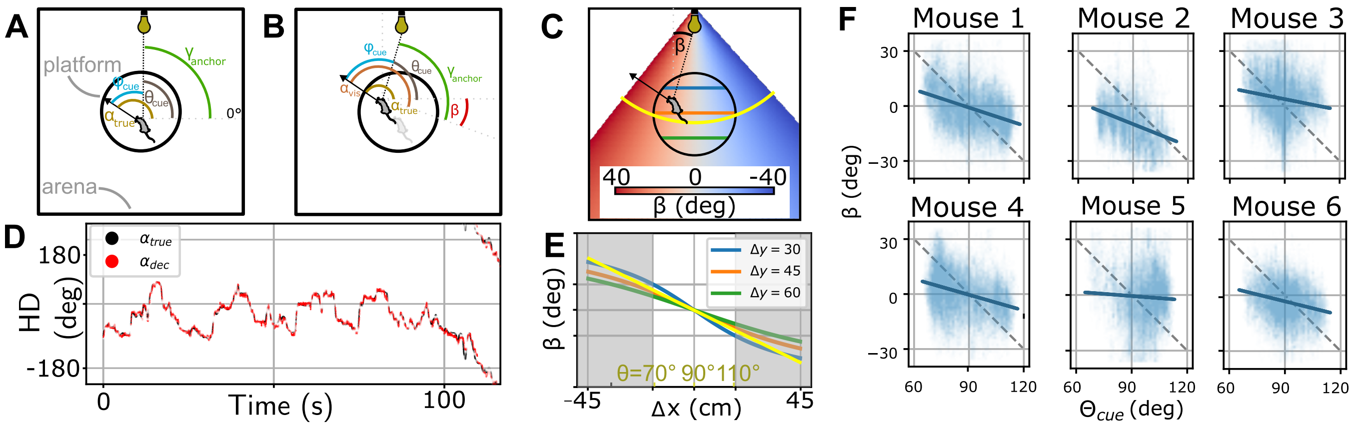

Figure 1: **Position-dependent parallax error in HD estimation.** (**A**) Experimental setup with an animal navigating a circular platform and a single visual cue. (**B**) Parallax effect: lateral movement while maintaining HD changes the egocentric angle, introducing bias β. (**C**) Spatial distribution of parallax-induced error across the arena. (**D**) Example data showing true vs. decoded HD and resulting error β_{dec}. (**E**) Parallax error as a function of lateral displacement for different distances from the cue, showing a linear relationship with the cue angle θ_{cue}. (**F**) Quantification of parallax-induced error across recording sessions. Each panel shows the relationship between allocentric cue angle θ_{cue} and observed angular error β_{dec}. Consistent nonzero slopes confirm parallax effect in HD cells.

parallax effect in the recorded data, we computed the decoding error β_{dec} between the decoded and camera-tracked HD. We then performed a linear regression to test for systematic parallax errors:

$$\beta_{\text{dec}}(t) = w \cdot \theta_{\text{cue}} + b + \varepsilon(t). \tag{3}$$

Pure visual anchoring would predict slope $w = -1$.

Key Findings

The analysis revealed systematic parallax errors in all recordings (Fig. 1F). Five of the six mice showed statistically significant slopes ($p << 0.001$), confirming a parallax effect. However, slope magnitudes were consistently lower than 1, indicating smaller errors than predicted by pure visual anchoring.

Interestingly, each animal exhibited a distinct anchoring angle to the cue, which can be calculated from the parallax as $\gamma_{\text{anchor}} = -b/w$ (see Fig. 1 F), suggesting individual learned mappings between retrosplenial bearing cells and postsubicular HD cells. These anchoring angles remained stable across cue switches and over time, indicating persistent associations.

Integration Model

To explain the reduced parallax magnitude, we implemented a model combining AHV integration with visual anchoring:

$$\alpha_{\text{iv}}(t) = \sigma \cdot \alpha_{\text{int}}(t) + (1-\sigma) \cdot \alpha_{\text{vis}}(t) \cdot v_{cue}(t) \tag{4}$$

where σ weights integration vs. vision, and v_{cue} indicates cue visibility. This model successfully reproduced the reduced parallax slopes observed in neural data, demonstrating that AHV integration passively attenuates parallax errors by averaging across different positions.

Discussion and Future Directions

This study provides the first systematic documentation of parallax errors in mammalian HD cells. The findings indicate that the HD system relies primarily on egocentric cue anchoring rather than complex position-dependent corrections. The observed error attenuation through AHV integration suggests that such corrections may not be necessary, particularly when multiple cues are available to average the amount of parallax error. This represents a computationally efficient strategy where the HD system maintains robust orientation estimates without requiring complex spatial calculations.

The unique anchoring angles per animal suggest learned associations between visual cues and HD, possibly reflecting stable mappings between cue-specific retrosplenial bearing cells and postsubicular HD cells. Future research should investigate whether these mappings are feature-based or experience-dependent.

While parallax errors appeared consistent across sessions, validation on additional datasets and environments is needed. The relatively low explained variance suggests other factors influence HD decoding beyond parallax, including decoding limitations and uncontrolled environmental cues. Additionally, future studies in larger environments with multiple cues could give insights into how the HD system integrates multiple cues to reduce the amount of parallax further.

Our findings have implications beyond neuroscience, informing the development of bio-inspired navigation systems (Krausse, Neftci, Sommer, & Renner, 2025a) where computational efficiency is crucial. The trade-off between accuracy and simplicity demonstrated here may guide the design of neuromorphic robotics applications requiring robust HD estimation. For more details, see our preprint (Krausse, Neftci, Sommer, & Renner, 2025b).

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