PBM GROUP 2B

A Computational Model Of Spatial Orientation

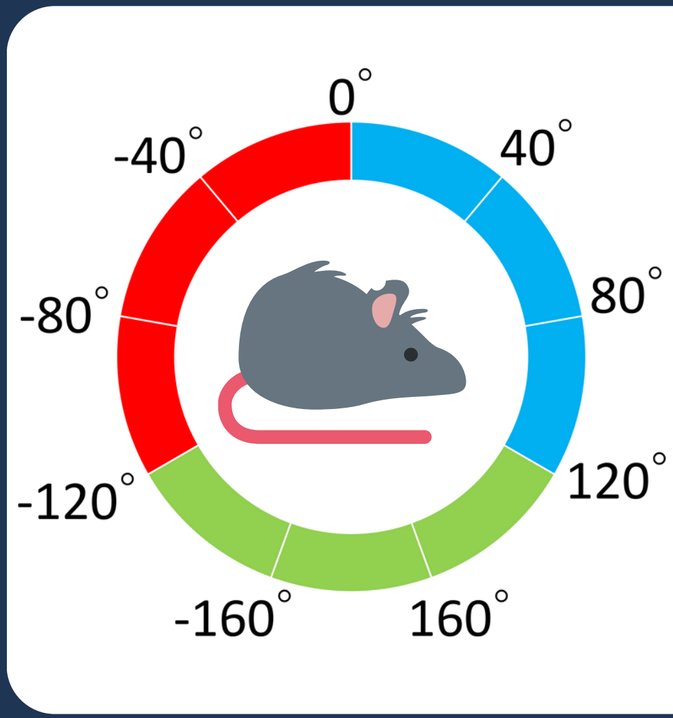
1. Introduction - from experiment to model
2. Implementing a model by Zhang (1996)[1]
   - Without movement (stationary)
   - With movement (dynamic)
3. Discussion

Presented by Laura K., Parrivesh N.S., and Reece H.

INTRODUCING...
THE INTERNAL COMPASS

Spatial orientation is necessary for accurate navigation (Zhang, 1996)[1].

INTERNAL COMPASS



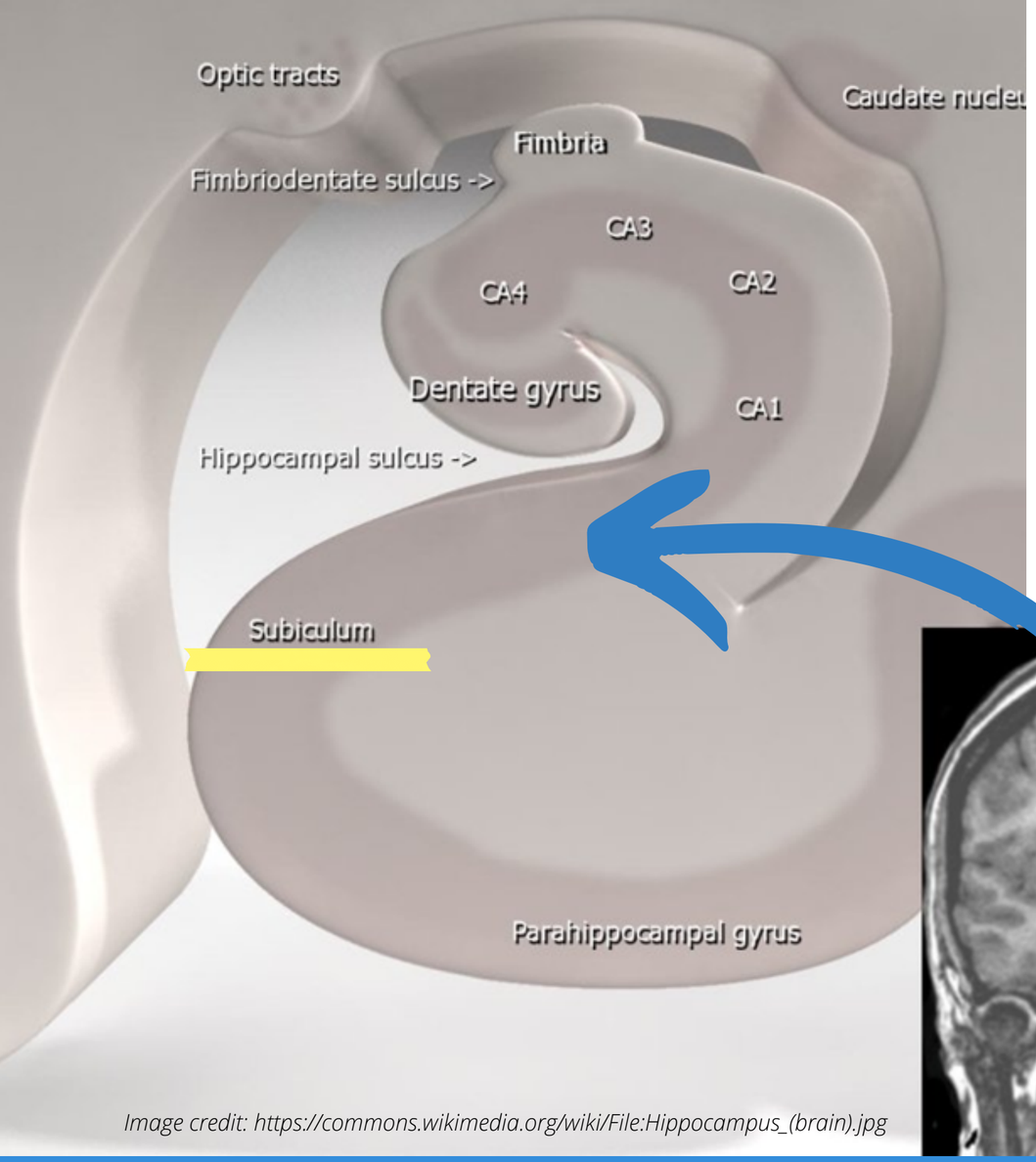
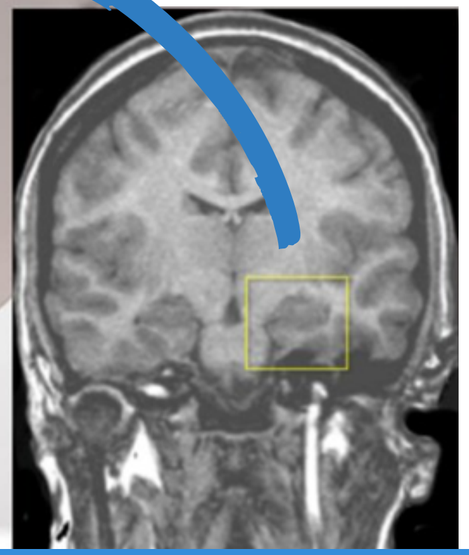
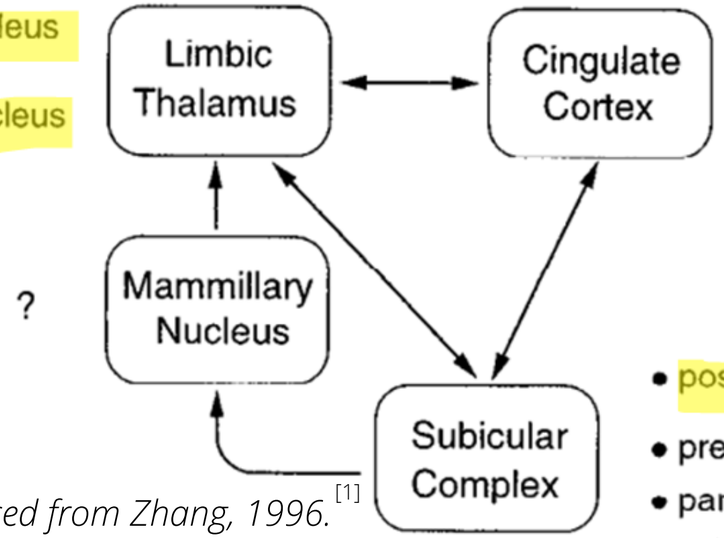


Image credit: https://commons.wikimedia.org/wiki/File:Hippocampus_(brain).jpg



- anterodorsal nucleus (AD): *60%* [a]
- lateral dorsal nucleus (LD): *60%* [b]

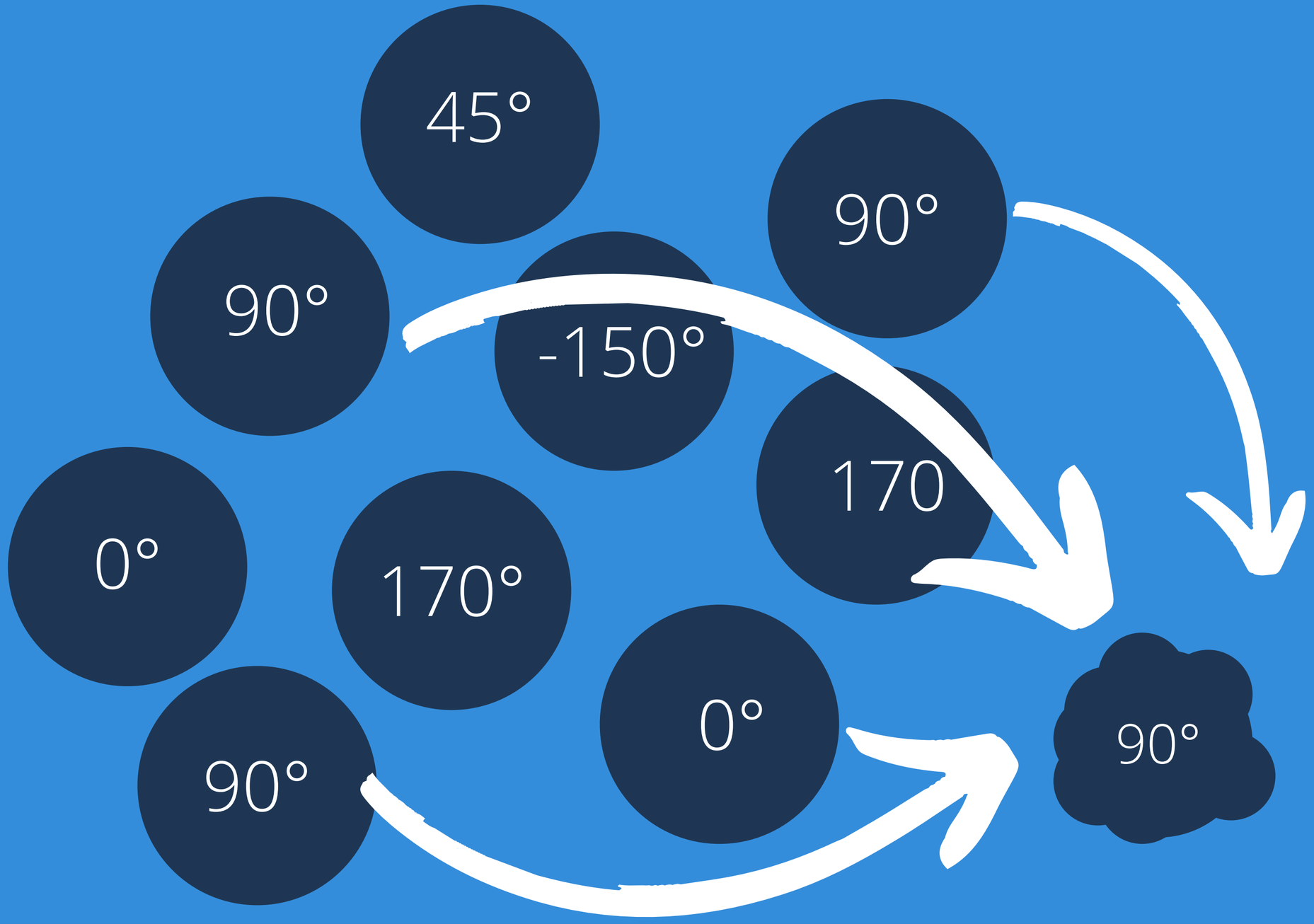


- agranular retrosplenial cortex (RSA): *8%* [f]
- granular retrosplenial cortex (RSG): *8%* [f]

- postsubiculum: *25%* [c]
- presubiculum (ventral): ?
- parasubiculum: *0%* [d]
- subiculum: *0%* [e]

Reproduced from Zhang, 1996.[1]

HD cells were first discovered in the subiculum in 1984 but have since been found elsewhere in the brain too.[1]

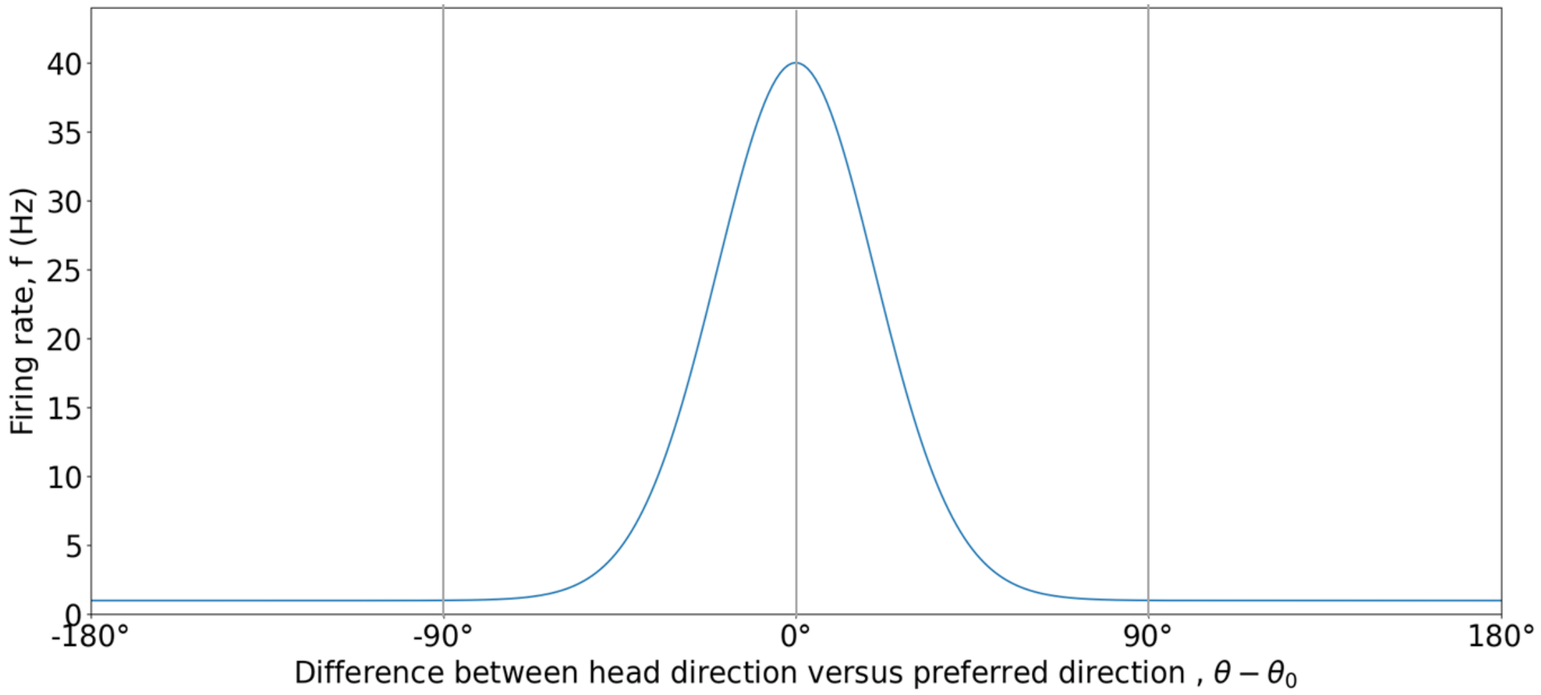


For simplicity, cells that share the same preferred direction can be considered as a single unit (or sub-population).

USING EXPERIMENTAL DATA

OBSERVED BEHAVIOUR

- Tuning curves are Gaussian-shaped.
- Sensory inputs (e.g., visual landmarks) are incorporated by HD cells.



DIRECTIONAL TUNING

A HD cell fires most when the head's current direction (θ) matches the neurone's preferred direction (θ_0).

RIGID FRAME

HD cells are coupled tightly together to form a system that can only be rotated as a whole.

RECENT LITERATURE...

HD CELLS ARE COMPLEX AND VARIED

Jacob et al. (2017)[2]

- Some HD cells have two preferred directions and can switch between them (**bidirectional firing**).

Kornienko et al. (2018)[3]

- HD cells can be further divided:
  - **theta** and **non-theta rhythmic sub-types**.
- Only theta cells follow attractor dynamics, and some cells don't respond to visual cues.

OUR MODEL (ZHANG, 1996)

DETAILS

- Simplified - assumes one HD cell type.
- One dimensional ring attractor.
- Continuous dynamics.
- Supports both static and dynamic cases.
- Uses self-motion information (so activity persists in total darkness).

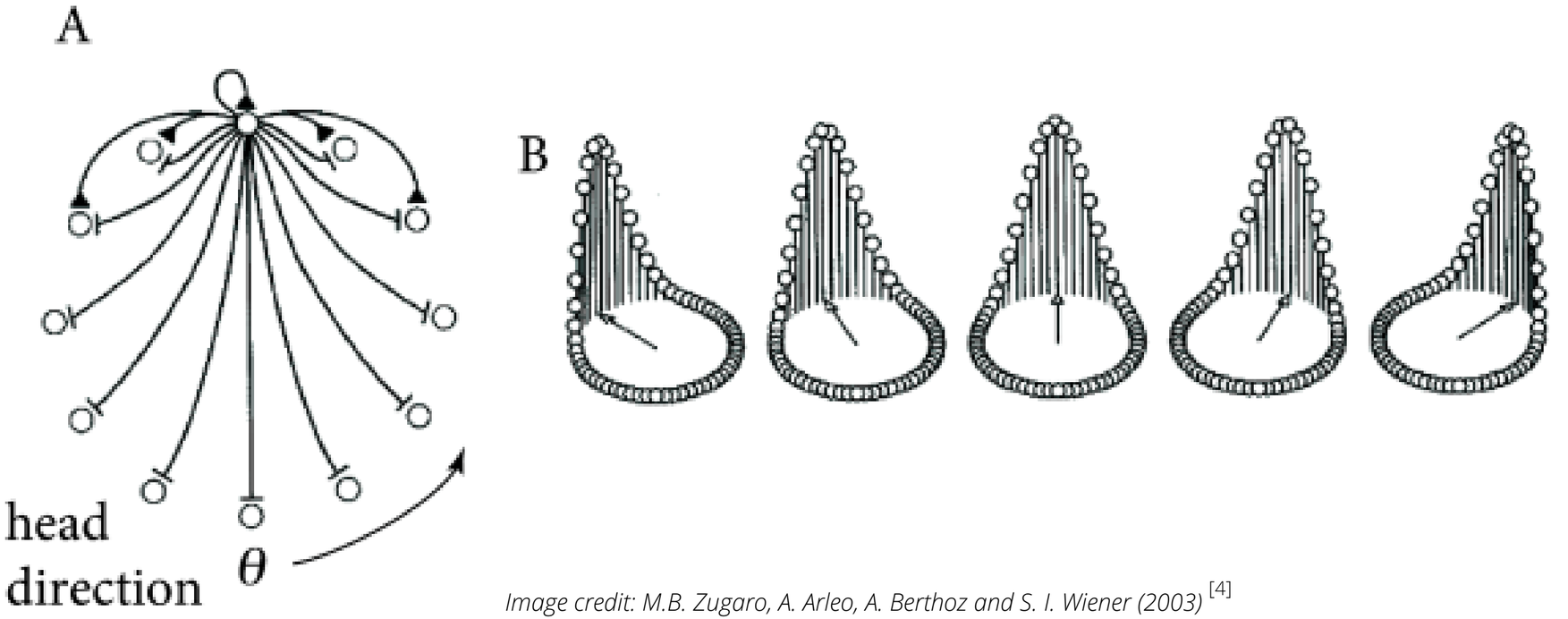


Image credit: M.B. Zugaro, A. Arleo, A. Berthoz and S. I. Wiener (2003) [4]

ROTATION-INVARIANCE

The weights between two neurones is dependent on the difference between their preferred directions, rather than absolute values:

$$w_{ab}(\theta_a - \theta_b, t)$$

NEURONES CAN BE INHIBITORY & EXCITATORY

A neurone will excite other neurones that have a similar preferred direction, and it will inhibit those that are tuned for distant directions.

INPUT

Average synaptic input, u

90°

Population of HD cells (θ_0 = 90°)

OUTPUT

Average firing rate, f

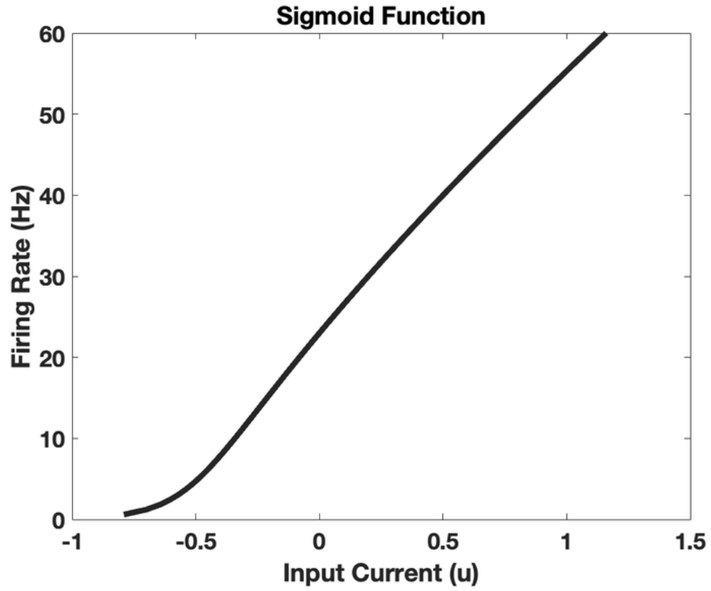
INPUT

Average synaptic input, u

90°

Population of HD cells (θ_0 = 90°)

Sigmoid function, σ

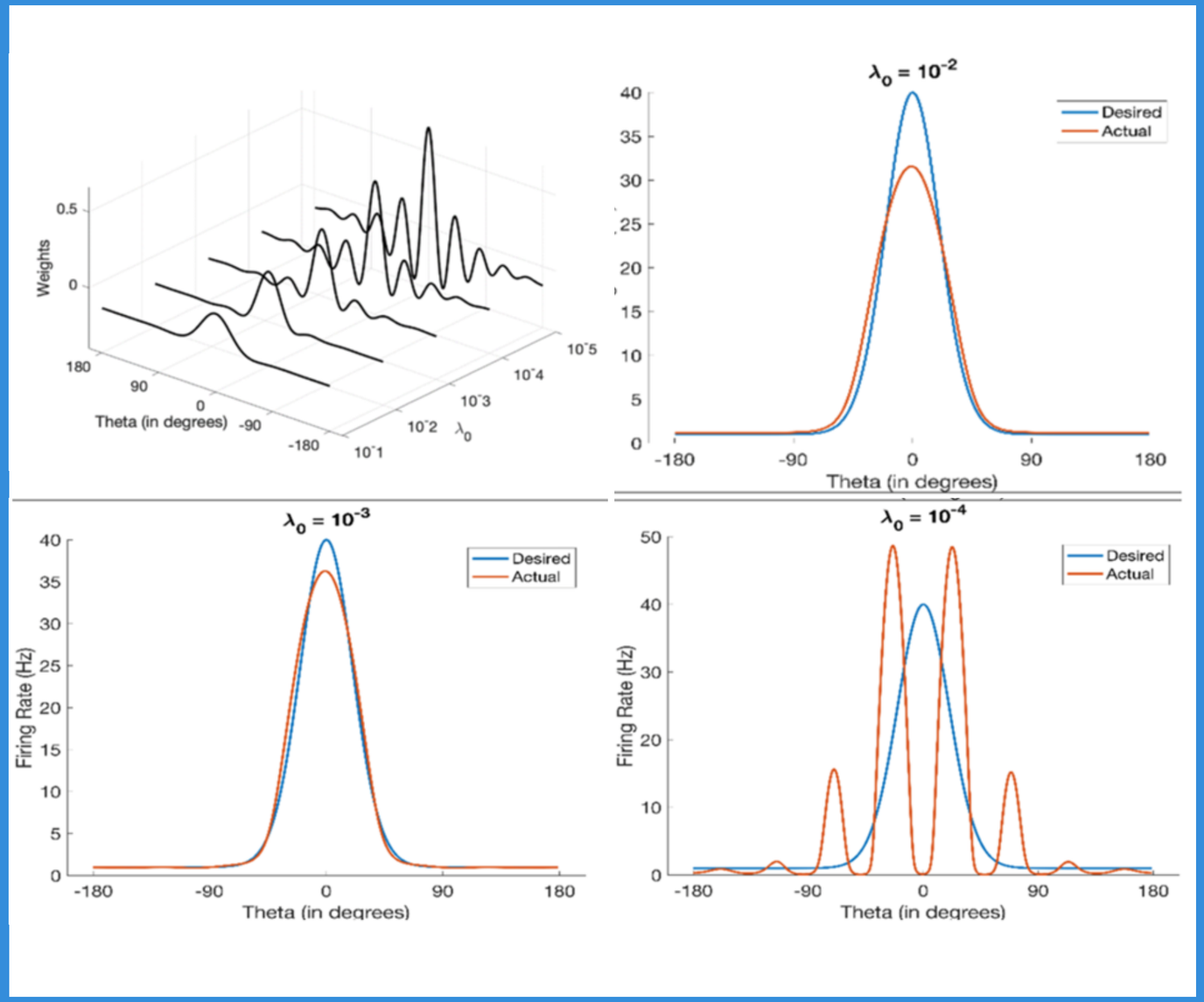


$$f = \sigma(u)$$

$$\sigma(u) = aln^{\beta}(1 + e^{b(u+c)})$$

OUTPUT

Average firing rate, f



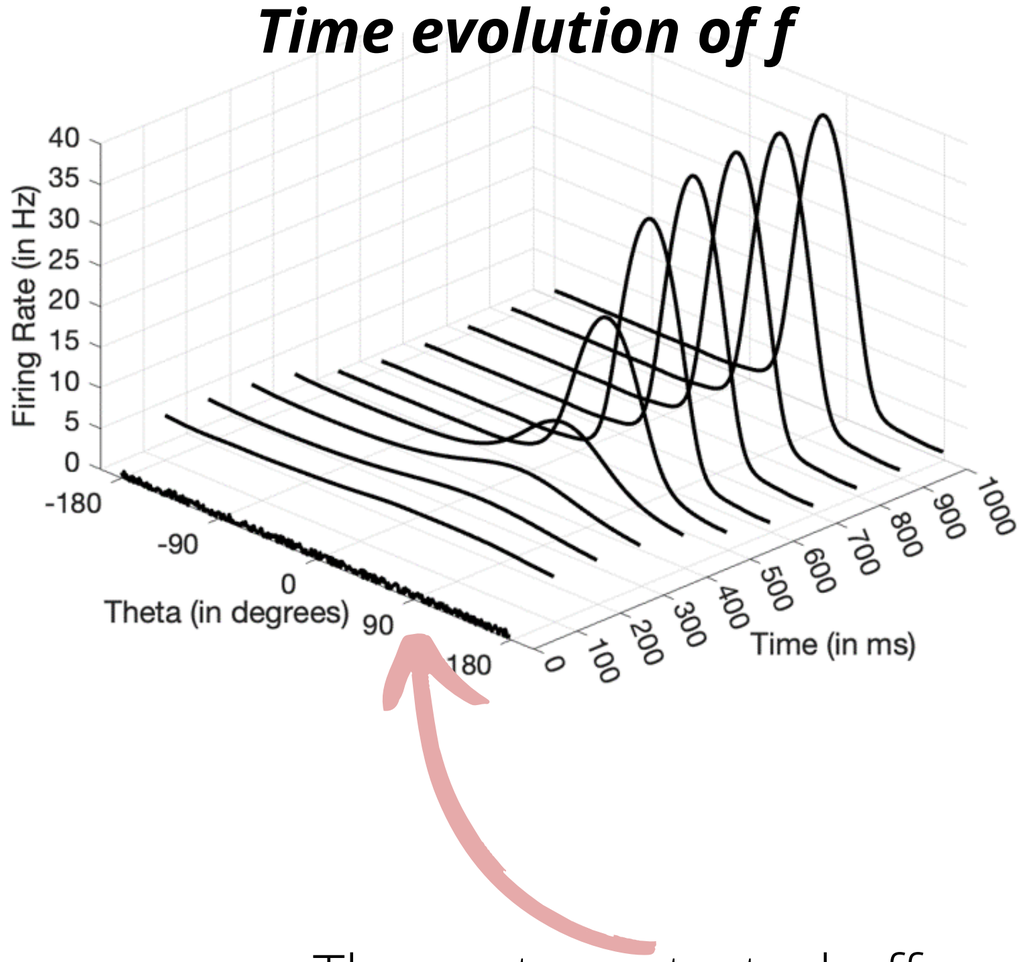
Weight Regularisation

$$\tau \frac{\partial u}{\partial t} = -u + w * f$$

$$\lambda = \lambda_0 * \max(|\widehat{f_n}|)^2$$

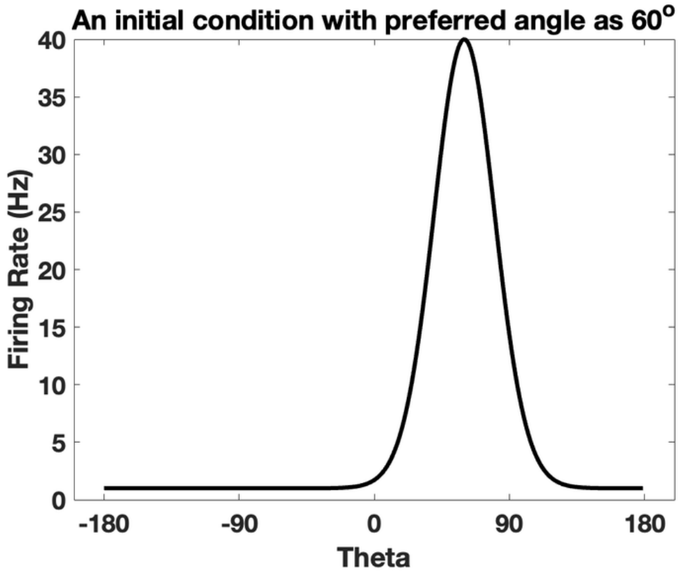
$$\widehat{w}_n = \frac{\hat{u}_n \hat{f}_n}{\lambda + |\hat{f}_n|^2}$$

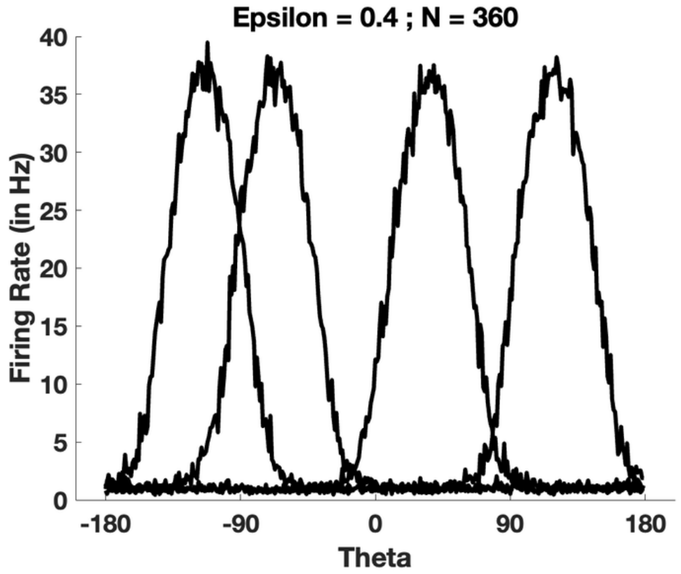
Emergence of stability from a noisy initial condition

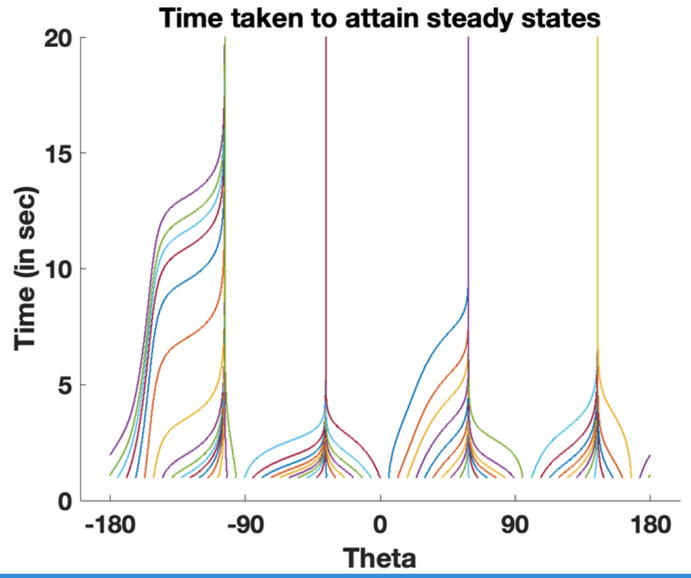


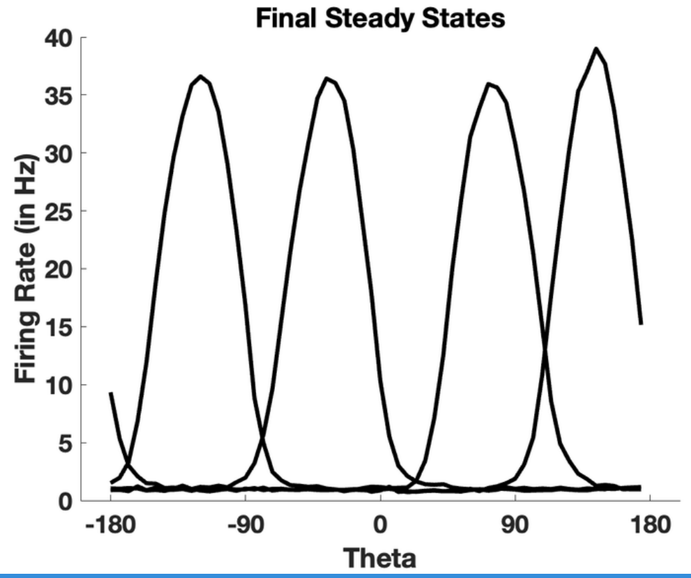
The system started off as noise

The effect of noisy weights on stability





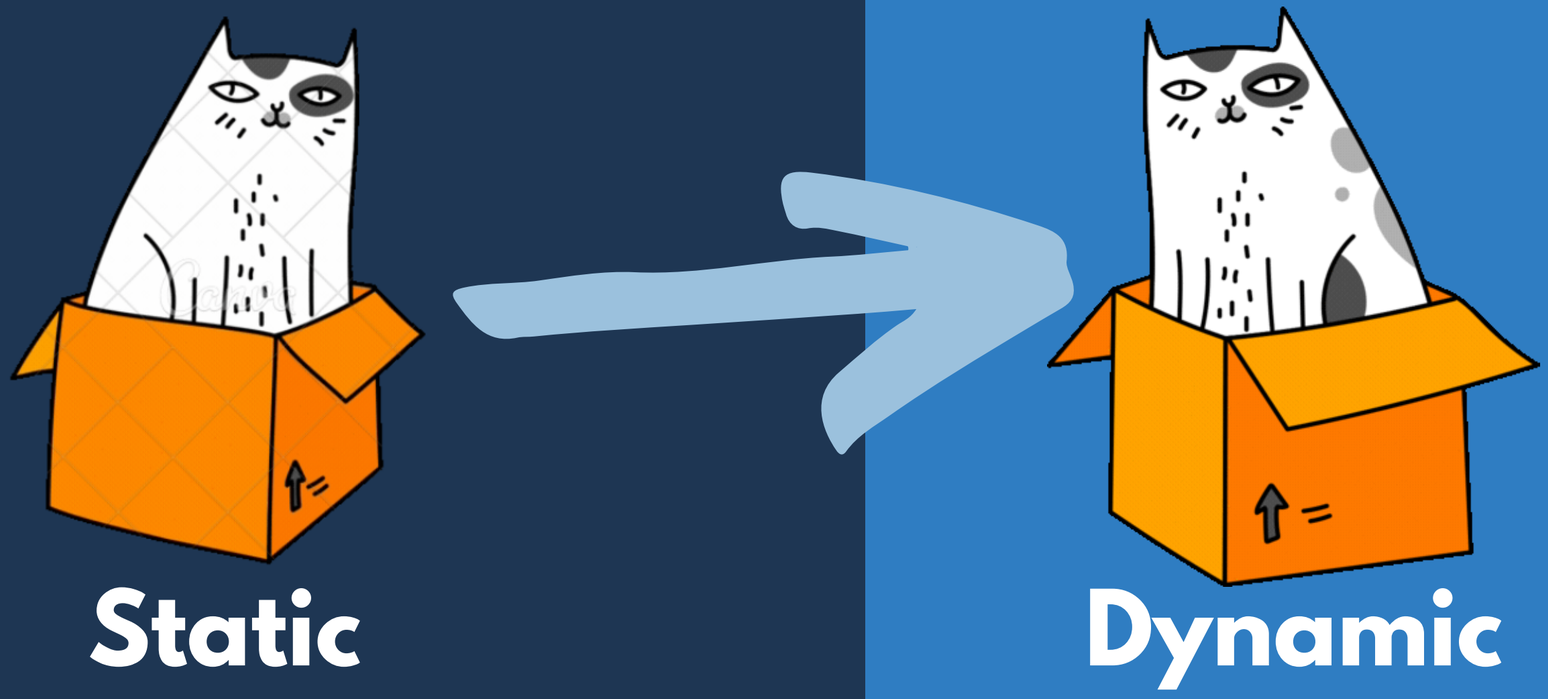




- White noise doesn't disturb the shape of the activity profile - only the number of possible stable states.
- ϵ increases the noisiness of the profile.
- Larger the network, more stable the profile.

DYNAMIC
THE SHIFT MECHANISM

- An animal's head is not fixed.
- So how do we change the activity profile of this model?
    - How do move its peak elsewhere?



DYNAMIC

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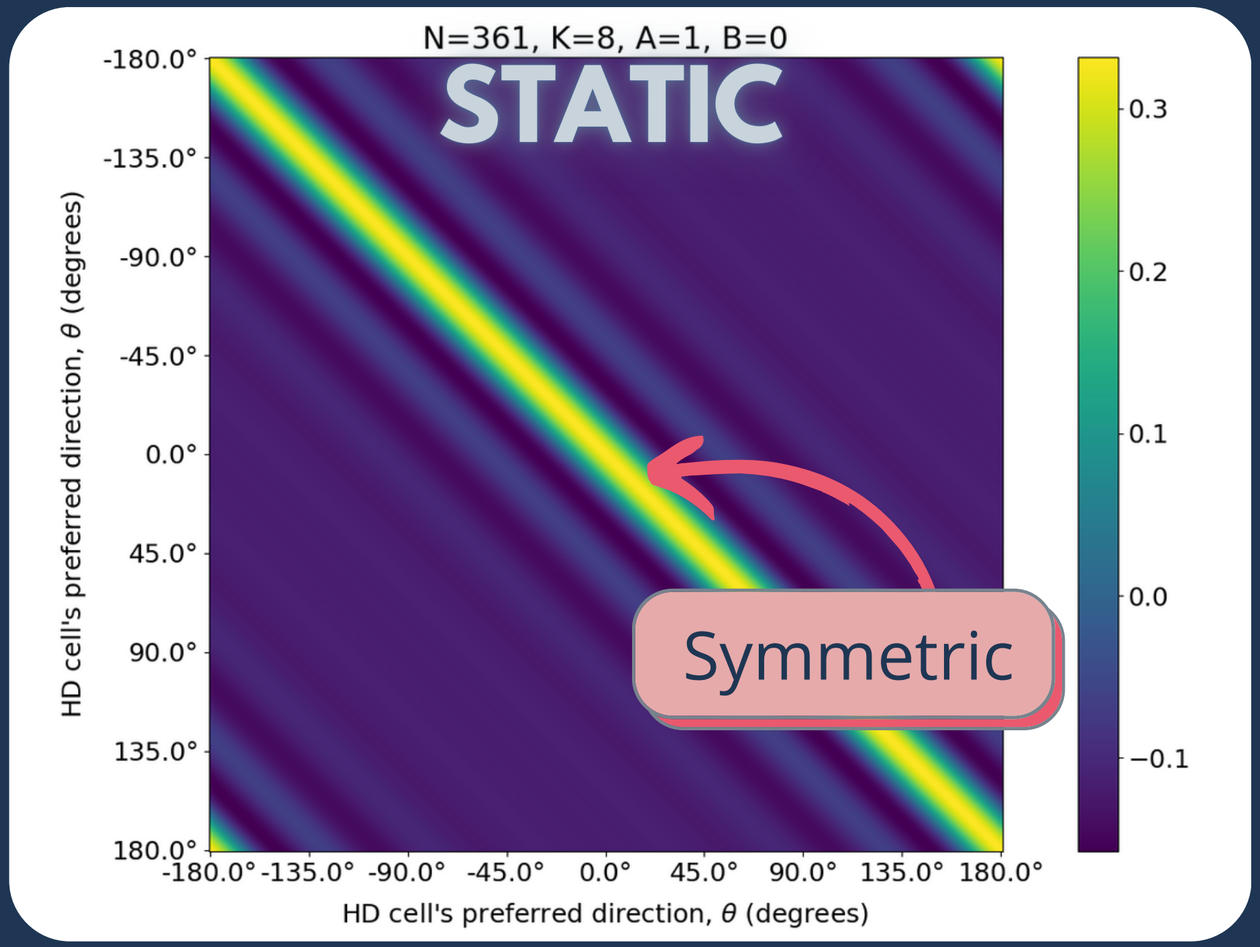

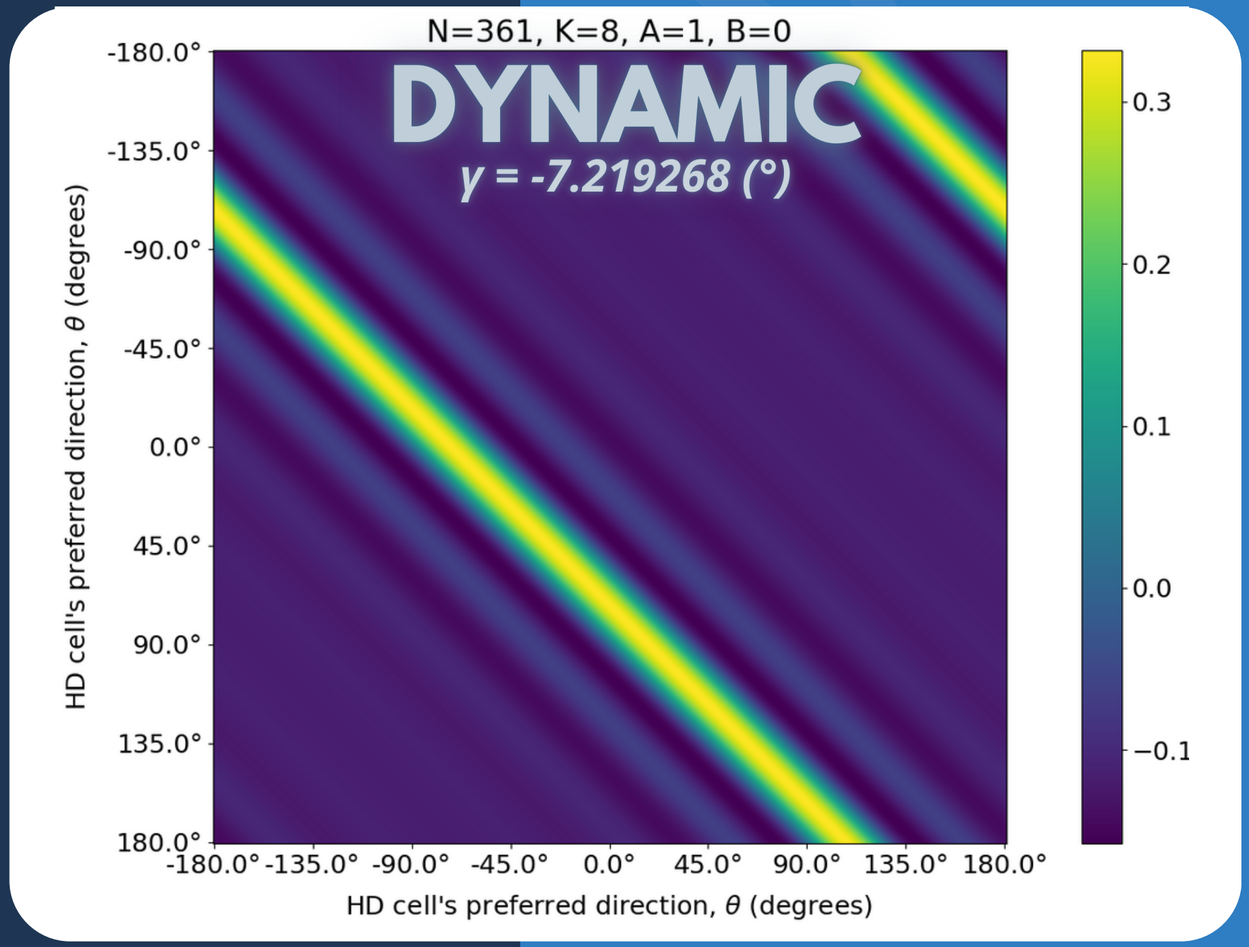

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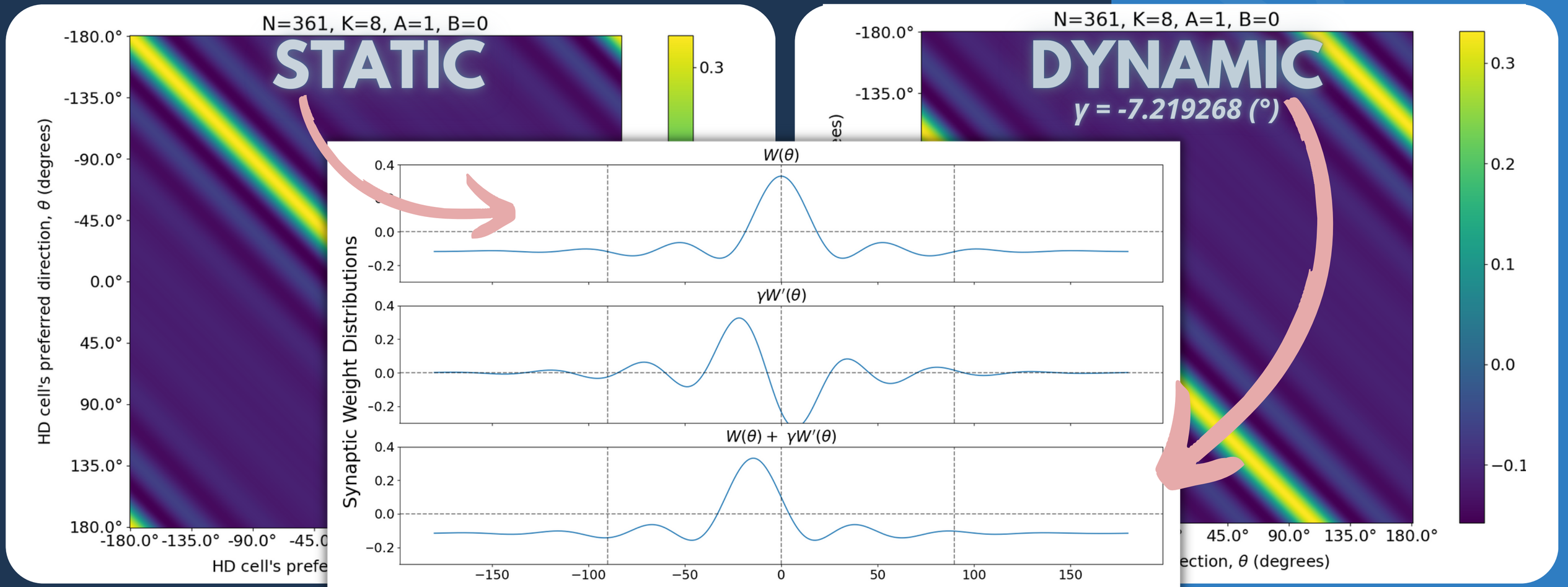
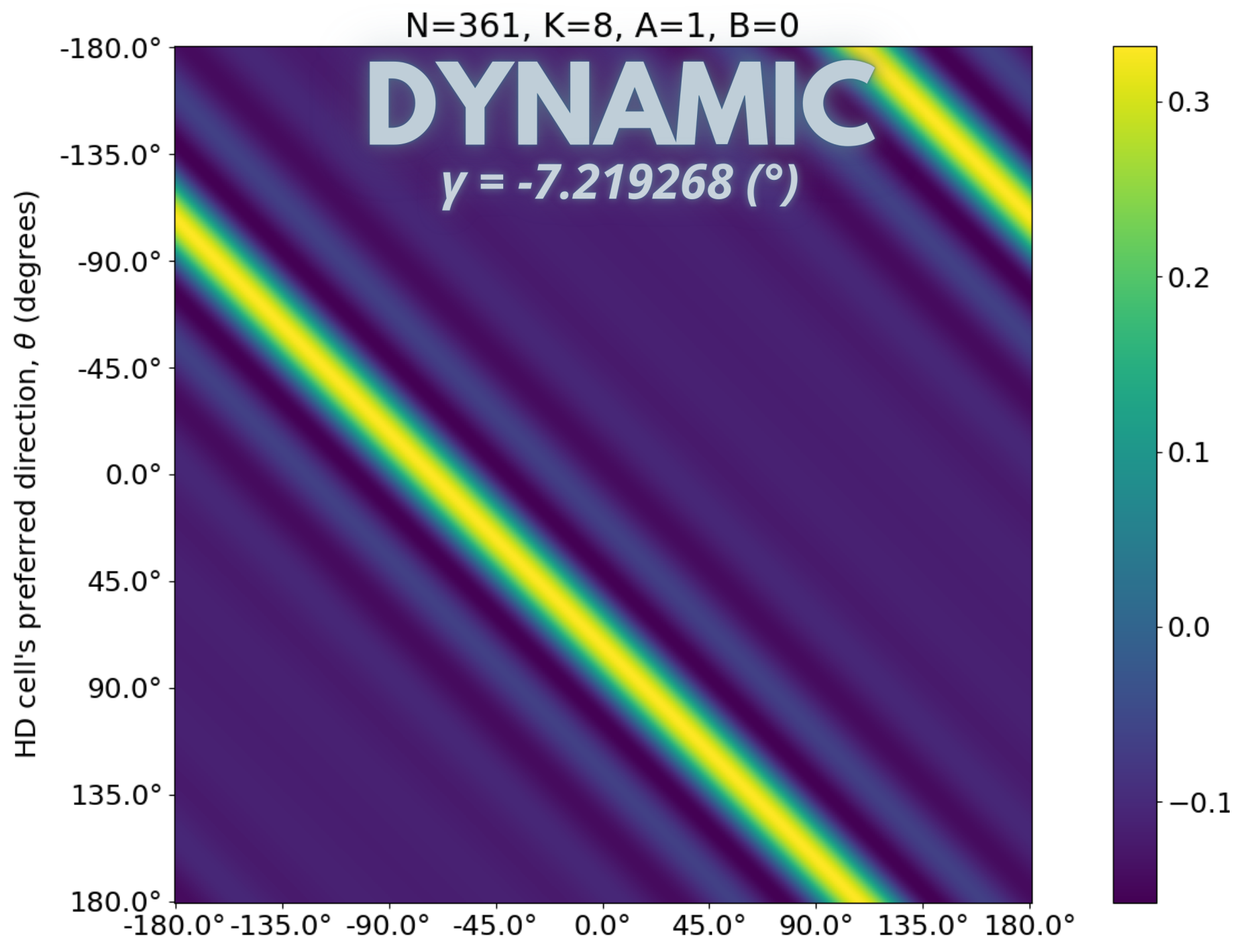
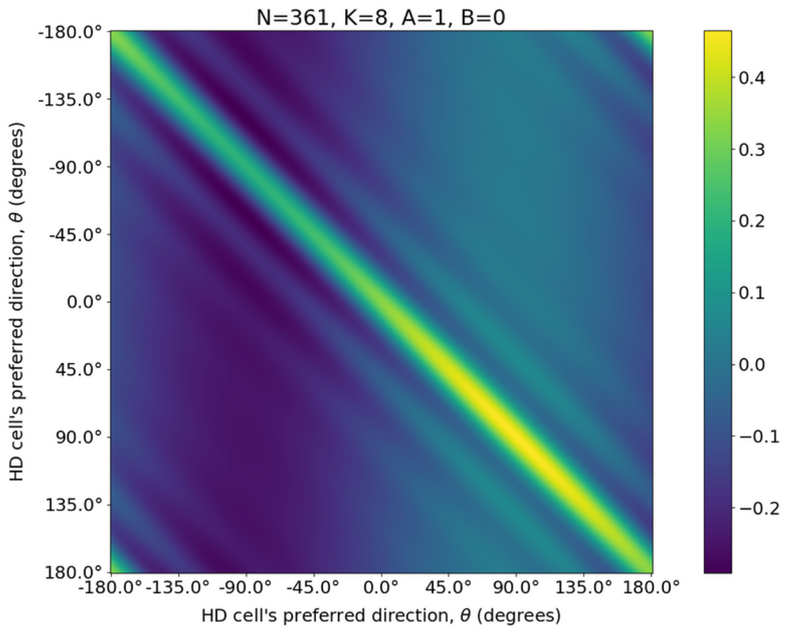


USING THE DERIVATIVE

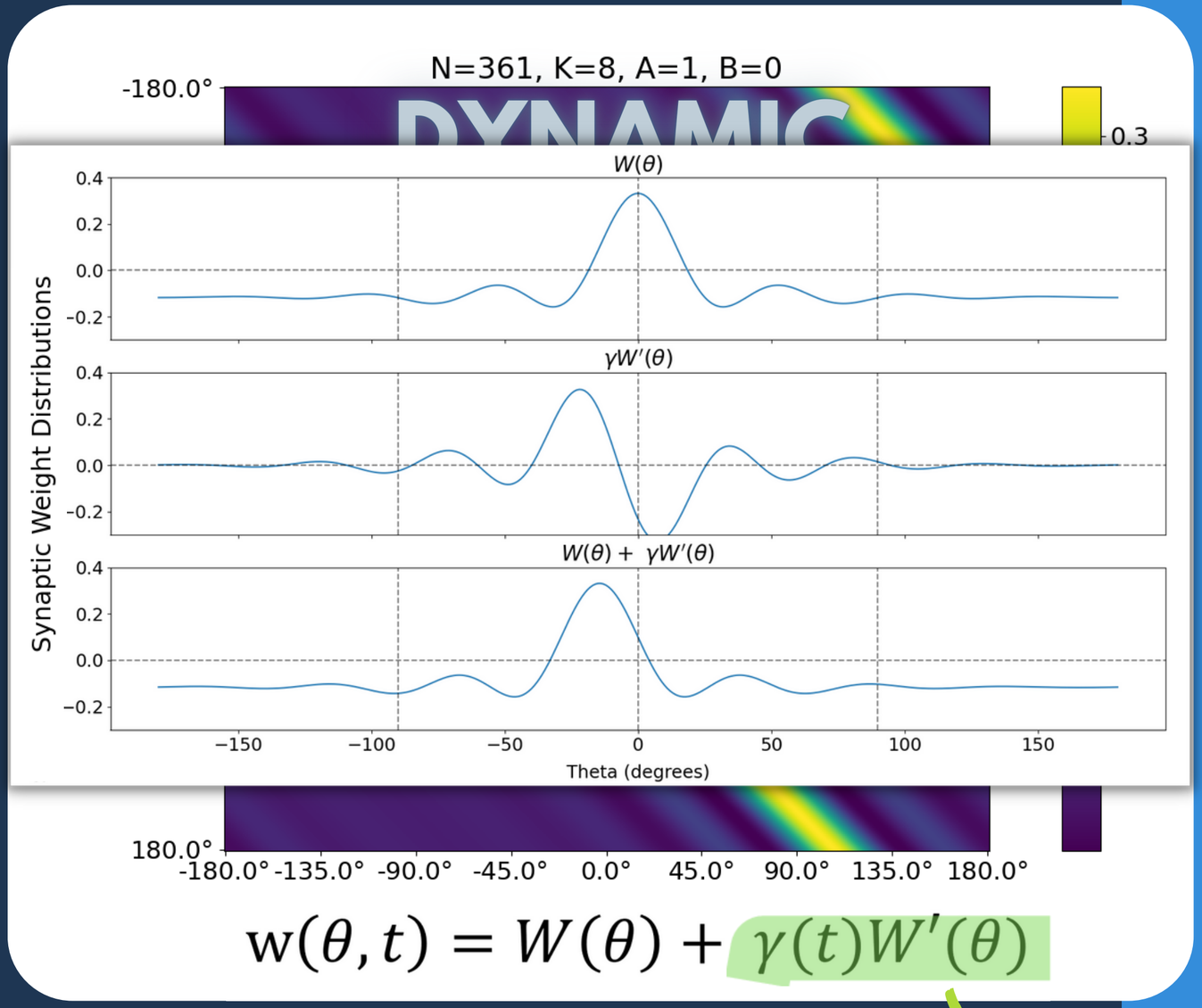


$$w(\theta, t) = W(\theta) + \gamma(t)W'(\theta)$$

USING SINE



$$w(\theta, t) = W(\theta) + \alpha(t)sin(\theta)$$



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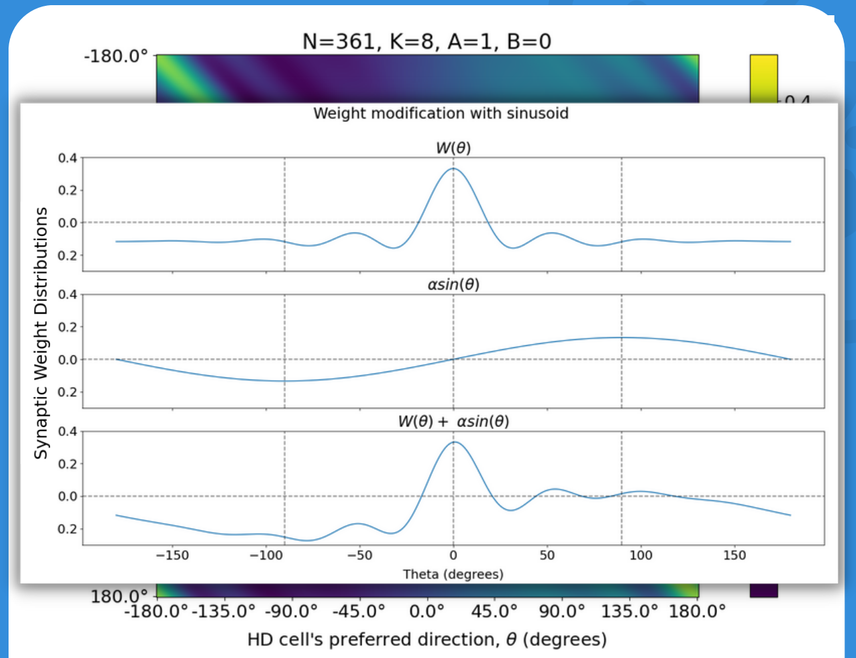

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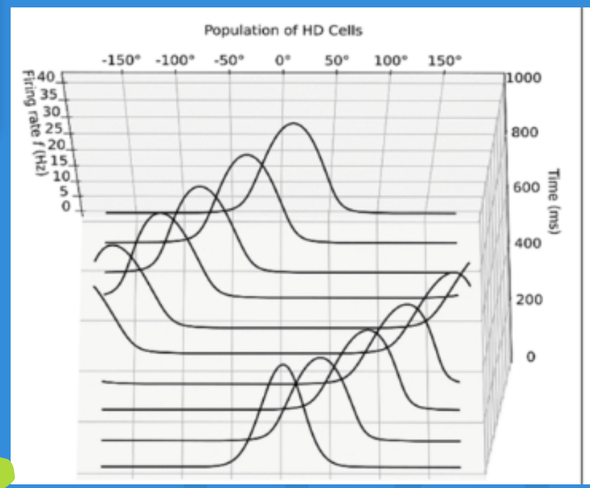

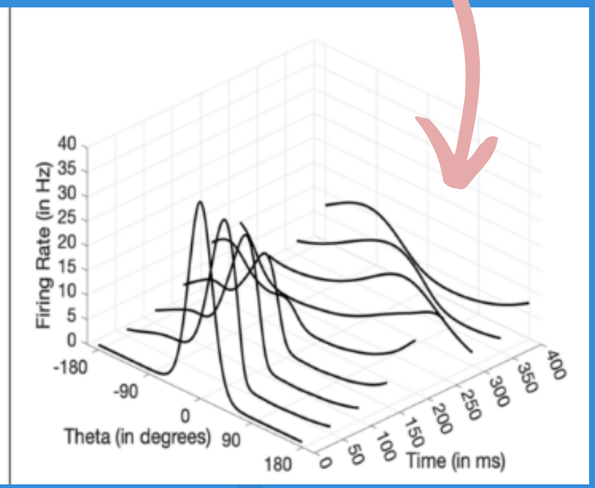

USING LANDMARKS

- HD cells continue firing even in total darkness, but their activity begins to drift with prolonged recordings.
- Visual landmarks are used to recalibrate the system.
- Zhang's model supports this behaviour, calling it "calibration by local-view detectors".

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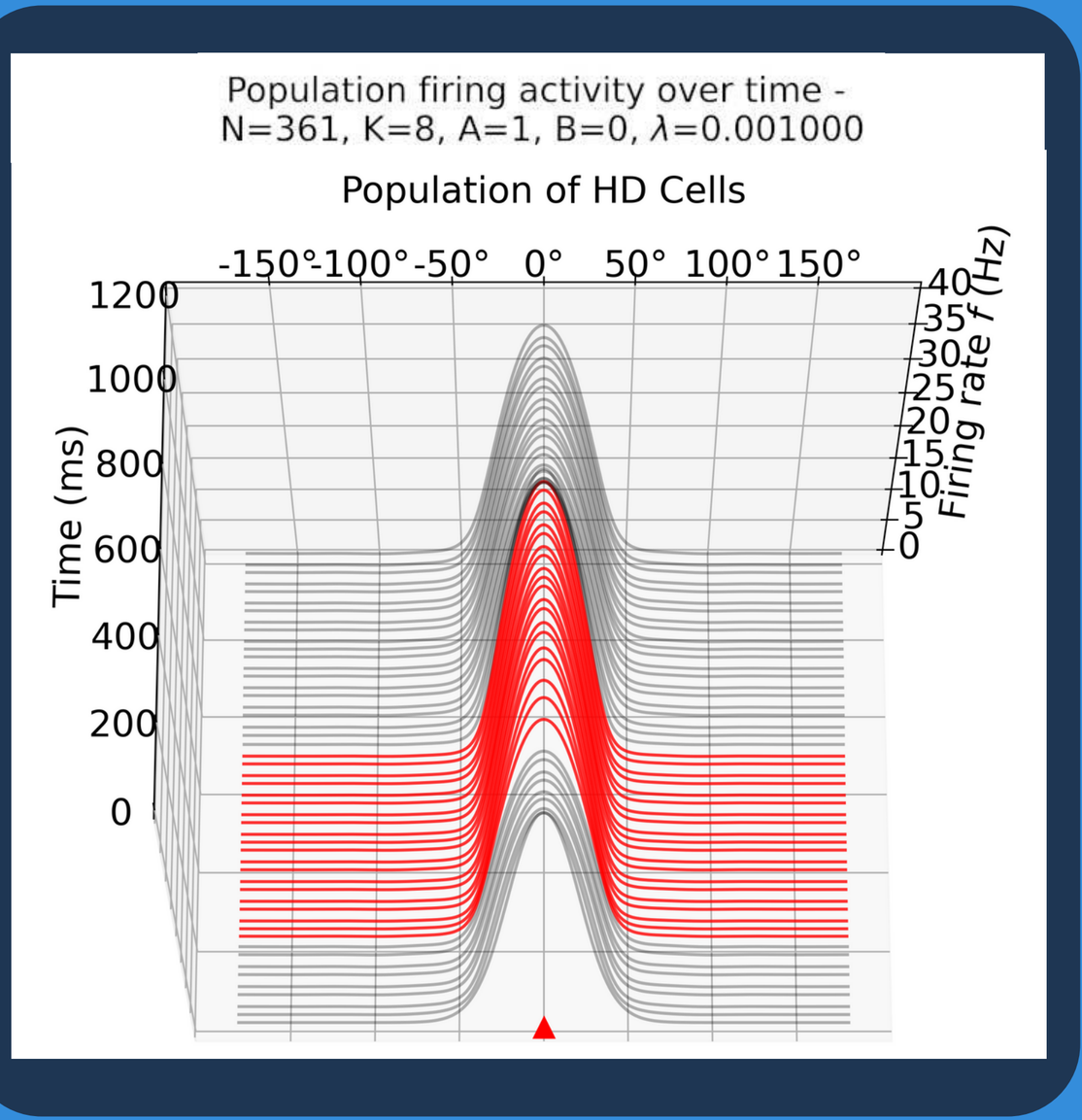

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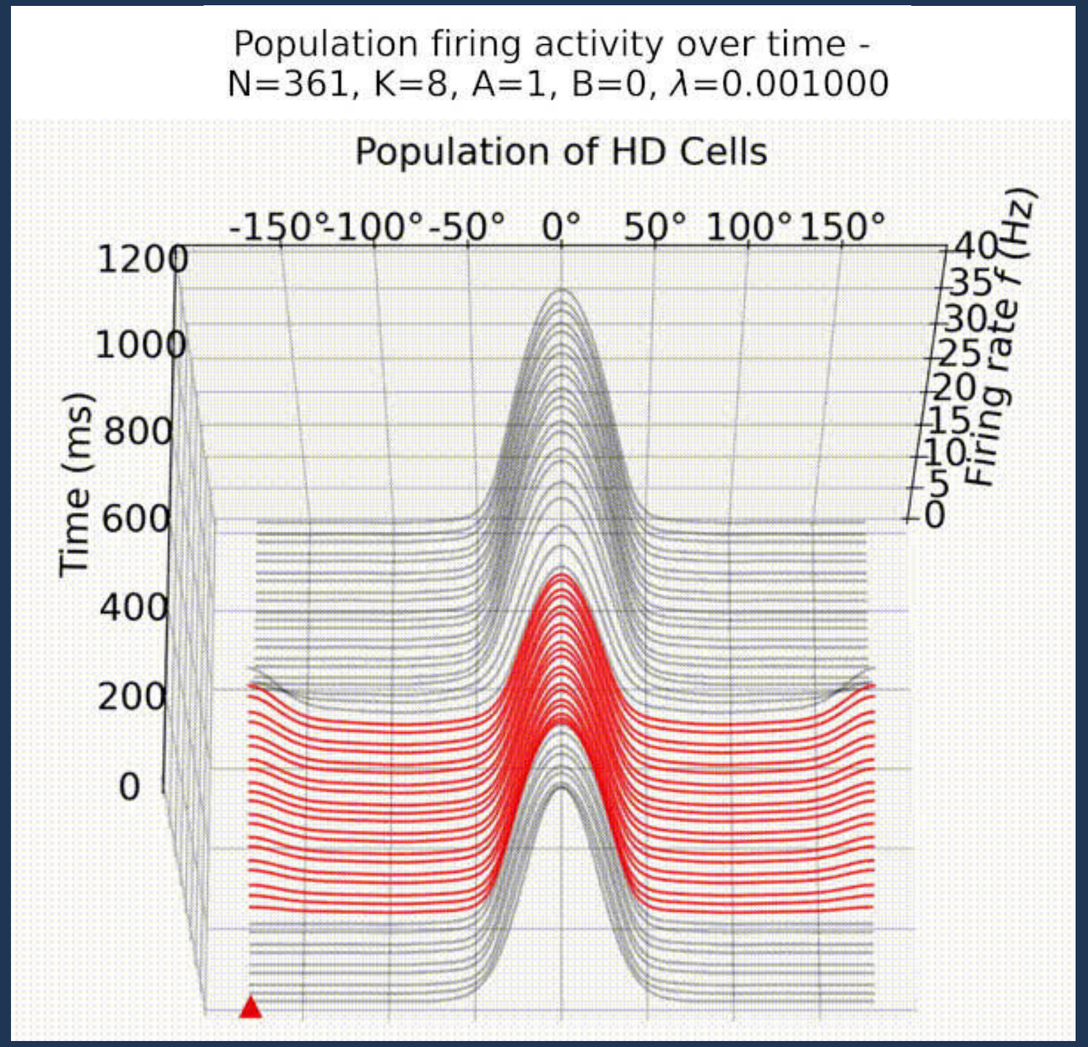

ADDITIONAL NOTES

DRIFT SPEED

Model the speed at which a network with noisy weights drifts.

ACCELERATION

Angular acceleration of the head can be considered.

2-D ANALOGY

This model, especially rhe dynamic shift mechanism, could be generalised to 2 dimensions.

REFERENCES

[1] Zhang, K. (1996). Representation of spatial orientation by the intrinsic dynamics of the head-direction cell ensemble: a theory. Journal of Neuroscience, 16(6), 2112-2126

[2] Jacob, P. Y., Casali, G., Spieser, L., Page, H., Overington, D., & Jeffery, K. (2017). An independent, landmark-dominated head-direction signal in dysgranular retrosplenial cortex. Nature neuroscience, 20(2), 173-175.

[3] Kornienko, O., Latuske, P., Bassler, M., Kohler, L., & Allen, K. (2018). Non-rhythmic head-direction cells in the parahippocampal region are not constrained by attractor network dynamics. Elife, 7, e35949.

[4] Zugaro, M. B., Arleo, A., Berthoz, A., & Wiener, S. I. (2003). Rapid spatial reorientation and head direction cells. Journal of Neuroscience, 23(8), 3478-3482

THANK YOU

Questions?