Multiple bumps can enhance robustness to noise in continuous attractor networks

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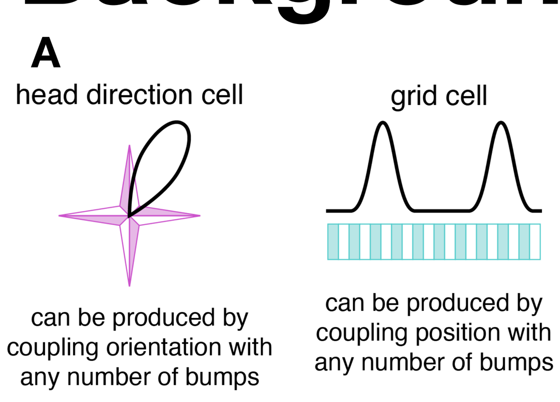
Abstract

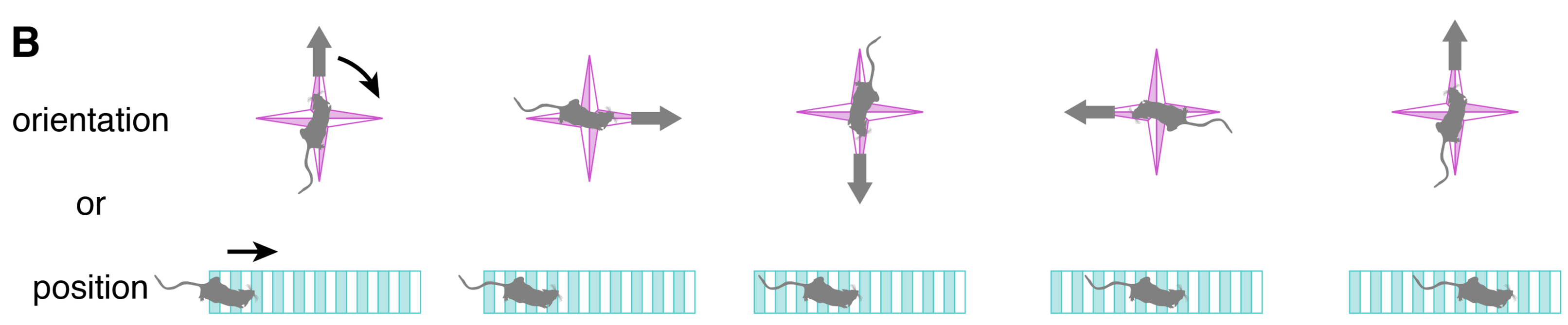
A central function of continuous attractor networks (CANs) is encoding coordinates and accurately updating their values through path integration. To do so, these networks produce bumps of activity that can represent position or orientation. However they can do so with different number of bumps, and the consequences of having more or fewer bumps are unclear. We find that CANs with different bump numbers have different responses to three types of noise: fluctuations in synaptic inputs, stochastic spiking, and connectivity deviations away from an ideal attractor configuration. Increasing the bump number improves robustness to all three sources of noise. This observation motivates the evolution of grid cell networks with multiple bumps, as observed by [1].

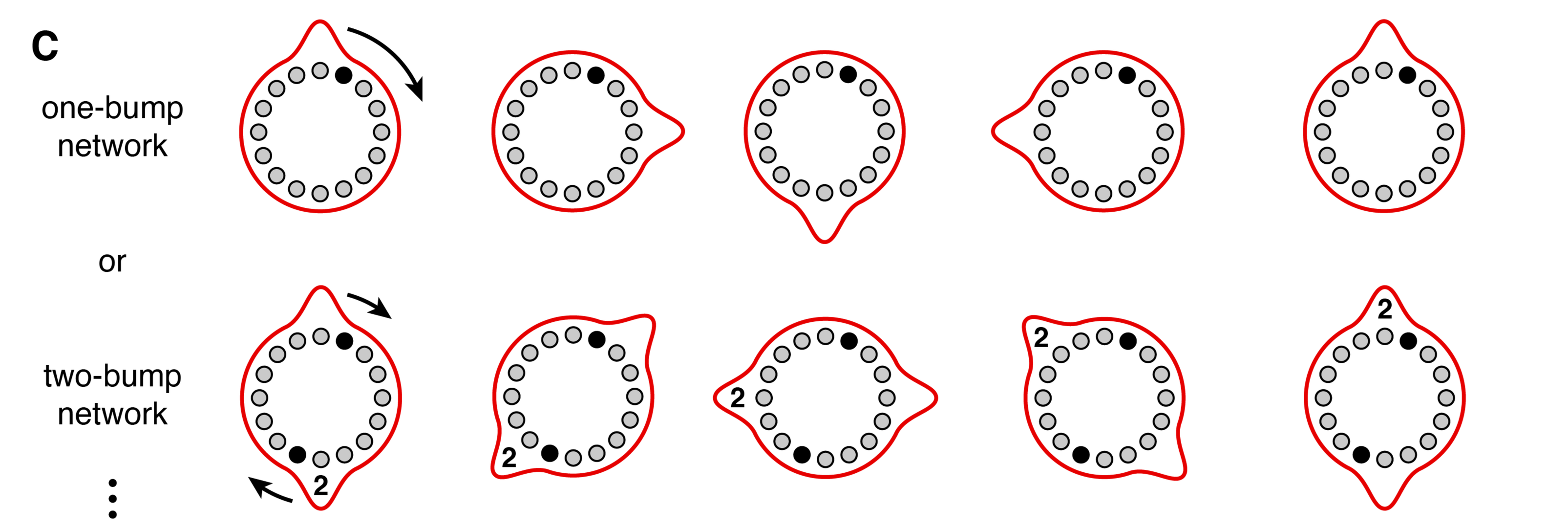
Background



The brain contains periodic representations of space in the form of head directional cells and grid cells. Grid cells encode position with lattices.

Continuous attractor networks can produce head direction cells and grid cells. They can do so with any number of attractor bumps.

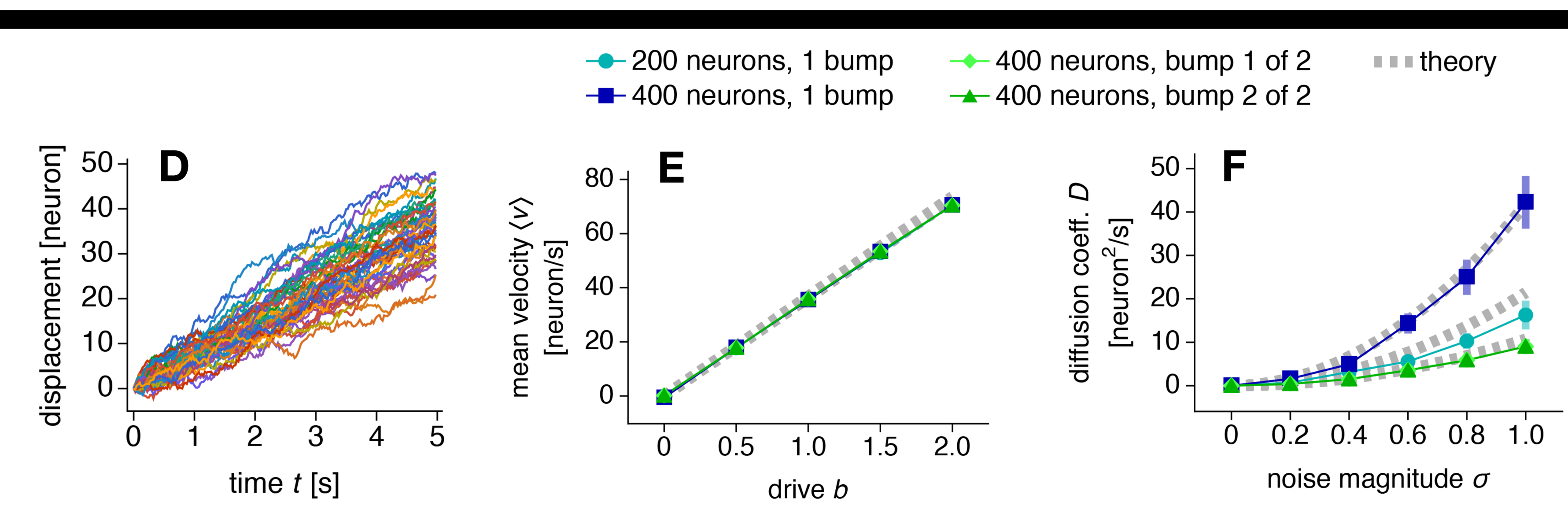


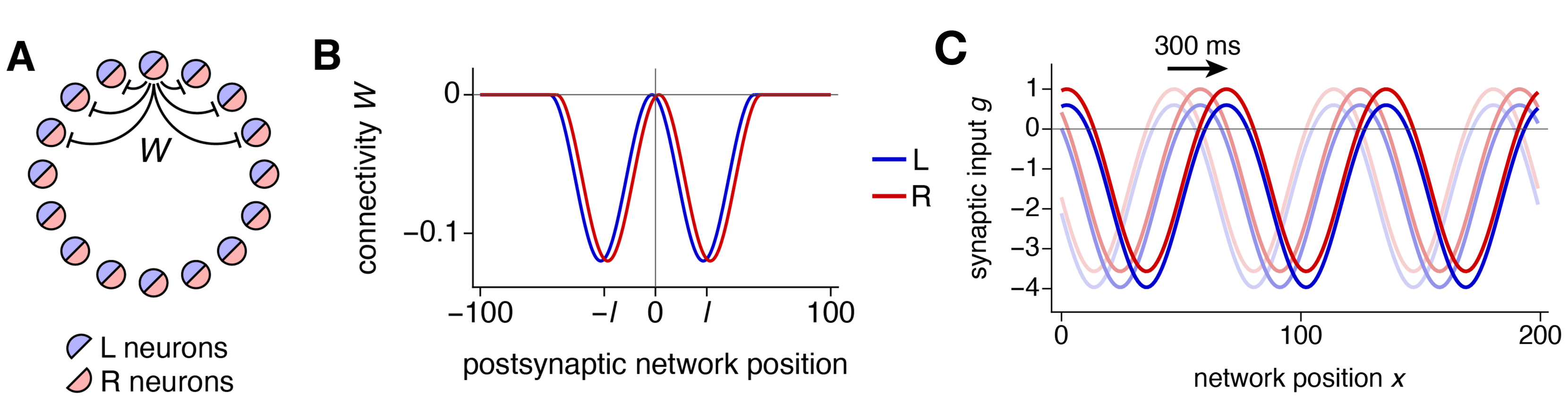


Methods

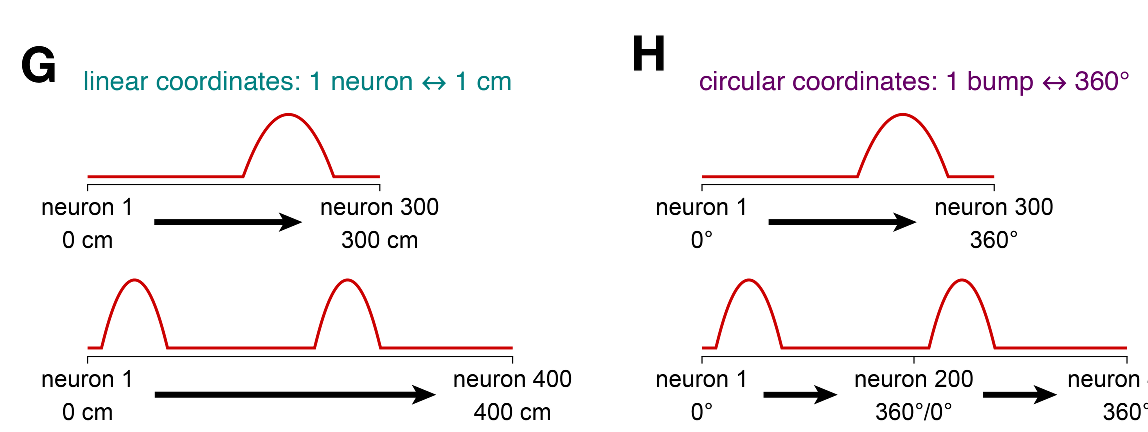
We construct a Periodic 1-D network in a ring configuration based on neural activities, s. At each neuron position, there are two neural populations, left and right. (See footnote (1) for equation)

In the standard fashion [2], the neuron connectivities exhibit inhibition that produces localized bumps of activity. Modifying the width of inhibition allows for multiple bumps to be formed. The scaled bump shape remains constant across bump numbers and network sizes.





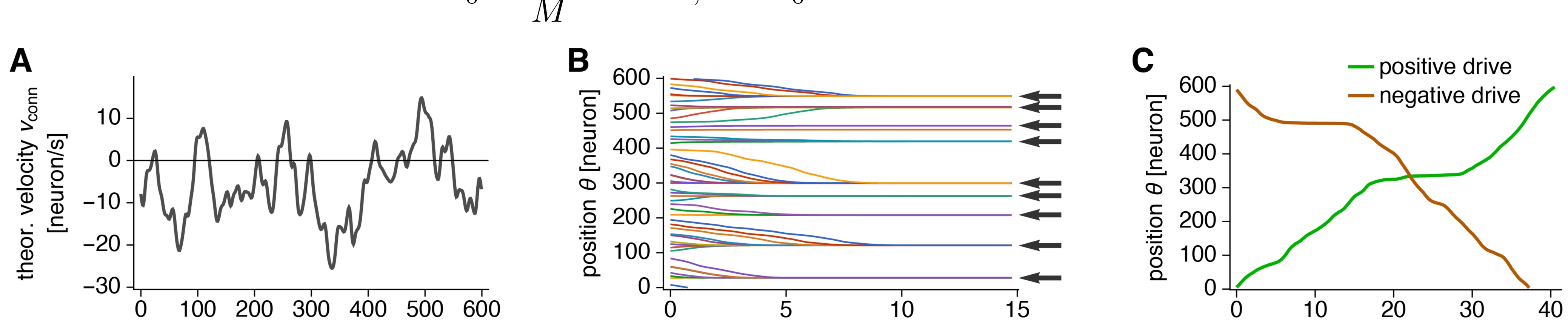
There are different ways to map the network back onto linear and circular physical coordinates.

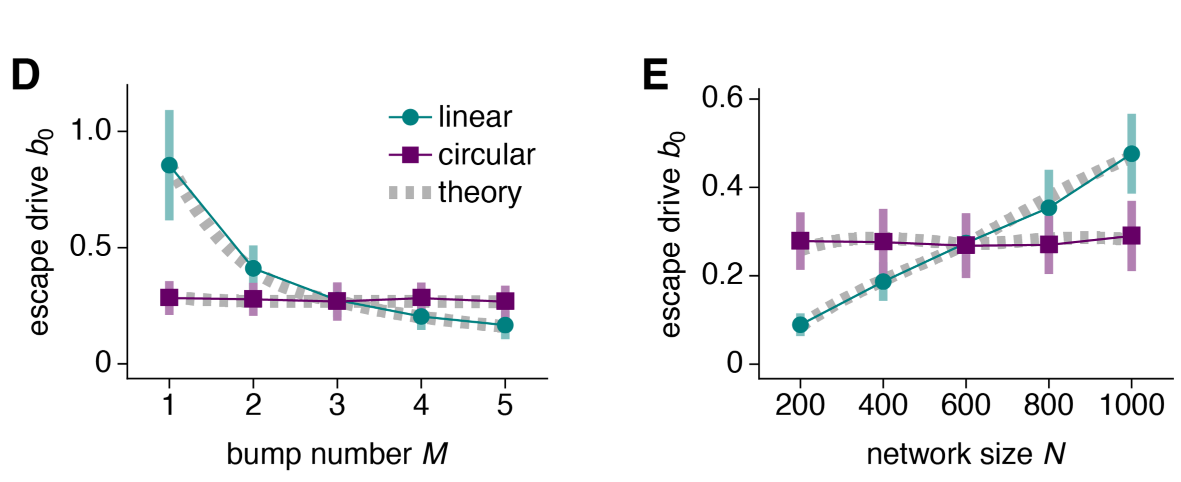


Results

Bump trapping occurs at low drive due to connectivity noise. Escape drive differs for different coordinates mappings shown in both simulation and theoretical derivation.

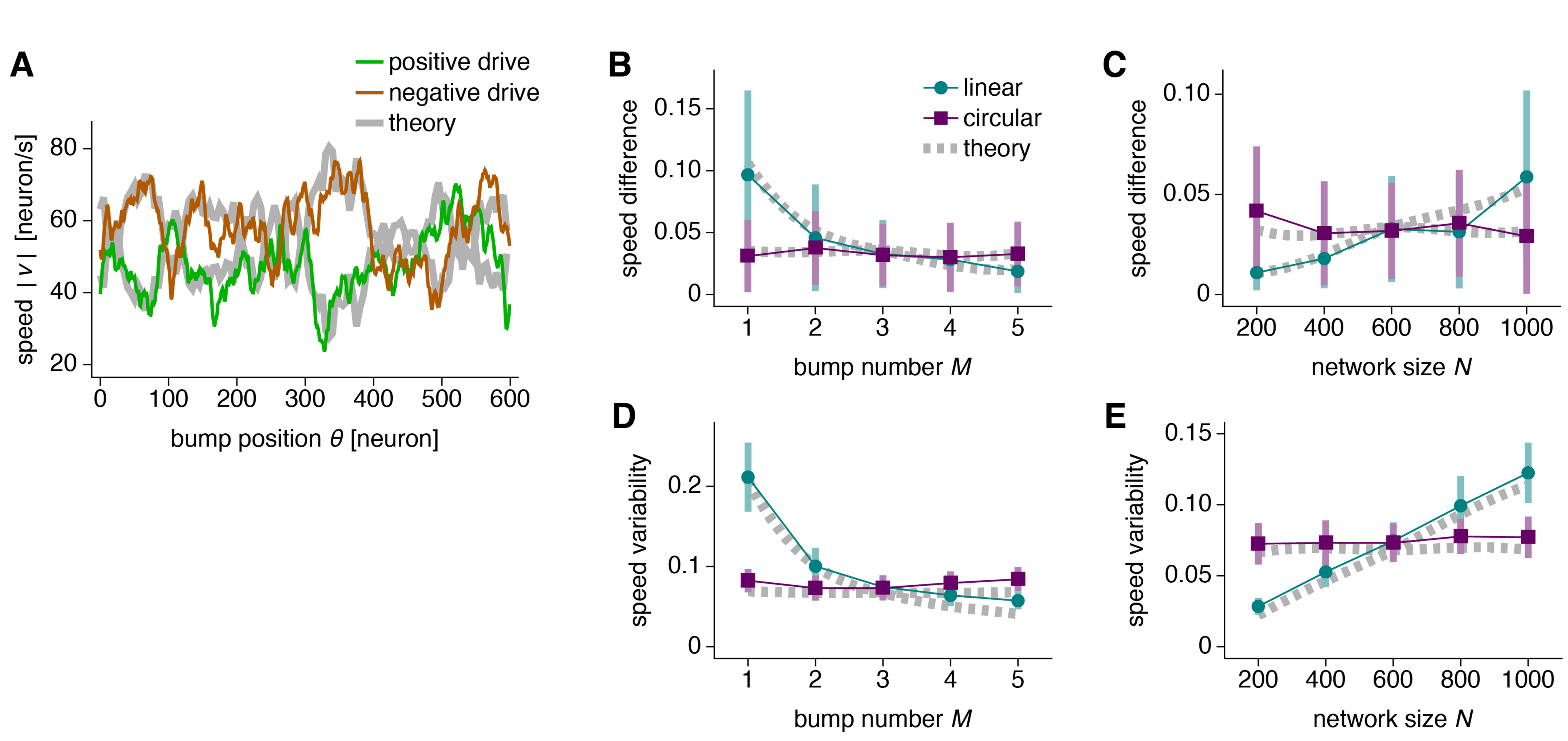
$$b_0 \propto \frac{N}{M} \quad \text{linear}, \qquad b_0 \propto 1 \quad \text{circular}.$$





At high drive, connectivity noise induces irregularity in bump speed over different positions within the network.

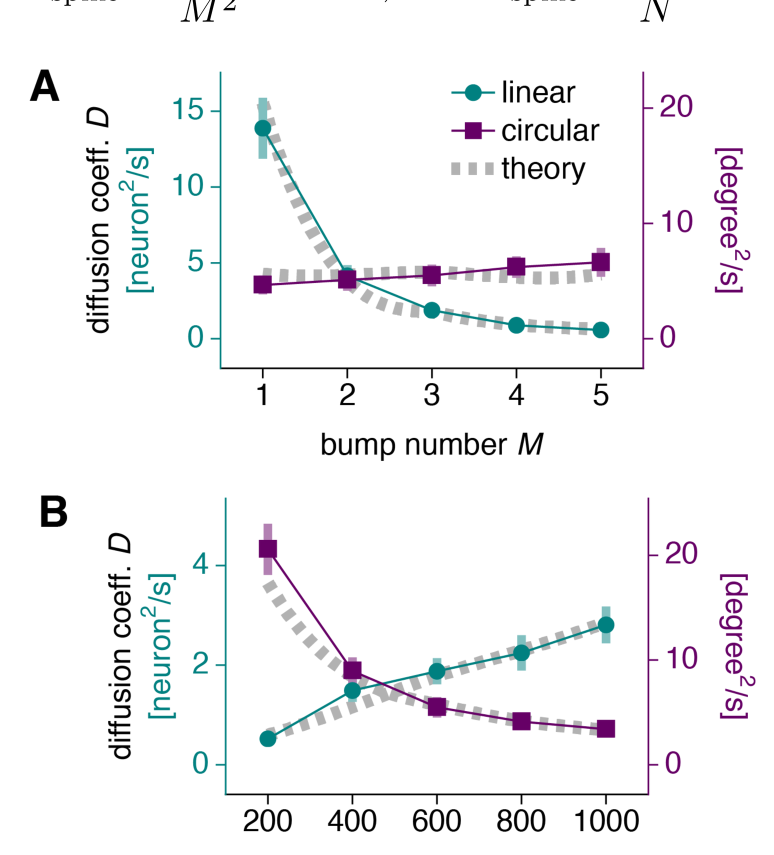
$$\text{speed difference and variability} \propto \frac{N}{M} \quad \text{linear}, \qquad \text{speed difference and variability} \propto 1 \quad \text{circular}.$$



Bump diffusion due to input and spiking noise affects linear and circular coordinate mappings differently.

$$D_{\mathrm{input}} \propto \frac{N}{M^2} \quad \text{linear}, \qquad D_{\mathrm{input}} \propto \frac{1}{N} \quad \text{circular}.$$

$$D_{\mathrm{spike}} \propto \frac{N}{M^2} \quad \text{linear}, \qquad D_{\mathrm{spike}} \propto \frac{1}{N} \quad \text{circular}.$$



Conclusion

To reduce noise-induced path integration errors in continuous attractor networks, linear coordinates like position should be encoded with multiple bumps while circular coordinates like head direction is indifferent to the number of bumps. Our findings provide motivation for the presence of multiple bumps in the mammalian grid network [1].

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References

[1] Y. Gu, S. Lewallen, A. A. Kinkhabwala, C. Domnisoru, K. Yoon, J. L. Gauthier, I. R. Fiete, and D. W. Tank. A map-like micro-organization of grid cells in the medial entorhinal cortex. Cell, 175(3):736–750, 655 2018.

[2] X. Xie, R. H. R. Hahnloser, and H. S. Seung. Double-ring network model of the head-direction system. Phys. Rev. E, 66(4):041902, 2002.

Acknowledgments

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(1) $$\tau \frac{\mathrm{d}g_\alpha(x,t)}{\mathrm{d}t} + g_\alpha(x,t) = \sum_\beta \int \mathrm{d}y\, W_\beta(x,y) s_\beta(y,t) + A \pm_\alpha \gamma b(t) + \zeta_\alpha(x,t)$$