How recurrent circuit connections shape neural population geometry

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Recent advances in large-scale neuronal recordings have revealed multi-dimensional structures of population activity beyond traditional averaged descriptions. Understanding how these structures emerge from circuit connectivity is fundamental to comprehending both normal brain function and dysfunction in neurological diseases. We propose using the covariance eigenvalue distribution, or spectrum, as a robust measure to characterize neural population geometry beyond simple dimensionality. Our linear dynamics framework reveals that the theoretical spectrum exhibits a characteristic long tail of large eigenvalues, quantitatively matching data from various brain regions. This match estimates the recurrent interaction strength in biological circuits, serving as a computational biomarker linking population activity patterns with network connections. Extensions to nonlinear dynamics show that the spectrum can be understood through an effective connection strength parameter capturing both synaptic weights and neuronal nonlinearity. This parameter provides unified interpretation for how dimension and spectrum evolve across dynamical regimes and reveals broad near-critical states without fine-tuning. These results offer mechanistic insights into how recurrent synaptic interactions shape collective neural dynamics and provide tools for identifying neural dynamic states.