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Parametric control of flexible timing through low-dimensional neural manifolds

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Biological brains possess an exceptional ability to infer relevant behavioral responses to a wide range of stimuli from only a few examples. This capacity to generalize beyond the training set has been proven particularly challenging to realize in artificial systems. How neural processes enable this capacity to extrapolate to novel stimuli is a fundamental open question. A prominent but underexplored hypothesis suggests that generalization is facilitated by a low-dimensional organization of collective neural activity, yet evidence for the underlying neural mechanisms remains wanting. Combining network modeling, theory and neural data analysis, we tested this hypothesis in the framework of flexible timing tasks, which rely on the interplay between inputs and recurrent dynamics. We first trained recurrent neural networks on a set of timing tasks while minimizing the dimensionality of neural activity by imposing low-rank constraints on the connectivity, and compared the performance and generalization capabilities with networks trained without any constraint. We then examined the trained networks, characterized the dynamical mechanisms underlying the computations, and verified their predictions in neural recordings. Our key finding is that low-dimensional dynamics strongly increases the ability to extrapolate to inputs outside of the range used in training. Critically, this capacity to generalize relies on controlling the low-dimensional dynamics by a parametric contextual input. We found that this parametric control of extrapolation was based on a mechanism where tonic inputs modulate the dynamics along non-linear manifolds in activity space while preserving their geometry. Comparisons with neural recordings in the dorsomedial frontal cortex of macaque monkeys performing flexible timing tasks confirmed the geometric and dynamical signatures of this mechanism. Altogether, our results tie together a number of previous experimental findings and suggest that the low-dimensional organization of neural dynamics plays a central role in generalizable behaviors.

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