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Title: The importance of neural diversity in complex cognitive tasks

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Complex animal behavior reflects a remarkable ability to use abstract rules and flexibly select the motor decision which is most appropriate given a specific context. The execution of a complex cognitive task can be described as a series of events that drive transitions between mental states, each encoding a certain disposition to behavior or a specific motor decision. We hypothesize that the neural substrates of these mental states are attractors of the neuronal dynamics. To test this hypothesis, we analyzed neural network models and we found that, surprisingly, the number of transitions induced by external events which can be actually be implemented in the neural dynamics is rather limited, implying that even very simple context-dependent tasks cannot be realized in general by simple recurrent networks.

This problem can be solved by introducing mixed selective neurons, i.e. neurons which respond to combinations of external events and specific mental states. Such an activity is widely observed in electrophysiological experiments, and can be easily built by introducing in a neural network the biological heterogeneity of the cell response properties and the synaptic connections. In particular we show that for Hopfield-like networks, the number of event-driven transitions between attractors can grow linearly with the number of mixed selectivity neurons which participate in the neural dynamics. Mixed selectivity can be generated by connecting these neurons randomly to the other neurons and by normalizing properly their synaptic connections with respect to the neuronal activation threshold. By changing the way the normalization is instantiated, we modify the average fraction of patterns of neuronal activities which activate the mixed selectivity neurons, ranging from extremely sparse representations to population coding in which each neuron is activated by half of all attractor patterns. We tested our theory using a firing-rate model to simulate an experiment in which monkeys perform an analogue of the Wisconsin Card Sorting Test, demonstrating the validity of our approach in a specific rule-based behavior task. Generally, we show that networks of threshold-linear neurons can implement arbitrarily complicated schemes of mental states and event-driven transitions, provided that enough mixed selectivity neurons are introduced. This work suggests an important role of neuronal heterogeneity in learning of abstract rules.

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