Attracting states in anterior cingulate cortex populations associated with decision making: Altered dynamics when targeting dopamine system with *d*-Amphetamine

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A frequent hypothesis in theoretical neuroscience is that cognitive entities are represented and processed by attracting states of the underlying neural system (Balaguer et al., 2011; Durstewitz et al., 2000). For instance, different attractor-like states may represent different spatial locations or cognitive entities, and transitions between these attracting sets could be associated with the recall of a memory sequence or the execution of a motor plan. Attractor states underlying cognition were previously proposed in the context of working memory (Balaguer et al., 2011; Durstewitz et al., 2000) and decision making tasks. However, although theoretically suggested, experimental evidence is still sparse for the hypothesis that higher cognitive processes proceed by moving between attracting states in higher cortical areas.

Using state space reconstruction theorems (Sauer et al., 1991) and statistical learning techniques (Schölkopf et al., 1998; Mika et al., 2000; Durstewitz and Balaguer, 2010; Braun et al., 2008), we were able to reveal dynamical properties, not easily accessible in previous studies, of anterior cingulate cortex (ACC) multiple single-unit activity (MSUA) during a cognitive task (Balaguer et al., 2011). The approach worked by constructing high-dimensional state spaces from delays of the original single-unit instantaneous firing-rates and all possible products (multinomials) among them up to some specific order. The dynamics within these sparse and high-dimensional spaces of neural activity interactions were then statistically accessed using optimally regularized kernel methods (Schölkopf et al., 1998; Mika et al., 2000; Durstewitz and Balaguer, 2010; Braun et al., 2008).

Results showed cognitive-epoch-specific neural ensemble states (dependent on behavioral performance (Lapish and Durstewitz et al., 2008)) in ACC while the rats performed an ecologically valid eight-arm radial arm-maze task. More interestingly, these cognitively defined ensemble states showed some hallmarks of attracting behavior which became apparent in high-dimensional expansions of the MSU spaces due to a proper unfolding of the neural activity flow .

Nevertheless, those network states where not observed in the original space of MSU recording; it turned out that optimal unfolding of neural trajectories was achieved in an embedding space characterized by a specific maximum order of neural interactions, common across different animals (Balaguer et al., 2011). From these analyses the *intrinsic* dimensionality which is relevant to the animal's arm choices could be computed (Braun et al., 2008). Analyses revealed that cognitively relevant network states were embedded in a lower-dimensional nonlinear manifold within the high-dimensional space.

Once established the optimal embedding space, attracting dynamics was also analyzed for animals treated with low- and high-doses of amphetamine. Consistently with our previous study (Balaguer et al., 2011) neural trajectories from animals treated with saline, 1 mg/Kg and 3 mg/Kg of amphetamine where indistinguishable the original MSUA space; while trajectories where properly unfolded for the optimally expanded state space.

However, and in sharp contrast, attracting dynamics was severely compromised for high-doses of amphetamine even in optimal state spaces containing high-orders of neural interactions. This result is consistent with predictions of working memory models, which proposed that high concentrations of dopamine should disrupt attractor dynamics in Frontal Cortex (Durstewitz and Seamans, 2008).

To summarize, results indicate that ACC networks may process different subcomponents of higher cognitive tasks by transitioning between different attracting states. Moreover attracting dynamics breaks down of for high-doses of amphetamine, in agreement with theories of prefrontal cortex function.

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