

response; this drift is persistent, not specifically tied to motor planning and related to/predictive of the drift in behavior. These results suggest that the central contribution to short time scale motor variability is minimal. Longer time scale drift is central in origin, and—as suggested by the (comparable) autocorrelation structures of both behavior and neural activity—may be the result of noise in a continuous online learning process (Cheng & Sabes 2007).

## T-5. Neural dynamics of reaching following incomplete or incorrect planning

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Reaction times (RT) are faster when subjects prepare an action before moving. During preparation, primary motor cortex (M1) and dorsal premotor cortex (PMd) neurons display activity specific to the upcoming reach. This has led to the model that during preparation, motor cortical activity achieves a state (“optimal subspace”) which is beneficial for generating the planned movement. We asked what happens if neural activity is outside the optimal subspace when movement initiation is instructed. One model suggests that passing through the optimal subspace is necessary for movement; the RT deficit for improperly planned trials results from “re-planning” before moving. Alternatively, the optimal subspace might convey an RT benefit, yet not be obligatory. In this model, movement can be initiated from outside the optimal subspace, albeit with a temporal penalty. We trained monkey N to perform two tasks while we recorded simultaneous M1 and PMd activity using two 96 electrode arrays. The first task contained interleaved blocks of delayed and non-delayed reaches (incomplete plan). The second was an instructed delay task in which the cued target changed locations in 20% of trials (incorrect plan). We computed low-dimensional neural trajectories by performing PCA on PSTHs for each neuron and condition. When a target switch was followed by a second delay, providing time to re-plan, neural activity changed from one plan to the other, indicating that re-planning is possible. However, when not given time to re-plan, improperly planned neural trajectories did not pass through the optimal subspace identified using “correctly planned” conditions. Instead, these neural trajectories took a parallel but separate path which converged with the correctly planned neural trajectories over the course of movement. This indicates that passing through the optimal subspace is not obligatory for movement, providing evidence against a strict “multi-step” model of movement generation.

## T-6. Energy-conservation and generalized power-law for curved hand movements

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In physics, equations of motion can be derived from optimizing the total integrated cost. Noether's theorem states that if such Lagrangian formulation is invariant under time-translation, then energy of the system must be conserved. Recently, it has been shown that human movements can be accurately modeled by the optimality principle in a similar manner. A crucial observation we made was that these optimal control models share the same time-translation invariance property, from which we successfully derived a novel conservation principle for human movements: Defining  $A$  as the minimum total cost, the conserved quantity (energy) is the partial differentiation of  $A$  with respect to time,  $E = -\delta A / \delta T$ . One important contribution of our energy-conservation-principle (ECP) is that it extends the optimal control models to predict movement durations. For example, ECP predicts  $T \propto D^{1/3}$  for reaching movements ( $T$ =duration,  $D$ =reaching distance), and  $T \propto R^{1/3}\Theta$  for circle-