Heterarchical Control in Sensorimotor Processing

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0.1 Preliminary center hold, reach out data

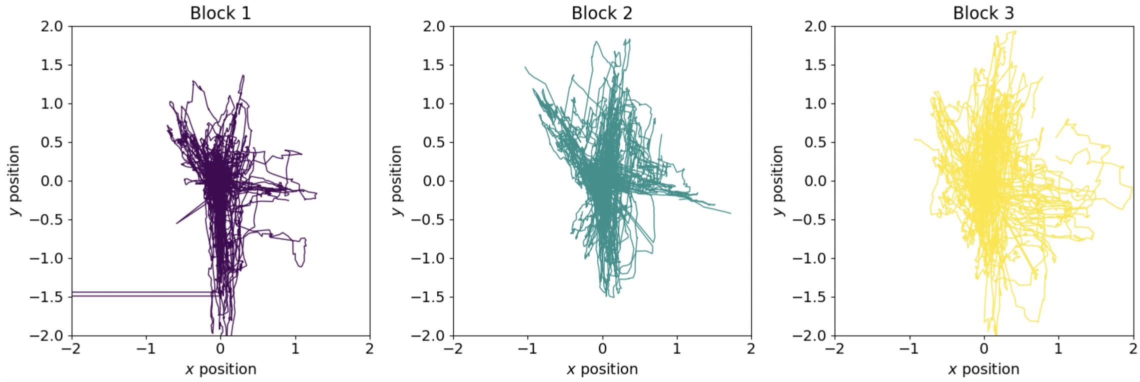
In this task, the muscles of a subject's arm are recorded using 32 channels of surface EMG. This EMG vector is mapped to a 2D force acting on a point mass shown on the screen. The mapping $M \in \mathbb{R}^{2x32}$ maps 8 "columns" each consisting of 4 electrodes placed in a line down the length of the forearm each to one 2D root of unity. Each column of electrodes is thus mapped to one of 8 force directions. These directions are randomly assigned to columns. Additionally, the point mass has zero inertia and zero friction and as such displays a direct, though redundant, readout of the EMG signal.

Note that while there are 8 target directions, the EMG mapping is ultimately a projection onto the 2D plane. Since the EMG signal is nonnegative, the subject could technically modulate four modes of electrode activity, the minimum number needed to span the task space, to achieve the target movements.

We can model the subject as selecting an EMG signal x which minimizes the distance between a target position b and the projection of the EMG signal through the mapping M as well as minimizes the norm of x in order to conserve metabolic energy. This optimization can be written as a regularized least squares problem:

$$\min_x \frac{1}{2}||Mx - b||_2^2 + \frac{\lambda}{2}||x||_2^2.$$

This problem is known to have a unique minimum for $\lambda > 0$, implying that the subject, if they are biophysically capable to do so, will learn distinct motor outputs for each target rather than reusing modes for multiple targets with different activation levels. That is the subject will, over time, learn to fractionate their muscle output to reach their goal in order to minimize effort. For instance, to reach the the target at position $(1, 0)$ in Cartesian coordinates, the subject could activate a bespoke activity mode or activity the combination of two modes for targets at $\pm 45°$ from this central target. If this is the case, the model predicts that the dimensionality of the EMG signal will increase over the course of training as the subject learns to construct bespoke activity modes for each of the eight targets.



Point mass position trajectories in two-dimensional task space during the center-hold, reach-out task with 8 targets spaced evenly around the unit circle. Training was conducted over 3 blocks each with 32 trials, 4 trials per target. The first block shows roughly four modes, the second block shows four modes more clearly, and the third blocks may show the beginnings of fractionation.

0.2 Bibliography