Modulation of the rate of error-dependent learning by statistical properties of the task. – Maurice Smith and Reza Shadmehr

Random sequences of externally imposed force perturbations can be applied to a series of movements to study the properties of motor learning. A traditional view has been that the rate of error-dependent motor adaptation is relatively constant for a given task. Here we show that random sequences with different amounts of trial-to-trial correlation of force-field magnitude require different learning rates for optimal adaptation. Using a simple error-dependent state-space model of motor learning we find that theoretical task performance improves as learning rate increases for sequences with high trial-to-trial correlations in force-field magnitude, but performance worsens as learning rate increases for sequences with low trial-to-trial correlations. This suggests that performance on a motor learning task can be improved by tuning the rate of learning according to the correlation structure in the history of errors experienced, i.e. adjusting the rate at which the system adjusts for error according to the statistics of the task.

We then tested whether the rate of error-dependent motor learning in people is held constant in the human motor system or could change when force-field sequences with different trial-to-trial correlations were experienced. If so, does the optimal learning rate computed for each sequence predict the actual learning rate displayed by subjects? And are the changes in learning rate observed from one sequence to another adaptive in the sense that they improve task performance?

After one set of practice trials, subjects made point-to-point reaching movements while force-field sequences with different trial-to-trial correlations were imposed. Each subject performed six sets of movements in three blocks of two sets. One block had positive,
one block negative, and one block zero trial-to-trial force-field correlation. Using a state space learning model similar to the one used in our simulations, we estimated the learning rate and arm compliance in each set. We found that learning rates are higher when subjects are exposed to positive correlation and zero correlation force-field sequences than when they are exposed to negative correlation sequences ($p<0.01$ in both cases).

We also found a trend toward higher learning rates in positive correlation force-field sequences than in zero correlation sequences, but this difference did not achieve significance($p=0.064$). Additionally, learning rates during negative correlation force-field sequences are not significantly different from zero ($p>0.4$). We found no significant differences between compliance parameters in the different force-field sequences. This is surprising because errors are larger in the negative correlation force-field than the other sequences, and increasing stiffness (decreasing compliance) can be a strategy to reduce error. Taken together, these results suggest that people display different rates of motor adaptation when exposed to different force-field sequences. Furthermore, the relative magnitudes of these learning rates are as predicted by a simple error-dependent learning model for optimal performance, suggesting that people are able to adapt the rate at which they learn based on the correlation structure of the history of errors they experience.

State Space Learning Model

$$\hat{Y}_n = D \cdot F_n - Z_n$$

$$Z_{n+1} = Z_n + B \cdot \hat{Y}_n$$

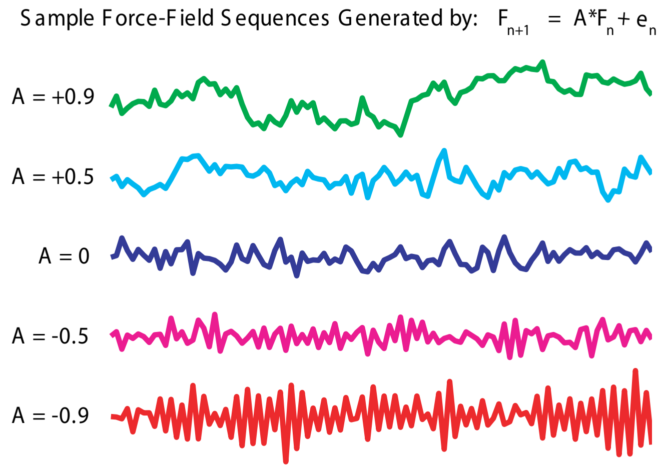
$\hat{Y}$ = *Error Estimate*

Z = *Motor Output*

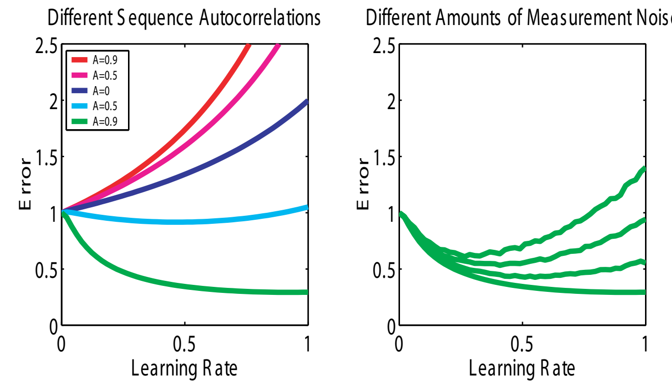
D = *Compliance*

B = *Learning Rate*

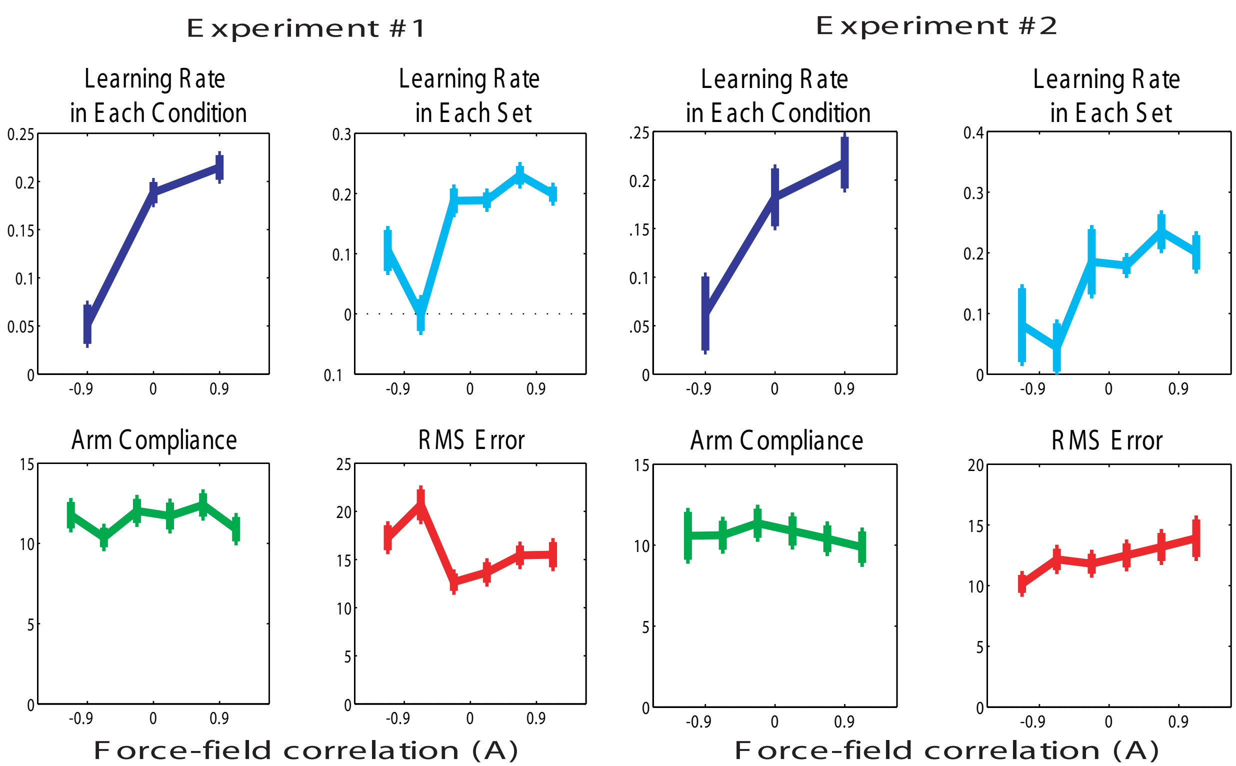
Error-dependent state-space learning model used in experimental and theoretical studies. This model adjusts the motor output for the next trial based on the error in the current trial.



Force-field sequences used in experimental and theoretical studies. These sequences vary in the correlation between the force-field applied on two successive trials. Note that when A is postive the sequence is similar to a random walk, and when A is negative successive force-field perturbations are likely to be in opposite directions.



Results from modelling studies. We find that error decreases (performance improves) as learning rate increases for force-field sequences with high positive correlations, but error increases with learning rate for negative correlation force-field sequences. When different amounts of measurement noise are applied to the positive correlation sequence, increased measurement noise reduces the optimal learning rate.



Results from experimental studies. We find that subjects display significantly decreased learning rates in negative correlation force-field sequences compared to positive correlation sequences or white noise (zero correlation) sequences. Arm compliance is not signicantly different in the different force-field sequences. In the first experiment, learning rate was decreased and RMS error was increased in the negative correlation sequences. So we conducted a second experiment to determine if this increased error (rather than a negative force-field correlation) was responsible for the learning rate decline. In the second experiment, the force-field magnitude was decreased in the negative correlation field only, in order to reduce RMS error in this sequence. In this experiment we found decreased learning rate, without decreased RMS error in the negative correlation sequences, suggesting that negative force-field correlation rather than RMS error was responsible for the significanly reduced learning rates.