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Distinct timescales of cortical reorganization in a long-term learning task using an intracortical brain-computer interface

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Introduction: Skill learning is associated with a functional reorganization of cortical neural activity. Traditionally it is difficult to study the link between changes in neural activity and the concurrent behavioral improvements during skill learning, primarily because in most tasks it is difficult to interpret the direct behavioral impact of particular changes in neural activity. Here we leveraged an intracortical brain-computer interface (BCI) learning paradigm to determine how long-term practice leads to skill acquisition in a BCI movement task. In a BCI, the experimenter provides the subject a definitive mapping between neural activity and the movement of an effector (in our case, a computer cursor). Each new BCI mapping thus provides the subject a new tool that must be mastered through continued practice. One unique advantage of this BCI learning paradigm is that the mappings of individual neurons to cursor movement can be manipulated to test the specificity of adaptive responses.

Materials & Methods: We trained two Rhesus macaques to perform a two-dimensional center-out cursor control task using an intracortical BCI. Each BCI mapped neural activity recorded from a 96-electrode recording “Utah” array placed in primary motor cortex to the velocity of the computer cursor using a population vector algorithm decoder [1]. Once subjects were proficient at the brain-control task with an intuitive mapping, we provided new mappings for them to learn where we rotated the directions in which a randomly selected half of the recorded neurons pushed the cursor. This specific type of perturbation to the BCI system allows us to dissociate whether adaptive changes in neural activity affect all neurons equally, or whether subjects can solve the credit assignment problem, and use global error signals to identify and selectively adapt the individual neurons responsible. We held this perturbed mapping fixed for several weeks by tracking neurons across sessions, to observe the longitudinal changes in activity that occur with practice.

Results & Discussion: Our prior work focused on short-timescale adaptive responses to this type of perturbation, lasting only a few hundred trials. There we identified both a global “re-aiming” response that impacted the activity of all neurons equally, and a local “re-tuning” response specific to the perturbed subset of neurons, indicating subjects were able to solve the credit-assignment problem [2, 3]. However, the global re-aiming response dominated the adaptive response, accounting for ~85% of the overall error reduction, while re-tuning accounted for only 15% of the error reduction. Here we found that the weak local re-tuning response gradually builds up with long-term training, eventually accounting for nearly 50% of the overall error reduction. Interestingly, the angular error, used here as a way to assess the subjects’ movement precision, reached asymptote after only one day of training on the new mapping. However, the local “re-tuning” response continued to build, slowly but consistently, for weeks after the angular error converged, indicating that it was not driven by rotational error. Instead, we found a slight but measurable decrease in the time of target acquisition that correlated with the build-up of the re-tuning response. The distinct timescales of the behavioral improvement and the neural reorganization during long-term practice on our unique BCI task suggests that skill learning is a two-stage process. In the first stage, rapid, coordinated changes in activity across all neurons act to quickly (within one day) reduce behavioral errors during task performance. In the second stage, long-timescale changes in the tuning of individual neurons act to gradually improve the efficiency of the movement over weeks of practice.

Significance: Learning is a fundamental principle of brain operation that impacts many aspects of neural function. The current study expands our understanding of the neural basis of learning at the system level, including its strategies, timescales, and the potential mechanisms involved. This work also has practical implications relating to how subjects learn to control an intracortical BCI, which may one day allow for shorter training times.

Reference

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