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Understanding de novo learning for brain-machine interfaces

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Abstract

De novo motor learning is a form of motor learning characterized by the development of an entirely new and distinct motor controller to accommodate a novel motor demand. Inversely, adaptation is a form of motor learning characterized by rapid, unconscious modifications in a previously established motor controller to accommodate small deviations in task demands. As most of the motor learning involves the adaptation of previously established motor controllers, de novo learning can be challenging to isolate and observe. The recent publication from Haith et al. (Haith AM, Yang CS, Pakpoor J, Kita K. J *Neurophysiol* 128: 982–993, 2022.) details a novel method to investigate de novo learning using a complex bimanual cursor control task. This research is especially important in the context of future brain-machine interface devices that will present users with an entirely novel motor learning demand, requiring de novo learning.

adaptation; brain-machine interface; de novo learning; motor control; motor learning

Motor learning is a complex phenomenon, yet somehow, we all know how to do it. In fact, it is so foundational to our daily lives that it often goes unnoticed as it continues in the background. In early life, humans undergo tremendous amounts of motor development that involves interacting with and learning from the environment. Some of us may grow up learning to play a musical instrument, whereas others may grow up learning to play a sport. These skills are independent of each other and the ability to play a difficult musical piece on the piano does not readily translate into the ability to throw a ball into a hoop from 15 ft away. This is to say that motor skills exhibit a degree of specificity.

Following the previous example, if a piano player takes up basketball, the motor patterns they will learn are entirely different from those they have learned for piano. They will form new sensorimotor associations as well as strengthen and reinforce any existing connections that are associated with dribbling, shooting a free throw, balance, coordination, etc. As this individual learns these new skills, they will form new motor representations. These motor patterns, generally speaking, should not overlap with those of the piano and likewise, they should see no detriment to or enhancement of their piano skills as they become more adept at basketball. This distinct phase of learning is referred to as, "de novo learning" and has important implications for how new motor skills are acquired.

The recently published work by Haith and colleagues explores this very notion. They posit that the acquisition of new skills entails learning how to form new associations between seemingly arbitrary actions, movements, and outcomes (1). This is in contrast with the more well-researched motor learning mechanism of adaptation, which is characterized by perturbation-induced changes in the performance of a previously established motor skill that persists even in the absence of the perturbation (2). To revisit the basketball example once more, de novo learning would entail learning to shoot a basketball for the first time, whereas adaptation would be learning to aim and make a shot from the three-point line afterward (fine-tuning the old skill).

In the study from Haith et al. (1), subjects were seated at a table with flat glass, mirrored surface, reflecting an above-mounted monitor display and a small cursor. The cursor was controlled by the movement of the hands in either one of two control settings: baseline or bimanual. The baseline condition was meant to represent a simple, intuitive movement control schema (right hand = position of cursor), whereas bimanual featured a nonintuitive control schema (left hand horizontal movement = cursor vertical position, right hand vertical movement = cursor horizontal position). In both conditions, subjects were asked to move the digital cursor from a starting position to a pseudorandomly determined target. After reaching the target, its location would change to another pseudorandomly selected position 12 cm away. Changes in speed and accuracy were assessed over the course of multiple sessions and/or days. To test for the existence of aftereffects in

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baseline performance caused by the bimanual task, some grouped subjects completed alternating rounds of both baseline and bimanual movements with and without target jumps.

To verify that the bimanual cursor control task was learned de novo, at the end of the first day, Haith et al. reverted subjects to the baseline controller and observed the effects of bimanual training on performance. Though a handful of subjects demonstrated a subtle movement error upon switching controllers, this was transient and diminished within 10 trials. These results suggest that the task was, indeed, de novo in nature. However, an argument could be made that despite these facts, the bimanual cursor control tasks still bore some resemblance to other more familiar things such as reaching, steering, or, perhaps mostly directly, using a computer mouse. Perhaps, then, it is impossible for any task to be entirely de novo so long as the medium through which control has a precedent motor action.

This work is especially interesting in the context of brain-machine interface (BMI) technologies, which have the potential to restore function, independence, and quality of life in individuals suffering from neurological injury or illness, amputation, or other motor deficits. BMIs can be used to directly translate neural activity of the cortex into the control of an external electronic device. Much like motor skills, relatively simple control paradigms, like moving a cursor on a two-dimensional screen, can be acquired and refined relatively quickly (3). However, exceptionally complex controllers such as moving a robotic arm in a three-dimensional space require significant amounts of training to refine (4).

In the study from Collinger et al. (4) a 52-yr-old individual with tetraplegia was implanted with a pair of 96-channel intracortical microelectrodes, which were used to translate the activity of the motor cortex into the control of a robotic arm. With the use of computer-assisted stabilization, the subject was able to freely move the arm by the second day of training, and over the course of 13 wk, the subject learned to control the robotic arm and perform a variety of tasks meant to simulate activities of daily living. Interestingly, by *week 10*, computer stabilization was no longer required and the subject continued to demonstrate improvements in performance (4). This study suggests that learning to control a BMI with motor circuitry involves motor learning processes. In addition, since the early stages of learning were characterized by large amounts of computer assistance, it is reasonable to postulate that control was not acquired through adaptation of a previously existing motor controller but instead through the formation of a de novo controller.

Adaptation typically involves subtle modifications to already established sensorimotor circuits (i.e., learning to account for movement perturbations), whereas de novo learning involves the formation of novel sensorimotor associations (i.e., learning to move a cursor with unfamiliar and unintuitive movements) (1, 5). Unlike motor tasks, which typically involve proprioception and touch sensation, many BMIs rely almost exclusively on visual feedback to drive learning (6). In this way, BMI control differs from traditional motor control paradigms and is learned de novo through unfamiliar modalities. Interestingly, Collinger and colleagues' (4) subject was able to rapidly learn basic movement control of the robotic arm but struggled with fine movements even after 13 wk of training. Perhaps because adaptation requires real-time, multimodal sensory feedback (7), sight alone is inadequate to drive the later stages of learning with complex BMIs.

This is important to consider for both the medical and commercial success of this technology. Current assistive technologies may allow individuals with significant motor impairments to type, speak, control a wheelchair, or operate a prosthetic limb, however, these technologies can be slow, inaccurate, and frustrating for the user (8). In order for BMIs to become viable, the learning curve must not be too steep, and the simplicity, reliability, and accuracy of interaction must provide an advantage over current medical and commercial devices (assistive technologies, touchscreens, or mouse and keyboard). This may, perhaps, be best achieved by designing BMIs to leverage preexisting control circuits and to incorporate multiple forms of surrogate sensory feedback (6), which may support learning for more complex BMIs. The research from Haith et al (1) is interesting because studying de novo learning will help us understand how control paradigms for more complex BMIs are acquired de novo, consolidated, and then refined.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

D.G., S.V., and J.F. drafted manuscript; D.G., S.V., and J.F. edited and revised manuscript; D.G., S.V., and J.F. approved final version of manuscript.

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