9-2021

Investigating the computations underlying complex motor skill learning

Christopher S. Yang

Investigating the computations underlying complex motor skill learning
Final Report for Link Foundation Modeling, Simulation, & Training Fellowship
Christopher S. Yang
Johns Hopkins University

1. Project

Introduction

In order for a person to learn a new skill from scratch such as riding a bike or playing the piano, their brain must generate a new motor controller (a policy which maps one's goal and current state to movements) that can perform this task, a process known as *de novo* learning. Despite the important role that *de novo* learning plays in acquiring motor skills, very little is understood about this learning process as the motor learning community has largely focused on investigating how existing skills are recalibrated, a process known as adaptation.

In the present project, I designed an experimental paradigm inspired by control theoretic principles which can be used to assess how people learn new skills *de novo*. I then used this paradigm to investigate how people learn continuous movement skills as well as how motor habits form during learning.

Results

***De novo* learning of continuous movement tasks.** Previous studies of motor learning have often investigated how people learn to perform "discrete" movement tasks where movement goals are stationary and the movements required to achieve the goal are simple. Such tasks can be solved by the application of cognitive strategies, i.e., planning the exact movements one will make before executing them. However, these strategies are cognitively demanding and time-consuming to deploy, meaning that they cannot be used to learn to perform "continuous" movement tasks which require people to continuously respond to ongoing external events at low latency, such as bike riding or juggling.

To better understand how people learn continuous movement skills, we had participants learn to counter either a mirror reversal or rotation of visual feedback while performing a continuous manual tracking task (Figure 1A-C). In this task, participants used an on-screen cursor to track a target moving in a sum-of-sines trajectory. The target moved quickly and pseudorandomly, limiting participants' ability to utilize cognitive strategies. We assayed participants' control capabilities at different stages of learning using a frequency-domain system identification approach (Figure 1D-E). Our results suggest that participants learned to counter the mirror reversal by building a new motor controller *de novo*. In contrast, participants learned to counter the rotation by both recalibrating an existing controller (adaptation) and building a *de novo* controller. The results of this study were published in eLife: https://elifesciences.org/articles/62578.

Dynamics of habit formation during *de novo* learning. Practice is crucial for people to acquire new movement skills. However, practice also causes behavior to become habitual (i.e., insensitive to changes in task goals or task structure). It is often assumed that as behaviors become *more* skilled with practice, those behaviors become *more* habitual. However, this assumption has never been rigorously examined; it is unclear how habits form during motor learning.

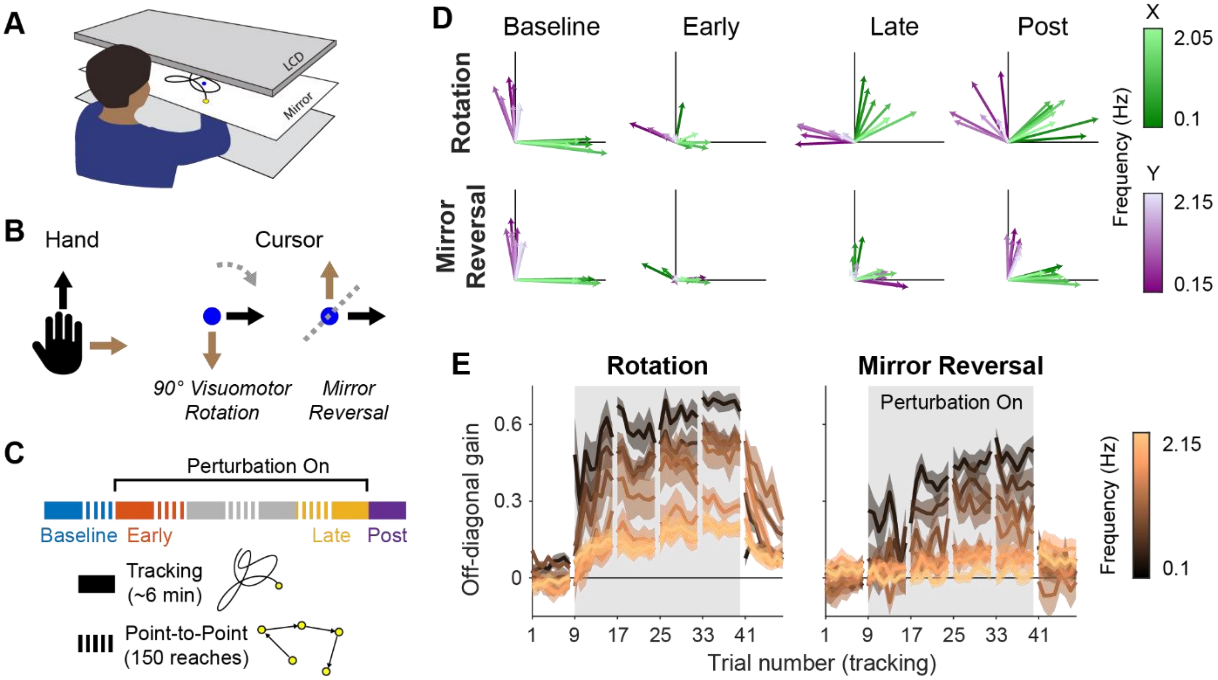

Figure 1. Experiment examining learning of continuous movement skills. **A.** Participants performed planar reaching movements on a table with their right hand while stimuli were displayed on a screen. **B.** Two groups of participants learned to counter either a 90° rotation or mirror reversal of visual feedback. **C.** Participants practiced moving the cursor under these visuomotor perturbations by performing point-to-point reaches and we assessed how well they learned to counter these perturbations by having them track a continuously moving target. **D.** We assessed the direction and amplitude that participants moved their hands in response to target movement in the positive x- (green) and y-axes (purple). Each arrow represents participants' hand movements at a particular frequency (darker colors represent lower frequencies). **E.** We performed statistical comparisons across groups by comparing the gain of participants' hand movements relative to the target. All panels from this figure were reproduced from Yang et al., 2020 (https://elifesciences.org/articles/62578).

Here, we examined the dynamics of how habits form in a *de novo* learning task. Participants learned to control an on-screen cursor using a non-intuitive bimanual hand-to-cursor mapping over two, five, or ten days of practice (Figure 2A). In this mapping, up-down movements of the left hand caused the cursor to move right-left while right-left movements of the right hand caused the cursor to move up-down. Participants practiced this mapping by performing both point-to-point reaches as well as the continuous tracking task mentioned previously. As expected, with more practice, participants became more skilled in using the bimanual mapping. To assess whether participants' use of the bimanual mapping had become habitual, on the final respective day of practice for each group, we flipped the left hand's mapping to cursor movement such that up-down hand movements caused the cursor to move left-right instead of right-left (Figure 2B). We found that in the point-to-point task, all groups exhibited habitual behavior, but the strength of habitual behavior was similar across groups (Figure 2C). In contrast, in the tracking task, the 2-day group (participants with the least practice on the bimanual mapping) did not exhibit any habitual behavior but the groups with more practice exhibited stronger habits (Figure 2D).

Why would the 2-day group express habitual behavior in the point-to-point task but not the tracking task while the other groups did? These data suggest that practice caused a change in the

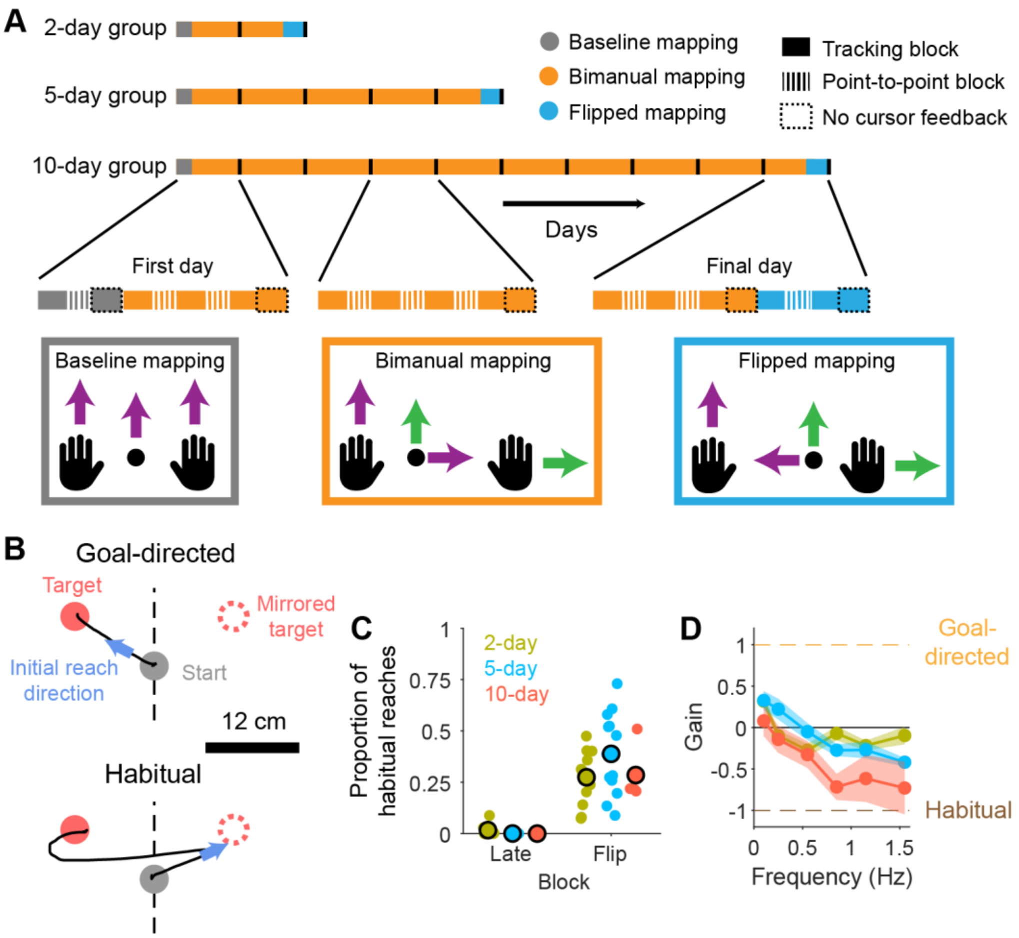

Figure 2. Experiment examining habit formation during motor learning. **A.** Participants learned to control a cursor using a bimanual hand-to-cursor mapping over two, five, or ten days of practice. Participants practiced these mappings by performing a combination of point-to-point reaches and continuous tracking. On each group's respective final day of practice, we flipped the left hand's mapping to cursor movements to assess whether participants would habitually use the originally learned bimanual mapping. **B.** Trajectories from individual trials in the point-to-point task under the flipped mapping. On some trials, participants reached directly towards the target, suggesting that they exhibited goal-directed behavior (top). But on other trials, participants reached across the mirroring axis (dashed line), suggesting that they exhibited habitual behavior (bottom). **C.** We fit a mixture model to participants' reach directions in order to estimate the proportion of trials where participants exhibited habitual behavior. We found that all groups exhibited habitual behavior under the flipped mapping, but the proportion of habitual reaches was similar across groups. **D.** In the tracking task, we measured the strength of habitual behavior by measuring the gain of participants hand movements in the x-axis (orthogonal to the mirroring axis). We found that with more practice, participants exhibited more negative gains (particularly at high frequencies), suggesting that habitual behavior became stronger with more practice.

underlying representation or expression of the habit. In the point-to-point task, participants had an unlimited amount of time to prepare their movements to each target whereas in the tracking task, the quick and pseudorandom nature of the target limited the amount of preparation time afforded to participants. After only two days of practice, the habit may have been associated with a mechanism that could only be expressed under high reaction times, limiting its expression in the tracking task. However, with more practice, the habit may have undergone a transition, becoming associated with a different mechanism which could be expressed under low reaction times, and thereby becoming apparent in participants' tracking behavior. The manuscript for these results is currently under preparation.

Significance and impact

The first major impact of these studies is methodological in nature. Here, we have introduced the continuous tracking task as an experimental method for assaying control capabilities during motor learning. Prior studies of motor learning have utilized relatively simple tasks (e.g., point-to-point reaching) with simple quantifications of learning progress (e.g., reach direction, reaction time, path length) that do not provide direct insight into how the brain generates movements—for instance, people do not generate movements by first selecting the path length of their movements. Instead, the continuous tracking method and system identification approach that we used here provides more direct insight into how people's motor controllers change during learning as they allow us to estimate the transfer function associated with the sensorimotor system. (Estimating the transfer function allows us to predict how the sensorimotor system would respond to any arbitrary input.)

The second major impact is that these studies push the boundaries of motor learning research forward towards examining *de novo* learning. As mentioned previously, most laboratory motor learning studies utilize simple tasks which can be solved using either sensorimotor adaptation or some form of cognitive strategy. However, these two learning processes are insufficient to explain how people learn complex real-world tasks like playing a sport or an instrument. Our studies break this mold by studying more complex tasks that require *de novo* learning, the process that is believed to underly learning of many real-world skills.

Where might this lead?

Thus far, the motor learning field has been dominated by simple laboratory tasks that are inadequate for modeling learning in the real world. Additionally, results from these tasks are often interpreted within conceptual frameworks that have—in my opinion—outlived their usefulness and preclude new and potentially more interesting interpretations from gaining ground. However, the motor learning field is gradually acknowledging these facts and has been making an effort to break away from the field's longstanding dogmas. Increasingly, I believe we will see more challenging and interesting learning tasks emerge that will provide deeper insights and newer perspectives into real-world skill learning. I also believe these efforts will synergize with the advent of new technologies that enable scientists to design scaled-down versions of real-world learning tasks such as virtual reality devices and brain-/body-machine interfaces.

2. List of Publications/Presentations

Publications

1. **Yang, C.S.**, Cowan, N.J., Haith, A.M. *De novo* learning versus adaptation of continuous control in a manual tracking task. *eLife*. 10:e62578.
2. **Yang, C.S.**, Cowan, N.J., Haith, A.M. Emergence of habitual control in a novel motor skill over multiple days of practice. (in preparation)

Refereed abstracts

1. **Yang, C.S.**, Cowan, N.J., Haith, A.M. Automatization of control under a complex visuomotor mapping. *ICRA Workshop on Learning of Manual Skills in Humans and Robots*. 2020.

Invited talks

1. Department of Neuroscience Annual Retreat, Johns Hopkins University, Baltimore MD (2021)
2. Cheese & Wine Seminar, Newcastle University, Newcastle upon Tyne, UK (2021)
3. Nu Rho Psi Seminar, Johns Hopkins University, Baltimore, MD (2021)

Other non-refereed oral presentations

1. Sensorimotor Research Day, Johns Hopkins University, Baltimore, MD (2019)

Posters

1. **Yang, C.S.**, Haith, A.M. Comparing the time course of skill versus habit development in a visuomotor control task. Cognitive Neuroscience Society Annual Meeting, March 2021.
2. Kita, K., **Yang, C.S.**, Du, Y., Haith, A.M. Comparing latencies of information processing supporting feedforward and feedback control of reaching. Society for Neuroscience Annual Meeting, October 2019.
3. **Yang, C.S.**, Cowan, N.J., Haith, A.M. Characterizing *de novo* learning of continuous motor skill. Society for Neuroscience Annual Meeting, October 2019.

3. Impact of Fellowship

This fellowship was immensely important to my intellectual development as a scientist, providing me the freedom to pursue the scientific questions that I found to be most interesting. With this funding, I was able to complete the research necessary to complete my PhD thesis and conduct this research to a high standard. Additionally, the fellowship also enabled me to engage in opportunities for professional development, presenting my work and developing new connections with other scientists at conferences associated with the Society for Neuroscience, the Cognitive Neuroscience Society, and the International Conference on Robotics and Automation.