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Research Report

Deconstructing skill learning and its physiological mechanisms

Danny Spampinato [a,b,1] *and Pablo Celnik* [b,c,d,*]

[a] *Department of Biomedical Engineering, Johns Hopkins School of Medicine, USA*
[b] *Department of Physical Medicine and Rehabilitation, Johns Hopkins School of Medicine, USA*
[c] *Department of Neuroscience, Johns Hopkins School of Medicine, USA*
[d] *Department of Neurology, Johns Hopkins School of Medicine, USA*

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ABSTRACT

Acquiring complex motor skills involves learning a number of distinct motor components. Two fundamental elements that constitute a skill are the internal representation (i.e., the calibration of a sensorimotor map) and the sequence of movements needed to execute the task. Learning each of these likely rely on different neural substrates such as the cerebellum and primary motor cortex (M1), and physiological mechanisms. However, the specific neurophysiological processes underlying the acquisition of these components remains poorly understood. Here we used non-invasive brain stimulation to identify distinct physiological contributions arising from the cerebellum and M1 associated with learning the internal representation and the sequence of movements to execute a skill. Experiment one evaluated neurophysiological markers of the cerebellum and M1 while participants learned a sensorimotor map. Participants learned to calibrate the appropriate motor outputs to interact with a new device, prior to learning a new motor skill. We found that plastic changes in the cerebellum, but not in M1, are linked to learning the internal representation. Experiment two assessed the same neurophysiological markers while participants learned a sequence of movements, independent of acquiring a novel sensorimotor map. Here, both M1 LTP-like plasticity and cerebellar plasticity mediated movement sequence learning. Our findings indicate that learning the different components that will constitute a motor skill engages multiple nodes of a brain network in a concerted manner. In addition, it calls into question the expectation that targeting specific brain regions, such as M1, with brain stimulation to augment complex skill learning will have positive results.

* *Corresponding author*. Johns Hopkins School of Medicine, 600 North Wolfe St., Phipps 160, Baltimore, MD, 21287, USA.
E-mail addresses: dspampi1@jhmi.edu (D. Spampinato), pcelnik@jhmi.edu (P. Celnik).
[1] Johns Hopkins School of Medicine, 707 North Broadway, G-04, Baltimore, MD 21205.
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1. Introduction

Successfully executing a motor skill, such as hitting a baseball, requires our brain to develop an understanding of how to interact with the specific properties of a new object or environment (e.g., the weight of the bat), as well as to coordinate an appropriate sequence of movements (i.e., fluid swing). Despite the enormous amount of computations needed to acquire each of these motor components, we are seamlessly capable of learning them simultaneously. We posit that skill learning is accomplished by engaging different brain regions, each acquiring distinct motor components through different physiological mechanisms.

Performing smooth and accurate movements are thought to rely on internal forward models—representations of the body capable of predicting sensory consequences of our own action (Shadmehr & Krakauer, 2008; Todorov, 2004; Wolpert, Ghahramani, & Jordan, 1995). Electrophysiological (Herzfeld et al., 2014; Pasalar, Roitman, Durfee, & Ebner, 2006), imaging (Diedrichsen, Hashambhoy, Rane, & Shadmehr, 2005; Schlerf, Ivry, & Diedrichsen, 2012a), and patient studies (Bhanpuri, Okamura, & Bastian, 2014; Martin, Keating, Goodkin, Bastian, & Thach, 1996; Smith & Shadmehr, 2005) have all implicated that one important role of the cerebellum in motor control is to acquire and maintain internal models. Human motor adaptation studies have indicated that reducing sensory-prediction errors (error-based learning) leads to the formation of internal models in the cerebellum (Izawa, Criscimagna-Hemminger, & Shadmehr, 2012; Taylor, Krakauer, & Ivry, 2014; Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007). Similarly, animal and human research have shown this type of learning leads to neurophysiological changes within the cerebellum (Jayaram, Galea, Bastian, & Celnik, 2011; Schlerf, Galea, Bastian, & Celnik, 2012b; Yang & Lisberger, 2014a). Although prior work has evaluated error-based learning by introducing systematic perturbations, this learning mechanism likely also contributes to forming an internal model representation of a novel task (Bastian, 2011; Haith & Krakauer, 2013). Here, we investigated whether acquiring de novo a sensorimotor map (or internal model) that is necessary for a skilled task performance, also engages the cerebellum.

It has been suggested that linking multiple elements into a single action and optimizing the performance of a sequence of movements relies on both the cerebellum and motor cortical regions (Hardwick, Rottschy, Miall, & Eickhoff, 2013; Penhune & Steele, 2012). For instance, cerebellar patients' show learning impairments in novel coordination patterns and sequences (Molinari et al., 1997; Pascual-Leone et al., 1993; Shin & Ivry, 2003), and damaging cerebellar nuclei in monkeys impairs automatization of motor sequences (Nixon & Passingham, 2000). Although these studies indicate cerebellar involvement movement sequences acquisition, the neurophysiological changes associated with this role remain largely unknown. On the other hand, the primary motor cortex (M1) is also known to play an active role in acquiring and encoding movement sequences (Matsuzaka, Picard, & Strick, 2007; Wiestler & Diedrichsen, 2013). Repetition of the same movement pattern rapidly alters the output organization of M1 (Classen, Liepert, Wise, Hallett, & Cohen, 1998; Liepert, Terborg, & Weiller, 1999; Nudo, Milliken, Jenkins, & Merzenich, 1996; Pascual-Leone et al., 1995), a process that is thought to rely on mechanisms of synaptic efficacy, such as long-term potentiation (LTP) (Harms, Rioult-Pedotti, Carter, & Dunaevsky, 2008; Rioult-Pedotti, Donoghue, & Dunaevsky, 2007). Interestingly, LTP-like plasticity of M1 has been described as a neurophysiological phenomenon associated with motor skill learning and retention in humans (Cantarero, Tang, O'Malley, Salas, & Celnik, 2013b; Spampinato & Celnik, 2017). These studies, however, assessed acquisition of complex skills that involved learning including both sensorimotor maps and movement sequences. In other words, prior investigations cannot disentangle the roles of M1 and cerebellum in the learning of individual motor skill components.

Since learning motor skills involves acquiring the sensorimotor map and sequence components simultaneously, here we deconstructed a skill task to assess the distinct physiological contributions of the cerebellum and M1 when participants learn the skill components separately. We predicted that learning a sensorimotor map results in modulation of cerebellar excitability (CBI), but not in M1 LTP-like plasticity changes; whereas learning a sequence of movements leads to CBI changes and M1 LTP-like plasticity. We argue that the nature of motor components that constitute a skill determines which brain regions and physiological mechanisms mediate overall motor skill learning. This raises the question whether developing interventions targeting multiple brain regions, rather than a single-site, results in a more efficient modulation of motor learning.

2. Materials and methods

We recruited a total of 44 naïve healthy right-handed individuals (mean age = 24.11 ± 4.36 years; 26 female) with no history of neurological disorders. Exclusion criteria included the use of alcohol, recreational drug use and prescribed medication affecting the central nervous system, all of which may alter plasticity and motor learning. This study was approved by the Johns Hopkins University School of Medicine Institutional Review Board. All participants provided written informed consent before participating in the study.

2.1. *Neurophysiological assessments*

2.1.1. *Transcranial magnetic stimulation (TMS)*

We used a 70 mm-diameter figure-of-eight TMS coil (Magstim 200^2) over the left M1 to elicit motor evoked potential (MEP) of the first dorsal interosseous (FDI) muscle of the right hand. We used a neuro-navigation system (BrainSight; Rogue Research) to ensure that the stimulation location over the desired M1 location remained consistent across sessions. To do this, we identified and registered a "hot spot" with the best representation of the right FDI muscle. MEPs were recorded with electromyographic (EMG) activity via disposable surface electrodes placed over the FDI muscle. EMG signals were sampled at 2 kHz, amplified at 1 kHz and band-pass filtered (10–500 Hz) using an amplifier (Octopus AMT 8; Bortec Biomedical, Alberta, Canada) and data acquisition software (Signal 4.02;