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Perception as a Route for Motor Skill Learning: Perspectives from Neuroscience

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Abstract—Learning a motor skill requires physical practice that engages neural networks involved in movement. These networks have also been found to be engaged during perception of sensory signals associated with actions. Nonetheless, despite extensive evidence for the existence of such sensory-evoked neural activity in motor pathways, much less is known about their contribution to learning and actual changes in behavior. Primate studies usually involve an overlearned task while studies in humans have largely focused on characterizing activity of the action observation network (AON) in the context of action understanding, theory of mind, and social interactions. Relatively few studies examined neural plasticity induced by perception and its role in transfer of motor knowledge. Here, we review this body of literature and point to future directions for the development of alternative, physiologically grounded ways in which sensory signals could be harnessed to improve motor skills.

Key words: motor skill learning, action perception, sensory feedback, human.

INTRODUCTION

In the process of learning, as the idiom states, ‘practice makes perfect’. However, performance gains can be attained through many different forms of practice, and what constitutes optimal practice is still an active field of scientific research pursued across multiple disciplines including psychology, education, neuroscience, sports, music, artificial intelligence, child development and also clinical fields of rehabilitation such as physical and occupational therapy. When acquiring new motor-skills, voluntary physical movement is considered most efficient for inducing short- and long-term changes in performance. Nonetheless, training that involves physical movement can be highly demanding and time consuming. It can take months or years for one to master highly complex motor skills such as those performed by professional athletes, or musicians. Moreover, this form of practice is extremely challenging in the context of rehabilitation following neurological insult, in which voluntary control of the affected limb is very limited or absent altogether. Therefore, finding alternatives to voluntary physical movement as a means for improvement in motor skill performance is of great importance. Gaining a better understanding of the underlying biological processes that support the acquisition of motor skills is a necessary step in the development of such alternatives.

During the past two decades, a growing body of literature has demonstrated that sensory signals, especially those associated with actions, elicit significant neural activity in brain regions formerly considered as predominantly responsible for their overt execution (Rizzolatti and Sinigaglia, 2016). The fact that passive action perception and overt motor execution share neural representations raises the exciting possibility that sensory signals may be used as an alternative, or in addition to, physical practice, to modify and improve performance of motor skills. Although this potential is well recognized, and generally accepted, there is paucity of data to support it, and the underlying mechanism by which sensory signals affect motor performance and learning remains unclear.

In the current manuscript, we review existing behavioral and neural evidence showing that action perception not only evokes activity in motor pathways but also modifies behavior and facilitates learning. We begin by characterizing sensory-evoked neural activity in motor pathways, continue with how action perception implicitly modifies short-term behavior, and then

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Abbreviations: AON, action observation network; CP, Cerebral Palsy; FES, functional electric stimulation; IFG, inferior frontal gyrus; MEP, motor-evoked potentials; PD, Parkinson’s disease; rsfcMRI, resting-state functional connectivity; SMA, supplementary motor area; SPL, superior parietal lobule; TMS, transcranial magnetic stimulation; TMS, transcranial magnetic stimulation; VR, virtual reality.

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highlight the effects of perception on motor skill acquisition. We conclude by pointing to future directions for the development of alternative, physiologically grounded ways in which sensory signals could be harnessed to improve motor skills. Although imitation is a highly efficient form of learning that relies heavily on action perception, it entails concurrent voluntary physical movement during the training (imitation) phase and therefore beyond the scope of this review (Hurley and Chater, 2005).

ACTION PERCEPTION ELICITS NEURAL ACTIVITY IN MOTOR PATHWAYS

Perception and action have been traditionally considered distinct and independent neural processes. Perceptual mechanisms provide information about the external world, while action-related mechanisms are involved in selection, preparation and execution of goal-directed behavior. However, the ideomotor principle, first described by Lotze (1852) and James (1890), suggests that these two functions share common representations at the behavioral and physiological levels, and are therefore linked. This prominent idea has provided the basis for the Common Coding approach (Prinz, 1997) and the Theory of Event Coding (Hommel, 2009; Shin et al., 2010). These theories posit that the final stages of perception and the early stages of action generation share common features that allow a translation of information from one system to another. For example, according to the Theory of Event Coding, perceived events are represented in the same format as planned actions. It is therefore plausible that neural changes in sensory systems (e.g., visual, auditory or tactile), lead to neural changes in the motor system, and vice versa.

Evidence from animals

At the physiological level, substantial evidence has accumulated over the last two decades for the notion of sensory-evoked neural activity in motor pathways. The most influential discovery was of a particular class of visuo-motor cells that discharge not only when executing an action but also when passively perceiving similar actions performed by someone else (Rizzolatti and Sinigaglia, 2016). These neurons, termed mirror neurons, were originally discovered using single cell recordings in sector F5 of the ventral premotor cortex of macaque monkeys (di Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996). Following the original discovery, the existence of mirror neurons has been demonstrated in other regions of the monkey motor pathway, including primary, premotor and parietal regions (Fogassi et al., 2005; Tkach et al., 2007; Kraskov et al., 2009; Dushanova and Donoghue, 2010; Vigneswaran et al., 2013). Although extensively studied in the visual domain, mirror neurons with audio-motor properties have also been reported (Kohler et al., 2002; Keysers et al., 2003). Today, neurons with mirroring properties have been reported also in marmosets (Suzuki et al., 2015) and song birds (Prather et al., 2008; Keller and Hahnloser, 2009), demonstrating the pervasive nature of such sensory-evoked neural activity in motor pathways across the phylogenetic line.

Evidence from humans

In humans, the opportunities to directly record neural activity are rare, and limited to specific clinical situations. Nevertheless, one study with epileptic patients provides direct evidence for the existence of cells with mirroring properties in the supplementary motor area (SMA), and also limbic areas such as the Hippocampus, Para-Hippocampal Gyrus and Entorhinal Cortex (Mukamel et al., 2010). Extensive indirect evidence using non-invasive techniques (such as functional magnetic resonance imaging; fMRI), suggests that the anatomical distribution of regions with overlapping representations of executed and perceived actions might constitute a functional network (Buccino et al., 2001; Gazzola and Keysers, 2009; Caspers et al., 2010; Molenberghs et al., 2012). However, since the ability to perform physical movement in an fMRI scanner is limited, most studies rely on visual depictions of actions to delineate an 'action-observation-network' (AON) (Cross et al., 2009) which is responsive to visual perception of actions performed by others. This network comprises frontal and parietal regions typically considered as part of the motor pathway (e.g., premotor, and supplementary motor areas). Interestingly, some regions within the AON respond to subliminally presented actions (i.e., in lack of reported conscious perception) while other regions are sensitive to the degree of visual awareness (Simon and Mukamel, 2017). Evidence from other techniques such as EEG (Muthukumaraswamy and Johnson, 2004; Simon and Mukamel, 2016), MEG (Hari et al., 1998) and transcranial magnetic stimulation (TMS) (Fadiga et al., 1995) provide further support for sensory-evoked responses in motor regions. Once again, although mainly studied in the visual domain, there is ample evidence supporting the existence of audio-motor mirroring properties in humans as well (Haueisen and Knosche, 2001; Lahav et al., 2007; Margulis et al., 2009).

ACTION PERCEPTION INDUCES IMPLICIT CHANGES IN MOTOR PERFORMANCE

Action-related sensory input (such as observing someone else perform an action) not only evokes neural activity in motor pathways, but also implicitly affects motor behavior. For example, during social interactions, people tend to adopt the gestures and mannerisms of interacting partners in an automatic, often unconscious manner (Chartrand and Bargh, 1999; Kuhn et al., 2010). Priming effects of observed actions have also been reported – either facilitating or interfering with ongoing actions even when the perceived actions do not directly pertain to the task (Sturmer et al., 2000; Craighero et al., 2002; Kilner et al., 2003; Ferguson and Bargh, 2004). Mere action observation has been shown to implicitly modulate various movement parameters such as grip force (Salama et al., 2011), squeeze force (Obhi and