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The missing link between action and cognition

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Abstract

The study of the neural correlates of motor behaviour at the systems level has received increasing consideration in recent years. One emerging observation from this research is that neural regions typically associated with cognitive operations may also be recruited during the performance of motor tasks. This apparent convergence between action and cognition – domains that have most often been studied in isolation – becomes especially apparent when examining new complex motor skills such as those involving sequencing or coordination, and when taking into account external (environment-related) factors such as feedback availability and internal (performer-related) factors such as pathology. Neurally, overlap between action and cognition is prominent in frontal lobe areas linked to response selection and monitoring. Complex motor tasks are particularly suited to reveal the crucial link between action and cognition and the generic brain areas at the interface between these domains.

Keywords: Motor control; Skill complexity; Motor learning; Attention to action; Neural plasticity

Contents

Abbreviations: SMC, primary sensorimotor cortex; M1, primary motor cortex; SMA, supplementary motor area; pre-SMA, pre-supplementary motor area; PMC, premotor cortex; PMCd, dorsal premotor cortex; PMCv, ventral premotor cortex; pre-PMCd, rostral part of the dorsal premotor cortex; PC, parietal cortex; PFC, prefrontal cortex; ACC, anterior cingulate cortex; RCZ, rostral cingulate zone; RCZp, posterior division of the rostral cingulate zone; RCZa, anterior division of the rostral cingulate zone; CMA, cingulate motor areas; IPS, intra-parietal sulcus; PD, Parkinson's disease; EEG, electroencephalography; MEG, magnetoencephalography; fMRI, functional magnetic resonance imaging

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1. Introduction

Skilled movement is an essential part of our daily life activities and covers a wide range in terms of intricacy. Furthermore, skill complexity can be characterized by two complementary components. Whereas objective complexity refers to the motor task structure and requirements, subjective complexity encompasses how the action plan is shaped by cognitive and emotional processes that drive the performer towards achievement of a particular goal (Fig. 1). We argue that these aspects of subjective complexity draw on brain structures that are not typically associated with motor control such as prefrontal areas. However, with the recent evolution towards the study of complex motor tasks and the manipulation of various factors, these brain structures have come to be seen as an integral part of a network involved in the organization of skilled movement. Identifying these brain regions and their associated functions is of importance for an enhanced understanding of human behaviour.

2. Motor skill complexity

Some motor tasks are performed with ease whereas others are complex, requiring considerable effort. Hence, which facets determine whether a motor action is experienced as complex or not? Picard and Strick (1996) specified that motor complexity co-varies with the pattern of brain activation, and thus the degree of information processing. Accordingly, it can be assumed that neural functioning will be affected by restrictions on information processing. One example refers to the postponed selection of a response when two stimuli occur in rapid succession. This delay known as the psychological refractory period suggests that response selection constitutes a critical processing constraint (Pashler, 1994) or a limitation on cognitive resources that relies on a supervisory system (Logan and Gordon, 2001; Schumacher et al., 2001).

While complexity is an often used concept, it is difficult to operationalize it in an experimental context. Some researchers have drawn on definitions developed in mathematics, information theory and physics such as entropy and randomness. Accordingly tools have been developed to quantify complexity, resulting in explicit measurements such as the Kolmogorov index that describes the length of an algorithm for generating a given number sequence (Tononi et al., 1998). Generally the dictionary defines complexity as ‘‘an entity that is composed of a number of interconnected parts’’. More complex implies more distinct components and/or more connections between them. Hence, the duality of component (sequential elements) and connection (coordinative elements) determines two key dimensions that underlie complex behaviour. In terms of movement regulation, complexity reflects a crucial concept as motor tasks with high degrees of intricacy are commonly performed. Indeed many aspects of our motor behaviour are embedded in a sequential or coordinative framework. In this respect, sequential complexity entails movement responses that vary along a spatial (ordinal) and/or temporal component, e.g., the number of responses required, and the timing and order in which they occur. Harrington et al. (2000) have suggested that sequence complexity can be characterized by surface properties (such as the types of effectors and the number of movements) and a sequence-specific structure (such as the relations amongst the movements). Conversely, coordinative complexity involves the simultaneous performance of different effectors, giving rise to particular combinations of spatial and temporal association. Coordinative complexity has also been viewed in terms of deviations from basic coordination constraints that involve the egocentric principle (moving the limbs according to mirror symmetry) or the allocentric principle (moving the limbs in the same direction in extrinsic space) (Swinnen, 2002). Sequential or coordinative assignments can become very specialized and sophisticated as in sports, musical performances and work environments. Accordingly complex tasks typically entail a hierarchical organization, capturing the notion that their control does not involve decomposition into individual components or simple motor acts (Cordo and Gurfinkel, 2004).

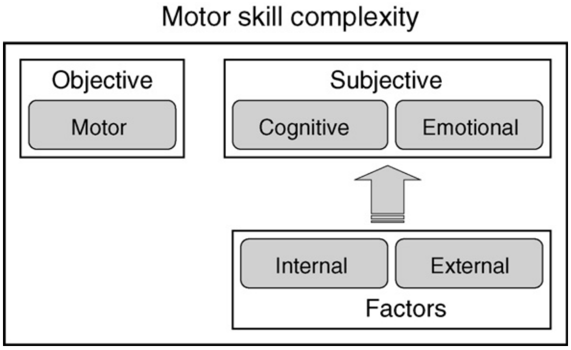

Fig. 1. Motor skill complexity. Whereas the motor dimension represents objective complexity, the cognitive and emotional dimensions refer to how complexity is experienced subjectively. The latter is influenced by external (environment-related) and internal (performer-related) factors, causing the subjective experience associated with the motor task to be variable and dynamic in contrast to the objective experience that is relatively fixed.

In this paper, we propose that taking into account sequential and coordinative dimensions is valuable for understanding the neural processes that are recruited during complex motor tasks. We first elaborate on the neural networks that underlie sequential and coordinative complexity, followed by evidence of the changes in these circuits induced by external (environmental-related) and internal (performer-related) factors. We will demonstrate that these aspects play a significant role in determining the pattern of neural activity, exposing in large part the degree of cognitive control; the ability of the brain to organize processing in relation to goals (Miller and Cohen, 2001). Next, we discuss the allocation of cognitive resources, with a particular emphasis on attention, and discuss the prime frontal lobe areas that are implicated. In exploring these issues, we draw on observations from healthy controls as well as from neurologically impaired populations. We focus here in particular on motor control that entails limb movements rather than skills such as speech or handwriting that are closely associated with cognitive elements.