Phenom Cogn Sci (2015) 14:349–359
DOI 10.1007/s11097-014-9376-9

Unreflective actions? complex motor skill acquisition to enhance spatial cognition

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Published online: 6 July 2014

Abstract Cognitive science has recently moved toward action-integrated paradigms to account for some of its most remarkable findings. This novel approach has opened up new venues for the sport sciences. In particular, a large body of literature has investigated the relationship between complex motor practice and cognition, which in the sports domain has mostly concerned the effect of imagery and other forms of mental practice on motor skill acquisition and emotional control. Yet recent evidence indicates that this relationship is bidirectional: motor experience also influences higher cognition, with a broad range of cognitive abilities being impacted in various ways. In this paper, I review the latest research exploring the effect of complex motor practice on spatial cognition. After emphasizing the versatility of processes that are recruited in the acquisition of complex motor skills, I present further experimental evidence to suggest that the process of acquiring new motor skills triggers specific adaptions in the brain, which in turn can be critical in numerous aspects of daily life. Finally, I propose a mechanistic explanation to account for motor-induced improvements, within an embodied framework of cognition.

Keywords Motor cognition · Embodied cognition · Spatial ability · Complex motor skills · Cognitive training · Neuroplasticity

1 Introduction

The motor system is involved in a wide variety of our actions. Catching a ball, performing a somersault, or running across a football field while trying to avoid being tackled. Less evidently, storing content in memory, performing a complex spatial task, or describing an event to a friend. Beyond its primary function of enabling movement, the motor system has been associated with numerous domains of experimental studies, such as visual perception (Flanagan and Johansson 2003), attention (Schuch et al. 2010), working memory (Moreau 2013b), spatial cognition (Moreau 2012a), and

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language (Beilock et al. 2008; Holt and Beilock 2006). This ubiquity has led some researchers to argue that cognition is based on motor simulation, and therefore that our body constraints have profound influence over cognitive processing (Barsalou 1999; Clark 1997; Glenberg 1997). The consequences of such a theoretical position reach far beyond quarrels over the reappraisal of the motor system to a more central place in our behaviors. Rather, it calls for a profound change in the way we study and interpret human behavior as a whole, within interactive and dynamic environments. Based on recent findings in cognitive psychology and neuroscience, I argue in this paper that sensorimotor experience influences cognition, by enabling the motor system to support a wide range of cognitive processes.

The case for a central importance of motor processes in cognition is supported by research on the mirror neuron system (Rizzolatti and Craighero 2004), which emphasizes motor simulation in the process of action observation. The properties of this system help to explain, for example, the capacity for humans to learn by imitation (see for a review Oztop et al. 2006). This body of work also highlights the social role of mirror neurons in the understanding of others' actions and behaviors (Wilson and Knoblich 2005), thus underlining the generic involvement of the motor system beyond individual behaviors. Because of their obvious importance in motor learning, these mechanisms have been largely exploited in the sports domain, to improve movement acquisition, reduce undesirable variability and enhance overall performance.

In sports, a substantial body of work has established the role of motor imagery on performance (e.g. Munzert and Lorey 2013), further refining the dependence of neural networks activated in covert and overt actions (Jeannerod 2001). Although not exempt from caveats (Dietrich 2008), this line of research has proven extremely fruitful to provide applied support for the motor cognition framework. Motor simulation, in the absence of overt action, allows learning, correcting, and fine-tuning motor commands, with important consequences on performance (Jeannerod and Decety 1995). However, as the framework postulates common neural mechanisms and processes in motor execution and motor simulation, these alterations should be bidirectional – in other words, the repetition of overt actions should impact motor simulation (de Lange et al. 2008), and by extent, other cognitive processes that rely on some form of motor simulation. The idea that prior sensorimotor experience shapes cognitive reasoning will be central in this paper.

A note on the scope of this paper. The interrelation between motor processes and cognition is a vast topic, with numerous areas of investigations (see for a recent discussion Engel et al. 2013). In this review, I will focus on the motor underpinnings of *spatial* cognition, for two reasons, theoretical and practical, respectively. First, although spatial and motor mechanisms have been dissociated in areas such as perception (Smeets and Brenner 1995) and working memory storage (Wood 2007), for example, both domains remain highly interdependent, as we shall see hereafter. Knowing where an object is in space and the actions that can be performed on it or with it are intrinsically related properties, usually processed together. Second, spatial cognition is known to be critical in many academic and professional fields, but remains underrepresented in school curriculums (Moreau 2012b). This is slowly changing, based on latest research findings growing public awareness, but additional measures could be implemented, with sports at the core of effective interventions.

A related note concerning the focus of this paper – and of this special issue – on sports. Quite evidently, complex motor skill acquisition is not a specificity of the sports domain. Other activities, such as playing a musical instrument, some forms of art, and numerous kinds of practice-dependent professional activities require considerably challenging motor aptitudes. The sports domain includes, however, particularities in the way motor sequences are implemented. In most activities, the environment is highly challenging, due to constraints in space and time. Opponents look for ways to ensure each other's failures, in a codified manner, resulting in particularly intense confrontations. In such environments, motor skills have to be adjusted at all times, and adapted to the particular situations encountered. These adaptive properties are critical to optimize cognitive improvements (Shipstead et al. 2012), an idea we will return to shortly.

2 The versatility of processes involved in motor learning

Consistent with other forms of learning, motor learning is not linear. In the process of acquiring a diverse repertoire of motor sequences, one goes through successive stages, each involving different demands, an idea already established in early work by Fitts and Posner (Fitts and Posner 1967) and later refined by Schmidt (Schmidt 1975; Schmidt and Lee 1998). Based on this work, learning a new movement includes three successive stages: stimulus identification, response selection, and response programming (Schmidt and Lee 1998). The acquisition of motor sequences requires adequate levels of performance in each of these stages (Tenenbaum 2003), thus involving relatively diverse neural mechanisms in the process.

Recent neuroimaging evidence has confirmed the wide range of cortical structures recruited in motor learning, based on studies of various experimental design and structure, such as phase coordination paradigms (Puttemans et al. 2005; Remy et al. 2008), adaptive movements in unstable environments (Inoue et al. 2000; Nezafat et al. 2001), or even more complex motor patterns (Buccino et al. 2004; Tracy et al. 2003). This line of work further underlines the complexity of motor learning, and contrasts with dichotomist views separating higher cognitive processing and lower motor networks. Motor learning involves a diverse set of processes, depending on stages of learning, motor demands, and previous experience.

Because of the versatility of processes involved in motor learning, researchers have explored elite athletes' performance in various tasks in the laboratory. Over the years, they have accumulated evidence demonstrating that elite athletes excel in numerous domains, such as perception (Wright et al. 2011), attention mechanisms (Memmert and Furley 2007), decision-making (Raab and Johnson 2007), spatial ability (Moreau et al. 2011), working memory (Furley and Memmert 2010) and long-term memory (Dijkstra et al. 2008). In an observational study with athletes of various levels, my colleagues and I pointed out that some of the discrepancies between elites and novices might be based on differences in strategies when facing a particular problem (Moreau et al. 2011), a finding that was later corroborated by a training design (Moreau et al. 2012) and consistent with work by independent research groups (e.g. Güldenpenning et al. 2011). Additional evidence has confirmed and extended on these initial findings, elite athletes showing higher abilities in different spatial ability tasks (e.g. Jansen and Dahmen-Zimmer 2012; Pietsch and Jansen 2012).

Altogether, these findings suggest that motor activities provide a suitable environment to develop spatial ability. Nevertheless, observational studies such as detailed previously do not present sufficient evidence for a directional effect of complex motor skill training on cognitive processing. As these studies usually compare elite and novice athletes in laboratory tasks at a specific time point, it is not possible to distinguish between practice effects and other confounds, such as preferences and predispositions, for instance. The answer to this issue is, however, quite straightforward: well-designed training experiments, tracking performance over an adequate period of time. The following section presents experimental work that falls into this category.

3 Beyond theoretical assumptions: enhancing spatial cognition via motor training

Recent behavioral research in the field of cognitive enhancement has shown disparate results, especially concerning transfer to non-trained tasks (see for a recent review Moreau and Conway 2013). Targeting cognitive improvements via complex motor activities represents, however, a promising venue for applied research (Moreau and Conway 2014). A pilot study demonstrated that training in a complex activity, wrestling, once a week for an academic year led to improvements in mental rotation, an ability known to be highly correlated with performance in numerous professional fields (Moreau et al. 2012). Conversely, the same amount of practice in running, an activity including high physical effort but arguably lower cognitive demands, did not induce similar improvements. These findings suggest that the spatial skills trained and enhanced by wrestling can benefit other spatial tasks, outside the scope of sports practice. This is particularly informative given the scarcity of transfer effects from training studies in cognitive psychology. However, the absence of multiple tasks measuring spatial ability prevented strong claims regarding transfer to a spatial ability construct. Some task-specific components of the mental rotation task used in the study could have been responsible for the observed effects, independently from a more general transfer pattern. In addition, the extent to which benefits compared to traditional cognitive training paradigms (e.g. working memory training) was not directly assessed in this experiment.

These limitations were addressed in a subsequent study (Moreau et al. 2013). To test the efficacy of a complex motor activity to enhance cognitive abilities against other forms of behavioral training, participants were randomly assigned to one of three conditions: working memory training, physical exercise and designed sport – an intervention specifically tailored to include both physical and cognitive demands. After training for 8 weeks, the designed sport group presented the largest gains in spatial ability and working memory, whereas working memory training and physical exercise resulted in weaker overall improvements. Besides cognitive gains, designed sport training also induced health benefits, a definite advantage over traditional computer-based training program. Taking part in designed sport training allowed targeting critical physiological markers of health and longevity, offering an interesting means to prevent or delay naturally occurring cognitive decline associated with aging, for example. These results are novel and need replication, as well as the identification of the specific neural alterations underlying behavioral changes. Yet, they provide strong arguments to suggest that motor problems can generalize to tasks that do not require motor learning.

The combination of motor and cognitive demands is not exclusively restricted to sports. As alluded to earlier in this paper, this line of work mirrors research in a related domain of expertise, music. Although learning an instrument is rarely compared with the kind of practice that takes place in sports, these activities share important similarities, as they are based on mastering motor sequences to be subsequently performed in a codified and activity-specific environment. Studies in the music domain have shown that musicians go through substantial cognitive changes when learning an instrument (see for a review Herholz and Zatorre 2012). For example, a training study pointed out that music reading triggers corresponding motor sequences (e.g. finger patterns on a keyboard), even in the absence of overt action (Stewart et al. 2003), suggesting that learning an instrument involves durable mapping of visuospatial codes with motor patterns. In addition, reading music was shown to modify spatial processing in pianists, even in tasks not directly related to music, suggesting that acquired visuomotor mapping transfers across domains (Stewart et al. 2004). This line of work emphasizes the often-overlooked similarities between sports and music, from a motor standpoint – a parallel that helps to understand the effectiveness of training programs based on either of these domains to enhance cognitive abilities.

4 Motor-induced improvements in spatial cognition: a mechanistic view

Considering that the motor system is involved in a wide variety of processes, even in the absence of overt action, it seems reasonable to expect that changes in motor networks could induce changes in general cognitive processing. This idea is in line with an impressive body of experimental evidence showing the influence of the motor system on perception (Skippera et al. 2005), memory (Dijkstra et al. 2007; Dijkstra et al. 2008), concept knowledge (Borghi et al. 2004; Connell 2007), and language comprehension (Gallese and Lakoff 2005; Glenberg and Gallese 2012; Glenberg and Kaschak 2003; Zwaan and Taylor 2006).

The notion of a direct relation between the motor system and other cognitive processes is further supported by compelling evidence showing that action observation induces different patterns of simulation depending on whether or not a particular action is part of one's motor repertoire (Calvo-Merino et al. 2006). In this study, the authors compared cortical activation in male and female dancers observing dance moves either from their own repertoire or from the other gender's repertoire. They found greater premotor, parietal and cerebellar activation when dancers viewed moves from their respective motor repertoire, compared to moves they have not practiced. In other words, action simulation depends on one's motor experience, which in turn leads to differences in action understanding.

Because of their inherent dynamic properties, spatial problems have long been prime candidates to demonstrate the interrelation of motor and cognitive problems. Over three decades ago already, anatomical constraints were shown to affect mental rotation (Sekiyama 1982). This finding was corroborated a few years later (Parsons 1987) and is consistent with more recent motor simulation theories of cognition postulating the involvement of motor processes in a wide range of cognitive mechanisms (see for example Jeannerod 2001; and Jeannerod and Decety 1995). To fully understand these mechanisms, however, a critical step was to assess the extent of such findings beyond the manipulation of body parts. In two important studies, congruent hand movements were found to improve mental rotation speed (Wexler et al. 1998) and accuracy (Wohlschläger and Wohlschläger 1998). This phenomenon was later shown to be independent from spatial equivalence between overt and covert actions (Schwartz and Holton 2000). Therefore, imagined and executed movements need not be identical to induce facilitation. This trend of research is also consistent with work showing the involvement of motor processes in spatial reasoning tasks (Amorim et al. 2006; Steggemann et al. 2011; Wraga et al. 2003) and facilitation effects induced by gestures in spatial problem solving (Chu and Kita 2011; Janczyk et al. 2012), and has been corroborated by neuroimaging studies showing premotor (Lamm et al. 2007) and motor (Richter et al. 2000) cortical activation in mental rotation of abstract objects.

Although compelling, these findings were nonetheless challenged by a series of neuroimaging studies showing no or little activation of motor cortex in mental rotation of abstract objects (Harris et al. 2000; Jordan et al. 2001; Kosslyn et al. 1998; Vingerhoets et al. 2002). What could be responsible for these rather substantial discrepancies (see for a review and meta-analysis Zacks 2008) among the spatial cognition literature? A closer look at this apparent issue reveals a more complex pattern than previously thought, based on intra and inter-individual variations. For example, one of our training studies demonstrated that individual strategies in mental rotation evolve with motor expertise (Moreau et al. 2012), a finding in line with previous cross-sectional research comparing elite and novice athletes (Moreau et al. 2011). Therefore, assessing mental rotation performance and strategies at a particular time point is informative for this particular moment in time, but it might correlate more or less with past or future performance depending on individual experiences.

Additional evidence for the interrelation between motor experience and spatial cognition comes from the study of elite athletes. In this regard, mental rotation paradigms have been extremely fruitful because of the diversity and the malleability of strategies required to solve this type of problems. A recent study showed that although most individuals recruit visual processes when presented with spatial problems such as mental rotation tasks (Hyun and Luck 2007), elite wrestlers favor motor processes to perform the same tasks, with better overall performance, as demonstrated by different detrimental effects of concurrent load of visual or motor content across individuals, depending on whether visual or motor processing is favored (Moreau 2012a). In particular, motor experts who naturally favor motor processes to solve spatial problems were more affected than non-experts when forced to concurrently attend additional motor content, whereas the converse was true when motor experts and non-experts were exposed to additional visual content. These findings suggest that different individuals recruit different processes to do the same task, and that the underlying mechanisms may evolve with experience and exposure to motor content.

To further understand how these processes interact, a related study looked at mental rotation of hands and polygons in elite wrestlers and non-athletes. In previous research, mental manipulation of hands and other body parts has shown to implicitly trigger motor simulation (Georgopoulos and Massey 1987; Parsons 1987, 1994; Pellizzer and Georgopoulos 1993; Sekiyama 1982), whereas abstract shapes such as polygons do not consistently induce such motor activation (Harris et al. 2000; Jordan et al. 2001; Kosslyn et al. 1998; Vingerhoets et al. 2002). In addition, motor restriction has shown to disrupt mental rotation performance when motor simulation is required (Ionta and

Blanke 2009; Ionta et al. 2007), in line with similar research on action observation (Ambrosini et al. 2012) and with work on the visual system showing that visual cortex activation differs if active interaction with stimuli is permitted, compared with passive viewing (Gallant et al. 1998; Mazer and Gallant 2003; Niell and Stryker 2010). Consistent with this body of research, both elite wrestlers and non-athletes exhibited poorer performance in mental rotation of hands when their ability to move was artificially restricted, whereas under identical constraints only wrestlers' performance dropped in the mental rotation of polygons (Moreau 2013a).

Besides confirming that motor experts rely on motor processes to perform spatial tasks, these findings also demonstrated that such strategies are not easily adaptable and are deeply engrained within motor experts reasoning procedures. More flexibility would allow switching to a different system – visual, for example – to overcome the problem of motor constraint. An alternative hypothesis is that experts do switch to the visual system, but because it lacks substantial practice in solving this kind of problems it remains less effective. Regardless of the specific underlying mechanism, the absence of a successful flexible behavior corroborates the idea of strongly entangled motor and spatial processes in motor experts.

This phenomenon is not restricted to spatial ability tasks. Similar patterns of results were also found in working memory tasks. For example, motor expertise induced recruitment of different processes when storing body configurations for further recall. Specifically, motor experts were more prone to motor distraction than non-athletes when presented with movements to remember, whereas the reverse was true in the face of verbal distraction (Moreau 2013b). Following an extensive body of literature on dual-task paradigm demonstrating a distinction between visual and motor content in working memory (Smyth et al. 1988; Smyth and Pendleton 1989, 1990, 1994; Wood 2007, 2011), this study suggests the contribution of different processes to store movements depending on motor experience, namely verbal for controls and motor for experts.

Altogether, these findings provide strong support for an experience-dependent view of motor cognition, in which the involvement of the motor system heavily depends on previous interactions with the environment. This idea opens up new venues for training programs based on complex motor skills (Moreau and Conway 2014). For example, one interesting way to target cognitive enhancement is to combine cognitive and physical demands within specifically designed activities. These activities could provide the basis for cognitive and physiological improvements, in line with what we have observed in our experiments (Moreau et al. 2012; Moreau et al. 2013). In addition, this approach allows great flexibility over training content, which can allow important adjustments based on individual needs and requirements. Flexibility is also critical to accommodate clinical populations, such as Alzheimer or Parkinson patients, or to integrate these training designs within rehabilitation programs, for instance after a stroke. Consistent with this idea, a current line of research in cognitive training aims to identify the underlying mechanisms driving improvement for some individuals but not for others, in order to provide a more personalized approach. These are ongoing research questions with no definitive answer at this point, but training programs based on motor activities have the potential to provide a refreshing and potent solution to such applied problems.

5 Conclusion and future directions

In this paper, I have argued for the role of complex motor activities to develop spatial skills based on the intertwined coupling between spatial cognition and action. After presenting the variety of cognitive processes involved in complex movements, I have provided evidence for the suitability of motor training to enhance spatial cognition, in an ecological fashion. Finally, the last section presented a mechanistic view of motor-induced improvements in spatial ability, based on the latest research in the field of motor cognition.

The work presented herein further underlines the complexity of actions in sports – the acquisition of complex motor skills triggers a cascade of adaptations, which favors, and is in turn favored by, the development of cognitive processes. In the sports domain, such actions may appear unreflective from an outsider's standpoint, because of their high degree of automatism, but the line of work introduced in this paper suggests that this should not be mistaken for low cognitive demands inherent to the activity itself.

The theoretical framework laid out in this paper allows more informed predictions regarding the particular processes involved in spatial cognition. In addition, it helps to understand the specific abilities that are being targeted in sports, and further emphasizes the highly cognitive component of motor skill acquisition. The critical validation of such a framework lies within interventional paradigms – if motor activities influence cognition, and if this effect is not context-specific, suitably designed motor training should induce general cognitive alterations, that is, changes that transfer to different context. Work in this field of research is novel and promising, with exciting early findings, and additional evidence is needed to confirm and extend on these initial findings.

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