7 Physical Exercise and Cognitive Enhancement

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Introduction

Perhaps counterintuitively, one of the most effective ways to look after one's brain is physical exercise. This idea is not yet fully engrained in common views of cognition – despite current scientific efforts emphasizing the interplay between brain and body, the Cartesian notion of a duality between the two is long-lived. However, evidence showing the importance of a healthy body for a healthy mind is rapidly accumulating, and the influence of physical fitness and exercise in this regard is well documented. Combining behavioral, neural, and neurobiological findings, this line of research is complemented by theoretical frameworks in cognitive science, together providing convincing support for the relationship between cognitive and motor systems. In this chapter, we review the evidence for the effect of physical exercise on cognition and the brain, discuss current trends of work exploring the potential of physical exercise – and particularly of complex motor activities – to enhance cognition and to remediate learning difficulties, and finally suggest promising directions for future research.

Cognitive Benefits of Physical Exercise

Numerous benefits of physical exercise have been documented over the last few decades, including a wide range of physical and mental health improvements.

For example, in observational studies, physical fitness appears to be associated with reduced occurrences of potentially fatal conditions, such as cardiovascular diseases, cancers, strokes, and diabetes (Blair 1995). Even more aligned with the perspective of this chapter, reduced risks in several cognitive or neurological conditions have also been reported. Neurological conditions such as autism, attention deficit/hyperactive disorder (ADHD), schizophrenia, dementia, and Alzheimer's disease all appear to be worsened by poor physical fitness, and to benefit from exercise interventions (Penedo & Dahn 2005). Importantly, this effect is not contingent on preexisting deficits, and can be generalized to non-clinical populations – physical exercise seems to be related to better cognitive function regardless of cognitive impairment. As such, individuals with better indices of physical fitness tend to perform above average on executive function tasks and spatial reasoning problems (Colcombe & Kramer 2003; Hillman, Erickson, & Kramer 2008). Although a few studies have suggested that the association between physical activity and performance is weaker when considering tasks that do not primarily tap executive function (Kramer, Hahn, & Gopher 1999), complementary findings support the idea of a strong relationship between physical exercise and a wide range of cognitive tasks (see for a review Moreau & Conway 2013).

Building upon this line of research, additional work has intended to elucidate the mechanisms underlying the association between physical fitness and cognitive health. In particular, and consistent with typical concerns when considering findings from observational studies, an important question is whether the link is causal or driven by confounding factors. Several studies have attempted to shed light on this issue. For example, exercise interventions have led to attention improvements in children with developmental coordination disorders (Tsai, Wang, & Tseng 2012) and in overweight children (Davis et al. 2007). A substantial body of research has also explored the relationship between physical activity and academic performance. Students who follow physical activity guidelines tend to have better grades than those who do not (Coe, Pivarnik, Womack, Reeves, & Malina 2006), while reading and mathematics competencies tend to correlate with measures of physical fitness (Castelli, Hillman, Buck, & Erwin 2007). These are not isolated cases – the literature concerning the relationship between physical exercise and academic achievement is well documented, with clear and robust findings (Keeley & Fox 2009).

Therefore, and perhaps contrary to popular belief, decreases in the amount of physical activity at school *negatively* impacts academic performance (see for a review Trudeau & Shephard 2008). Common responses to poor school achievement such as replacing physical education classes with so-called core academic components (i.e. English, mathematics) are thus profoundly counterproductive and worsen the problem they are intended to fix (Goh, Hannon, Webster, Podlog, & Newton 2016; Mahar et al. 2006; Trudeau & Shephard 2008). This is an important point of this chapter, since the work linking physical exercise and cognition is perhaps not appreciated as much as it deserves outside of exercise science and kinesiology, especially considering the vast amount of work that has been dedicated to explaining its mechanisms and ramifications.

At the other end of the lifespan continuum, physical exercise has also been found to be fundamental to healthy aging, leading to better associative learning (Fabre, Chamari, Mucci, Massé-Biron, & Préfaut 2002), better quality of life and general cognition (Cancela Carral & Ayán Pérez 2007), and enhanced mood and emotional stability (Blumenthal et al. 1991), although it should be noted that these findings have been questioned by a recent meta-analysis (Young, Angevaren, Rusted, & Tabet 2015). To be fair, we should point out that exercise interventions is an umbrella term and that these regimens come in many different flavors, in terms of type of training, duration, frequency, sample population, outcome measures, and several other factors. Therefore, pooling such disparate interventions together using meta-analytic techniques is only informative up to a point – eventually, what needs to be determined is not so much the absolute effectiveness of exercise interventions but the potential mediators of sizeable effects (Moreau 2014). What works and for whom, and under which circumstances, remains to be informed by future research.

When examined in isolation, the literature on young and middle-aged adults is slightly less consistent, for several reasons. Arguably, such individuals might be at their natural cognitive peak, thus making any large improvement difficult (Salthouse & Davis 2006). Given the lack of power most intervention studies suffer from by design, effects often need to be quite substantial to be detected. Adults typically experience environments that are typically complex and stimulating – these provide naturally enriched conditions, leaving little room for cognitive gains. From a research standpoint, there might also be smaller incentives to target non-clinical adult populations, as opposed to children, the elderly, or clinical populations, who all can greatly benefit from exercise interventions.

Structural and Functional Changes in the Brain

Importantly, cognitive improvements are typically accompanied by changes in brain structure and function. Due to the aforementioned difficulties of detecting such changes in adult populations, this line of research is mostly based on evidence in children and the elderly. For example, several studies indicate that children show greater integrity in two main neural networks after a physical exercise intervention: the uncinate fasciculus (Schaeffer et al. 2014), a white matter tract connecting parts of the limbic system and the prefrontal cortex; and in the superior longitudinal fasciculus (Krafft et al. 2014), a long bundle of axons linking frontal and occipital lobes, and part of parietal and temporal lobes. This line of research is based on Diffusion Tensor Imaging (DTI), an MRI technique that allows probing the brain's white matter tracts through detailed mapping of water molecules diffusion. Cross-sectional studies support the hypothesis of an effect of physical exercise on brain structure, via evidence for differences in white matter integrity between higher and lower fit children (Chaddock-Heyman et al. 2014).

In older adults, studies have shown that exercise interventions can counteract age-related brain atrophy (Colcombe et al. 2003), and that this effect might mediate the association between aerobic fitness and executive function (Weinstein et al. 2012). Higher physical fitness has also been associated with larger cortical areas, especially frontal regions (Weinstein et al. 2012), and larger hippocampus (Erickson et al. 2009; Makizako et al. 2015). Training interventions corroborate these findings, showing volume increases in frontal (Colcombe et al. 2006; Ruscheweyh et al. 2011) and hippocampal (Erickson et al. 2011; Ruscheweyh et al. 2011) areas after undergoing physical exercise training.

More subtle functional changes have also been documented. Until recently, most of this evidence in children was based on correlational findings, reporting an association between aerobic fitness or physical exercise and brain function mostly based on fMRI and EEG techniques (Chaddock et al. 2012; Moore, Drollette, Scudder, Bharij, & Hillman 2014). However, this line of research has also been strengthened by experiments (RCTs) highlighting the benefits of a physical exercise intervention on brain function (Chaddock-Heyman et al. 2013; Davis et al. 2011; Hillman et al. 2014; Kamijo et al. 2011). In parallel, cross-sectional evidence for the relationship between physical exercise and brain function is available for older populations (Berchicci, Lucci, Perri, Spinelli, & Di Russo 2014; Prakash et al. 2011; Smith et al. 2011), and these are also supported by more direct experimental findings (Chapman et al. 2013; Colcombe et al. 2004; Smith, Nielson, Woodard, Seidenberg, & Rao 2013). Specifically, physical exercise is associated with increased connectivity between prefrontal, cingulate, and hippocampal areas, which results in better performance on several cognitive tasks (Burdette et al. 2010; Voss et al. 2010).

Besides promising evidence at the behavioral and neural levels, the association between physical exercise and cognition is also consistent with findings at the neurobiological level, which help explain the mechanisms responsible for the observed correlations or improvements. Seeking corroborating evidence at the neurophysiological level is akin to zooming in further, from overt behaviors and neural correlates at the system level to their underlying mechanisms. This line of work is discussed in the next section.

Neurobiological Mechanisms of Exercise-Induced Improvements

Most of the neurobiological correlates of exercise-induced cognitive enhancement are now well understood (for a detailed account of the changes associated with exercise, see McMorris & Corbett 2016). Physical exercise leads to an increase in cerebral vascularization (Black, Isaacs, Anderson, Alcantara, & Greenough 1990), proteins and neurotransmitters (Mora, Segovia, & del Arco

2007), heightened insult resistance (Stummer, Weber, Tranmer, Baethmann, & Kempski 1994), enhanced neurogenesis (van Praag et al. 2002), synaptic metabolism (Vaynman, Ying, Yin, & Gomez-Pinilla 2006), angiogenesis (Black et al. 1990), neuronal survival (Vaynman et al. 2006), and enhanced overall brain volume (Colcombe et al. 2006). More specifically, brain-derived neurotrophic factor (BDNF) appears to play an active role in mediating the effect of physical exercise on cognition. Animal studies have found increases in hippocampal BDNF post-exercise (Neeper, Gómez-Pinilla, Choi, & Cotman 1995), particularly significant considering the central role of the hippocampus in learning and memory and its deterioration in many degenerative diseases including Alzheimer's. These effects have been found to last at least several weeks (Berchtold, Kesslak, Pike, Adlard, & Cotman 2001), therefore potentially playing a critical role in exercise-induced neural plasticity. Besides its effect on hippocampal areas, BDNF also increases post-exercise in the spinal cord (Gómez-Pinilla, Ying, Opazo, Roy, & Edgerton 2001), the cerebellum and several cortical regions (Neeper, Gómez-Pinilla, Choi, & Cotman 1996), possibly through increased levels of Insulin-like Growth Factor-1 (IGF-1), a growth factor involved in neuronal development (Arsenijevic & Weiss 1998). Based on this evidence, it has been suggested that IGF-1 might be a key determinant in the effect of physical exercise on BDNF levels (Cotman & Berchtold 2002), and thus on cognition more generally.

Increased BDNF levels in cortical areas are consistent with the documented effects of exercise on serum BDNF (sBDNF). Several studies have found that exercise induces an augmentation in sBDNF levels (Griffin et al. 2011; Schmolesky, Webb, & Hansen 2013), typically within a few hours, with the magnitude of the increase dependent on exercise intensity (Ferris, Williams, & Shen 2007). Thus, these findings provide additional support for the idea that aerobic exercise might not be the most optimal way to target cognitive improvement in healthy individuals, and that more intense forms of exercise could induce larger gains.

Overall, the remarkable consequence of these potent underlying mechanisms is that physical exercise provides a powerful way to stimulate general health. In addition to favoring positive changes, exercise also allows controlling harmful factors, such as stress. Corticosteroids, or stress hormones, have a damaging effect on BDNF concentration, and can therefore, if sustained, lead to neuronal degradation and dendritic atrophy (Gould, Woolley, Frankfurt, & McEwen 1990). Exercise prevents this debilitating effect by blocking downregulations of BDNF, particularly in the hippocampus (Russo-Neustadt, Ha, Ramirez, & Kesslak 2001). Further evidence has highlighted the impact of exercise on levels of monoamine neurotransmitters (e.g. dopamine, epinephrine, norepinephrine) and tryptamine neurotransmitters (e.g. serotonin, melatonin), which could be responsible for some of the benefits typically observed after physical training (Winter et al. 2007). This line of research therefore provides compelling evidence for the role of neurobiological factors in mediating the behavioral changes typically observed post-exercise.

The Embodied Cognition Framework

The coherent view emerging from the integration of behavioral, neural, and neurobiological findings also resonates well with motor theories currently getting traction in cognitive science (e.g. Jeannerod 2001). In particular, the embodied cognition framework (e.g. Barsalou 2008; Gallese & Sinigaglia 2011; Glenberg 2010) argues that the motor system is involved in most of our actions, and that motor processes influence cognitive function drastically.[1] Although legitimate criticisms have been raised against several findings and their embodied interpretation (Wilson 2002) or about the way the embodied framework is typically defined (Wilson & Golonka 2013), the framework remains informative to further understand the link between physical exercise, motor activities, and cognition.

Moreover, the embodied cognition framework is corroborated by numerous compelling findings, which indirectly support the link between exercise and cognition, and by extension the potential of motor activities to enhance cognition. For example, prior work has shown that different levels of motor expertise are associated with differences in performance on motor processing (Güldenpenning, Koester, Kunde, Weigelt, & Schack 2011). These findings also extend beyond motor tasks – spatial ability (Moreau 2012) and working memory capacity tasks (Moreau 2013), good indicators of cognitive abilities known to be central to human cognition (Carroll 1993) and to have tremendous ramifications on numerous everyday tasks (Hegarty & Waller 2005; Kane et al. 2004), are also influenced positively by motor expertise.

In addition, other components of cognition, such as the ability to solve complex problems, are improved when gestures are consistent with the motor actions naturally associated with a particular task, suggesting that gestures ground mental representation in action (Beilock & Goldin-Meadow 2010). Further research indicates that such associations are also found in linguistic domains, with motor actions influencing language comprehension (Holt & Beilock 2006), a finding corroborated by neural changes in language comprehension depending on motor experience (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small 2008).

Beyond these correlational associations, experimental evidence has also demonstrated that the link is causal – motor training leads to enhanced performance on spatial ability and working memory capacity tasks (Moreau, Clerc, Mansy-Dannay, & Guerrien 2012; Moreau, Morrison, & Conway 2015), and these behavioral changes are mediated by cortical changes (Adkins, Boychuk, Remple, & Kleim 2006). This line of research paves the way for interesting applications intended to target cognitive gains via behavioral interventions, which we discuss in the next section.

Beyond Mere Physical Exercise: Complex Motor Activities

The effect of physical exercise on cognition is well documented and largely replicated – alternative forms of cognitive enhancement based on behavioral interventions can hardly compare with the extensive literature linking physical exercise and cognition (see for a review Moreau & Conway 2013). However, that physical exercise appears to be one of the most effective ways to trigger substantial and durable changes does not mean that it should be exclusive – adequate combinations can provide interesting benefits over interventions solely based on physical exercise.

Approaches seeking to combine cognitive training activities have flourished in the past few years. For example, research has investigated the potential of combining physical exercise with meditation (Astin et al. 2003), with cognitive training (Shatil 2013), or with transcranial Direct Current Stimulations (tDCS; Ditye, Jacobson, Walsh, & Lavidor 2012; Madhavan & Shah 2012; Martin et al. 2013; Moreau, Wang, Tseng, & Juan 2015). These approaches all have merit of their own, as they represent a step toward more advanced frameworks of cognitive enhancement. Yet they typically combine two successful approaches separately – interventions focus on the different types of regimen either successively or in an interleaved fashion. This approach might be suboptimal considering the opportunity costs associated with cognitive training and techniques of enhancement (Moreau & Conway 2014). In addition, the potential side effects of these interventions can possibly be concerning, whether it is the psychiatric risks of mindfulness meditation (Lazarus 1976; Shapiro 1992) or the inherent blur over techniques that stimulate the brain with direct current (Davis 2014).

In a recent study, we tested the idea of integrating cognitive demands within a physical exercise regimen as an optimal solution to cognitive enhancement (Moreau, Morrison, & Conway 2015). The rationale was that aerobic workouts, typically favored in cognitive training interventions based on physical exercise (Hillman et al. 2008), might benefit from additional cognitive challenges. Because aerobic exercise is merely demanding cognitively, most of the cognitive gains typically observed post-training are due to neurophysiological mechanisms, either direct (e.g. BDNF, IGF-1) or in response to changes in a mediating factor, such as sleep or stress. These types of gains are potent, yet in our view they could be further maximized by the addition of specific components directly tapping cognitive abilities. Following this idea, we presented participants with perceptive, motor, and cognitive problems, to solve in a movement-based framework, while continuously sustaining moderate physical activity. Specifically, perceptive problems included situations where participants had to rely on different sensory inputs to make decisions, often including limited visual inputs. In everyday life, most of our motor actions are typically vision-centered; therefore, we hypothesized that depriving individuals of this source of information had the potential to improve processing quality of alternate inputs (see also Landry, Shiller, & Champoux 2013), along with favoring complex computations to circumvent atypical demands. Motor problems were intended to promote unusual motor coordination in three-dimensional space, for example with transitions from different levels of motion (e.g. standing, kneeling, lying). In a way, the underlying idea is somewhat similar to that used in Constraint-Induced (CI) therapy, either in stroke recovery or in motor impairment (Taub, Uswatte, & Mark 2014). Ad hoc motor problems prompted unfamiliar situations that had to be dealt with in a timely manner, based on little prior experience. Finally, cognitive problems included memorizing sequences of movements for subsequent recall and execution, or the presentation of situations where different strategies had to be considered and evaluated in order for participants to respond successfully. Throughout the program, difficulty was adjusted to participants' performance to ensure sustained motivation and continuously challenging material.

Consistent with our initial hypothesis, we found that an integrated approach combining physical and cognitive demands within a single activity was the most effective to induce cognitive and physiological gains. Specifically, we looked at transfer to working memory capacity and spatial ability, cognitive constructs with important ramifications to numerous activities (Moreau 2015). For both of these constructs, the integrated approach based on complex motor activities was superior to either cognitive or physical exercise components alone. In addition to cognitive changes, complex motor training also induced improvements in biomarkers associated with general health, namely blood pressure and resting heart rate, similar to those following the aerobic exercise regimen.

This training intervention lies within a broader line of research, with encouraging early findings. For example, a study assessing the potential for games combining exercise and cognitive challenges has shown promises in school settings, and provide additional evidence for the relevance of an integrated approach (Tomporowski, Lambourne, & Okumura 2011). In addition, several studies have demonstrated that a combination of executive function and physical demands (e.g. martial arts) might be particularly beneficial, especially in children (see for a brief review Diamond & Lee 2011).

Clearly, combining interventions also has pitfalls – researchers need to identify the effect of components in isolation, and a combined regimen can obscure their respective effects or require large sample sizes to compensate for the additional cells in a factorial design. Good experiments allow a comparison of the integrated approach with all the components in isolation – for example, a combination of physical and cognitive training compared with either physical or cognitive training alone, as described previously (Moreau et al. 2015). Obviously, this approach is costly in terms of sample size to achieve adequate power, and brings up problems of its own, such as matching duration, frequency, and motivational factors between regimens. Yet in our view it represents a necessary line of research if this field is to impact society meaningfully.

Taking Advantage of Developmental Plasticity: Applications in the Classroom

As we alluded to in the previous section, adopting an integrated approach also has ramifications in the classroom. In a period of intense neural plasticity, the influence of environmental factors on children is potentially greater than at any other age across the lifespan. This brings tremendous possibilities to teachers, educators, and the educational system in general, but also important responsibilities: the type and strength of learning children experienced will have large effects and repercussions on their lives.

Situations that favor multi-sensory integration of motor and cognitive demands in the classroom should therefore be encouraged. For example, research at the intersection of spatial and embodied cognition shows that the addition of passive or active motor features (e.g. action observation, gestures) helps reinforce learning and ensure it is integrated meaningfully with existing knowledge (Broaders, Cook, Mitchell, & Goldin-Meadow 2007; Cook, Mitchell, & Goldin-Meadow 2008). In addition, structured plays combining cognitive challenges and physical motion are also essential to optimal cognitive development, and school environments are especially suitable to this type of learning. This can come from blends across subjects – for example, physical exercise with mathematics, physics or biology, to understand *and* experience the concepts that are being taught. Facilitating these kinds of translational approaches also provide additional motivational components. More than at any other age, children are interested in novel and diverse items, a feature largely exploited in the preferential looking paradigm on which most psychology research in infants is based (Golinkoff, Hirsh-Pasek, Cauley, & Gordon 1987). Thus, an approach emphasizing diversity in learning content has the potential to remain more appealing to children in the long run.

Finally, through the process of knowledge generalization, transfer emerges given sufficient encounters with particular content (Christiansen & Curtin 1999). This means that multiple explanations of the same ideas are often needed before an idea or a concept is well understood and can be applied more generally. In the context of school learning, it follows that the process of extracting rules can be favored by concurrent or subsequent presentation of the same principle in different situations, either across subjects (gravitational forces in physics and mathematics, heart rate in biology and PE), or within a particular subject (e.g. concept introduced through geometry and further strengthened with algebra). The approach proposed here can help diversify learning content in this regard, a facet that increases chances of proposing content adapted to each individual, based on individual abilities and preferences. The implementation of original pedagogical situations requires creativity, willingness, and effort, but can have tremendous impact on children's experience in the classroom.

Other novel approaches are promising and could contribute further to bringing physical exercise to the classroom (e.g. High Intensity Training, HIT; see Moreau 2015). Most importantly, it is worth reiterating that common reductions in physical exercise classes in favor of "core" subjects are profoundly ill-conceived, and have shown disastrous consequences when implemented (Strong et al. 2005). On the contrary, more time should be dedicated to activities that challenge children cognitively and physically, and that encourage the development of complex motor coordination.

Concluding Remarks: Toward Personalized Regimens

The line of research discussed in this chapter comes at a time of sizeable excitement and promises, but also of greater awareness concerning the subtleties of the interaction between physical exercise, brain, and cognition. As the field of cognitive training matures, researchers are transitioning from dichotomous beliefs about the absolute effectiveness of training regimens toward a finer understanding of the inherent mechanisms at play in such complex dynamics. In particular, many would now argue that the possibility to impact cognitive abilities through training is not the core of the debate, which rather is currently focused on the effectiveness of respective components for given populations (e.g. Moreau 2015). This idea implies that cognitive abilities thrive in environments that are individualized, and thus underline the need to deliver content adapted to specific deficits and imbalances (Moreau 2014).

In addition, if the neurobiological and neural correlates of the association between physical exercise and cognitive improvement are well understood, the meaning of cognitive enhancement in general is not. What are the underlying mechanisms leading to improvement in cognitive abilities? Can gains last? Why do some individuals fail to improve at all? Are there potential tradeoffs? These are just a few of the numerous questions this trend of work is bound to explore and try to answer. Limitations of the current picture have been raised elsewhere (e.g. Hills & Hertwig 2011), and can be circumvented only with the establishment of a theoretical framework of cognitive enhancement. Until then, cognitive training studies will remain a heterogeneous collection of work with no clear common mechanism and connection.

Eventually, one important goal for research at the crossroad of cognitive neuroscience and exercise science is to inform policies more directly, so that individuals can have access to the tools and knowledge they need to make more informed choices when it comes to cognitive health and to maximizing their cognitive potential. Advances in this regard, although less dramatic than a novel drug or a groundbreaking treatment in the eyes of the public, are nonetheless critical, as they can allow dysfunctions or disorders to be alleviated, postponed, or even prevented by early interventions.

Note

1 Caution is required when defining such a broad field, because this oversimplification has often led to a misperception of embodied theories and of their core differences with more traditional models of cognition. One particular point that has done a disservice to the field of embodied cognition is the recurrent tendency to promote embodied theories by opposition to outdated approaches of cognitive processing. Some researchers still present embodied cognition as an alternative to purely amodal and propositional models of cognition, implicitly or explicitly suggested as the current state admitted in cognitive science. This approach is clearly misleading and does not make a compelling case for an embodied alternative to more traditional cognitive theories.

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