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Beyond Physical Exercise

Designing Physical Activities for Cognitive Enhancement

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Introduction

Human long-term memory is thought to be, for practical purposes, unlimited (Johnson & Hasher, 1987). We thus retain the capacity, throughout our lives, to accumulate knowledge without the risk of running out of storage space. By contrast, our ability to process and manipulate information decreases once we reach adulthood, with only subtle effects at first giving way to more dramatic changes eventually. In the scientific literature on intelligence, this difference is usually expressed with the distinction between crystallised and fluid intelligence, respectively (Cattell, 1963).

Consistent with the postulate of nearly infinite capacity, it is widely assumed that crystallised intelligence does not peak—that is, individuals keep gaining knowledge, skills, and experience well into older years. Therefore, apart from clinical conditions, intelligence can undoubtedly be enhanced via the acquisition of new skills and knowledge. What remains to be established, however, is the extent to which we can meaningfully influence fluid intelligence, so as to allow more efficient processing of information. This is a particularly important question given that fluid intelligence predicts performance in a wide range of settings, including professional and academic (Deary, Strand, Smith, & Fernandes, 2007). The malleability of cognitive abilities is also a critical area of investigation considering that fluid and crystallised intelligence are genetically determined in large part, with respective estimates of about 50% and 40% (Davies et al., 2011).

The notion that our cognitive abilities are strongly influenced by genetic factors does not imply however, that seeking improvement is a vain endeavour. *Strongly* here is not akin to *solely*, and there remains variance that is influenced by environmental—and possibly epigenetic—factors (Henikoff et al., 2016; Nikolova & Hariri, 2015). Consistent with this view, recent evidence suggests that the interaction between heritable traits and culture is more complex than initially postulated (Kan, Wicherts, Dolan, & van der Maas, 2013). As a result, the potential for enhancement has generated a lot of interest in different methods and techniques, ranging from pharmaceutical enhancers (i.e. nootropics) to brain stimulation and behavioural interventions. In this chapter, I will discuss the latter, with a particular focus on one of the most potent regimens, physical exercise (see for a review Moreau & Conway, 2013). Specifically, I will focus on how physical exercise interventions can be designed to promote cognitive growth. Behavioural interventions present important advantages over other approaches: they are usually safe, their underlying mechanisms are well understood, and they can be adapted to specific requirements.

As is the case for many research questions worth pursuing, definitive answers regarding the effectiveness of training programmes on cognition are elusive. In the computerised cognitive training literature, results have been mixed results thus far—several studies have suggested that fluid intelligence can be enhanced meaningfully via cognitive training (Astle, Barnes, Baker, Colclough, & Woolrich, 2015; Au et al., 2014; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Jaeggi, Buschkuehl, Shah, & Jonides, 2014; Karbach, Strobach, & Schubert, 2014; Nouchi et al., 2013), while others have shown more scepticism (Redick et al., 2013; Shipstead, Redick, & Engle, 2012; Thompson et al., 2013). At the core of this disagreement lies the concept of transfer, or the extent to which a trained ability influences outcomes in ecological settings. Most would concur on the notion that improvements restricted to training are not the goal of cognitive interventions. This is because training-specific gains are by and large the norm rather than the exception – in typical settings, practice leads to enhanced performance. Professional musicians are well aware of that, as are elite athletes or students preparing for standardised tests. This justifies dedicated hours of practice, over years or even decades.

What is therefore targeted in cognitive training paradigms is enhancement *outside* training settings and demands, so as to potentially benefit numerous aspects of life. As alluded to earlier, and perhaps surprisingly, the most effective way to improve general cognitive abilities non-invasively is physical exercise. I explore the underlying processes of this remarkable effect in the next section.

Physical Exercise and Cognitive Enhancement

Physical exercise is known to be associated with numerous benefits, both in terms of physical and mental health. Low fitness indices are linked to decreases in incidence of a wide range of conditions, from stroke and cancer to diabetes and cardiovascular diseases (Blair, 1995). Sedentary habits are also correlated with higher risks for neurological conditions such as autism, schizophrenia, attention deficit/hyperactive disorder (ADHD), dementia and Alzheimer's disease, which all have been shown to benefit from exercise interventions (Penedo & Dahn, 2005).

Beyond neurological impairment, higher fitness is also associated with better executive function, an umbrella term relating to an array of important abilities such as planning, problem-solving, reasoning, and inhibiting (Colcombe & Kramer, 2003). Additional research has demonstrated that this association is not specific to executive tasks, and extend to a wider range of abilities in many domains of cognition (Moreau & Conway, 2013). Experimental designs have further confirmed that the link between physical exercise and cognition is causal: exercise interventions lead to cognitive improvements and enhanced performance both in academic settings and in the professional workplace (Castelli, Hillman, Buck, & Erwin, 2007; Coe, Pivarnik, Womack, Reeves, & Malina, 2006; Keeley & Fox, 2009). These findings also extend into studies with older populations, in which exercise typically elicits enhanced cognitive performance and quality of life (Cancela Carral & Ayán Pérez, 2007), as well as more stable mood and emotions (Blumenthal et al., 1991).

The underlying mechanisms mediating this association are now well understood. Physical exercise promotes neurogenesis—the creation of new neurons—(van Praag, Kempermann, & Gage, 1999; van Praag et al., 2002), neuronal survival (Vaynman, Ying, Yin, & Gomez-Pinilla, 2006), brain volume (Colcombe et al., 2006) and brain vascularisation (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990). Chemical reactions in the brain are also altered by physical exercise, with changes in the concentration of hormones and neurotransmitters (Mora, Segovia, & del Arco, 2007). In particular, one of the key mediators of the relationship between physical exercise and cognitive enhancement is brain-derived neurotrophic factor (BDNF). Shortly after exercising, BDNF increases substantially in the hippocampus (Neeper, Gómez-Pinilla, Choi, & Cotman, 1995), a structure involved in learning, memory formation, and spatial navigation central to many aspects of cognitive function. In addition, enhanced concentrations of BDNF have been found in the spinal cord (Gómez-Pinilla, Ying, Opazo, Roy, & Edgerton, 2001), the cerebellum, and several cortical regions (Neeper, Gómez-Pinilla, Choi, & Cotman, 1996). These effects typically last at least several weeks (Berchtold, Kesslak, Pike, Adlard, & Cotman, 2001), and are thus thought to play a critical role in exercise-induced neural plasticity (Knaepen, Goekint, Heyman, & Meeusen, 2010).

Neurobiological changes also lead to alterations at the structural level. For example, fitness indices are associated with white matter integrity in children (Chaddock-Heyman et al., 2014), a finding corroborated by intervention designs (Krafft et al., 2014; Schaeffer et al., 2014). White matter tracts constitute the connections between neurons, and higher integrity is thought to enhance the processing and channelling of information throughout the brain. This line of research is based on diffusion tensor imaging (DTI), a technique that allows measuring the diffusion of water molecules along axonal pathways. Training influences the microstructural architecture of specific brain regions (Alexander, Lee, Lazar, & Field, 2007), and the diffusion of water is a proxy to measure these changes.

Functional changes in the brain are also associated with physical exercise. These differences are typically investigated with electroencephalography (EEG) or with functional magnetic resonance imaging (fMRI). Though the underlying rationales and assumptions of the two techniques are different, resulting in respective advantages and limitations that need to be considered depending upon the research question of interest, progress made via both techniques of investigation has been tremendous for the field in the past decades (Chaddock-Heyman et al., 2013; Davis et al., 2011; Hillman et al., 2014; Kamijo et al., 2011). A striking example comes from a study by Chaddock-Heyman and colleagues (2013), who reported decreases in neural activity in the right anterior prefrontal cortex while children were engaged in cognitive control tasks after a 1-year exercise intervention. Not only did children see alterations in neural activity with exercise, they also improved on behavioural measures of cognition, indicating that the underlying neural changes were beneficial to their cognitive abilities. Though the behavioural outcomes are typically consistent across studies, others have found increases in prefrontal activity following an exercise intervention (Davis et al., 2011). These results indicate that prefrontal activity is complex, and therefore requires further investigation with precise imaging techniques. Regardless, the benefits of physical exercise on cognition are well established (see for a review Moreau & Conway, 2013), and exciting questions have emerged as a result. For example, what type of intervention yields the best benefits? Related to this idea, do different regimens induce improvements in different cognitive functions? These and related questions represent promising avenues for future research, as they provide food for thought towards a better understanding of the fundamental process of enhancement, while also having obvious applications for diverse populations.

Increasing Cognitive Demands in Physical Activities

That physical exercise is the most effective way to elicit cognitive enhancement does not imply, however, that is should be used in isolation. It is possible that other forms of enhancement could induce gains that are additive and thus complement those elicited by physical exercise. This idea has been the basis for blended or combined regimens, where more than one method of enhancement is used, and has led to interventions pairing physical exercise with meditation (Astin et al., 2003), cognitive training (Curlik & Shors, 2013; Shatil, 2013), or transcranial direct current stimulation (tDCS, Ditye, Jacobson, Walsh, & Lavidor, 2012; Madhavan & Shah, 2012; Martin et al., 2013; Moreau, Wang, Tseng, & Juan, 2015).

If potential negative side effects are a concern with some of these approaches—for example, uncertainty over long-term effects in the case of tDCS (Davis, 2014), or unintended psychological stressors induced by mindfulness meditation (Lazarus, 1976; Shapiro, 1992)—behavioural interventions based on physical exercise induce remarkable health benefits in a very broad fashion. Effectiveness when multiple factors is particularly appealing considering recent concerns about opportunity costs related to computerised cognitive training regimens (Moreau & Conway, 2014). Many computerised programmes do not deliver on their promises, which is problematic given that training-specific skills improved as part of these regimens have limited relevance to ecological settings, in contrast with domains such as music, sports, or the arts. Indeed, if time and effort are to be invested in an activity solely intended to enhance brain function, it needs testing and validation.

Recently, several studies have questioned whether aerobic exercise, making up the vast majority of exercise interventions targeting cognitive enhancement, is indeed the most potent approach. Developments in the field of exercise physiology suggest that interventions based on short and intense bursts of exercise can induce physiological changes similar to those following aerobic exercise on a wide range of outcomes, including cardiovascular measures (Gayda, Ribeiro, Juneau, & Nigam, 2016), physical fitness and general health (Milanović, Sporiš, & Weston, 2015). HIT-induced improvements have in some instances surpassed those resulting from aerobic regimens (Rognmo, Hetland, Helgerud, Hoff, & Siørdahl, 2004). In line with the physiological literature, regimens based on resistance training have also shown sizeable effects on cognition (Best, Chiu, Liang Hsu, Nagamatsu, & Liu-Ambrose, 2015; Liu-Ambrose, Nagamatsu, Voss, Khan, & Handy, 2012), despite somewhat different mediating processes from those induced by aerobic exercise (Goekint et al., 2010).

Beyond mere physical exercise regimens, complex forms of motor training that combine high physical and cognitive demands further confirm the appeal of alternatives to traditional exercise-based cognitive training (Moreau, Morrison, & Conway, 2015). This type of regimens can elicit gains in measures of spatial ability and working memory capacity, together with health benefits (Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012; Moreau et al., 2015; Moreau, 2015a). It should be noted that these effects are to be distinguished from short-term improvements immediately following acute bouts of exercise (Tomporowski, 2003), which typically dissipate after a few hours (Chang, Labban, Gapin, & Etnier, 2012).

Importantly, a large body of research on motor expertise supports the notion that the motor system exerts influence on cognitive abilities. For example, mental rotation problems that typically tap visual processes (Hyun & Luck, 2007) have been shown to recruit motor processes in elite athletes, resulting in better performance (Moreau, 2012). Interestingly, concurrent demands on the motor system impairs performance to a greater degree in elite athletes than novices, indicating that it is not the capacity to simultaneously manipulate motor content that increases with practice, but the propensity to involve motor processes in non-motor task (Moreau, 2012).

The underlying mechanisms of these differences are also well understood. It has been demonstrated consistently that mental manipulation of body parts (e.g. hands) implicitly induces motor simulation (Parsons, 1987a, 1987b, 1994; Sekiyama, 1982). As a result, measures that disrupt motor simulation, such as physically constraining movement, leads to decreased mental rotation performance (Ionta & Blanke, 2009; Ionta, Fourkas, Fiorio, & Aglioti, 2007). In contrast, the mental manipulation of abstract shapes (e.g. polygons) typically does not elicit motor activation (Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998), and thus restricting movement has little to no effect on performance (Moreau, 2013a). A radically different picture emerges when testing motor experts, however. When performing these mental rotation tasks with movement restriction, motor experts show impairment *both* with body parts and abstract shapes, as opposed to body parts only for controls (Moreau, 2013a). This finding suggests that motor experts recruit motor processes to perform tasks that are typically non-motor, and indicates that such strategies are not easily adaptable—more flexibility would allow recruitment of a different system (e.g. visual) to circumvent motor constraints (Moreau, 2015b). More generally, this phenomenon extends beyond mental rotation tasks, with similar results observed on working memory tasks (Moreau, 2013b).

This line of work, together with the idea of increasing cognitive demands via motor activities, stem from the motor simulation framework, which posits common neural mechanisms for motor simulation and execution (Jeannerod & Decety, 1995; Jeannerod, 2001). According to this view, overt actions shape motor simulation (de Lange, Roelofs, & Toni, 2008), and, transitively, cognitive tasks that can be supported or facilitated by motor simulation. Countless studies have confirmed this hypothesis, with observational or experimental evidence. Besides mental rotation and working memory (Amorim, Isableu, & Jarraya, 2006; Janczyk, Pfister, Crognale, & Kunde, 2012; Moreau, 2012, 2013b; Steggemann, Engbert, & Weigelt, 2011; Wraga, Thompson, Alpert, & Kosslyn, 2003), the interrelation between motor processes and other aspects of cognition have been largely documented, from language (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008) to problem solving (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007), reasoning (Beilock & Goldin-Meadow, 2010; Cook, Mitchell, & Goldin-Meadow, 2008), and decision-making (Raab & Johnson, 2007). Overall, this body of work suggests that motor activities are a remarkably potent way to stimulate a vast array of cognitive abilities, with numerous possibilities and variations.

Implications for Education

Recent developments in the new-fangled field of educational neuroscience suggest prudence and caution when extrapolating laboratory findings to the classroom. Over the years, vernacular and concepts borrowed from neuroscience have spread remarkably well within education. Yet oftentimes, the new jargon adds very little, if anything, to discussions in education, sometimes blurring ideas to the detriment of clear understanding. Simple concepts become obscure. Children are reduced to brains capable of plastic changes, by opposition to so-called old views of a fixed brain. Nothing could be farther from the truth: that some brain regions retain plasticity across the lifespan has been known since the 1960s with the pioneer work of Joseph Altman (Altman, 1962) and James Hinds (Hinds, 1968). More strikingly perhaps, developmental plasticity was never really questioned, even prior to these seminal studies. As it turns out, manifestations of neuroplasticity presumably witnessed by teachers actually relate to changes in behaviour, or learning. The terminology might be new, but the rationale hardly is.

In contrast with the abuse of neurospeak in didactic settings, there are clear implications for the work bridging motor activities and cognition in the classroom. Experimental evidence has directly demonstrated the value of motor activities to enhance cognition, with encouraging results. Indeed, structured plays that incorporate cognitive demands within motor activities allow creating ecological situations that have the potential to elicit meaningful cognitive gains. As such, they represent an interesting avenue for teachers and educators, with great adaptability. The specific characteristics of this type of intervention matter less than the importance to get involved with any such programme; whether it is physical games (Tomporowski, Davis, Miller, & Naglieri, 2008), exergames (Staiano & Calvert, 2011), martial arts (Diamond & Lee, 2011), or designed sport (Moreau et al., 2015), the results have been extremely promising. Content can be adapted based on goals, feasibility and motivation, to offer interventions suitable to anyone.

Directly stemming from this idea, an important component inherent to programmes that target cognitive enhancement via physical activities is the range of possibilities they offer. Voluntary movement ranges from very simple, relying mostly on automated coordination, to extremely complex, requiring heightened and sustained attention. Due to complexity arising from the multiplicity of motor commands operating in synchrony, the latter often involves a progression through trial and error (Pritchett & Carey, 2014; Takiyama, Hirashima, & Nozaki, 2015). This represents a continuum educators can harness, adapt and tweak, to obtain the intended effects. Complex motor activities have the unique advantage of being more elaborate and diverse than the sum of their parts; in effect, situations are deliberately unconstrained so as to favour creative solutions. Product of this emergent property, challenging situations evolve in a unique way, directed but not constrained. The effects of these types of regimen on cognitive abilities have been remarkable (Moreau et al., 2015; Pesce et al., 2016; Tomporowski, Lambourne, & Okumura, 2011), to the point that they have become the preferred approach in numerous independent research groups (e.g. Curlik & Shors, 2013; Moreau et al., 2015; Tomporowski, McCullick, & Pesce, 2015).

Designing an intervention framework from a continuum also allows regimens to be adaptive, that is, propose individualised content to facilitate learning. Practice can thus be sustained at an optimum level of difficulty, to provide challenging but attainable goals. Adaptive training is a fundamental component of effective cognitive training (e.g. Zelinski et al., 2011), known in motor rehabilitation research as the "optimal challenge point" hypothesis (Guadagnoli & Lee, 2004). According to this view, skill learning is maximised when task difficulty is proportional to individual levels. Too easy, and individuals will stagnate and waste time. Too difficult, and they will not improve and might get frustrated. More generally, the idea stems from long-known mechanisms in motor learning, whereby demands of the environment slightly beyond an individual's capabilities yield the fastest learning rates (see for a review Schmidt & Wrisberg, 2008).

Further exploiting the blend of physical and cognitive demands, difficulty can also be nurtured in a different way. Concurrent physical and cognitive demands introduce competition for resources at various levels, especially related to physiological systems (Gómez-Pinilla, 2008). As exercise intensity increases, fewer resources (e.g. blood supply, oxygen, nutrients) are available for the brain to cope with cognitive demands, and maintaining adequate performance on a given task thus requires individuals to do more with less. This is consistent with the framework process of expertise acquisition—individuals typically recruit less cortical structures to perform a given task after learning (Wiesmann & Ishai, 2011). Concurrent exercise is therefore a positive stressor on the neural system, forcing efficiency. Cognitive tasks performed post-training without concurrent exercise often appear easier to most individuals, as the brain can then take advantage of plentiful resources and reclaim its place as the most energy-consuming organ (Tomasi, Wang, & Volkow, 2013).

Complex motor activities are also ideal to promote creativity, by setting the stage for an unlimited range of situations, without the need to plan and design each one of them *a priori*. Participants can modify existing situations, create new ones, and therefore produce unique conditions in which to solve problems and improve. Rich training environments that include variety and diversity are also critical factors to sustain motivation, which in turn may influence training outcomes. Loss of motivation is a common factor for dropping out of software-based cognitive regimens and aerobic exercise interventions, and physical exercise seems to be less effective when not voluntary, at least in rodents (Yuede et al., 2009).

However, great flexibility in an intervention program comes at a cost—the regimen is typically difficult to standardise, because the degrees of freedom are deliberately relaxed. In terms of validation, this is a major hurdle, because experiments require precise and constrained designs to facilitate reproducibility. With this limitation in mind, it is worth noting that constraining interventions too drastically prevents the very component targeted to develop, leading to an impoverished, simplified regimen. This approach might be suitable for laboratory-based testing, but it often reduces or annihilates the effects of interest, especially when the intervention under study is a complex blend.

How can these factors, seemingly antagonists, be reconciled? A promising solution lies in the combination of laboratory-based experiments to explore the basic processes of enhancement with large-scale ecological interventions that help quantify effect sizes in ecological settings. These two types of design can thus inform each other, and refine knowledge and applications. Such a combined approach also allows the study of cognitive malleability at different levels, from brain to behaviour. Each level of investigation can then inform others, leading to more scientifically sound interventions. This approach also facilitates theoretically driven hypotheses, thus reducing the rate of false positives and optimising the scientific enterprise as a whole. The trade-off between controlled laboratory experiments and ecological studies cannot be entirely circumvented, and has in fact bothered psychologists for decades (Brewer, 2000; Gibson, 1979). Yet combining findings from different research designs under a common framework will lead to better, more potent, interventions.

Concluding Remarks

Throughout this chapter, I have provided an overview of the vast amount of research dedicated to studying the link between physical exercise and cognition, and I have presented recent trends of research that advocate for complex physical activities, with potential for greater impact on cognitive abilities. These trends of research are promising, and are expected to provide ground for years of research to come.

Although the general feeling is one of optimism, there are still major challenges facing the field of cognitive enhancement. Among them, the personalisation of interventions holds a central place. Individuals differ in the extent to which they benefit from an intervention—some show impressive trends of improvement, while others do not seem to benefit at all, at least cognitively. Understanding the variability between individuals, as well as the dynamics of individual rates of improvement, is crucial to further our insight regarding the underlying mechanisms at play. Research at the intersection of psychology, neuroscience, physiology and genetics is particularly promising in this regard, providing footing for a more holistic approach of exercise-induced cognitive enhancement.

For practical concerns, acknowledging individual variability also allows training content needs to be adapted to specific demands, either based on expectations, or on inherent cognitive deficits. The potential of this type of approach has been underlined recently in the context of remediation for learning disorders (Moreau & Waldie, 2016); when cognitive deficits are identified in specific areas of cognition, training can be personalised so as to provide regimens optimised individually. Personalising regimens represents a promising but difficult endeavour—it is easy to fall intro the trap of modelling noise, via the personalisation of every single situation, when this approach might not be optimal.

Ultimately, understanding precisely mechanism of improvement requires solid theoretical grounds, still lacking at the moment. Researchers are only beginning to understand the dynamics of cognitive abilities induced by training—methods are progressively being refined, findings are better contextualised, and eventually these will call for an integrating framework. Only then can we envision accurate probabilistic estimates of training outcomes for a given individual, so as to maximise chances for a programme to be effective. This prospect holds remarkable promises, and constitutes a pivotal step for future research and applications.

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