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Cognitive enhancement: a comparative review of computerized and athletic training programs

David Moreau* and Andrew R.A. Conway

Department of Psychology, Princeton University, Green Hall, Princeton, NJ, USA

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Cognitive enhancement refers to any type of improvement in cognitive performance following targeted interventions. Cognitive training is a rapidly growing market with potential to further expand in the future. Several computerized software programs promoting cognitive enhancement have been developed in recent years, with controversial results and implications. Within the research field, advances have been made regarding our understanding of the benefits inherent to cognitive programs, mainly involving working memory mechanisms and videogame training paradigms. In a distinct literature, physical exercise has been shown to broadly enhance cognitive functions, in humans and animals. In this article, we bring together these two trends of research in a comparative review, leading the discussion to an emerging third approach: designed sports training. Specifically designed sports, which tax working memory and spatial ability by incorporating motion in three-dimensional space, are an optimal way to combine the benefits of traditional cognitive training and physical exercise into a single activity. We discuss these findings in the context of embodied cognition, and argue that sensorimotor learning in designed sports is a key mechanism linking training and cognitive enhancement.

Keywords: cognitive enhancement; working memory training; videogame training; physical exercise; embodied cognition

In recent years, a myriad of websites and software programs promising cognitive enhancement have been commercialized, giving birth to a new lucrative market accessible around the globe. Although the effects of such training programs on general cognition are not yet entirely clear, one conclusion that can be drawn with confidence from this expanding market is that people are genuinely interested in and concerned about their own cognitive performance. Further evidence of this comes from the videogame market, with the rise in popularity of games designed not only to entertain but also to foster specific cognitive abilities, via so-called brain training products.

In response to this growing interest in cognitive performance, there has been a surge in research on cognitive enhancement. Broadly defined, cognitive enhancement refers to temporary and/or long-term gains in cognitive performance as a result of targeted interventions. For example, evidence of superior spatial reasoning after extended play of certain action videogames is a form of cognitive enhancement. The notion that one's cognitive abilities can be improved is an appealing one, as it helps to

*Corresponding author. Email: dmoreau@princeton.edu

put individual differences in cognitive ability into perspective, and is in line with current research on neuroplasticity. In this regard, training paradigms complement a large body of literature in differential psychology. Assessing individual differences in cognition, particularly in the field of intelligence testing (Binet & Simon, 1904; Galton, 1879), psychologists have gathered an extensive amount of data documenting cognitive differences across individuals, paving the way for more accurate theoretical models of human cognition.

However, findings based on a differential approach have sometimes been misinterpreted, leading, for example, to the assumption of immutable differences between individuals while undermining the influence of environmental factors. Considering these shortcomings, new trends of research in cognitive science help bring a fresh look at previous findings. In contrast with the long-standing view of a limitation in brain structural changes to developmental stages, the idea that the brain remains plastic throughout life and therefore that cognitive processes can be altered continually is far reaching. It centers the debate on the tremendous and permanent possibilities to improve one's abilities, departing from the notion of an unchangeable set of cognitive limitations. In sum, the idea of cognitive enhancement is being embraced in the scientific community and represents a specific type of 'human enhancement'.

This emerging literature on cognitive enhancement can also be viewed from a more applied perspective. Some studies have utilized invasive or artificial techniques, such as in vitro stem cell growth and pharmacological interventions (for reviews and comments, see Elliott & Elliott, 2011; Farah & Smith, 2011; Smith & Farah, 2011; Swanson, Wigal, & Volkow, 2011), while others have primarily concerned classical learning effects induced by various types of cognitive programs (for reviews in children and adults, see Diamond & Lee, 2011; Rabipour & Raz, 2012), such as working memory (WM) training (for reviews, see Morrison & Chein, 2011; Shipstead, Redick, & Engle, 2012) or videogame interventions (for a review, see Green & Bavelier, 2008).

The present review focuses on non-invasive behavioral interventions targeting cognitive enhancement, and strives to unveil the key mechanisms underlying training effects. In particular, we discuss computerized and physical training, two popular approaches that are rarely considered together despite remarkable similarities in terms of findings. In an attempt to optimize cognitive training, we conclude with a theoretically driven reflection toward alternative interventions to enhance human cognition, via a combination of cognitive and motor solicitations within ad hoc activities.

To help guide our evaluation of training studies, we begin with a brief review of basic but essential methodological issues, specifically: (1) observational studies vs. randomized controlled experiments; (2) random assignment to conditions; (3) control conditions; (4) amount and frequency of training; (5) measurement of constructs; and (6) near- and far-transfer.

Experimental designs in cognitive training

Observational studies vs. randomized controlled experiments

Cross-sectional observations comparing experts and non-experts in diverse activities, such as music, sports, or videogame playing, have provided a great deal of knowledge concerning the particular skills critical to excel in these activities and their relationship with general cognitive abilities (for a comprehensive review of expertise, see Ericsson, 2006). For example, elite athletes perform significantly better than novices in spatial reasoning tasks (Moreau, Mansy-Dannay, Clerc, & Guerrien, 2011), musicians demonstrate faster processing of visual and spatial features than non-musicians (Brochard, Dufour, & Despres, 2004), and videogame players navigate more efficiently than non-gamers within a virtual environment (Richardson, Powers, & Bousquet, 2011).

However, such designs systematically fail to provide information regarding causation, namely whether differences are training based or due to pre-existing abilities, and/or simply due to confounding variables (for example, experts in a given activity might also be more likely either to avoid or to engage in other practices). These issues can largely be overcome via controlled experiments in which recruited participants are randomly assigned to different conditions, including at least one experimental and one control group. We discuss in this section the critical points to consider when designing behavioral interventions intended to target cognitive enhancement.

Random assignment

Typically, training studies are based on the assumption that a particular program benefits single or sets of abilities. Given a sufficient sample, random assignment ensures control over confounding factors. With smaller samples, semi-random alternatives are often used, assigning individuals to different conditions after grouping around one or more variables. This manipulation allows equalizing ratios in all conditions, when confounding factors such as gender, age, or IQ need to be controlled. Ideally, individuals should not be aware of experimenters' expectations or hypotheses regarding the different conditions, to control for placebo and expectancy effects, such as the 'Hawthorne effect' (French, 1953), the experimental equivalent of the Pygmalion effect (Rosenthal & Jacobson, 1968).

Control conditions

Training experiments typically employ a pre-test/post-test design and so a control condition is necessary to isolate training effects from test-specific practice effects (te Nijenhuis, van Vianen, & van der Flier, 2007). Ideally, the control group should be engaged in the experiment to the same degree as the experimental group. For example, if computers or other devices are used, they should be present in all conditions even when they do not represent a variable of interest. Also, it is ideal for the control group to be active, meaning that participants engage in an equally stimulating alternative to the experimental condition. Finally, state-of-the-art training designs include an active control condition that allows for quantifiable improvement in performance during training – to control for group differences in self-achievement, which could influence motivation (Shipstead et al., 2012). This is a recurrent problem in studies using either a non-adaptive version of the task present in the experimental condition (Holmes, Gathercole, & Dunning, 2009; Klingberg et al., 2005) or, more generally, a less taxing version of the task for the active control group (Klingberg, Forssberg, & Westerberg, 2002; Persson & Reuter-Lorenz, 2008).

One solution around this problem has been the use of cognitively demanding tasks that are adaptive, but are thought to rely upon different constructs than those being trained (Redick et al., in press).

Amount and frequency of training

The optimal amount and frequency of training has not received much attention in the cognitive training literature, which is surprising given the abundance of attention devoted to this topic in the design of athletic training programs (D. J. Smith, 2003). This aspect of the design includes both the overall amount of training and the length of each single training session. What amount is needed to achieve significant improvements? Can cognitive abilities be over-trained, just as athletes' bodies, resulting in a dip in subsequent performance? These are still open questions in the field of cognitive training. As more training studies are conducted, meta-analyses of the cumulative data should provide some insight into optimal design choices.

Similarly, training frequency, defined by the amount of time between two training sessions, has been relatively unexplored in the recent trend of cognitive enhancement. This contrasts with a massive amount of data concerning optimal frequency in learning. As such, the idea that information is better remembered when spaced over time than when massed together (the spacing effect) has been well documented in cognitive and skill learning (Hintzman, 1974; Spear, 1978). However, because the surge for cognitive training is recent, the field still lacks unequivocal claims regarding the optimization of training amount and frequency.

As past research has strongly emphasized training content itself, future research should determine what training amount and frequency are optimal to develop particular abilities, how these factors may influence the enhancement of specific cognitive abilities, and what minimum amount of training is necessary to maintain prior enhancement.

Measurement of constructs

Assessment tasks are another critical feature of training experiments. Many different approaches have been used to assess cognitive levels before and after training, yet a key component for reliable measurement remains the plurality of assessment tasks for each construct (Morrison & Chein, 2011; Shipstead et al., 2012). As well as increasing reliability, this precaution also facilitates data inclusion in subsequent meta-analysis studies.

A related factor, the number of assessment sessions, is critical when comparing data across experiments. Information regarding this component is crucial to interpret findings, as additional assessment sessions provide more data to evaluate the trend of performance variations but also augment the risk of magnifying the impact of prior testing sessions on final performance, rather than the consequence of training per se. Multiple assessments also lead to reduced statistical power due to multiple comparison corrections (Morrison & Chein, 2011), resulting in a subtle trade-off between the need to provide more details about the evolution of a particular construct and the rise of measurement artifacts.

Other factors should also be considered when comparing data across experiments, such as assessment location and conditions, including explicit or implicit encouragements by the experimenters. Although it is merely impossible to introduce all these parameters in reviews and meta-analyses, their inclusion in research reports ensures contextual interpretations of cognitive enhancement. Finally, if possible, multiple constructs should be evaluated to demonstrate both convergent and divergent validity of the training effect. By analogy, particular circumstances (e.g. weight class sports) may require that a conditioning program targets muscle strength but not muscle mass to be successful.

Enhancement: near- and far-transfer

Another subtle measurement issue is the distinction between the notion of enhancement and transfer. Training enhancement is demonstrated when an experimental condition shows significant improvement in any kind of measurement task, relative to the control condition. This restriction ensures control over practice effects in the measurement tasks (test-retest). Such a definition is rather vague and broad, however, and further distinction can be established. In particular, enhancement can be observed in one of the training tasks or in different tasks. In the latter case, distinction needs to be made between near- and far-transfer.

Near-transfer represents a positive effect of training on assessments involving materials similar to the training tasks. It is generally assessed via tasks that tap the same construct targeted by training (e.g. WM) but that were not included in the training sessions. Far-transfer evidence is less frequent. Typically, far-transfer is established when practice leads to enhancement in different cognitive constructs than those targeted in the training tasks. Ideally, this is demonstrated through latent variable analysis, to provide an accurate measure for each construct and account for shared variance between constructs. Within training interventions, the underlying idea behind far-transfer is to impact real-life situations.

In the present review, we will focus on training interventions with a potential to yield near- or far-transfer effects. Simple enhancement is too broad to be tackled in a single article and represents a quasi-systematic consequence of training, therefore less appealing to enhance general cognition.

Converging evidence

Finally, we will adopt a converging operations approach to further evaluate claims of cognitive enhancement. Are the claims logically consistent with evidence from other disciplines, such as neuroscience and development, and other levels of analysis, for example animal models? The diversity of approaches available to assess the efficacy of training programs is crucial to ensure consistency over theoretical models. We explore in the next section the growing body of evidence surrounding computerized cognitive training.

Computerized interventions

The underlying idea

In line with the traditional individual differences approach of cognition, a recent trend of research has assessed the efficacy and validity of computerized cognitive training interventions. For example, significant cognitive benefits have been found following specific training on attention (Tang & Posner, 2009), attentional control (Bherer et al., 2008), cognitive control (Keizer, Verment, & Hommel, 2010), memory (Mahncke et al., 2006), perceptual skills (Norton, McBain, Ongur, & Chen, 2011), speed of processing (Dux et al., 2009), and reaction time (Tong, Melara, & Rao, 2009). The capacity to enhance a particular skill given the appropriate amount of practice is not to be disputed. However, these changes are usually specific and constrained to the abilities trained.

When targeting general cognitive enhancement, however, a more fruitful approach is to seek transfer from a particular training program to different tasks. Two different approaches have been pursued in this direction. On the one hand, some researchers believe that training a single construct underlying numerous abilities can lead to improvements and transfer in a broad range of tasks. Because of its potential to irrigate diverse aspects of human cognition, WM seems to be a strong candidate for such a central role, and has therefore received a lot of attention recently. On the other hand, defenders of a more diversified training have advocated for different kinds of intervention, tapping varied cognitive constructs to induce large and extensive effects. This approach includes videogame training and brain training software programs. We describe succinctly these trends of research as well as their main findings in this section.

Working memory training

WM can be defined as a cognitive system responsible for short-term storage and manipulation of information. It is essential to an individual's ability to reason about ideas and concepts, and to direct and maintain attention in the face of distraction or interference. Originally introduced by Baddeley and Hitch in a seminal paper (Baddeley & Hitch, 1974), the WM construct has since evolved to include additional components (Baddeley, 2000) and incorporate mechanisms traditionally associated with long-term memory (Ericsson & Kintsch, 1995; Unsworth & Engle, 2007). Other general theoretical shifts in cognitive science have also influenced the concept of WM. For example, as the field transitioned away from information processing models to connectionist models, WM became conceived more as a workspace rather than a gateway linking perception and long-term memory (Logie, 2003). This was accompanied by a shift in emphasis from the structure of WM to the function of WM (Engle & Oransky, 1999; Postle, 2006).

Although WM capacity (WMC), the maximum amount of information an individual can maintain in a WM task, is generally assumed to be limited in all individuals (Cowan, 2001; Miller, 1956), considerable differences can be found across individuals. Recently, studies have underlined WMC plasticity through different forms of training (for reviews, see Morrison & Chein, 2011; Shipstead et al., 2012), but arguments remain with respect to construct measurement. As training and testing tasks involved different but highly similar items, it is not clear if these are examples of near- or far-transfer effects (Kramer & Willis, 2002).

WMC training-induced cognitive improvement is a powerful idea in the field of cognitive psychology, as WM is a central construct strongly correlated with performance in a wide variety of cognitive and intelligence tasks (Cowan et al., 2005; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Hambrick, & Conway, 2005; Kane et al., 2004; Oberauer, Schulze, Wilhelm, & Suss, 2005), as well as with reading and mathematical skills (Alloway, 2007; Gathercole, Alloway, Willis, & Adams, 2006), or even overall academic achievement (Aronen, Vuontela, Steenari, Salmi, & Carlson, 2005).

Perhaps the most pervasive limitation in the field at this stage is the use of a single assessment to measure constructs (Morrison & Chein, 2011; Shipstead et al., 2012). Typically, a single measurement is thought to reflect changes in overall abilities. This is problematic, because differences could be driven by systematic and random influences, besides those yielded by the ability being assessed (Loehlin, 2004). As a consequence of this issue, the source of improvements in such studies cannot be positively identified (McArdle & Prindle, 2008; Moody, 2009; Schmiedek, Lövden, & Lindenberger, 2010; Sternberg, 2008).

Other major difficulties pertain to the absence of active control groups (Shipstead et al., 2012) and to discrepancies over the content of WM training programs. Because of these limitations and relative inconsistencies, two different trends have emerged, one being rather enthusiastic about WM training transfer effects (Klingberg, 2010; Morrison & Chein, 2011; Perrig, Hollenstein, & Oelhafen, 2009), the other showing more caution over the lack of strong evidence for such effects (Conway & Getz, 2010; Moody, 2009; Shipstead et al., 2012; Redick et al., in press). The fundamental distinction between these two trends lies in far-transfer improvements, particularly in fluid intelligence (Gf) tasks.

There is clear evidence for near-transfer following WM training (Shipstead et al., 2012). For example, Chein and Morrison found significant improvements in WM capacity following WM training, even though the assessment tasks were different to the training tasks (Chein & Morrison, 2010). In contrast, far-transfer to Gf tasks has mainly been found in no-active control group designs (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Olesen, Westerberg, & Klingberg, 2003; Schmiedek et al., 2010; Vogt et al., 2009), even though a few recent studies have confirmed these findings in stronger experimental settings (Jaeggi et al., 2010). Although Jaeggi and colleagues' original findings were impressive (Jaeggi et al., 2008), they claimed far-transfer on Gf when they in fact showed transfer on a single task (the Bochumer Matrizen-Test, or BOMAT) commonly used as an indicator of Gf. This nuance is important, especially considering that recent work has failed to replicate Jaeggi's findings using similar experimental designs (Chooi & Thompson, 2012; Redick et al., in press). These and other related issues have already been pointed out in the literature (Moody, 2009; Morrison & Chein, 2011; Shipstead et al., 2012) and have been taken into account in latent-variable approaches (Colom et al., 2010; Schmiedek et al., 2010).

Less controversially, far-transfer has been established in other constructs. Often assessed with the Stroop task, cognitive control was shown to benefit from WM training in some cases (Chein & Morrison, 2010; Klingberg et al., 2002; Klingberg et al., 2005; Olesen et al., 2003), but not in others (Dahlin, Nyberg, Backman, & Neely, 2008; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009; Westerberg & Klingberg, 2007; Wykes, Reeder, Corner, Williams, & Everitt, 1999). Interestingly, Chein and Morrison also found significant improvements in reading comprehension, assessed via the Nelson-Denny reading comprehension task (Chein & Morrison, 2010). Although not replicated since, this result deserves further investigation, especially considering the impact that an effective method to train reading skills could have in our modern society.

Neuroimaging and neuropsychological evidence

The changes subsequent to WM training are also detectable at the neural level (see, for example, Jaušovec & Jaušovec, 2012). Generally, results show that far-transfer effects depend on the recruitment of domain-general aspects of WM, relying on the basal ganglia, the dorsolateral prefrontal and the posterior parietal cortices. In particular, a recent study underlined the decrease in neocortical activation associated with the increase of activity in subcortical areas following cognitive training, thus suggesting intervention-related increases in neural efficiency (Brehmer et al., 2011). These results were observed after a WM training program in older adults who were divided into an adaptive training group and a control group. The findings were corroborated by large improvements in WMC, but also in other non-trained cognitive processes, such as attention or episodic memory (Brehmer et al., 2011). Similarly, Olesen and colleagues found an increase of activity in the middle frontal gyrus and the superior and inferior parietal cortices after five weeks of WM training (Olesen et al., 2003). The authors interpreted these findings as evidence for neural plasticity induced by WM training. Similar results by Westerberg and Klingberg emphasized the similarities between WM-induced changes and alterations found in primate studies of skill learning (Westerberg & Klingberg, 2007). In contrast, Hempel and colleagues showed increased cortical activation of the right inferior frontal gyrus and the right intraparietal sulcus when performing a visual spatial WM task after two weeks of training, but a decrease after four weeks of training, following an inverse quadratic function (Hempel et al., 2004).

In addition to these findings concerning neural activation, Takeuchi and colleagues showed, in a series of studies, WM training-induced changes in structural connectivity (Takeuchi et al., 2010; Takeuchi et al., 2011; Takeuchi, Taki, & Kawashima, 2010), via measures of activation in white matter regions adjacent to the intraparietal sulcus and the corpus callosum, as well as measures of gray matter in the bilateral fronto-parietal regions and in the left superior temporal gyrus. The authors propose changes in myelination associated with gray matter plasticity as a potential explanation for these findings and for other broader cognitive changes following WM training.

At a chemical level, studies pointed out the fluctuation of dopamine levels associated with WM training (Bellander et al., 2011; Brehmer et al., 2009; Gruber, Dayan, Gutkin, & Solla, 2006; McNab et al., 2009). Computerized adaptive training seems to alter concentration of a dopamine transporter (DAT1) and of dopamine-related genes, indirectly participating in overall dopamine increases. Furthermore, training has been shown to induce changes in cortical dopamine D1 receptor density, in both prefrontal and parietal cortical areas, after as little as 14 hours of practice (McNab et al., 2009). These results suggest a close relationship between dopamine levels and WM plasticity, highlighting how neurochemistry and cognitive functioning are intertwined.

Altogether, neuroimaging findings provide further insight into the mechanisms of WM training, but they still have to be complemented by additional data and coupled to behavioral designs to yield a comprehensive picture of the processes at play. Within this paradigm, the underlying reasons for brain activation increases and decreases are still unclear, as both might be interpreted as neural support for behavioral changes, either in terms of greater use and improved function when activation increases, or in terms of gains in efficiency when activation decreases.

An alternative approach: videogame training

Another training paradigm potentially leading to general changes in cognition is based on videogame playing. Recent evidence underlines the efficacy of action videogames in a wide variety of tasks, such as tracking or identifying objects, thus involving processes useful in numerous everyday activities. Enhanced performance supposedly stems from increases in cognitive process capacity, in particular the attentional system (for a review, see Green & Bavelier, 2008). Interestingly, near-transfer is rather common in the videogame literature (Green & Bavelier, 2008), in contrast with traditional research on cognitive skill acquisition showing that even minor changes in stimuli orientation or frequency affect transfer (Hertzog, Kramer, Wilson, & Lindenberger, 2009). The reliability of near-transfer effects might in fact depend on the complexity of the training itself – the broader the abilities targeted, the more likely transfer will emerge.

Far-transfer is less evident and remains rare from training in traditional videogames. Although promising neuroimaging evidence has established changes in neural connectivity after videogame training (Colom et al., 2012; Voss et al., 2012), one particular concern in training studies is that the abilities targeted by videogames are multiple. Therefore, when training-induced improvements exist, it is difficult to define what type of transfer has been achieved, as most games require a vast panel of cognitive abilities. For example, a study by Green and Bavelier (2003) showed substantial improvements in visual selective attention after six months of training with various videogames, yet the difficulty to identify precisely the cognitive abilities trained obscures the type of transfer in this case. Subsequent studies have demonstrated improvements in visual acuity (Green & Bavelier, 2007), contrast sensitivity (Li, Polat, Makous, & Bavelier, 2009), resistance to masking (Li, Polat, Scalzo, & Bavelier, 2010), visuospatial attention (Green & Bavelier, 2006a), enumeration and object tracking (Green & Bavelier, 2006b), decision making (Green, Pouget, & Bavelier, 2010), or even mental rotation, but there remain questions over the exact demands of these videogames and over potential confounds such as placebo effects (Boot, Blakely, & Simons, 2011).

Coupling this trend of research and WM training, many companies have strived to develop software programs specifically targeting cognitive enhancement. Typically, these programs include various exercises designed to tap into diverse processes, such as memory, attention, processing speed, flexibility, or problem solving. Although they are mainly intended for elderly people, these programs are presented as being suitable and adaptable to wider populations, including children. An important question that remains unanswered, however, is whether brain training software improvements transfer outside the tasks practiced on a computer, as the consequences are severely restricted if improvements only concern trained tasks.

To investigate this issue, many experiments have demonstrated the efficacy of training programs based on computer software. One recurrent limitation, however, is that most of these studies were conducted by researchers either employed or funded to some extent by the software companies themselves, raising concerns over potential conflicts of interest. Recently, an independent large study by Owen and colleagues included 11,430 volunteers aged from 18 to 60 who were recruited to participate in a cognitive training program. Participants practiced for 24 sessions of 10 minutes each, over six weeks. The researchers concluded there were no significant transfer effects from the training tasks to more general cognitive assessments (Owen et al., 2010). Although defenders of brain training interventions have criticized the length of the overall training in this study, it remains the largest to date to have looked into transfer from brain training software programs. At the very least, this finding calls for more research in the field of cognitive interventions before firm conclusions can be drawn.

Physical exercise interventions

The underlying idea

In contrast to the mixed evidence surrounding computerized cognitive training, the field of physical exercise has a long tradition of research clearly demonstrating wide and reliable effects on diverse cognitive processes. Over the years, physical exercise has proven to be one of the most efficient ways to promote cognitive function enhancement, with a line of research that originated in animal experiment a few decades ago (Gould, Beylin, Tanapat, Reeves, & Shors, 1999; Kaplan & Hinds, 1977).

Although typically targeting different changes than computerized interventions – the primary objective of computerized cognitive training is always cognitive enhancement, whereas physical exercise interventions often target more general health changes – aerobic exercise has been associated with remarkable alterations of cognitive functioning. Interestingly, the two fields have remained segregated from each other, possibly because they involve researchers from different backgrounds, interests, and experimental methods. Here, we attempt to demonstrate how these fields share similarities in designs and results.

Aerobic training

Regular physical exercise has been related to numerous beneficial effects on physical and mental health. Being fit physically has been associated with reduced risk in many potentially life-threatening conditions, from cardiovascular diseases to strokes, diabetes, and cancers. Reduced risks have also been reported in a wide variety of mental conditions, ranging from Attention Deficit Hyperactive Disorder and schizophrenia, to autism, dementia, cognitive decline, and Alzheimer's disease (for a review, see Penedo & Dahn, 2005).

In addition to this relationship with general health, a growing body of evidence indicates moderate to strong correlations linking physical exercise and cognitive functioning. Physically fit individuals perform significantly better than non-fit individuals in a large panel of cognitive tasks, with the strongest associations for executive functioning and, to a lesser extent, spatial reasoning (Colcombe et al., 2003; Hillman, Erickson, & Kramer, 2008). Performance on cognitive tasks that do not strongly tap executive functioning, however, does not seem to be enhanced by physical activity (Kramer, Hahn, & Gopher, 1999). Other studies have also emphasized the association between exercising, learning, and memory (for a review, see Hillman et al., 2008; Stroth, Hille, Spitzer, & Reinhardt, 2009), as well as between exercising and fluid intelligence (Singh-Manoux, Hillsdon, Brunner, & Marmot, 2005).

Experimental evidence complements these findings, but conclusions are often restricted to specific populations. For example, exercise interventions have resulted in attention improvements in children with coordination disorder (Tsai, Wang, & Tseng, 2012) and in enhanced associative learning in elderly subjects (Fabre, Chamari, Mucci, Massé-Biron, & Préfaut, 2002), but there is no evidence for generalized effects. The vast majority of the aerobic exercise training literature has dealt with either children or elderly populations, largely neglecting young adults, for several obvious reasons. First, young adults are at a cognitive peak (Salthouse & Davis, 2006) that allows weaker cognitive improvements due to ceiling effects (Hillman et al., 2008). Because young adults are cognitively stimulated through their professional occupations, they are less likely to display large training effects. Second, children and elderly populations have the remarkable advantage to evolve in less diverse environments across individuals, in schools for the former and in retirement homes or often stimulation-deprived environments for the latter. This factor allows partial control over several confounding variables critical to provide representative findings, although it should be noted that children and the elderly are populations that also include additional sources of variability, such as cognitive development and cognitive decline.

In children, a consequent body of research has concerned the relationship between physical activity and academic performance (for a review, see Keeley & Fox, 2009). This vivid interest lies in the current trend initiated by some educational institutions, in the United States and in other countries, to cut physical activity classes in favor of more 'academic' subjects. Not only do these decisions generally fail to lead to improvements in students' grades, but conversely, adding time to physical activity classes seems to induce increases in academic scores (Trudeau & Shephard, 2008). These results are in line with cross-sectional studies underlining the association between physical fitness and academic achievement. In particular, Coe and colleagues found that students who meet specific standards on weekly amounts of exercise had significantly higher grades than students who were below these requirements (Coe, Pivarnik, Womack, Reeves, & Malina, 2006). Corroborating evidence was reported by Castelli and colleagues, who showed that fitness measures thought to be related to aerobic capacity, such as Body Mass Index (BMI), were correlated with overall academic achievement as well as with reading and mathematics competencies (Castelli, Hillman, Buck, & Erwin, 2007). Other factors such as developmental maturation, perceptual skills, executive control, IQ, achievement levels, or verbal and mathematical tests have all been related to physical exercise in children (Buck, Hillman, & Castelli, 2008; Davis et al., 2007; Etnier, Nowell, Landers, & Sibley, 2006). Physical activity also seems to induce better cognitive readiness in subsequent tasks, which underlines its specific value in children's daily routines (Ratey & Loehr, 2011). An experimental study by Davis and colleagues confirmed the latter findings. Assessing the effect of aerobic training on executive functions in an intervention with overweight children, they found a linear relationship between the amount of physical activity and cognitive control (Davis et al., 2007), providing further support for causal claims.

In older adults, evidence for a relationship between exercise and cognition originally comes from the observation that several lifestyle factors, including regular physical activity, seem related to cognitive function maintenance and to a reduction in risks of dementia and other neurodegenerative disorders (Karp et al., 2006; Wilson, Barnes, & Bennett, 2003; Wilson et al., 2002). In a meta-analytic study, Colcombe and Kramer found that fitness training has selective benefits on older adults' cognitive functioning, with the strongest effects on executive and control processes (Colcombe & Kramer, 2003). These effects were affected by different variables, namely the length and type of intervention, the duration of each training session, and gender. Moreover, this result was found for both healthy and cognitively impaired patients, highlighting a consistent trend across meta-analyses (Colcombe & Kramer, 2003; Etnier et al., 2006; Heyn, Abreu, & Ottenbacher, 2004). Although these findings are robust, additional research is needed to investigate whether the underlying factors for such cognitive benefits are similar to those observed in children. To further comprehend the basis of behavioral modifications, a related body of research has explored the neurobiological foundations of training-induced cognitive improvements.

Neuroimaging and neurobiological evidence

Based on an extensive trend of research in animals, the neurobiological substrates underlying physical exercise benefits are now well understood. As well as augmentations of brain vascularization (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990) and brain insult resistance (Stummer, Weber, Tranmer, Baethmann, & Kempski, 1994), voluntary exercise leads to increases in proteins and neurotransmitters (Mora, Segovia, & del Arco, 2007), which in turn favor neurogenesis (see, for example, van Praag et al., 2002), neuronal survival (Vaynman, Ying, Yin, & Gomez-Pinilla, 2006), angiogenesis (Black et al., 1990), and overall brain volume enhancement (Colcombe et al., 2006).

Specifically, brain-derived neurotrophic factors (BDNF) have been shown to be of particular importance to mediate exercise benefits on cognition. Research in animals has found increased post-exercise levels of BDNF in the hippocampus (Neeper, Gomez-Pinilla, Choi, & Cotman, 1995), a part of the limbic system that plays an important role in the consolidation of information into long-term memory and in spatial navigation. Interestingly, these improvements are usually visible within days of exercise and last for several weeks (Berchtold, Kesslak, Pike, Adlard, & Cotman, 2001). These changes might provide the foundations for improved learning and memorization processes, through more efficient and plastic cognitive systems (van Praag, Shubert, Zhao, & Gage, 2005). In addition to hippocampus plasticity, exercise triggers the increase of BDNF levels in the lumbar spinal cord (Gomez-Pinilla, Ying, Opazo, Roy, & Edgerton, 2001), in the cerebellum and in several cortical regions (Neeper, Gomez-Pinilla, Choi, & Cotman, 1996), possibly via augmentations of Insulin-like Growth Factor-1 (IGF-1), a growth factor involved in neuronal development (Arsenijevic & Weiss, 1998). Thus, IGF-1 increased levels following exercise could be mediating BDNF effects on cognition (Cotman & Berchtold, 2002), as peripheral administration of IGF-1 leads to BDNF synthesis in the brain (Carro, Nunez, Busiguina, & Torres-Aleman, 2000).

Consistent with this idea, stress hormones (e.g. corticosteroids) have a detrimental impact on BDNF levels and therefore participate in neuronal degradation, dendritic atrophy and spine reduction (Gould, Woolley, & McEwen, 1990). Because it can relieve stress and have a positive effect on anxiety and depression (Byrne & Byrne, 1993), exercise may act as a shield preventing stress-induced downregulations of BDNF in the hippocampus, therefore counteracting stress damage (Russo-Neustadt, Ha, Ramirez, & Kesslak, 2001). In humans, although ethical concerns have prevented invasive research procedures, BDNF has been shown to facilitate learning, which in turn triggers BDNF release (Kesslak, So, Choi, Cotman, & Gomez-Pinilla, 1998). This interactive coupling makes BDNF a compelling candidate for cognitive enhancement through exercise (Cotman & Berchtold, 2002).

Additional mediating factors, monoamine neurotransmitters (including catecholamines and tryptamines) have been studied extensively, traditionally outside the exercise paradigm. Critical substrates targeted by exercise, catecholamines include dopamine, epinephrine, and norepinephrine. In a randomized crossover design, Winter and colleagues found that central concentrations of catecholamines such as dopamine and epinephrine were positively correlated with higher recall of previously encoded verbal material. The authors concluded that catecholamines could be the mediating factors responsible for improved learning following physical exercise (Winter et al., 2007). However, it should be noted that this interpretation was based on the assumption that brain and systemic levels of catecholamines both vary to the same extent with exercise, which was challenged by a prior PET study by Wang and colleagues (Wang et al., 2000).

Other neurotransmitters of particular importance in the cognitive benefits of physical exercise, tryptamines include serotonin and melatonin. Serotonin is critical to regulate important functions such as mood, appetite, or sleep. Exercise leads to an increase in serotonin levels by increasing the release rate and the production of tryptophan, an amino acid responsible for serotonin synthesis. In addition, exercise positively or negatively affects concentrations of melatonin, important in rhythm regulation, with effects ranging from a few minutes to 24 hours depending on timing and nature (type, intensity, duration) of the training sessions. In accordance with this idea, late-night naturally occurring increases of melatonin levels can also be weakened by exercise sessions, thereby altering circadian rhythms (Buxton, L'Hermite-Baleriaux, Hirschfeld, & Cauter, 1997). As such, melatonin secretion may be increased the day following exercise, with a shift toward late night.

An alternative approach: acute bouts of exercise

A related – although separately studied – trend of research has concerned the effect of acute bouts of exercise on cognition. Acute exercise refers to single sessions of physical practice, as opposed to the programs of regular (multi-session) exercise emphasized thus far in the article. Typically, these studies assess cognitive performance either during or after a bout of exercise (e.g. running, cycling) sometimes reaching anaerobic thresholds, via progressive or constant intensities. Usually, the benefits do not last for more than a few hours, yet understanding the underlying mechanisms of these short-term improvements is informative to fully comprehend the cognitive effects of exercise.

This trend of literature remains equivocal, however, as early studies reached the conclusion that exercise impacts were non-existent or exclusive to simple reaction time performance (Adam, Teeken, Ypelaar, Verstappen, & Paas, 1997; Paas & Adam, 1991), possibly via an increase of arousal levels, whereas some of the latter work has pointed out broader changes (Tomporowski, 2003). Although reaction time improvements are fairly robust across studies and design, regardless of the types of task and exercise, confusion has emerged due to the aggregation of data obtained from testing sessions at different time, namely during or after exercising. In fact, previous facilitation sometimes vanishes (Audiffren, Tomporowski, & Zagrodnik, 2008) or even turns to impairment if exercise reaches a certain threshold or if it is sustained over time (Cian, Barraud, Melin, & Raphel, 2001). Therefore, this distinction (cognitive performance while exercising vs. cognitive performance post-exercise) is critical as it helps explain inconsistencies in the literature (Brisswalter, Collardeau, & Rene, 2002).

Another reason put forward to explain these discrepancies is the failure to distinguish between executive functions and other cognitive processes (Dietrich & Audiffren, 2011). To account for this distinction, Dietrich and Audiffren argue that exercise is accompanied by a disengagement of executive functions, confirmed by the decrease in prefrontal cortex blood flow. This process would allow an active engagement of the implicit system at the expense of the explicit system, to support optimal motor execution, as a product of a general evolutionary process (Dietrich & Audiffren, 2011). The model proposed by Dietrich and Audiffren is supported by a growing body of evidence, clearly showing executive processing impairment with acute bouts of exercise (see, for example, Davranche & McMorris, 2009). In that sense, their findings are of particular contrast with the aerobic exercise literature.

Clearly, different types of physical exercise programs have different influences on cognition. Developing this idea, we argue in the next section that physical exercise can be specifically manipulated to optimize cognitive benefits, leading to broad and transferable changes.

Optimizing the cognitive benefits of exercise

The underlying idea

At first blush, combining cognitive and physical training programs in a single activity might seem counterintuitive, or even challenging. In fact, one could argue for the antinomy of the two approaches. After all, mind and body have historically been distinguished, and although it is nowadays difficult to argue for radical dualism, beliefs and habits are strongly rooted in our languages and cultures. How then can we conceive an alternative that would bring together cognitive and physical demands?

Although impressive and informative to explain many important changes in cognitive functioning, the physiological consequences of aerobic exercise leave out a fundamental component of the relationship between physical activity and cognition. Most physical activities require more than mere aerobic exercising, via specific goals and subgoals to attain either individually or as a team. This general objective prompts, in single activities, numerous processes involved in everyday life, ranging from decision making, often under time constraints, to spatial reasoning, as well as directed attention, stimuli inhibition, resistance to interference, and multiple-modality perception, to name a few. Over a long process, this goal-directed enterprise has provided an answer to the question posed earlier: physical and cognitive demands can be met in single activities. Quite logically, both demands have already been reconciled in specific activities, offering tremendous rewards to those who excel in them. These are modern sports.

In numerous sports, aerobic exercise represents a means to sustain effort toward the objectives initially set and constantly updated, rather than a goal per se. Thus, sports involve much more than a simple workout, and force individuals to adapt to particular situations in a malleable environment. This emphasis on uncertainty is fundamental to brain plasticity and therefore to cognitive improvements because it requires a permanent adjustment of one's behavior to fit the particular cognitive demands of the activity.

It is quite remarkable that beyond simple aerobic exercise, the effects of complex and coordinated motor patterns have received little attention when considering cognitive enhancement training. The consequences of participating in sport activities have been studied through diverse angles such as social benefits (Martin, McCaughtry, Flory, Murphy, & Wisdom, 2011), mental health improvements (McGale, McArdle, & Gaffney, 2011), or dietary habits (Christensen et al., 2011), yet the core mechanisms involved have remained largely ignored within the cognitive enhancement literature.

Despite a lack of consideration within the cognitive enhancement paradigm, sports practice represents the most suitable way to make cognitive training and exercise interventions meet in an activity that can be adapted and diversified at will. This idea is supported by a whole trend of research in the field of sport sciences (for a review, see Moran, 2009), which has shown that athletes excel in many cognitive tasks in the laboratory, in domains such as perception (Wright, Bishop, Jackson, & Abernethy, 2011), attention (Memmert & Furley, 2007), decision making (Raab & Johnson, 2007), spatial ability (Moreau et al., 2011), working memory (Furley & Memmert, 2010), long-term memory (Dijkstra, MacMahon, & Misirlisoy, 2008), and dual-processing (Moreau, 2012).

The argument for sport as suitable cognitive training is also supported by a robust literature on behavioral enrichments, such as environmental enrichment (van Praag, Kempermann, & Gage, 2000), but also rehabilitation (Biernaskie & Corbett, 2001) and learning paradigms (Geinisman, 2000; Rampon & Tsien, 2000), inducing structural changes as well as regulation of growth factors and neurogenesis. In a synthetic review, Cotman and Berchtold pointed out that the similarities between these paradigms and exercising could in fact reveal shared mechanisms (Cotman & Berchtold, 2002).

Designed sports training

One of the main advantages of using sport activities to promote cognitive enhancement is the versatility they induce. Sports can be adapted to suit the particular needs of an individual, and individuals can engage in different sports depending on their demands. Furthermore, individuals can modify the way they practice to seek new patterns of coordination. When considering physical activity as a way to improve cognitive ability, a few key points can be drawn from the fields of neuroplasticity and cognitive enhancement.

The first critical component of a training program based on physical activity is novelty. New environments tend to stimulate cognitive functions (van Praag et al., 2000), as individuals in new surroundings need to set general goals and intermediate steps toward a desired outcome, along with determining the best course of action from their motor repertoire. If appropriate motor actions are not available in an individual's repertoire, practice and repetition will allow new coordination to emerge, to attain the objectives initially set. This functional demand and the cognitive load that ensues lead to an active engagement of WM and executive processes, the very components targeted by computerized training programs. Engaging in novel activities or new ways to practice is obviously not restricted to physical activities, but sports allow combining novelty with other critical features of cognitive enhancement programs, detailed hereafter.

Related to the idea of novelty, another key component to successful training programs is diversity. In fact, research in the field of neuroplasticity suggests that diversity is critical to increase neural and synaptic growth (Brown et al., 2003; Kempermann, Kuhn, & Gage, 1997; van Praag et al., 2000). Physical activity provides an adequate opportunity to meet this criterion, allowing involvement in different sports that require various cognitive abilities and creative skills (Memmert, 2007). For example, an activity that places tremendous emphasis on ballistic open skills (e.g. tennis or golf) can be combined with one that requires predetermined movement sequences in a closed environment (e.g. gymnastics or dancing). In addition, participation in an activity that emphasizes individual concerns (e.g. swimming, judo) can be complemented with another that relies on team performance to reach collective goals (e.g. soccer, football, lacrosse). Potential combinations are endless, and are obviously not limited to pairs of activities. Furthermore, greater diversity can also be accomplished within the particular settings of a single activity. Changing field position (e.g. offense vs. defense) or game type (e.g. active favoring attack vs. passive favoring counter offense), for instance, can lead participants to face new constraints while engaging new sensorimotor coordination.

An additional benefit of this approach, diversity will also influence motivational factors. Seeking changes via different situations, besides the cognitive adaptation it enforces, plays an important role in individual involvement over time by helping to maintain sport's attractiveness. This point is crucial, as long-term commitment is a major challenge for anyone who engages voluntarily in physical training (Hardcastle & Hagger, 2011). In accordance with this notion, studies have shown that exercise-induced neural plasticity is more significant and long-lasting when it is self-motivated rather than forced by external factors (Farmer et al., 2004).

Combining novelty and diversity is sometimes possible through increases in task complexity. As such, an interesting feature in sports is the constant challenges placed on cognitive functions. As participants' levels increase, so does the complexity of the environment in which they evolve. This phenomenon occurs naturally, due to higher demands either self-generated or provoked by opponents. This means that the training level is constantly adjusted to each individual, an aspect that has proven to be fundamental to cognitive interventions and has been particularly emphasized in the WM training literature (Morrison & Chein, 2011; Shipstead et al., 2012).

A closer look at the process of expertise acquisition provides further insight into this particular point. At a novice level, handling motor actions requires all attentional resources available. Coordination patterns are often new and hardly adapted to the task at hand. With practice, some motor actions eventually become automatic, allowing attentional resources to be directed to other sources of information, such as the environment. As the other players or opponents improve as well, the inherent difficulty provided by the environment increases, offering situations constantly taxing to the individuals involved. Hitting the ball during warm-up is not challenging for an elite tennis player, but once the game starts, the complexity imposed by the opponent, among other factors, forces sustained attention. Advance cue usage in all players, combined with expert probabilistic expectations based on prior game patterns, leads players to perform in an environment continually demanding and dynamic.

Finally, a paramount factor in an exercise-based program seems to be the aerobic component of training. This does not mean that aerobic training is sufficient in itself to reach maximized outcomes, but it remains a solid foundation for any physical training that has cognitive objectives (Cotman & Berchtold, 2002). In addition, motor skill acquisition is a long process based on the ability to handle repeated movements over time, which in turns relies on adequate physical conditioning. Interestingly, most sports involve some amount of aerobic exercising; even in sports that do not tap into aerobic processes directly, modern conditioning often involves complementary sessions of aerobic workout. This means that complex motor interactions and aerobic workout are often combined, potentially leading to greater changes.

Corroborating evidence: the embodied approach of cognition

The idea that motor actions and complex cognitive processing are closely tied is at the core of the embodied cognition approach. Although not a unitary framework, the embodied approach of cognition can roughly be presented as one that emphasizes the importance of the body when considering cognitive processes, thus underlining the relevance of motor processes in the study of cognition.

In the process of building a more comprehensive view of human cognition, embodied cognition and behavioral enhancement through sports might benefit from the development of one another (Beilock, 2008; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). Recent evidence suggests that gestures ground mental representation in action; complex problem solving is optimal when gestures are consistent with the motor actions associated with a particular reasoning task (Beilock & Goldin-Meadow, 2010). Further research has pointed out the relation between motor actions and language comprehension (Holt & Beilock, 2006), processes traditionally thought to have very little influence on each other. This finding was subsequently confirmed by fMRI data in elite athletes, showing neural changes in language comprehension depending on sports experience (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008). The relation between sensorimotor experience and cognition was further demonstrated comparing different activities that do not tax particular cognitive processes equally. As such, elite wrestlers showed better spatial ability performance than elite runners, based on differences in strategies as a function of sport level (Moreau et al., 2011). Subsequent work indicated that the differences between experts and non-experts in sports might lie within the underlying processes recruited to solve a particular task (Güldenpenning, Köster, Kunde, Weigelt, & Schack, 2011). For example, a dual-task experiment showed that elite wrestlers rely on motor processes when solving mental rotation problems, whereas non-athletes treated similar content visually (Moreau, 2012).

Consistent with this idea and with our argument for designed sport interventions, experimental evidence suggests that the cognitive benefits of a training program based on physical activity also depend on the particular type of activity practiced during training sessions. For example, in a recent study a particular subcategory of spatial ability, mental rotation, was positively affected by a sport training program in wrestling – an activity that places tremendous demands on spatial manipulations – but not by a running program (Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012). Participants benefited from the specific demands of the activity they practiced, relative to mere aerobic exercise. Although demonstrating a distinction between different types of physical activities, these findings do not contradict traditional research linking aerobic exercising and cognitive improvements. In fact, runners also improved mental rotation performance, but wrestlers showed larger benefits, consistent with the idea that a combination of cognitive and physical demands represents an optimal way to apprehend training interventions.

Furthermore, changes were observed in strategic behaviors, better mental rotation performance being associated with more adaptive strategies (Moreau et al., 2012). Participants involved in a wrestling program tended to adapt their strategy throughout testing to select the best alternative to the problems encountered, whereas runners' strategies were more stereotyped across problems. This idea was supported by a related study comparing elite wrestlers and runners in a cross-sectional design (Moreau et al., 2011). This trend of research is in line with work showing the involvement of motor processes in spatial reasoning tasks (Amorim, Isableu, & Jarraya, 2006; Moreau, 2012; Steggemann, Engbert, & Weigelt, 2011; Wraga, Thompson, Alpert, & Kosslyn, 2003) and the facilitation induced by gestures in spatial problem solving (Chu & Kita, 2011; Janczyk, Pfister, Crognale, & Kunde, 2012).

Taken together, these findings suggest an experience-based embodied mechanism in cognition, with consequences in a wide variety of processes. Evidence from a careful comparison of expertise groups suggests that the involvement of sensorimotor processes varies along a continuum, rather than in all-or-none fashion. Therefore, the embodied approach of cognition needs to take into account individual differences, as variations across individuals might explain discrepancies in the literature and could help to build an exhaustive theoretical framework.

An alternative approach: new trends in physical training

As pointed out in this article, the study of motor expertise underlines that individual differences are clearly malleable, and that they can be trained with appropriate programs. Many important points have been made to allow redesigning physical activities in ways that will enhance both cognitive function and our understanding of cognition. Supported by decades of research, one critical aspect that was addressed is the need to favor aerobic exercise, within a particular activity, to induce broad and wide changes.

One should bear in mind, however, that aerobic training might not be the only physiological way to target cognition through exercise. Recent evidence suggests that weight lifting and resistance training might also lead to significant changes in terms of cognitive performance (Nagamatsu, Handy, Hsu, Voss, & Liu-Ambrose, 2012). Whether these changes can match those of aerobic training is not currently known, nor is the influence of each type of training on particular cognitive abilities precisely understood yet, but future studies should allow more rigorous conclusions to be drawn. In addition, other booming trends in physiology of exercise, such as interval training or high-intensity training, have shown remarkable efficacy in improving physiological components (Duffield, Edge, & Bishop, 2006; Esfarjani & Laursen, 2007), but have not been used to date in cognitive enhancement programs. These training paradigms might represent interesting perspectives for future research, in order to foster our understanding of exercise-induced cognitive enhancement.

Concluding remarks and future directions

After a review of popular interventions to enhance human cognitive functioning, we have provided arguments to consider specifically-designed sports as a viable alternative to stimulate cognitive ability improvements. This idea lends itself nicely to recent theories of embodied cognition, an approach currently receiving a lot of attention in the field of cognitive science.

Within this fast-growing trend of research, the field of behavioral cognitive enhancement is an exciting one, as it opens up new possibilities and paths to prospective discoveries. We believe a few lines of research need to be explored in the near future to foster our understanding of training programs based on sports. Firstly, one important question that remains is the extent to which the effects of the different behavioral interventions presented in this article add up. Can the benefits be combined through ad hoc multi-modal interventions (e.g. WM training *and* exercising) targeting a vast panel of cognitive components? This could provide possibilities to train individuals via diverse means, hence favoring sustained motivation over time. This concern is central, as lack – or loss – of motivation is one of the most common reasons for dropping out of a training program. Secondly, a central facet of training paradigms is the extent to which they can be individualized to suit specific needs. Different individuals have different expectations when voluntarily starting a training program, due to distinct goals and objectives and to differences in baseline performance. The outcomes of an intervention could be maximized via individualized procedures, although this implies a clear understanding of the mechanisms involved in cognitive function improvement. The latter remark leads to the last line of research that appears crucial to the two mentioned above: there is a need to better define and understand the underlying processes that mediate cognitive enhancement, as well as the non-dissociable neural substrates associated with the observable changes, via carefully designed experiments including neural data over the course of training programs.

Beyond the arguments that have been presented herein, physical activity seems to be an ecologically valid way to enhance cognition, inducing wide and versatile changes. The impact on general health and the benefits it therefore represents for society leads us to believe that the risk is minimal in terms of training paradigm. A cognitive intervention based on physical activities has the dramatic advantage of emphasizing pleasure rather than monotonous and prosaic work. It therefore represents an easily accessible way to train cognitive abilities.

Sitting in front of a computer to enhance one's cognition, on the other hand, seems to us a rather constrained approach to cognitive training. Undeniably, computerized tasks are a suitable way to isolate cognitive abilities in the laboratory, and, to some extent, to develop particular cognitive abilities. To be sure, the idea that computerized cognitive training serves critical purposes to assess the differentiated roles of specific abilities and their prevalence in human cognitive functioning is not to be debated. However, when it comes to ecological training dedicated to improving people's lives outside the laboratory, computer-based interventions appear to be an unnatural and limited way to influence a wide range of cognitive processes.

Obviously, more work is needed to clarify the specific implications of training programs in such complex activities as sports, but the potentialities they offer, particularly due to their inherent flexibility and endless possibilities, are promising. In this sense, the field of brain plasticity broadens the possibilities we are given to shape our own cognitive abilities, and physical training might prevail as a constructive and natural way to incite profound and general changes. It is up to us to design activities and training programs in suitable ways that allow us to reach our full cognitive potential.

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