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An ecological approach to cognitive enhancement: Complex motor training

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ABSTRACT

Cognitive training has received a lot of attention recently, yielding findings that can be conflicting and controversial. In this paper, we present a novel approach to cognitive training based on complex motor activities. In a randomized controlled design, participants were assigned to one of three conditions: aerobic exercise, working memory training or designed sport — an intervention specifically tailored to include both physical and cognitive demands. After training for eight weeks, the designed sport group showed the largest gains in all cognitive measures, illustrating the efficacy of complex motor activities to enhance cognition. Designed sport training also revealed impressive health benefits, namely decreased heart rate and blood pressure. In this period of skepticism over the efficacy of computerized cognitive training, we discuss the potential of ecological interventions targeting both cognition and physical fitness, and propose some possible applications.

1. Introduction

Can cognition be enhanced via training? Given the relationship between one's cognitive capabilities and numerous factors such as educational and professional achievement (Deary, Strand, Smith, & Fernandes, 2007), socioeconomic status and stress levels (Evans & Schamberg, 2009), and happiness (Pe, Koval, & Kuppens, 2013), the idea that cognitive performance can be improved is extremely appealing. Among other incentives, the potential applications have led researchers to explore the issue intensely in recent years. The resulting body of work includes disparate results and disparate interpretations of the same results that range from optimistic to skeptical (for reviews, see Hillman, Erickson, & Kramer, 2008; Moreau & Conway, 2013; Morrison & Chein, 2011; Rabipour & Raz, 2012; Shipstead, Redick, & Engle, 2012). Here we adopt a new perspective on training and propose a novel paradigm in which both cognitive training and physical fitness are combined into an ecologically valid regimen of complex motor training, which we refer to as designed sport. We compare this novel training with training regimes that primarily tax either cognitive (computerized working memory training) or physical resources (aerobic training) in order to test whether a combined approach can significantly bolster the effects of extant training regimes.

1.1. The cognitive training paradox

Performance enhancement following practice of a particular task is an extremely robust finding in psychology (see for example Schmidt, 1982, for a review in the motor learning domain). The flip side to this well-established finding is that such improvements are often task-specific and therefore rarely transfer to other tasks. A compelling example of task-specific improvement comes from the study of chess grandmasters. In a seminal experiment, Chase and Simon (1973) showed that masters could recall accurately more piece locations on a chessboard than novices in an actual chess game, but this effect disappeared when pieces were placed randomly on the board. Thus, memory enhancement associated with chess expertise is specific to chess patterns and does not transfer to random configurations. Similar effects have been observed among experts in a multitude of activities, and the specificity of training improvements is largely supported in expertise research (see Ericsson, 2006; Ericsson & Charness, 1994 for reviews of expertise-specific improvements).

In 2008, Jaeggi and colleagues questioned the long-standing view of specific improvements and fixed cognitive abilities in adulthood (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). In an influential study, they

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reported improvement in fluid intelligence following working memory training, in line with previous work in clinical populations (Klingberg, Forssberg, & Westerberg, 2002; Klingberg et al., 2005). This finding has been replicated since (Jaeggi et al., 2010), and further evidence for transfer from computerized working memory training paradigms to other cognitive abilities has been established by independent research groups (Chein & Morrison, 2010; Jaušovec & Jaušovec, 2012; Perrig, Hollenstein, & Oelhafen, 2009; although see Chooi & Thompson, 2012, Harrison et al., 2013 and Redick et al., 2013, for failures to replicate).

Neuroimaging evidence has also been presented to illustrate the efficacy of working memory training. For example, Olesen et al. (2003) reported increased activity in the middle frontal gyrus and the superior and inferior parietal cortices after five weeks of working memory training, a finding corroborated by a single-subject analysis (Westerberg & Klingberg, 2007), and Hempel and colleagues found increased cortical activation in the right inferior frontal gyrus and the right intraparietal sulcus when performing a spatial working memory task after two weeks of training, but decreased activation after four weeks of training, revealing an inverse quadratic function (Hempel et al., 2004).

This line of research has brought excitement but also skepticism in the field (for recent meta-analyses, see Au et al., 2014; Karbach & Verhaeghen, 2014; Melby-Lervåg & Hulme, 2013). Why would working memory training engender general cognitive improvements where other interventional approaches have systematically failed? The rationale underlying working memory training is perhaps best explained with an analogy. In the sports domain, aerobic conditioning is a prerequisite for performance in many activities. Preseason conditioning often includes an aerobic component to allow building a strong aerobic base necessary to subsequent activity-specific workouts. Aerobic conditioning is only one of many factors that can influence performance, yet because of its central role in numerous physical activities, improvements in aerobic conditioning will often allow general improvements. Similarly, working memory capacity, the maximum amount of information an individual can maintain in working memory, can be thought as the base of many cognitive operations, an idea supported by the relationship between working memory capacity and performance in many cognitive tasks (e.g. Kane et al., 2004). Drawing on this evidence, proponents of working memory training assert that increases in working memory capacity can improve performance in diverse cognitive tasks. However, a strong correlation between two constructs does not guarantee that training one will produce improvements in the other (Moreau & Conway, 2014; Shipstead et al., 2012), as training might tap unshared components. Accordingly, some researchers remain reserved about the potential of working memory training to improve general cognition (Chooi & Thompson, 2012; Owen et al., 2010; Redick et al., 2013; Shipstead et al., 2012), while others have emphasized the need for more research before strong claims can be established (Conway & Getz, 2010; Moody, 2009; Morrison & Chein, 2011; Sternberg, 2008).

1.2. The potential of complex motor activities

There seems to be a contradiction between training on restricted monotonous tasks and expecting wide and generalized changes in cognition (e.g. McDaniel & Bugg, 2012). Given this possible limitation, interventions based on rich and more diverse training environments appear to be a step in the right direction, with a growing amount of literature supporting the efficacy of such programs to produce wide cognitive changes (for reviews, see Green & Bavelier, 2008; Moreau & Conway, 2013) along with observable alterations in neural connectivity (Colom et al., 2012; Voss et al., 2012). Following this idea, complex motor activities combining physical and cognitive demands appear to be a promising way to train cognition.

Previous studies have highlighted the potential of complex motor learning to enhance cognitive abilities, such as spatial ability (Jansen, Titze, & Heil, 2009; Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012). Experts in motor activities also excel in a wide range of cognitive tasks in the laboratory, most notably in domains such as perception (Wright, Bishop, Jackson, & Abernethy, 2011), attention (Memmert & Furley, 2007), decision-making (Raab & Johnson, 2007), working memory (Furley & Memmert, 2010; Moreau, 2013b), long-term memory (Dijkstra, MacMahon, & Misirlisoy, 2008) and dual-processing (Moreau, 2012a). This line of work is corroborated by experimental studies of motor experts' performance in spatial and working memory tasks (Moreau, 2013a,b; Moreau, Mansy-Dannay, Clerc, & Guerrien, 2011). Despite these impressive benefits, complex motor activities have been largely ignored as cognitive enhancers. Most research assess differences in performance between levels of expertise, with very few experimental manipulations being conducted longitudinally to determine how changes in motor activities result in different cognitive improvements and therefore how motor activities can be altered to induce greater or personalized improvements.

Complex motor activities are also appealing because they offer possibilities to bridge cognitive training and physical exercise, which impact on cognition is well documented (for reviews, see Colcombe & Kramer, 2003; Hillman et al., 2008). Aerobic exercise triggers wide neurophysiological changes, such as increases in brain vascularization (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990) and brain insult resistance (Stummer, Weber, Tranmer, Baethmann, & Kempski, 1994). In addition, aerobic exercise leads to increases in proteins and neurotransmitters (Mora, Segovia, & del Arco, 2007), therefore triggering neurogenesis (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). Despite these impressive changes at the neural level, this type of training has not been combined with high cognitive demands to optimize the effects of training on cognition. Exercise studies generally reduce physical activity to its physiological component, therefore ignoring the potential of complex motor coordination embedded within aerobic exercise sessions.

Addressing this shortcoming in the exercise literature, we have proposed that specifically designed motor activities, which tax working memory and spatial ability by incorporating motion in three-dimensional space, represent an optimal way to induce transfer across tasks, while combining the benefits of traditional cognitive training and physical exercise into a single activity (Moreau & Conway, 2013). Moreover, the emphasis on spatial ability is especially relevant to cognitive training given the underrepresentation of spatial activities in educational curricula (Moreau, 2012b; Newcombe & Frick, 2010).

1.3. Current experiment

The aim of the present study was to assess the potential of a novel cognitive training program based on complex motor skills, which we have labeled designed sport. Designed sport includes spatial ability and working memory demands while concurrently requiring sustained physical activity. Therefore, this regimen offers an integrated approach to cognitive training, bridging psychology and exercise sciences literatures.

In order to assess its validity against current cognitive training paradigms, designed sport was compared with a working memory training regimen. Complex span working memory training was selected as a desirable computerized cognitive training comparison because of prior evidence of a strong relationship between complex span and various other cognitive measures (e.g. Kane et al., 2004) and because of prior demonstrations of the effectiveness of complex span training to enhance performance on untrained measures of working memory and cognitive control (Chein & Morrison, 2010; Harrison et al., 2013). Moreover, complex span training includes two components — spatial and verbal — that have been shown to activate overlapping but also distinct cortical regions (Chein, Moore, & Conway, 2011).

Importantly, the designed sport and working memory conditions were compared with an aerobic exercise control group that was active and adaptive. This point is critical in the present experiment because the validation of designed sport training rests on the assumption that it is superior to aerobic exercise alone, and that it can therefore offer practical applications outside academia.

We measured working memory capacity and spatial ability constructs via multiple tasks administered before and after training for eight weeks. In addition to transfer effects, we measured in-training performance throughout the intervention to monitor improvements and to provide participants with an adaptive and individualized regimen. Consistent with the theoretical rationale outlined in this introduction, we predicted the largest gains across constructs following designed sport training, along with physiological improvements. Based on prior research in working memory training using complex span tasks, we predicted working memory — but not spatial ability — gains after training working memory. Finally, we predicted limited cognitive gains but substantial physiological improvements following aerobic exercise training in the control group.

2. Method

2.1. Participants

An a priori power analysis based on previous studies using conditions similar to the present design (Chein & Morrison, 2010; Moreau et al., 2012) suggested an *n* of at least 21 per condition to detect an effect (power $= .80$) and reject the null hypothesis ($\alpha = .05$). A total of 67 participants (39 females; range of 18–52; $M = 29.73$; $SD = 7.83$) were recruited via public advertisement. Pre-requisites included the following: (a) age over 18 years old, (b) physician's approval for physical exercise, and (c) willingness to commit to the entire training program. No monetarily reward was offered.

2.2. Training

Prior to training, participants were randomly assigned to one of three conditions: designed sport (DS, $n = 22$), working memory training (WM, $n = 23$), and aerobic exercise (AE, $n = 22$). Age and gender did not differ significantly between conditions [$F(2,64) = 0.55$, $p = .58$ and $F(2,64) = 0.02$, $p = .98$, respectively]. In all conditions, 1-hour training sessions were scheduled three times per week. The programs lasted eight weeks, for a total of 24 training sessions. The duration of training was longer than previous training studies using complex span tasks (e.g. Chein & Morrison, 2010; Harrison et al., 2013) as it was predicted that the two exercise conditions might require longer exposure to show benefits (e.g. Moreau et al., 2012). The content of each condition is detailed below.

2.2.1. Designed sport

Participants started with a progressive warm-up and light stretching (10 min), immediately followed by the core of the session (40 min). Each session was concluded by a recovery period including movements performed at a moderate intensity and stretching (10 min). All sessions included unusual movements to induce specific motor constraints and trigger adaptive behaviors. The training content was loosely based on freestyle wrestling (see Fig. 1). Training favored new motor coordination via demonstrations and active trial-and-error problem-solving with a partner. More specifically, it emphasized:

- Perceptive problems, via situations channeling unusual perceptive information (proprioceptive/kinesthetic). For example, in the first three weeks participants were occasionally blindfolded for 15 to 20 min per session to emphasize proprioceptive and kinesthetic information over more common visual inputs. In other situations, visual information was restricted by specific positions (e.g. back-to-back, or standing in stance looking down), forcing participants to integrate and evaluate proprioceptive inputs to determine the most efficient course of actions. The underlying logic of perceptive problems was to reduce participants' reliance on visual information in order to prompt somatosensory processing.
- Motor problems, via situations introducing increasingly complex motor coordination. For example, participants transitioned from one to another of three levels of motion (i.e. standing — intermediate — on the mat) throughout the program, while increasing or decreasing execution speed. Other situations involved lateral inversions, or body rotations in three-dimensional space. Here, the goal was to encourage the emergence of novel, non-automatic motor sequences via unfamiliar situations.
- Cognitive problems, via situations requiring active updating over time. For example, participants had to maintain and update series of motor elements in every session, for further recall and execution at given times signaled via auditory tones. Upon hearing the signal along with a number, participants had to execute one or several movements within the series, specified by their respective number (e.g. a signal accompanied by number 3 would necessitate recall and execution of the third movement of the initial series). These situations required constant maintenance and update of a series of movements. On an increasing continuum of difficulty, recall could be identical to the initial movement, or necessitate further alterations (e.g. recall and lateral inversion). Cognitive problems were designed to stimulate participants' ability to process and maintain information in the face of interference, under relatively strenuous physical constraints.

It is important to note that perceptive, motor and cognitive problems were intrinsically related, as every situation clearly involved multiple demands rather than a specific category of problems. Eventually, as participants' level improved, all these problems were combined in ad hoc situations, such as duel matches requiring open skills. These situations led to a wider variety of problems to cope with in a timely fashion. The variety of the situations encountered, along with strict time constraints, provided a rich framework to increase motor complexity over time, and therefore to match the adaptive and individualized features implemented in other training conditions.

2.2.2. Working memory

The working memory training was adapted from previous work (Chein & Morrison, 2010; Richmond, Morrison, Chein, & Olson, 2011). It included verbal and spatial complex span tasks, tailored to participants' individual performance. In the verbal task, participants had to maintain a list of letters for subsequent recall, while making decisions about lexicality (word vs. non-word). In the spatial task, participants had to maintain a series of spatial locations in a matrix, while making decisions about symmetry (symmetrical patterns vs. non-symmetrical patterns). Memory items were presented for 1 s each and lexicality of symmetry decisions were made for 4 s between each item. Verbal and spatial tasks were evenly divided in each session, in a randomized blocked fashion. Participants began the first day of training at level four, i.e. with four letters or four locations to remember. The level of difficulty was adapted by increasing or decreasing the list length on subsequent trials. Difficulty increased by adding a memory item when all items were recalled properly for two trials in a row and at least 75% of the decisions were correct. Conversely, recall performance below this threshold for two trials in a row resulted in a decrease in difficulty by subtracting a memory item from the list length of the next trial. These rules also applied

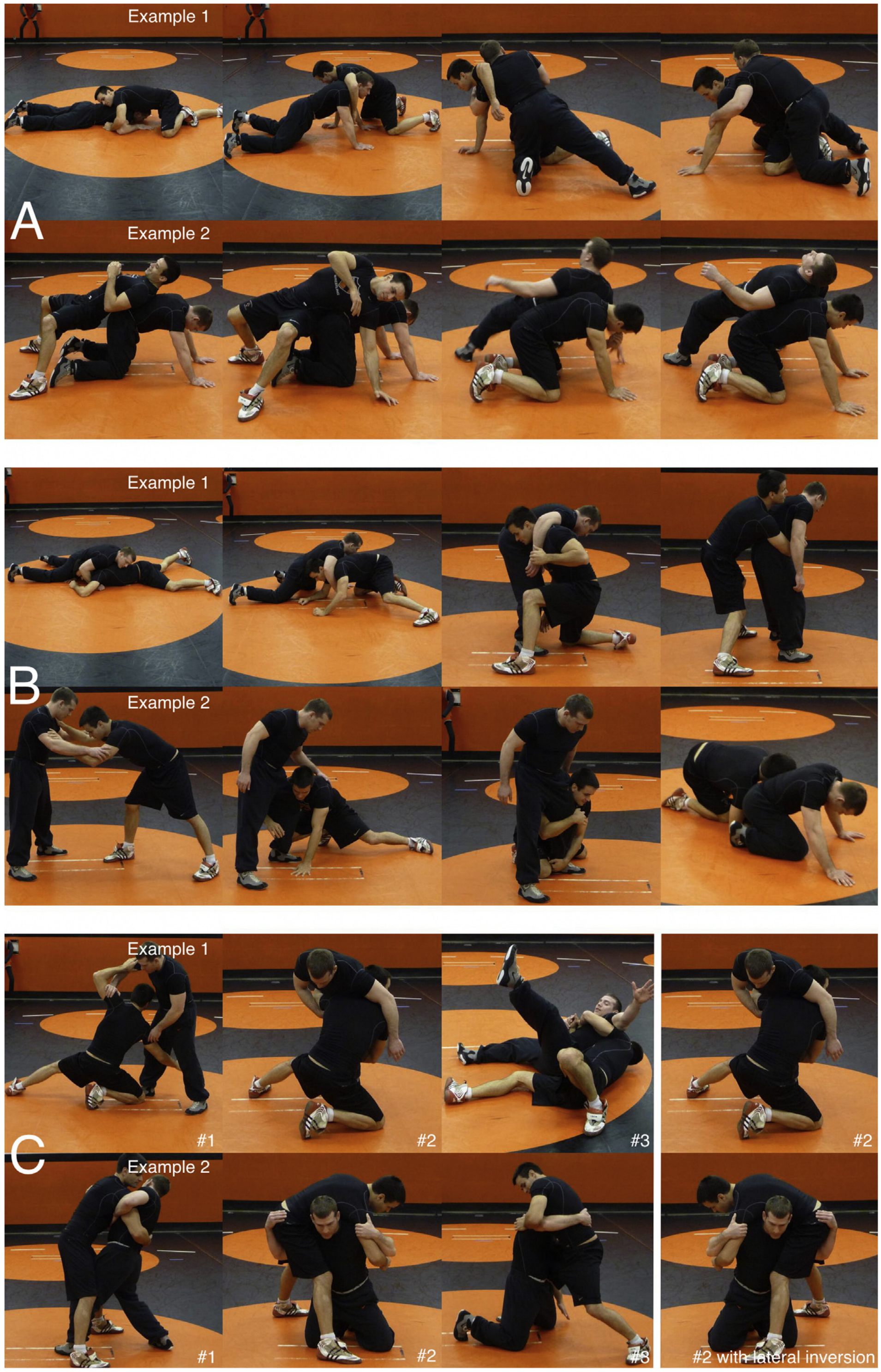

Fig. 1. Example-situations from the designed sport training condition. A: Perceptive problems. Participants react to proprioceptive cues (partner's changes in position) to determine the course of actions to undertake. In both examples, a change in top position provides an opportunity for the bottom partner to transition to a top position. B: Motor problems. Situations trigger unusual motor coordination, with transitions from different positional levels (i.e. lying–quadrupedal–standing, Example 1) or combinations of body translations and rotations (Example 2). C: Cognitive problems. Participants execute a series of movements. A number prompts recall and execution of the corresponding movement in the series. Level of difficulty can be increased with lateral inversions. In both examples shown in the figure, the second of a series of three movements was to be recalled, either without (Example 1) or with additional lateral inversion (Example 2).

across training sessions. For example, the starting level of session two was the final level of session one.

2.2.3. Aerobic exercise

The aerobic exercise condition was designed to match the structure of designed sport sessions, without the cognitive demands. A typical session included three successive parts. Participants started with a progressive warm-up and light stretching (10 min). Following warm-up, the core of the session was composed of an aerobic workout, on treadmills, spinning bikes, or rowing machines (40 min). Each session was concluded by a recovery period including moderate exercise and stretching (10 min).

Each session was individualized. Participants' aerobic target zone was determined from individual heart rate (HR), based on Karvonen, Kentala, and Mustala's (1957) method. This method includes three steps:

- Measuring resting HR (HR_{Rest}).
- Calculating maximum HR (HR_{Max}):

$$HR_{Max} = 220\text{–age}. \tag{1}$$

- Determining target HR (HR_{Targ}):

$$HR_{Targ} = HR_{Rest} + \alpha(HR_{Max}\text{–}HR_{Rest}) \tag{2}$$

where α represents the intensity of exercise in percent.

To target the aerobic zone of each individual, we used a moderate intensity of exercise throughout training, with target ranges increasing over time (weeks 1 and 2: $\alpha = 60\text{–}65\%$ range, weeks 3 and 4: $\alpha = 65\text{–}70\%$, weeks 5 and 6: $\alpha = 70\text{–}75\%$, weeks 7 and 8: $\alpha = 75\text{–}80\%$). Therefore, individualized target zones were readjusted weekly, depending on the latest individual measurement of HR_{Rest}.

2.3. Assessments

Physiological measurements were recorded for all participants on a weekly basis. These measurements included resting heart rate, oxygen saturation, and systolic/diastolic blood pressure. Measures were non-invasive, using blood pressure monitors and pulse oximeters. In addition, performance in the working memory training tasks was compiled automatically for each session in the WM condition. These measurements served as critical manipulation checks to ensure training improvements in each condition. In addition, they were used to provide participants with an adaptive training tailored to individual performance.

Before and after training, participants completed a battery of assessments to measure two cognitive constructs: spatial ability (SA) and working memory capacity (WMC). Pre-testing took place before any training, while post-test assessments were completed two days after the last training day, to avoid any confounds due to differential states of arousal or fatigue in the physical exercise groups. The spatial ability construct included four tasks, whereas the working memory capacity construct was measured based on three tasks. The WMC construct did not include any complex span task because the WM training condition was itself based on the complex span paradigm. Therefore, gains on complex span measures would not have qualified as transfer effects. The order of task administration for pre-test and post-test was the order of presentation below.

2.3.1. Mental rotation (SA)

We used the redrawn version (Peters et al., 1995) of the original Mental Rotations Test (MRT, Vandenberg & Kuse, 1978). The test consisted of two sets of 12 items to solve in 2 × 3 min separated by a 3 min break. Each item included a target three-dimensional figure on the left and four possible responses on the right. Of the four responses, two were rotated versions of the target (correct alternatives) and two were distractors (incorrect alternatives). MRT-A and MRT-B were presented before and after training, respectively.

2.3.2. Paper folding (SA)

The paper folding test (Ekstrom, French, Harman, & Dermen, 1976) consisted of 10 items to complete in 3 min. Each item presented a piece of paper being folded and a hole punched through the paper once or twice. Participants had to select the correct outcome out of five possibilities after the piece of paper was unfolded. Part 1 and part 2 were presented before and after training, respectively.

2.3.3. Form board (SA)

The form board test (Ekstrom et al., 1976) consisted of 24 items to complete in 8 min. Each item displayed a set of five two-dimensional shapes that could be combined together to make a target figure drawn at the top of the page. Participants had to mark a plus sign below the item they selected and a minus sign below the ones they did not use. The entire test was composed of 6 items per target figure, for a total of four target figures. Part 1 and part 2 were presented before and after training, respectively.

2.3.4. Surface development (SA)

The surface development test (Ekstrom et al., 1976) consisted of six items to complete in 6 min. Each item depicted a three-dimensional shape and its corresponding flat depiction when unfolded. Participants had to match the letter-marked edges of the three-dimensional shape with the number-marked edges of the unfolded depiction. Part 1 and part 2 of the ETS version were presented before and after training, respectively.

2.3.5. Immediate free recall (WMC)

The task consisted of 10 lists of 10 words each (common nouns), presented for 1 s. After 10 words were presented, participants had 30 s to recall as many words as they could in any order. Prior to the test, two practice lists with letters instead of words were presented. We designed two versions of the task, to be used before and after training.

2.3.6. Backward digit span (WMC)

The task consisted of 15 trials of 3 to 7 digits to recall in backward order (starting with the last digit up to the first digit). Prior to the test, participants practiced with three sample trials. Item presentation was randomized.

2.3.7. Letter-number sequencing (WMC)

The task consisted of 15 trials of 3 to 7 letters or numbers to be reordered and recalled with numbers first in a crescent order, and then letters in the alphabetical order. Prior to the test, participants practiced with three sample trials. Item presentation was randomized.

3. Results

We used R (R Core Team, 2014) for all statistical analyses and figures presented herein. We first report in-training improvements (gains in performance in the practiced tasks within each condition) and then report transfer effects (gains from pre-training to post-training in spatial ability and working memory capacity measures).

3.1. In-training improvements

All participants attended at least 21 of the 24 training sessions ($M = 23.54$). Attendance did not differ between conditions [$F(2,64) = 0.64$, $p = .53$]. Importantly, all groups improved on the scales explicitly targeted by their respective program. DS and AE groups showed improvements in physiological measures. The WM group improved in spatial and verbal working memory capacities. These improvements are detailed below.

A series of one-way ANOVAs was conducted examining gain scores between groups for each physiological measure. There was a significant effect of condition on resting heart rate [$F(2,64) = 38.92$, $p < .001$, $\eta_p^2 = .55$], systolic blood pressure [$F(2,64) = 29.72$, $p < .001$, $\eta_p^2 = .48$] and diastolic blood pressure measures [$F(2,64) = 25.26$, $p < .001$, $\eta_p^2 = .44$]. Follow-up dependent t-tests showed the difference between the first and the last session to be significant for DS and AE groups only (Fig. 2), indicating an improved physical condition for these groups (Cohen's $d = 2.22$ and $d = 1.59$ for resting heart rate; $d = 1.48$ and $d = 0.93$ for systolic blood pressure; $d = 1.48$ and $d = 2.01$ for diastolic

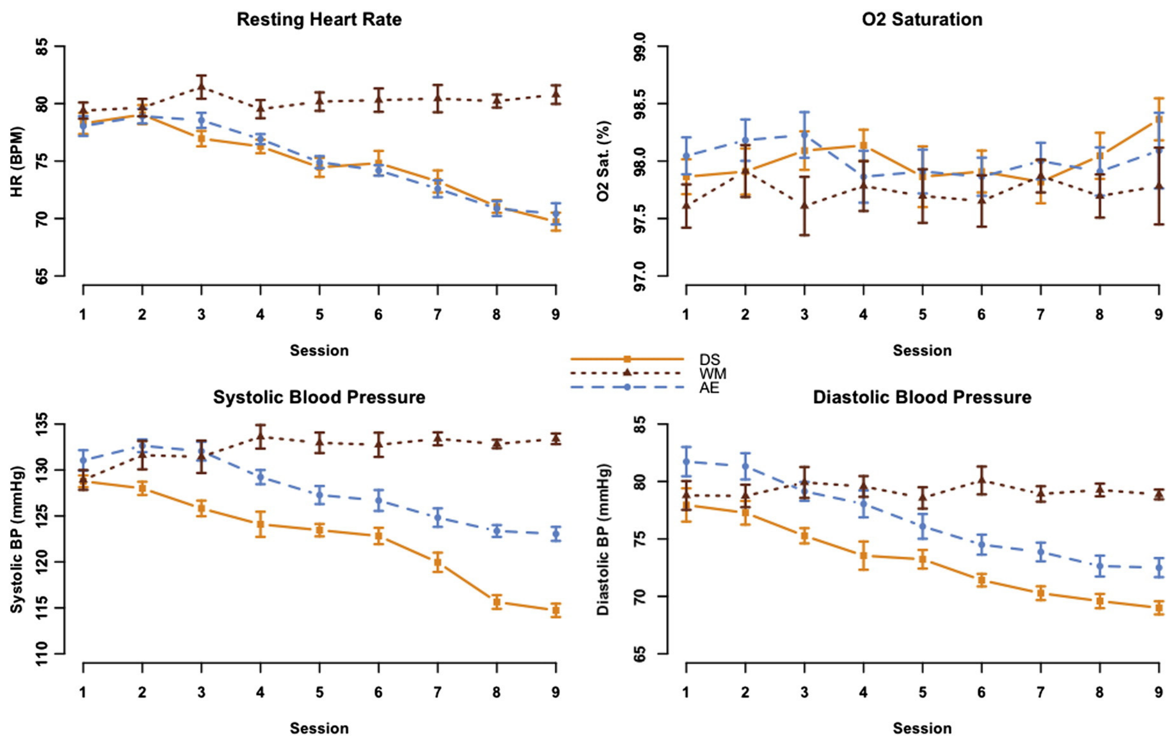

Fig. 2. Physiological measures for all training groups across weekly testing sessions. A: Resting heart rate expressed in beats per minute. B: Oxygen saturation, in percentage of blood oxygen. C and D: Systolic and diastolic blood pressure, respectively, in millimeters of mercury. Error bars represent standard errors of the means corrected for repeated measurements.

blood pressure, respectively for the DS and the AE group). Conversely, the WM group did not show any physiological improvements.

Participants in the WM group showed a steady rate of improvement in spatial and verbal span across the eight weeks of training as demonstrated by a linear trend analysis and session-to-session mean comparisons (Fig. 3). Dependent t-tests on the first and last sessions confirmed the gains [$t(22) = 4.48$, $p < .001$, $d = .93$; and $t(22) = 6.07$, $p < .001$, $d = 1.27$ respectively for spatial and verbal]. Spatial and verbal increases were initially unequal, with spatial capacity significantly superior to verbal capacity from session one through session six, as demonstrated by dependent t-tests with a significance level of .05 (two-tailed). In subsequent sessions, spatial and verbal capacities did not differ significantly.

3.2. Transfer effects

Besides in-training measurements performed at multiple time-points throughout the program, we also assessed cognitive ability before and after training. Specifically, our design included four tasks measuring spatial ability and three tasks measuring working memory capacity. Separate 3 (Condition) × 2 (Session) mixed factorial ANOVAs with repeated measures on the latter variable were conducted for each tasks, to probe transfer effects for each training group. For all results reported here, there was no significant difference between groups at pre-test. Inferential statistics and corresponding effect sizes are presented in Table 1. Means and standard errors for each group and task are presented in Fig. 4.

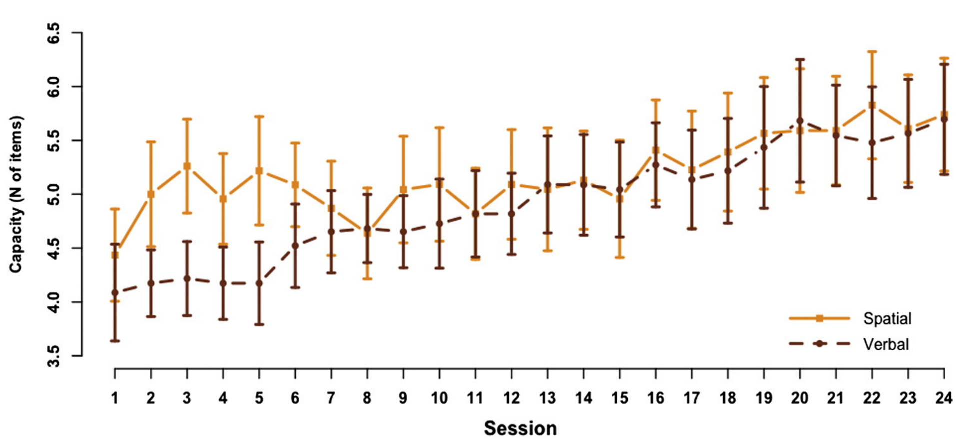

Fig. 3. Working memory capacity increase across 24 training sessions for spatial and verbal complex span tasks. Training data were compiled automatically at the end of each training session. Error bars represent standard errors of the means.

Table 1
Inferential statistics for all transfer tasks and constructs. All interactions between Condition (DS, WM, AE) and Session (pre-test, post-test) are based on mixed factorial ANOVAs with repeated measures on the latter variable. Simple effects are computed from follow-up dependent *t*-tests (two-tailed). Cohen's *d* values represent effect sizes for the mean difference between pre-test and post-test.

Measures	Interaction condition × session	Training condition					
		DS		WM		AE	
		Simple effect	Cohen's *d*	Simple effect	Cohen's *d*	Simple effect	Cohen's *d*
Spatial ability	$F(2,64) = 15.72^*, \eta_p^2 = .33$	$t(21) = 9.61^*$	2.05	$t(22) = 4.34^*$	0.90	$t(21) = 2.15^*$	0.46
Mental rotation	$F(2,64) = 3.81^*, \eta_p^2 = .11$	$t(21) = 5.66^*$	1.21	$t(22) = 2.55^*$	0.53	$t(21) = 1.06$	0.22
Paper folding	$F(2,64) = 4.13^*, \eta_p^2 = .11$	$t(21) = 3.68^*$	0.79	$t(22) = 1.00$	0.21	$t(21) = 0.12$	0.25
Form board	$F(2,64) = 5.19^*, \eta_p^2 = .14$	$t(21) = 4.67^*$	1.00	$t(22) = 1.32$	0.27	$t(21) = 0.81$	0.17
Surface development	$F(2,64) = 8.41^*, \eta_p^2 = .21$	$t(21) = 7.66^*$	1.63	$t(22) = 4.78^*$	1.00	$t(21) = 4.70^*$	1.00
Working memory capacity	$F(2,64) = 10.18^*, \eta_p^2 = .24$	$t(21) = 5.78^*$	1.14	$t(22) = 4.84^*$	0.90	$t(21) = 0.34$	0.08
Immediate free recall	$F(2,64) = 4.45^*, \eta_p^2 = .12$	$t(21) = 3.63^*$	0.77	$t(22) = 3.08^*$	0.64	$t(21) = 0.19$	0.04
Backward digit span	$F(2,64) = 3.64^*, \eta_p^2 = .10$	$t(21) = 5.03^*$	1.07	$t(22) = 2.67^*$	0.56	$t(21) = 0.09$	0.02
Letter–number sequencing	$F(2,64) = 4.96^*, \eta_p^2 = .13$	$t(21) = 2.94^*$	0.63	$t(22) = 3.60^*$	0.75	$t(21) = 0.53$	0.11

* $p < .05$.

3.2.1. Spatial ability

We first report our findings for all spatial ability measures (mental rotation, paper folding, form board, surface development). Interactions between Condition (DS, WM, AE) and Session (pre, post) were significant for all spatial ability tasks, indicating a different impact of training across conditions. Simple effect analyses indicated that training in the DS condition resulted in the largest improvements in all spatial ability measures. The WM group showed gains only in mental rotation and surface development. The AE showed improvement only in surface development.

3.2.2. Working memory capacity

We report here our findings for all working memory capacity tasks (immediate free recall, backward digit span, letter–number sequencing). Interactions between Condition (DS, WM, AE) and Session (pre, post) were significant for all working memory capacity tasks, indicating a different impact of training across conditions. The largest gains were found for the DS and the WM groups. AE training did not lead to significant gains in any of the working memory capacity measures.

3.2.3. Cognitive constructs

Table 2 presents the correlation matrix and descriptive statistics for each task. The table shows strong correlations between all spatial ability tasks and between all working memory capacity tasks. This suggests two different constructs in our data, which was confirmed by an exploratory factor analysis using principal component extraction and promax rotation. Inspection of the scree plot and eigenvalues suggested a two-component solution, which we refer to as spatial ability and working memory capacity (factor loadings are presented in Table 3). The correlation between the two constructs was $r = .20$.

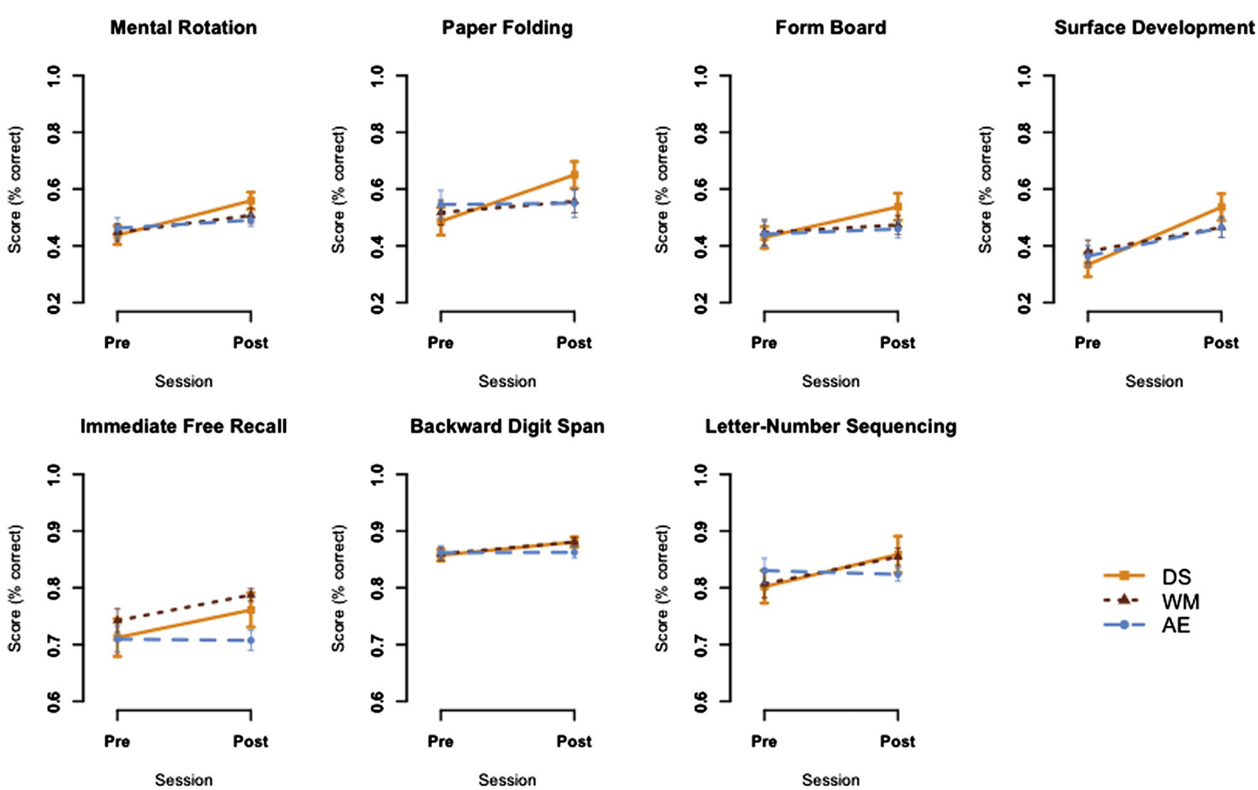

Fig. 4. Spatial ability tasks. Mean performance for all spatial ability tasks (mental rotation, paper folding, form board, surface development) and working memory capacity tasks (immediate free recall, backward digit span, letter–number sequencing) as a function of testing session, for each condition. Error bars represent standard errors of the means. All groups were statistically equivalent at baseline.

Table 2
Correlation matrix and descriptive statistics for all spatial ability (mental rotation, paper folding, form board, surface development) and working memory capacity tasks (immediate free recall, backward digit span, letter–number sequencing) at pre-test ($N = 67$).

Task	1	2	3	4	5	6	M	SD
1. Mental rotation	–						.45	.16
2. Paper folding	.45**	–					.52	.22
3. Form board	.66**	.46**	–				.44	.20
4. Surface development	.68**	.40**	.49**	–			.36	.19
5. Immediate free recall	.21	.23	.19	.34**	–		.72	.11
6. Backward digit span	.09	.25*	.21	.14	.31*	–	.86	.05
7. Letter–number sequencing	−.19	−.08	−.09	.01	.16	.62**	.81	.12

* $p < .05$ (two-tailed).
** $p < .01$ (two-tailed).

The initial analyses on each task provided us with general trends for both constructs, with reliable measures due to multiple measurements per construct. In order to get further insight into the particular effects for each underlying construct, separate 3 (Condition) × 2 (Session) mixed factorial ANOVAs with repeated measures on the latter variable were conducted for each constructs (see Table 1).

Within the spatial ability construct, the analysis revealed a significant interaction between condition and session, indicating a different impact of training across conditions. Simples effects conducted with dependent *t*-tests showed improvements for all groups, yet of different magnitudes. The DS group showed the largest improvements, followed by the WM group and the AE group. Within the working memory capacity construct, the analysis also revealed a significant interaction between condition and session. DS and WM groups showed large improvements. The AE group showed no significant difference between pre- and post-test. These results and their interpretation are discussed in the next section (Fig. 5).

4. Discussion

The present experiment was designed to assess the efficacy of complex motor activities to enhance cognition. In particular, we hypothesized that a training program based on complex coordination in a physical activity, labeled designed sport, could lead to improvements in working memory capacity and spatial ability. The designed sport condition was compared with a group training working memory and with an active and adaptive control group involved in aerobic exercise.

4.1. In-training improvements

Importantly, all groups improved on the scales that were explicitly targeted in training. Both the designed sport and aerobic exercise groups exhibited health-related physiological improvements, whereas training working memory resulted in improvements in the working memory training task. These results serve as a critical manipulation check on a key aspect of our experimental design, which was to compare active conditions, in an attempt to mitigate motivational confounds that have plagued previous cognitive training experiments (for reviews, see Boot, Simons, Stothart, & Stutts, 2013; Shipstead et al., 2012).

Participants in the two exercise conditions showed significant decreases in resting heart rate, as well as in systolic and diastolic blood pressure. In itself, this is an encouraging result because these measures are good indicators of general health, and their improvement plays an important role in preventing diabetes (Imano et al., 2001), obesity (Landsberg, Troisi, Parker, Young, & Weiss, 1991), and cardiovascular diseases (Warnier et al., 2013). More generally, these physiological parameters are also associated with longevity and healthy aging (Stessman, Jacobs, Stessman-Lande, Gilon, & Leibowitz, 2013). Therefore, individuals training in the exercise conditions were getting healthier throughout their respective program. This is a definite advantage over computerized cognitive training regimen as benefits of this type have not previously been demonstrated with computerized training and were not found in the working memory training condition in the present study.

The working memory training group showed gains in working memory capacity consistent with previous work using complex span training (Chein & Morrison, 2010; Harrison et al., 2013). Interestingly, participants' capacity for spatial content initially improved at a faster rate than for verbal content, with significant differences for the first six sessions. This effect might be due to differences in the ubiquity of the verbal items in everyday settings. Arguably, storing verbal information in the face of interference is an ability that is required for a wide range of tasks in our daily activities, whereas storing spatial content is not as ubiquitous. This might provide an explanation for the initial trend of improvements in the spatial component of the task — because the capacity to store this kind of items is generally less exploited, it responded more quickly to training. Eventually, the capacity to store verbal and spatial contents did not differ, perhaps because the underlying reason for the initial difference is one of prior exposure, not capacity itself. These gains are interesting because they provide further evidence for the malleability of working memory capacity given intensive and adaptive training. However, the main focus of the present experiment was to measure cognitive gains after training, which we refer to as transfer effects.

4.2. Transfer effects

An exploratory factor analysis on all tasks at baseline yielded two underlying constructs, which we labeled spatial ability and working memory capacity. Designed sport was the most effective to induce gains in spatial ability and matched the working memory training group — which training content specifically targeted working memory capacity — on working memory capacity gains. We discuss each construct in details hereafter.

Improvements following designed sport training were expected for all spatial ability tasks, although the scope and robustness of the effects could hardly be anticipated. Previous studies have shown the potential of particular motor activities to enhance mental rotation (Jansen et al., 2009; Moreau et al., 2012), based on shared underlying activation of cortical motor areas (for a meta-analysis, see Zacks, 2008), but the direct impact on other measures of spatial ability was not documented to date. Designed sport training seems to have taped a component underlying all spatial ability tasks, therefore leading to generalized changes in spatial performance. Typically, this condition led to the greatest improvements in all of the spatial ability measures, and therefore in the spatial ability construct overall. However, we found slight variations across tasks. For example, surface development seemed to be extremely sensitive to test–retest effects, since all groups showed improvements after training. This is perhaps not surprising given the inherent difficulty of this task confirmed by its low mean score at baseline. Specifically, high task demands require some time and practice to perform adequately. Prior exposure to the task — even when using different versions

Table 3
Cognitive measurements before training. F1 (spatial ability) and F2 (working memory capacity) refer to the factor loadings of each measure from an exploratory factor analysis with promax rotation ($N = 67$).

Measure	Spatial ability	Working memory capacity
Mental rotation	.90	
Paper folding	.68	
Form board	.81	
Surface development	.80	
Immediate free recall	.34	.43
Backward digit span		.88
Letter number sequencing		.90

Note: Only factor loadings greater than .30 are included in the table.

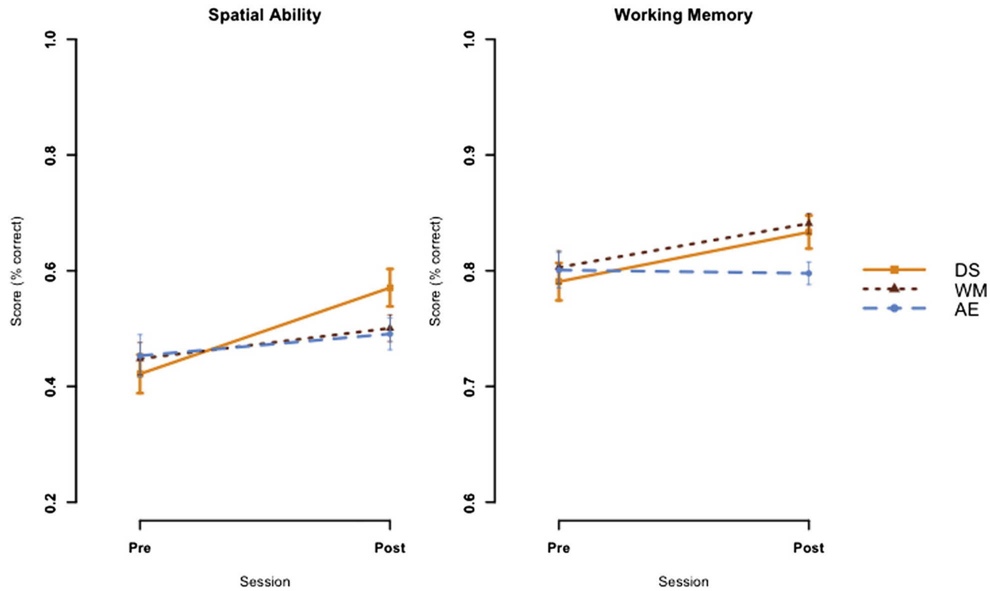

Fig. 5. Spatial ability and working memory capacity constructs. Mean performance for all transfer tasks aggregated as spatial ability and working memory capacity constructs, for each training condition. Error bars represent standard errors of the means. All groups were statistically equivalent at baseline.

for pre- and post-measures — helps performance tremendously. Similarly, mental rotation performance has shown to be extremely sensitive to prior exposure in previous research (Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006). Our findings for this particular task were more nuanced, however, since only the designed sport and working memory groups showed improvements in mental rotation performance. Likewise, performance in paper folding and form board was enhanced following designed sport training, but not after training programs targeting working memory or aerobic exercise alone. As a result, we can minimize concerns about test–retest effects in the present case.

Training working memory also resulted in spatial ability gains, although weaker than with designed sport training. Presumably, higher working memory capacity plays an important role in spatial ability tasks that require maintenance of a spatial pattern while comparing it with different possibilities (e.g. mental rotation). Previous research has pointed out that mental rotation is inherently complex, with dynamic manipulations in three-dimensional space such as transformation from a two-dimensional depiction and conservation of spatial properties (Kosslyn, 1994). This idea is corroborated by findings showing the multitude of cortical areas involved in mental rotation, with important variations across individuals (Zacks, 2008). Therefore, the need to maintain three-dimensional representations of spatial transformations might tap into working memory capacity more than other spatial ability tasks. This is consistent with our analyses on spatial tasks, showing an increase in performance after working memory training only in mental rotation. Other spatial tasks either showed no effect of working memory training or improvements following training in all three conditions. These findings are consistent with the idea that individuals who perform poorly often fail to maintain intermediate mental representations of three-dimensional figures (i.e. failure to maintain objects in working memory), therefore forcing them to start over several times and resulting in delayed responses (Kosslyn, 1994).

As expected based on previous work (e.g. Chein & Morrison, 2010; Harrison et al., 2013), working memory training led to improvements in all working memory capacity tasks, and therefore in the overall working memory capacity construct. Working memory can be trained via complex span tasks including memory retrieval in the face of interference, and training effects transfer across working memory tasks. In the present study, working memory training comprised letters and spatial locations to remember with unrelated decisions between item presentation, but transfer tasks — deliberately different in design but valid measures of working memory capacity (Unsworth & Engle, 2007) — included words, digits, or letters, with no concurrent decisions to make between each to-be-remembered item. These differences between training and transfer tasks displayed did not prevent transfer, providing further support for the idea that complex span training taps domain-general components and for the notion that combining verbal and spatial components places emphasis on prefrontal regions (Chein et al., 2011).

In our effort to propose a training regimen that induces the largest improvements possible, it is interesting to note that designed sport training also led to working memory capacity improvements, whereas aerobic exercise did not. Although training was based on movements, performance improved when participants were tested with numerical and verbal items. This result indicates that working memory capacity can be improved via motor content, an idea that has not been documented previously but is consistent with neuroimaging evidence demonstrating the association between working memory and motor learning (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010).

Conversely, mere aerobic exercise did not appear to be an optimal way to enhance performance in the particular tasks we included in the design. Apart from the one case of test–retest effect discussed previously (surface development), aerobic exercise did not induce gains in spatial ability or working memory tasks, a result further reflected when comparing pre-test and post-test in each construct. This finding might seem intriguing given the large body of literature demonstrating the link between exercise and cognition (Hillman et al., 2008), however, a few fundamental differences with previous research need to be emphasized. First, we provided measures of only two constructs, spatial ability and working memory capacity. Previous studies have yielded extremely disparate improvements, with gains mostly on tasks tapping executive functions and cognitive control — constructs that were not directly measured here (Diamond & Lee, 2011; Guiney & Machado, 2013; Stroth et al., 2010). The absence of a transfer effect from aerobic training to the particular constructs we measured is in fact consistent with this literature. Second, training duration was relatively short for an aerobic program. Most human exercise studies are carried out for longer periods (e.g. one or two semesters) (Colcombe & Kramer, 2003; Etnier, Nowell, Landers, & Sibley, 2006; Hillman et al., 2008), and animal experiments typically provide unlimited access to running wheels or similar devices (Farmer et al., 2004; van Praag, Kempermann, & Gage, 2000). Our primary concern in the present study was to compare training conditions that are equivalent in duration. In this regard, extending working memory training would have introduced other important issues (e.g. motivation, comparison with previous training studies). However, because triggering purely neurophysiological adaptations after aerobic exercise takes time and continuity, it is possible that a 2-month program was too brief to lead to significant changes. In addition, we only offered behavioral measures, and it is conceivable that aerobic exercise induced alterations in brain structure (Thomas, Dennis, Bandettini, & Johansen-Berg, 2012) that did not translate to behavioral changes from pre-test to post-test.

A related point concerns the effect of age in exercise training experiments. Typically, prior studies have involved either children or older populations, for various reasons. As opposed to young adults who are at a cognitive peak (Salthouse & Davis, 2006), these populations have the remarkable advantage of being largely malleable cognitively, therefore leaving more room for improvements (Hillman et al., 2008). Moreover, the environment in which they evolve is usually less diverse (e.g. schools or retirement homes), allowing additional control over potential confounds (Moreau & Conway, 2013). The present experiment involved adults, and this fundamental difference might help to explain the lack of clear cognitive improvements following aerobic exercise.

4.3. Corroborating evidence and practical application

Throughout this paper, we have emphasized the ecological validity of our approach. Designed sport offers a rich and diverse environment to trigger adaptive changes. This is a definite advantage over computerized training and we firmly believe that integrated approaches such as the one proposed in this experiment is where the field needs to be heading to offer relevant applications to society (Moreau & Conway, 2014). Although applying this approach to cognitive training is novel, our findings can be embedded within an extensive body of research at the intersection of various independent but related fields, especially neuroscience, experimental psychology and movement sciences.

For example, the present findings are consistent with a wide range of observational (Moreau et al., 2011) and experimental research in the sports literature (Moreau, 2012a, 2013a,b), including studies conducted by independent laboratories (Güldenpenning, Köster, Kunde, Weigelt, & Schack, 2011; Pietsch & Jansen, 2012; Steggemann, Engbert, & Weigelt, 2011). Elite athletes consistently show greater performance than novices or controls in many cognitive tasks in the laboratory, even when measurement tasks are not designed to resemble sport-specific demands. The results reported herein are also in line with previous training experiments, either in the field of physical exercise (Hillman et al., 2008; Moreau et al., 2012) or working memory training (for a review, see Shipstead et al., 2012). Some cognitive abilities, especially spatial ability, appear to be malleable (Uttal et al., 2013) and to respond well to training programs targeting general improvements, such as designed sport training. In addition, our findings can be accounted for by the embodied framework of cognition, and fit particularly well within the literature demonstrating a close relationship between motor processes and spatial cognition (Amorim, Isableu, & Jarraya, 2006; Chu & Kita, 2008, 2011; Wraga, Thompson, Alpert, & Kosslyn, 2003). In particular, a large body of research has investigated this relationship via mental imagery and its influence on motor skills, yet conversely it also suggests that motor learning can impact higher cognitive abilities (see Moreau, 2015, for a review). Given that sensorimotor experience does shape cognitive processing, even in tasks that do not require physical motion (e.g. Moreau, 2012a), it is plausible that learned motor components can be transferred to other non-motor tasks. In a cognitive training approach, the interdependence between cognitive and motor components therefore suggests that optimized improvements can be induced when both demands are engaged in a training regimen.

Moreover, the argument of ecological validity does not rest solely on previous literature. A cost–benefit analysis indicates that training cognition via complex motor activities is a better investment than working memory training, because of the plurality of expected returns (i.e. cognitive and health improvements, Moreau & Conway, 2014). Our findings present an appealing alternative to traditional cognitive training, providing a framework for regimens that can be fine-tuned and individualized. Beyond cognitive gains, designed sport training led to improvements in key components of general health, resting heart rate and blood pressure, therefore emphasizing its effectiveness to enhance physical condition. Although we have mostly presented these improvements as collateral in this paper, they represent a strong benefit of designed sport, especially in the worrisome context of growing health-related medical conditions in our societies. Future studies should examine whether designed sport might impact other factors related to physical exercise habits in previous studies but not measured in the present experiment, such as well-being, stress levels and general mental health (for a review, see Penedo & Dahn, 2005).

An additional point deserves attention. In this experiment, we specifically targeted spatial ability and working memory capacity. The focus on these two constructs was deliberate, particularly motivated by the documented potential of motor activities to improve spatial ability (Moreau et al., 2012) as well as the substantial literature exploring the impact of cognitive training experiments on working memory capacity (for a meta-analysis, see Melby-Lervåg & Hulme, 2013). Although spatial ability and working memory capacity are critical to many activities in daily life, we did not, however, make any claim regarding transfer effects to intelligence tasks or to constructs beyond those measured in our battery. Therefore, while we are optimistic about the potential of design sport as a training tool, we believe it is important to be cautious and precise about the improvements we observed.

In this regard, it is equally important to acknowledge the limitations of the present study. Although we see it as a strength, the ecological component of our approach also limits experimental control over extraneous variables, as rich and complex situations are difficult to standardize. This is a necessary step if we are to discover novel ways to enhance cognition, but it also calls for replications in more confirmatory settings. In addition, our study did not include a follow-up post-test, for practical reasons. It could have been informative to assess whether the observed effects are sustained over time — can training gains outlast the training period? The lack of a follow-up, however, was also motivated by our skepticism about short-term programs that induce long-term changes. Just like health-related improvements would reverse after physical training stops, it is likely that cognitive gains need to be nurtured in order to last.

5. Conclusion

We would like to conclude by highlighting and advocating for the designed component of the type of training programs we present in this paper. As it has been suggested in the cognitive training literature (Kliegel & Bürki, 2012), our findings emphasize that it is possible to personalize programs to suit an individual's cognitive needs, interests, and personal limitations or strengths. By no means do we argue that designed sport is the only way to successfully engender cognitive and physiological improvements. Other domains (e.g. dancing, orienteering) might provide equally interesting frameworks in implementing ecological training programs. Rather, we hope that our findings will help to spark constructive discussions about the most effective way to design cognitive training programs. In our view, a promising finding in this paper is that general cognitive abilities can be improved by training, and that the intervention leading to cognitive gains needs not be tiresome or unexciting — activities that offer challenging situations via complex motor skill acquisition can induce remarkable changes in a pleasant and healthy manner accessible to all.

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References

Amorim, M.A., Isableu, B., & Jarraya, M. (2006). Embodied spatial transformations: "Body analogy" for the mental rotation of objects. *Journal of Experimental Psychology: General*, *135*(3), 327–347.
Anguera, J.A., Reuter-Lorenz, P.A., Willingham, D.T., & Seidler, R.D. (2010). Contributions of spatial working memory to visuomotor learning. *Journal of Cognitive Neuroscience*, *22*, 1917–1930.
Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2014). Improving fluid intelligence with training on working memory: a meta-analysis. *Psychonomic Bulletin & Review*. http://dx.doi.org/10.3758/s13423-014-0699-x.
Black, J.E., Isaacs, K.R., Anderson, B.J., Alcantara, A.A., & Greenough, W.T. (1990). Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. *Proceedings of the National Academy of Sciences*, *87*(14), 5568–5572.
Boot, W.R., Simons, D.J., Stothart, C., & Stutts, C. (2013). The pervasive problem with placebos in psychology: Why active control groups are not sufficient to rule out placebo effects. *Perspectives in Psychological Science*, *8*(4), 445–454.
Chase, W.G., & Simon, H.A. (1973). The mind's eye in chess. In W.G. Chase (Ed.), *Visual information processing* (pp. 215–281). New York: Academic Press.
Chein, J.M., Moore, A.B., & Conway, A.R.A. (2011). Domain-general mechanisms of complex working memory span. *NeuroImage*, *54*, 550–559.
Chein, J.M., & Morrison, A.B. (2010). Expanding the mind's workspace: Training and transfer effects with a complex working memory span task. *Psychonomic Bulletin & Review*, *17*(2), 193–199.
Chooi, W. -T., & Thompson, L.A. (2012). Working memory training does not improve intelligence in healthy young adults. *Intelligence*, *40*(6), 531–542.
Chu, M., & Kita, S. (2008). Spontaneous gestures during mental rotation tasks: Insights into the microdevelopment of the motor strategy. *Journal of Experimental Psychology: General*, *137*(4), 706–723.
Chu, M., & Kita, S. (2011). The nature of gestures' beneficial role in spatial problem solving. *Journal of Experimental Psychology: General*, *140*(1), 102–116.
Colcombe, S.J., Erickson, K.I., Scalf, P.E., Kim, J.S., Prakash, R., McAuley, E., et al. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *61*(11), 1166–1170.
Colcombe, S.J., & Kramer, A.F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science*, *14*(2), 125–130.
Colom, R., Quiroga, M.Á., Solana, A.B., Burgaleta, M., Román, F.J., Privado, J., et al. (2012). Structural changes after videogame practice related to a brain network associated with intelligence. *Intelligence*, *40*(5), 479–489.
Conway, A.R., & Getz, S.J. (2010). Cognitive ability: Does working memory training enhance intelligence? *Current Biology*, *20*(8), R362–R364.
R Core Team (2014). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing Retrieved from http://www.r-project.org/.
Deary, I.J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence*, *35*(1), 13–21.
Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4–12 years old. *Science*, *333*(6045), 959–964.
Dijkstra, K., MacMahon, C., & Misirlisoy, M. (2008). The effects of golf expertise and presentation modality on memory for golf and everyday items. *Acta Psychologica*, *128*(2), 298–303.
Ekstrom, R.B., French, J.W., Harman, M.H., & Dermen, D. (1976). *Manual for kit of factor-referenced cognitive tests*. Princeton, NJ: Educational Testing Service.
Ericsson, K.A. (2006). The influence of experience and deliberate practice on the development of superior expert performance. In K.A. Ericsson, N. Charness, P. Feltovich, & R.R. Hoffman (Eds.), *Cambridge handbook of expertise and expert performance* (pp. 685–706). Cambridge, UK: Cambridge University Press.
Ericsson, K.A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American Psychologist*, *49*(8), 725–747.
Etnier, J.L., Nowell, P.M., Landers, D.M., & Sibley, B.A. (2006). A meta-regression to examine the relationship between aerobic fitness and cognitive performance. *Brain Research Reviews*, *52*(1), 119–130.
Evans, G.W., & Schamberg, M.A. (2009). Childhood poverty, chronic stress, and adult working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(16), 6545–6549.
Farmer, J., Zhao, X., van Praag, H., Wodtke, K., Gage, F.H., & Christie, B.R. (2004). Effects of voluntary exercise on synaptic plasticity and gene expression in the dentate gyrus of adult male Sprague–Dawley rats in vivo. *Neuroscience*, *124*(1), 71–79.
Furley, P., & Memmert, D. (2010). The role of working memory in sports. *International Review of Sport and Exercise Psychology*, *3*, 171–194.
Green, C.S., & Bavelier, D. (2008). Exercising your brain: A review of human brain plasticity and training-induced learning. *Psychology and Aging*, *23*(4), 692–701.
Guiney, H., & Machado, L. (2013). Benefits of regular aerobic exercise for executive functioning in healthy populations. *Psychonomic Bulletin & Review*, *20*(1), 73–86.
Güldenpenning, I., Köster, D., Kunde, W., Weigelt, M., & Schack, T. (2011). Motor expertise modulates the unconscious processing of human body postures. *Experimental Brain Research*, *213*(4), 383–391.
Harrison, T.L., Shipstead, Z., Hicks, K.L., Hambrick, D.Z., Redick, T.S., & Engle, R.W. (2013). Working memory training may increase working memory capacity but not fluid intelligence. *Psychological Science*, *12*, 2409–2419.
Hempel, A., Giesel, F.L., Garcia Caraballo, N.M., Amann, M., Meyer, H., Wustenberg, T., et al. (2004). Plasticity of cortical activation related to working memory during training. *The American Journal of Psychiatry*, *161*(4), 745–747.
Hillman, C.H., Erickson, K.I., & Kramer, A.F. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience*, *9*(1), 58–65.
Imano, E., Miyatsuka, T., Motomura, M., Kanda, T., Matsuhisa, M., Kajimoto, Y., et al. (2001). Heart rate elevation and diabetic retinopathy in patients with type 2 diabetes mellitus and normoalbuminuria. *Diabetes Research and Clinical Practice*, *52*(3), 185–191.
Jaeggi, S.M., Buschkuehl, M., Jonides, J., & Perrig, W.J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(19), 6829–6833.
Jaeggi, S.M., Studer-Luethi, B., Buschkuehl, M., Su, Y. -F., Jonides, J., & Perrig, W.J. (2010). The relationship between n-back performance and matrix reasoning — Implications for training and transfer. *Intelligence*, *38*(6), 625–635.
Jansen, P., Titze, C., & Heil, M. (2009). The influence of juggling on mental rotation performance. *International Journal of Sport Psychology*, *40*, 351–359.
Jaušovec, N., & Jaušovec, K. (2012). Working memory training: Improving intelligence — Changing brain activity. *Brain and Cognition*, *79*(2), 96–106.
Kane, M.J., Hambrick, D.Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., & Engle, R.W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189–217.
Karbach, J., & Verhaeghen, P. (2014). Making working memory work: A meta-analysis of executive control and working memory training in older adults. *Psychological Science*, *25*, 2027–2037.
Karvonen, M.J., Kentala, E., & Mustala, O. (1957). The effects of training on heart rate: A longitudinal study. *Annales Medicinae Experimentalis et Biologiae Fenniae*, *35*, 307–315.
Kliegel, M., & Bürki, C. (2012). Memory training interventions require a tailor-made approach: Commentary on McDaniel and Bugg. *Journal of Applied Research Memory Cognition*, *1*, 58–60.
Klingberg, T., Fernell, E., Olesen, P.J., Johnson, M., Gustafsson, P., Dahlstrom, K., et al. (2005). Computerized training of working memory in children with ADHD—A randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry*, *44*(2), 177–186.
Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology*, *24*(6), 781–791.
Kosslyn, S.M. (1994). *Image and brain*. Cambridge, MA: MIT Press.
Landsberg, L., Troisi, R., Parker, D., Young, J.B., & Weiss, S.T. (1991). Obesity, blood pressure, and the sympathetic nervous system. *Annals of Epidemiology*, *1*(4), 295–303.
McDaniel, M.A., & Bugg, J.M. (2012). Memory training interventions: What has been forgotten? *Journal of Applied Research in Memory and Cognition*, *1*, 45–50.
Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, *49*(2), 270–291.
Memmert, D., & Furley, P. (2007). "I spy with my little eye!": Breadth of attention, inattentional blindness, and tactical decision making in team sports. *Journal of Sport and Exercise Psychology*, *29*(3), 365–381.
Moody, D.E. (2009). Can intelligence be increased by training on a task of working memory? *Intelligence*, *37*(4), 327–328.
Mora, F., Segovia, G., & del Arco, A. (2007). Aging, plasticity and environmental enrichment: Structural changes and neurotransmitter dynamics in several areas of the brain. *Brain Research Reviews*, *55*(1), 78–88.
Moreau, D. (2012a). The role of motor processes in three-dimensional mental rotation: Shaping cognitive processing via sensorimotor experience. *Learning and Individual Differences*, *22*(3), 354–359.
Moreau, D. (2012b). Training spatial ability: Comment on Pietsch and Jansen (2012) and prospective research trends. *Learning and Individual Differences*, *22*(6), 882–883.
Moreau, D. (2013a). Constraining movement alters the recruitment of motor processes in mental rotation. *Experimental Brain Research*, *224*(3), 447–454.
Moreau, D. (2013b). Motor expertise modulates movement processing in working memory. *Acta Psychologica*, *142*(3), 356–361.
Moreau, D. (2015). Unreflective actions? complex motor skill acquisition to enhance spatial cognition. *Phenomenology and the Cognitive Sciences* (Online First).
Moreau, D., Clerc, J., Mansy-Dannay, A., & Guerrien, A. (2012). Enhancing spatial ability through sport practice: Evidence for an effect of motor training on mental rotation performance. *Journal of Individual Differences*, *33*(2), 83–88.
Moreau, D., & Conway, A.R.A. (2013). Cognitive enhancement: A comparative review of computerized and athletic training programs. *International Review of Sport and Exercise Psychology*, *6*(1), 155–183.
Moreau, D., & Conway, A.R.A. (2014). The case for an ecological approach to cognitive training. *Trends in Cognitive Sciences*, *18*(7), 334–336.
Moreau, D., Mansy-Dannay, A., Clerc, J., & Guerrien, A. (2011). Spatial ability and motor performance: Assessing mental rotation processes in elite and novice athletes. *International Journal of Sport Psychology*, *42*(6), 525–547.

Morrison, A.B., & Chein, J.M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin and Review*, *18*(1), 46–60.

Newcombe, N.S., & Frick, A. (2010). Early education for spatial intelligence: Why, what and how. *Mind, Brain and Education*, *4*(3), 102–111.

Olesen, P.J., Westerberg, H., & Klingberg, T. (2003). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience*, *7*(1), 75–79.

Owen, A.M., Hampshire, A., Grahn, J.A., Stenton, R., Dajani, S., Burns, A.S., et al. (2010). Putting brain training to the test. *Nature*, *465*(7299), 775–778.

Pe, M.L., Koval, P., & Kuppens, P. (2013). Executive well-being: Updating of positive stimuli in working memory is associated with subjective well-being. *Cognition*, *126*(2), 335–340.

Penedo, F.J., & Dahn, J.R. (2005). Exercise and well-being: A review of mental and physical health benefits associated with physical activity. *Current Opiniatry on Psychiatry*, *18*(2), 189–193.

Perrig, W., Hollenstein, M., & Oelhafen, S. (2009). Can we improve fluid intelligence with training on working memory in persons with intellectual disabilities? *Journal of Cognitive Education and Psychology*, *8*(2), 148–164.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse Mental Rotations Test: Different versions and factors that affect performance. *Brain and Cognition*, *28*, 39–58.

Peters, M., Lehmann, W., Takahira, S., Takeuchi, Y., & Jordan, K. (2006). Mental rotation test performance in four cross-cultural samples ($n = 3367$): Overall sex differences and the role of academic program in performance. *Cortex*, *42*(7), 1005–1014.

Pietsch, S., & Jansen, P. (2012). Different mental rotation performance in students of music, sport and education. *Learning and Individual Differences*, *22*(1), 159–163.

Raab, M., & Johnson, J.G. (2007). Expertise-based differences in search and option-generation strategies. *Journal of Experimental Psychology: Applied*, *13*(3), 158–170.

Rabipour, S., & Raz, A. (2012). Training the brain: Fact and fad in cognitive and behavioral remediation. *Brain and Cognition*, *79*(2), 159–179.

Redick, T.S., Shipstead, Z., Harrison, T.L., Hicks, K.L., Fried, D.Z., Hambrick, D.Z., et al. (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General*, *142*(2), 359–379.

Richmond, L.L., Morrison, A.B., Chein, J.M., & Olson, I.R. (2011). Working memory training and transfer in older adults. *Psychology and Aging*, *26*(4), 813–822.

Salthouse, T.A., & Davis, H.P. (2006). Organization of cognitive abilities and neuropsychological variables across the lifespan. *Developmental Review*, *26*(1), 31–54.

Schmidt, R.A. (1982). *Motor control and learning: A behavioral emphasis.* Champaign, IL: Human Kinetics Press.

Shipstead, Z., Redick, T.S., & Engle, R.W. (2012). Is working memory training effective? *Psychological Bulletin*, *138*(4), 628–654.

Steggemann, Y., Engbert, K., & Weigelt, M. (2011). Selective effects of motor expertise in mental body rotation tasks: Comparing object-based and perspective transformations. *Brain and Cognition*, *76*(1), 97–105.

Sternberg, R.J. (2008). Increasing fluid intelligence is possible after all. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(19), 6791–6792.

Stessman, J., Jacobs, J.M., Stessman-Lande, I., Gilon, D., & Leibowitz, D. (2013). Aging, resting pulse rate, and longevity. *Journal of the American Geriatrics Society*, *61*(1), 40–45.

Stroth, S., Reinhardt, R.K., Thone, J., Hille, K., Schneider, M., Hartel, S., et al. (2010). Impact of aerobic exercise training on cognitive functions and affect associated to the COMT polymorphism in young adults. *Neurobiology of Learning and Memory*, *94*(3), 364–372.

Stummer, W., Weber, K., Tranmer, B., Baethmann, A., & Kempski, O. (1994). Reduced mortality and brain damage after locomotor activity in gerbil forebrain ischemia. *Stroke*, *25*(9), 1862–1869.

Thomas, A.G., Dennis, A., Bandettini, P.A., & Johansen-Berg, H. (2012). The effects of aerobic activity on brain structure. *Frontiers in Psychology*, *3*(86), 1–9.

Unsworth, N., & Engle, R.W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132.

Uttal, D.H., Meadow, N.G., Tipton, E., Hand, L.L., Alden, A.R., Warren, C., et al. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402.

van Praag, H., Kempermann, G., & Gage, F.H. (2000). Neural consequences of environmental enrichment. *Nature Reviews Neuroscience*, *1*(3), 191–198.

van Praag, H., Schinder, A.F., Christie, B.R., Toni, N., Palmer, T.D., & Gage, F.H. (2002). Functional neurogenesis in the adult hippocampus. *Nature*, *415*(6875), 1030–1034.

Vandenberg, S.G., & Kuse, A.R. (1978). Mental rotation, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 599–604.

Vaynman, S.S., Ying, Z., Yin, D., & Gomez-Pinilla, F. (2006). Exercise differentially regulates synaptic proteins associated to the function of BDNF. *Brain Research*, *1070*(1), 124–130.

Voss, M., Prakash, R.S., Erickson, K.I., Boot, W.R., Basak, C., Neider, M.B., et al. (2012). Effects of training strategies implemented in a complex videogame on functional connectivity of attentional networks. *NeuroImage*, *59*(1), 138–148.

Warnier, M.J., Rutten, F.H., Numans, M.E., Kors, J.A., Tan, H.L., De Boer, A., et al. (2013). Electrocardiographic characteristics of patients with chronic obstructive pulmonary disease. *Journal of Chronic Obstructive Pulmonary Disease*, *10*(1), 62–71.

Westerberg, H., & Klingberg, T. (2007). Changes in cortical activity after training of working memory—A single-subject analysis. *Physiology & Behavior*, *92*(1–2), 186–192.

Wraga, M., Thompson, W.L., Alpert, N.M., & Kosslyn, S.M. (2003). Implicit transfer of motor strategies in mental rotation. *Brain and Cognition*, *52*(2), 135–143.

Wright, M.J., Bishop, D.T., Jackson, R.C., & Abernethy, B. (2011). Cortical fMRI activation to opponents' body kinematics in sport-related anticipation: Expert–novice differences with normal and point-light video. *Neuroscience Letters*, *500*(3), 216–221.

Zacks, J.M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of Cognitive Neuroscience*, *20*(1), 1–19.