

ORIGINAL ARTICLE

## Chronic participation in externally paced, but not self-paced sports is associated with the modulation of domain-general cognition

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### Abstract

The present study investigated the role of chronic sport participation in the modulation of vigilance and inhibitory control. We also aimed to disentangle the relative contribution of different types of sport expertise and sport-related fitness to the exercise-cognition relationship. Three groups of young adults differing in their chronic sport expertise (externally-paced sports,  $n = 22$ , self-paced sports,  $n = 22$ , non-athletes,  $n = 22$ ) took part in the study. Participants completed a cardiovascular fitness test, a hand-eye coordination test and two different types of vigilance tasks: (1) Psychomotor Vigilance Task (PVT) and (2) Oddball Task, which were designed to gain insight into the cognitive processes involved in sustaining attention over time and allocating selective attention by exerting inhibitory control, respectively. No differences were found in PVT performance between the two athlete groups and between self-paced sports athletes and non-athletes, whereas athletes from externally-paced sports outperformed non-athletes. Crucially, athletes from externally-paced sports also differed from those of self-paced sports and non-athletes in the Oddball task, showing less omission and commission errors. The sport expertise effect was independent of participant’s cardiovascular fitness while hand-eye coordination modulated vigilance and inhibitory control performance. Our findings add novel empirical evidence to the role of expertise in cognitively demanding sports as an important factor in the relationship between exercise and cognition.

**Keywords:** Cognition, aerobic fitness, neuroscience, psychology, team sports

### Highlights

- Externally-paced athletes showed better vigilance performance (PVT) than non-athletes and better inhibitory control (Oddball task) than both non-athletes and self-paced athletes.
- Cardiovascular fitness did not modulate the differential effects of externally-paced and self-paced sport expertise on vigilance and inhibitory control.
- Training in an externally-paced sport environment may benefit domain-general, higher-level cognitive functions as vigilance and inhibitory control that are relevant for both sport and everyday life situations.
- Our results contribute to the actual trends in exercise and cognition research toward gaining a more fine-tuned appreciation of the influence of qualitative factors deriving from exercising in different physical activity and sport environments.

### Introduction

In the last decades, there has been an exponential growth of interest in elucidating the relationship between physical activity (PA) and cognition (McMorris, 2016). Most studies have focused on the role of cardiovascular fitness as the main outcome of PA associated with enhanced brain health and cognition (e.g. Hillman, Erickson, & Kramer, 2008) through metabolic-physiological mediating mechanisms (Stillman, Cohen, Lehman,

& Erickson, 2016). Recently, a more differentiated view on potential – not only metabolic – mechanisms has been developed (Stillman et al., 2016), according to evidence that qualitatively different types of PA and PA-related outcomes are associated with structural and functional brain changes (Voelcker-Rehage & Niemann, 2013).

This line of research has extended the focus of research toward relevant aspects of the PA and sport environment that may contribute to cognitive

efficiency (Diamond, 2015; Pesce, 2012), as the cognitive demands inherent in sensorimotor learning and performing complex sport tasks (Moreau & Conway, 2013). Consistently, some sport expertise researchers have proposed the “cognitive component skills approach”, which considers the sport training context beneficial to develop not only sport-specific cognitive skills, but also sport-general, basic cognitive abilities transferable to a multiplicity of specific cognitive tasks in sport and everyday life domains (Voss, Kramer, Basak, Prakash, & Roberts, 2010). Since the major focus of this approach to basic cognitive abilities in expert athletes is on executive control and attentional capacity, we adopt the term “domain-general cognition”, as it is used to indicate that those core functions are general in nature and underlie a range of domain-specific cognitive skills (García-Madruga, Gómez-Veiga, & Vila, 2016).

Recent studies have shown superiority in expert athletes, compared to amateur athletes and non-athletes, in perceptual and cognitive tasks that are non-sport-specific, as they do not display stimuli designed to simulate their sport context (Heppe, Kohler, Fledermann, & Zentgraf, 2016; Huijgen et al., 2015; Wang et al., 2013). Meta-analytically, sport type has been investigated as a potential moderator of the exercise-cognition relationship, probably due to the distinctive perceptual-cognitive demands of different sport contexts (Voss et al., 2010).

Athletes from externally-paced (EP), open skill sports such as tennis or team ball games generally show better processing speed than athletes from self-paced (SP), closed skill sports such as swimming or track and field (Singer, 2000; Voss et al., 2010). More interestingly, differences have been found for higher-level cognition and particularly core executive functions responsible for goal-oriented behaviours, as inhibitory control. This latter is the most multifaceted among core executive functions. Diamond (2013) distinguishes between response inhibition that is inhibition at the level of behaviour to avoid acting impulsively or prematurely, and interference control that is inhibition at the level of attention or memory to selectively attend to relevant information and avoid being distracted by interfering stimuli and memories (Diamond, 2013). Athletes practicing EP sports show better response inhibition (Wang et al., 2013), whereas athletes practicing SP sports outweigh EP athletes in interference control (Jacobson & Matthaeus, 2014). These divergent results in inhibitory control has been justified according to the perceptual-attentional demands that these athletes usually face in their sport context. EP athletes are continuously required to inhibit prepotent responses to irrelevant or misleading stimuli by opponents. SP athletes' primary mental challenge is to suppress external and

internal distractors to keep the focus in order to maximize performance in a constant environment.

Fewer studies have investigated the association between different types of sport expertise and attention. A series of studies by Nougier and colleagues (reviewed in Nougier & Rossi, 1999) and a study by Lum, Enns, and Pratt (2002) showed that EP athletes were better able than SP athletes in the strategic modulation of the orienting and allocation of visual attention in non-sport-specific tasks. Lum et al. (2002) also found athletes, regardless of sport type, having overall higher reaction speed in the attentional task than non-athletes, interpreted as an indicator of better vigilance performance.

Vigilance is the capacity to maintain attention over time and to react efficiently to relevant stimuli required in different daily life, work and sport activities (Schmidt et al., 2009; Voss et al., 2010; Zheng et al., 2011). In exercise and cognition research, vigilance has been investigated in relation to either cardiovascular fitness, or type of sport expertise. Studies on fitness showed better vigilance performance for high-fit young adults compared with their low-fit counterparts (Luque-Casado et al., 2016b; Luque-Casado, Perakakis, Ciria, & Sanabria, 2016a). Studies on type of sport expertise showed that preadolescents practicing an EP sport outperformed, in a vigilance task, not only preadolescents not practicing any sport (Ballester, Huertas, Yuste, Llorens, & Sanabria, 2015), but also age-matched SP athletes, who did not differ in vigilance performance from non-athletes (Ballester, Huertas, Molina, & Sanabria, 2017).

In sum, researchers have examined the relationship between vigilance and either cardiovascular fitness, or type of sport expertise, but there is no investigation considering these two factors in the same study. Indeed, there is evidence of their interactive beneficial effect in response inhibition, which is involved also in vigilance tasks to suppress the response to irrelevant stimuli. Highly experienced EP athletes showed better response inhibition than their less experienced counterparts, but not when their high sport expertise was associated with an only average fitness level (Chan, Wong, Liu, Yu, & Yan, 2011). Therefore, cardiovascular fitness may act as a moderator of the relationship between sport-related expertise and inhibitory efficiency.

Thus, the aim of the present study was to investigate the contribution of different types of sport expertise to vigilance performance and inhibitory control. Given the potential overlapping or joint role of type of sport expertise and cardiovascular fitness for cognitive efficiency, but the limitation of Chan et al.'s (2011) indirect estimation of cardiovascular fitness, we included a direct cardiovascular fitness measure.

In the light of the non-sport-specific cognitive advantage of being an expert athlete (Voss et al., 2010), we expected better vigilance performance for both groups of athletes than for non-athletes. More importantly, considering the specific demands in EP sports to maintain focus over time amid distraction under situational uncertainty and time pressure, we hypothesized that EP athletes would exhibit better response inhibition than athletes from SP sports and non-athletes (Wang et al., 2013). Finally, in line with Chan et al. (2011), we expected an interactive contribution of type of sport expertise and cardiovascular fitness specifically in the case of athletes practicing EP sports.

## Method

### *Ethics statement*

The study's protocols and procedures were approved by the ethical local committee, UCV/2015/2016/22. The study was performed in full compliance with the Declaration of Helsinki 1964 (updated in Fortaleza, 2013). All participants were informed about their right to leave the experiment at any time and signed written informed consent.

### *Participants*

An a priori power analysis was conducted to determine the minimum sample size required for a power level of .80 for an alpha level of .05 based on data from a similar study (Ballester et al., 2015). This analysis gave an outcome of 19 participants per group. Consequently, sixty-six young adults (see Table I) participated in this study, with 22 (8 females) practicing EP sports (football, basketball, volleyball, tennis, martial arts) and 22 (10 females) practicing SP sports (track & field, swimming, triathlon, cycling). The athletic groups did not differ in years of training ( $p = .285$ ), but SP athletes reported more actual training hours per week than EP athletes,  $t(42) = -2.43$ ,  $p = .019$ ,  $d = .75$ . The remaining 22 participants reported no historical specialty in any sport and were not physically active (less than 2 h per week). Participants reported normal or corrected-to-normal vision and neither having a history of neurological problems or cardiovascular diseases, nor taking any medications that may affect cognitive functions. To control for potential confounding factors that could act on the sport expertise-cognition relationship of interest, participants were also assessed in competitiveness, sleep quality, perceived arousal and task motivation. Instruments and procedures of assessments are described in the next section.

### *Apparatus, materials and procedure*

All participants were evaluated in the same season and at the same time of the day. They were fitted with a Polar RS800CX HR monitor (Polar Electro Ltd., Kempele, Finland). Subsequently, they rested for seven minutes in a laid back position to record the baseline pre-testing heart rate (HR). Then, they were administered a modified computerized version of the Global Vigor (GV) rating scale developed by Monk (1989), where the participant were requested to rate their sleep quality (previous night), perceived arousal, and task motivation in a 0–100 visual analogue scale. Successively, participants, sitting on a chair at 60 cm from a computer monitor in a dimly illuminated and noise-reduced room, completed in a counterbalanced order either the Psychomotor Vigilance task (PVT), or the Oddball Go/No-go RT task using a laptop PC (HP 15-inch colour screen) running the E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA). Thereafter, participants completed a questionnaire to evaluate Competitiveness, composed of 10 items on a 1–3 likert scale (C-10, for more detailed information see Remor, 2007). Then, participants performed the Soda Pop Hand-Eye Coordination Test (Hoeger & Hoeger, 2015). Finally, the cardiovascular fitness test was performed on a cycle ergometer (Cardi-girus Medical, G&G Innovación, Spain).

### *Psychomotor vigilance task*

The PVT is a simple and reliable task to measure vigilance (Drummond et al., 2005). During the task, on each trial, a Gabor patch ( $4.20^\circ \times 4.20^\circ$ ) with a horizontal orientation appeared at the centre of the screen in a grey background. Later, at a random time interval (between 2000 and 10,000 ms), the lines abruptly changed their orientation to vertical. Participants were instructed to respond to this change as rapidly as possible by pressing the space bar on the laptop PC with the index finger of their dominant hand. Feedback on response time, or the message “You did not answer” after the maximum RT limit (5000 ms) was displayed before the next trial began. Three experimental blocks of 88 trials, lasting about 3 min, were presented without interruption.

### *Oddball Go/No-Go reaction time task*

Each trial began with a 500 ms central fixation cross. Following the offset of this cross, four numbers were presented to the left or right of the fixation at  $9^\circ$  eccentricity on the horizontal meridian. Participants were required to make a key-press response with the index finger of their dominant hand, when the

Table I. Mean [SE] of participants' demographic, fitness, coordination, PVT and Oddball task performance indicators.

	EP athletes ( <i>n</i> = 22)	SP athletes ( <i>n</i> = 22)	Non-athletes ( <i>n</i> = 22)
<i>Demographic characteristics</i>			
Age (years)	24.6[0.9]	22.5[0.9]	22.3[0.6]
Height (cm)*	176[1]	179[1]	171[2]
Weight (kg)	74.5[2.5]	72.7[1.9]	68.1[3.5]
Physical activity per week (hrs)*	4.5[0.2]	5.5[0.3]	0.7[0.1]
<i>Cardiovascular fitness measures</i>			
Pre-testing HR (bpm)*	61[2]	57[2]	67[3]
Maximal HR (bpm)	186[2]	186[2]	187[2]
Time to exhaustion (sec)*	1248[47]	1432[50]	851[57]
Relative power (W/kg)*	3.1[0.1]	3.7[0.1]	2.5[0.1]
HRR <sub>180</sub> index (%)*	38.9[1]	40.8[1.2]	34.7[1]
<i>Hand-eye coordination</i>			
Soda pop test (sec)	8.1[0.2]	8.2[0.2]	7.9[0.3]
<i>Psychomotor vigilance task</i>			
Mean RT (ms)*	269[4]	281[5]	291[7]
RT <sub>var</sub> (ms)*	53[3]	60[5]	82[11]
Lapses*	0.9[0.2]	1.2[0.2]	1.8[0.2]
<i>Oddball task</i>			
Mean RT (ms)	472[12]	469[11]	477[13]
RT <sub>var</sub> (ms)	103[6]	110[7]	121[7]
Commission errors*	8[1]	26[3]	26[4]
Omission errors*	4.5[0.7]	7.8[1.3]	10.1[1.3]

Notes: SE = Standard Error, PVT = Psychomotor Vigilance Task, EP = Externally-paced sport expertise, SP = Self-paced sport expertise, RT = Reaction Time, RT<sub>var</sub> = Reaction Time variability.

\**p* < 0.05 indicates significant main effect of sport expertise.

target number “3” was presented in one of the four possible positions (go trials, 25%), but to refrain from responding, when it did not appear (no-go trials, 75%). The occurrence and order of trial conditions within blocks was randomized. A practice block preceded the series of three experimental uninterrupted blocks of 110 trials, lasting 3 min each.

#### *Cardiovascular fitness test*

The protocol consisted of a maximal graded exercise test until volitional exhaustion at cycle ergometer with stable stages of 2 min and incremental periods of 1 min at a constant cadence between 60 and 100 rev min<sup>-1</sup> after 3 min warm-up at 60 W (Llorens, Sanabria, & Huertas, 2015). The HR<sub>max</sub> was registered and the HR Recovery index was computed as the percentage of reduction of the HR from HR<sub>max</sub> following 180 s of recovery. The relative power output, calculated by the power output of the last stage completed divided by the participants' weight, and time to exhaustion were used as the main cardiovascular fitness variables.

#### *Soda pop test*

This field test of hand-eye coordination consisted in turning, as fast as possible, a series of cans placed

on a table sequentially upside down and then back to their original positions for two round-trips (Hoeger & Hoeger, 2015 for a detailed description). Participants completed two trials and the best performance time was registered.

#### *Design and statistical analysis.*

The participants' descriptive, cardiovascular and motor coordination data were analyzed using a one-way between-groups design. For the analysis of behavioural data from the PVT and Oddball task, we used a 3 × 3 mixed model design, with type of sport expertise (SP, EP and non-athletes) as between-participants factor, block (1, 2, 3) as the within-participants repeated measures factor, and cardiovascular fitness and hand-eye coordination as covariates. For the PVT, mean RT, RT variability (RT<sub>var</sub>) and lapses (slow responses with RT > 500 ms) were analyzed as the main indices of performance. Trials with RTs below 150 ms (1.0%) were considered anticipations and discarded. For the Oddball Go/No-go RT task, mean RT and RT<sub>var</sub> were also analyzed, but two different types of errors were considered as the main performance indicators: (1) Omission Errors (OE), when the target stimulus appeared, but the participant did not respond; (2) Commission Errors (CE), when the target stimulus did not appear, but the participant responded.

Significant main effects and interactions were further explored by using Tukey HSD post-hoc and separate main effects analyses when appropriate.

To evaluate the individual and joint prediction of vigilance and inhibitory control accrued by sport-related expertise and cardiovascular fitness, controlling for the hand-eye coordination ability involved in both tasks, we performed hierarchical multiple regression analyses. Hand-eye coordination performance was statistically controlled by entering it in a first block. Then, cardiovascular fitness was entered in a second block to estimate its independent role, and the type of sport expertise main predictors (SP and EP) were entered in a third block after accounting for the prediction of vigilance and inhibitory performance accrued by coordination and fitness. Finally, to test the hypothesized moderating role of cardiovascular fitness in the relationship between type of sport expertise and cognition (Chan et al., 2011), the interaction terms (Cardiovascular Fitness  $\times$  SP and Cardiovascular Fitness  $\times$  EP) were entered in a last block. The three-category 'group' variable (SP, EP, non-athletes) was transformed in two dummy variables, with the non-athletes group being the reference category: (1) EP = 1 for the EP athletes; 0 otherwise, (2) SP = 1 for the SP athletes; 0 otherwise. The level of significance was set at  $p < .05$  and the effect size was reported ( $\eta_p^2$  for ANOVAs and  $R^2$  for regressions).

## Results

*Control measures: competitiveness, sleep, perceived arousal and motivation*

The ANOVAs did not reveal any significant between-group differences in Competitiveness and Sleep (both  $F_s < 1$ ), Perceived Arousal prior to the task ( $p = .29$ ), and Motivation toward the task ( $p = .17$ ).

*Cardiovascular fitness and coordination measures*

*Pre-testing HR:* The analysis revealed a significant main effect of type of sport expertise in pre-testing HR,  $F(2,63) = 4.24$ ,  $p = .018$ ,  $\eta_p^2 = .12$ . Post-hoc tests showed lower pre-testing HR values in SP athletes than non-athletes ( $p = .006$ ), but no significant differences between EP athletes and SP athletes ( $p = .337$ ), and between EP athletes and non-athletes ( $p = .062$ , see Table I).

*Cardiovascular fitness test:* Our analyses revealed a main effect of type of sport expertise, for time to exhaustion,  $F(2,63) = 33.12$ ,  $p < .001$ ,  $\eta_p^2 = .51$ , and for relative power output,  $F(2,63) = 20.54$ ,  $p < .001$ ,

$\eta_p^2 = .39$ . Post-hoc tests revealed a greater time to exhaustion and a higher relative power output in SP athletes than EP athletes ( $p = .014$  and  $p = .005$ , respectively), in EP athletes than non-athletes ( $p < .001$ ), and in SP athletes than non-athletes ( $p < .001$ ).

Differences as a function of type of sports expertise were not found in HR<sub>max</sub>, ( $F < 1$ ), but were found in HR recovery,  $F(2,63) = 8.67$ ,  $p < .001$ ,  $\eta_p^2 = .22$ . Both EP athletes and SP athletes showed faster HR recovery than non-athletes, ( $p = .007$  and  $p < .001$ , respectively). No differences were found between EP and SP athletes ( $p = .205$ ).

*Soda Pop Coordination test:* No between-groups differences were found in the hand-eye coordination test,  $F < 1$ .

*Cognitive functioning measures*

*Psychomotor Vigilance Task:* There was a main effect of type of sport expertise for all PVT variables: mean RT,  $F(2,61) = 7.01$ ,  $p = .002$ ,  $\eta_p^2 = .19$ , RT<sub>var</sub>,  $F(2,61) = 3.82$ ,  $p = .027$ ,  $\eta_p^2 = .11$ , and lapses,  $F(2,61) = 3.30$ ,  $p = .043$ ,  $\eta_p^2 = .10$ . As regards mean RT and lapses, post-hoc tests revealed only a significant difference between EP athletes and non-athletes ( $p = .001$  and  $p = .030$ , respectively), with EP athletes being faster than non-athletes (Figure 1) and committing fewer lapses. As regards RT<sub>var</sub>, both groups of EP and SP athletes were more consistent in their responses than non-athletes (SP:  $p = .036$ , EP:  $p = .006$ ) and did not differ between each other ( $p = .494$ ). For all three PVT variables, there was neither a main effect of time-on-task, nor a significant interaction between sport expertise and time-on-task ( $p_s < .24$ ).

*Oddball Go-No-Go reaction time task*

A main effect of type of sport expertise was found for RT<sub>var</sub>,  $F(2,61) = 3.36$ ,  $p = .041$ ,  $\eta_p^2 = .10$ , for commission errors,  $F(2,61) = 12.65$ ,  $p < .001$ ,  $\eta_p^2 = .29$ , and omission errors,  $F(2,61) = 3.85$ ,  $p = .027$ ,  $\eta_p^2 = .11$ , but not for mean RT ( $F < 1$ ). Post-hoc tests revealed only a significant difference between EP athletes and non-athletes, with EP athletes being more consistent in their responses than non-athletes ( $p = .046$ , Figure 1) and committing fewer errors ( $p_s < .001$ , Figure 2). There was no main effect of time-on-task for all RT and error variables ( $F_s < 1$ ), but a significant interaction between sport expertise and time-on-task for RT<sub>var</sub>,  $F(4,122) = 2.99$ ,  $p = .021$ ,  $\eta_p^2 = .09$ . Post-hoc tests revealed that the higher response consistency of EP athletes as

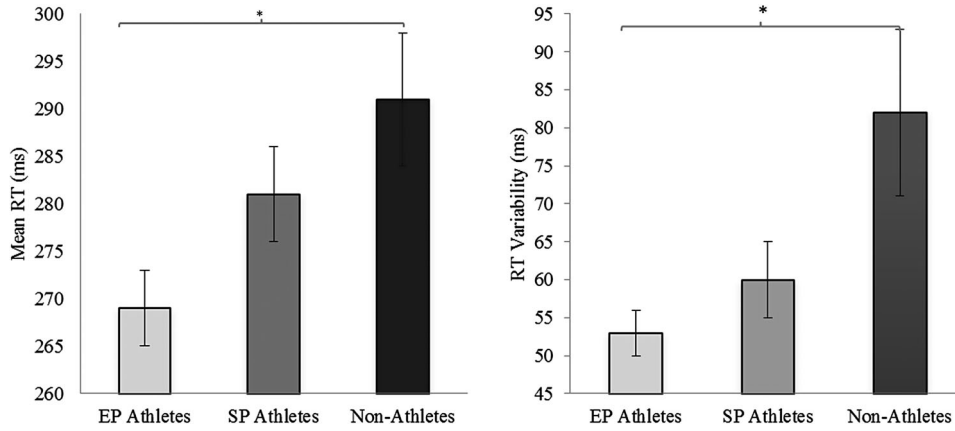


Figure 1. Mean RT (left) & RT Variability (right) as a function of sport expertise. Vertical bars represent Standard Error. Notes: EP = Externally-paced sport expertise, SP = Self-paced sport expertise, RT = Reaction Time. \* $p < 0.05$ .

compared to SP athletes ( $p = .012$ ) and non-athletes ( $p = .016$ ) was only significant in the first block.

*Hierarchical regression analysis of vigilance and inhibition variables*

The Durbin-Watson index (between 1.88 and 2.34) and the plot of residuals suggested independence and normality of the residuals, respectively. Tolerance values (between .289 and .505) indicated a lack of multicollinearity in the regression model. Table II provides a summary of the hierarchical regression analysis for each dependent variables of the PVT and Oddball task.

The hand-eye motor coordination entered in the first block of the regression model significantly predicted all performance indices of the PVT and

Oddball task except the omission error index of accuracy, with the largest percentage of explained variance of mean RT in the PVT (26%). Instead, cardiovascular fitness was not a significant predictor of any PVT or Oddball performance indices (except omission errors). After accounting for the prediction accrued by both coordination and fitness variables, type of sport expertise (SP, EP) variables added a significant percentage of explained variance of RT indices of PVT performance (mean RT and  $RT_{var}$ ), but not accuracy (lapses). In contrast, EP sport expertise was the only significant predictor of indices of performance accuracy in the Go/No go RT task (commission and omission errors), explaining the largest percentage of variance of commission errors (26%). The last block of the regression model, including the interaction terms, did not add any further significant percentage of variance explained.

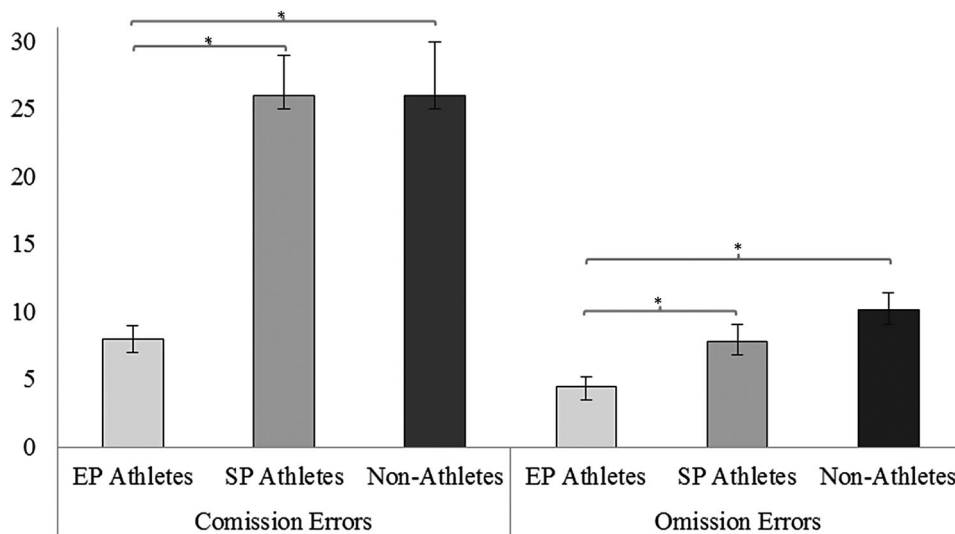


Figure 2. Commission and Omission Errors as a function of sport expertise. Vertical bars represent Standard Error. Notes: EP = Externally-paced sport expertise, SP = Self-paced sport expertise. \* $p < 0.05$ .

Table II. Hierarchical regression models testing moderated prediction of the PVT and Oddball task indicators of performance.

	Psychomotor vigilance task			Oddball task			
	Mean RT $\beta$ $p$	RT var $\beta$ $p$	Lapses $\beta$ $p$	Mean RT $\beta$ $p$	RT var $\beta$ $p$	Commission errors $\beta$ $p$	Omission errors $\beta$ $p$
Factors in block 1							
Coordination	<b>.51</b> <.001*	<b>.26</b> .04*	<b>.36</b> <.01*	<b>.38</b> <.001*	<b>.40</b> <.001*	<b>.34</b> <.01*	.06 .61
<i>Adj. R<sup>2</sup></i>	.24	.05	.12	.13	.15	.10	-.01
Factors in block 2							
Cardiovascular fitness	-.11 .30	.19 .12	-.08 .49	-.03 .77	-.06 .56	.02 .83	<b>.28</b> .02*
<i>Adj. R<sup>2</sup></i>	.27	.07	.11	.12	.14	.09	.05
Factors in block 3							
SP	<b>-.38</b> .02*	<b>.39</b> .04*	-.28 .15	-.18 .35	<b>-.38</b> .04*	-.07 .66	-.02 .09
EP	<b>-.52</b> <.001*	<b>.44</b> <.01*	<b>-.35</b> .04*	-.12 .48	<b>-.40</b> .01*	<b>-.56</b> <.001*	<b>-.34</b> .04*
<i>Adj. R<sup>2</sup></i>	.41	.15	.15	.10	.20	.33	.13
Factors in block 4							
SP × CF	-.10 .56	-.02 .90	.03 .88	-.11 .53	-.14 .40	-.25 .10	.09 .56
EP × CF	-.21 .15	-.06 .77	.12 .55	.21 .30	-.02 .93	-.01 .92	.26 .21
<i>Adj. R<sup>2</sup></i>	.43	.12	.12	.11	.19	.35	.13

Notes: PVT = Psychomotor Vigilance Task, EP = Externally-paced sport expertise, SP = Self-paced sport expertise, RT = Reaction Time, RT<sub>var</sub> = Reaction Time variability, CF Cardiovascular fitness, R<sup>2</sup> = Coefficient of determination. Adjusted R<sup>2</sup> and standardized coefficients with significance level are reported.

\* $p < 0.05$ .

## Discussion

The present study contributes to the actual trend in exercise and cognition research toward gaining a more fine-tuned appreciation of the moderators of the effects of physical activity and sport on cognition. Specifically, we aimed to determine whether the superior vigilance and inhibitory performance of athletes compared to non-athletes (Ballester et al., 2015; Wang et al., 2013) might be differentially modulated by the qualitative characteristics of different types of sport expertise. To this aim, we disentangled the effect of sport expertise from the influence of physical and motor fitness usually coupled with it. Overall, our results add new evidence in favour of the superior performance of athletes practicing cognitively demanding (EP) sports in these aspects of domain-general cognition. This advantage in higher-level cognition for athletes practicing EP sports seems independent of their physical and motor fitness. Indeed, a reverse pattern of the superiority of athletes practicing SP sports emerged concerning cardiovascular fitness performance (time to exhaustion and relative power).

In contrast, regarding vigilance performance, EP athletes showed higher reaction speed, consistency and accuracy in their responses than non-athletes,

in line with recent findings in preadolescent and adolescent athletes (Ballester et al., 2015, 2017). EP athletes also outperformed their SP counterparts in inhibitory accuracy (Figure 2). In contrast, Jacobson and Matthaeus (2014) found better inhibition for SP athletes compared to EP athletes. This divergence is probably due to the multifaceted nature of inhibition and the correspondingly wide array of tests used to measure its different facets (Diamond, 2013). Jacobson and Matthaeus (2014) found an advantage of SP athletes in interference control, whereas we found an advantage of EP athletes in response inhibition, as revealed by superior accuracy in the Go/No-Go visual search task. This is in line with other studies performed with athletes from EP sports (Verburgh, Scherder, van Lange, & Oosterlaan, 2014; Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012; Wang et al., 2013). The unique advantage of EP athletes in performing a visual attention task involving response inhibition could be due to their habitual need to react to relevant cues accurately in a changing and unpredictable environment, while suppressing the tendency to respond to irrelevant or misleading stimuli as feinting movements by opponents (Voss et al., 2010). This is consistent with studies reporting that EP athletes, compared to those practicing SP sports

or non-athletes, show a more flexible visual attention (Lum et al., 2002; Pesce, Tessitore, Casella, Pirritano, & Capranica, 2007), faster perception-action coupling (Faubert, 2013) and enhanced inhibitory control (Chan et al., 2011; Vestberg et al., 2012; Wang et al., 2013). The attentional benefits of practicing EP sports have neural correlates in a differential modulation of attention-related components of Event-Related Brain Potentials (Pesce & Bösel, 2001; Taddei, Bultrini, Spinelli, & Di Russo, 2012). In our study, the coupling of a higher attentional performance with a lower cardiovascular fitness of athletes practicing EP sports as compared to those practicing SP sports supports the view that factors different from the metabolic demands of sports practice are responsible for the attentional advantage of EP sport athletes. This supports the cognitive stimulation hypothesis in exercise and cognition research (Pesce, 2012) and the assumption of the cognitive component skill approach in the study of cognitive sport expertise (Voss et al., 2010).

Regression analyses were performed to disentangle the relative contribution of the type of sport expertise and fitness to vigilance and inhibitory control. In contrast to EP sport expertise, which predicted performance speed, consistency and accuracy, the predictive value of cardiovascular fitness was limited to one aspect of cognitive performance accuracy (i.e. omission errors in the Oddball task; Table II). The comparability with previous studies is limited by the prevalence of developmental and aging research on the cardiovascular fitness-cognition relationship (e.g. Hillman et al., 2008). The scarce studies conducted with young adults mainly regard different facets of attention and inhibitory control (e.g. Jacobson & Matthaeus, 2014), or different cognitive functions (e.g. Baym et al., 2014).

Based on findings suggesting that benefits of EP sport expertise for inhibitory control may require a minimum of cardiovascular fitness threshold to emerge (Chan et al., 2011), we expected an interactive contribution of EP sport expertise and cardiovascular fitness. Instead, cardiovascular fitness did not moderate the prediction accrued by sport expertise (Table II). Taken together, the strong role of sport expertise and the weak role of cardiovascular fitness for two interrelated cognitive functions such as vigilance and inhibitory control add to the view that cardiovascular fitness may not be responsible for all cognitive benefits of regular PA and sport practice (e.g. Etner, Nowell, Landers, & Sibley, 2006; Pesce, 2012). Our results support the assumption that the cognitive demands inherent to performing complex sport tasks may contribute to the positive association between chronic physical activity and cognition (Moreau & Conway, 2013). They also

add evidence supporting the “cognitive component skills approach”, which conceives sport training as a stimulating medium for training both domain-general and sport-specific cognitive skills. A rationale in line with the “cognitive skill transfer” (Taatgen, 2013) and “broad transfer” (Furley & Memmert, 2011) hypotheses, which state that learning and practicing certain activities may lead to adaptations in basic cognitive abilities, potentially transferable to different skill domains (Ducrocq, Wilson, Vine, & Derakshan, 2016).

Previous studies assessing the relationship between different types of sport expertise and cognitive functioning did not consider the cardiovascular fitness of the participants, or controlled for its influence by means of indirect evaluation (Chan et al., 2011; Wang et al., 2013). Our study represents a step forward by adding a direct cardiovascular fitness measurement plus an index of the hand-eye coordination to disentangle sport expertise from sport-related fitness effects and coordination skills from truly attentional and cognitive components of the employed attentional test, respectively. Moreover, we controlled for several potential confounding factors as sleep quality, perceived arousal, competitiveness or motivation.

While presenting the novel aspects and strengths of this study, some limitations must be addressed. We did not control for other activities, beyond sport, in which individuals might improve vigilance and executive control. Most relevantly, the cross-sectional design does not allow addressing the issue of self-selection in the sport context. Indeed, individuals with superior executive functions may be more likely to become athletes, thus further improving their cognitive functions with sport training in a reinforcing cycle (Vestberg et al., 2012; Voss et al., 2010). Longitudinal studies, as well as intervention studies reporting that EP sport practice, regardless of intensity, aids executive function as early as preschool age, when the self-selection issue is still uninfluential (Chang, Tsai, Chen, & Hung, 2013), represent suitable ways to complement cross-sectional evidence.

In conclusion, to our knowledge, the present study adds to the still scarcely considered line of research looking at the benefits of sports for domain-general cognition and especially executive function (Diamond & Ling, 2016). The findings suggest that an open sport environment with both physical and cognitive demands may provide a cross-culturally widespread, stimulating context to enhance two key self-regulatory functions (vigilance and inhibition) crucial in several sport, work and daily life activities.

From an applied perspective, these findings may serve to identify cognitive functions useful for talent identification (Vestberg et al., 2012). They also

suggest a venue for future research on the qualitative characteristics of exercise interventions useful for children and individuals with difficulties in vigilance and inhibitory control, such as patients with autism, Parkinson's disease or ADHD. This type of evidence may strengthen the joint advocacy of sport participation by policy makers of the education and health systems.

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### References

- Ballester, R., Huertas, F., Molina, E., & Sanabria, D. (2017). Sport participation and vigilance in children: Influence of different sport expertise. *Journal of Sport and Health Science*, In press. doi:10.1016/j.jshs.2017.05.008
- Ballester, R., Huertas, F., Yuste, F. J., Llorens, F., & Sanabria, D. (2015). The relationship between regular sports participation and vigilance in male and female adolescents. *PloS one*, 10(4), e0123898. doi:10.1371/journal.pone.0123898
- Baym, C. L., Khan, N. A., Pence, A., Raine, L. B., Hillman, C. H., & Cohen, N. J. (2014). Aerobic fitness predicts relational memory but not item memory performance in healthy young adults. *Journal of Cognitive Neuroscience*, 26(11), 2645–2652. doi:10.1162/jocn\_a\_00667
- Chan, J. S., Wong, A. C., Liu, Y., Yu, J., & Yan, J. H. (2011). Fencing expertise and physical fitness enhance action inhibition. *Psychology of Sport and Exercise*, 12(5), 509–514. doi:10.1016/j.psychsport.2011.04.006
- Chang, Y.-K., Tsai, Y.-J., Chen, T.-T., & Hung, T.-M. (2013). The impacts of coordinative exercise on executive function in kindergarten children: An ERP study. *Experimental Brain Research*, 225(2), 187–196. doi:10.1007/s00221-012-3360-9
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, 64, 135–168. doi:10.1146/annurev-psych-113011-143750
- Diamond, A. (2015). Effects of physical exercise on executive functions: Going beyond simply moving to moving with thought. *Annals of Sports Medicine and Research*, 2(1), 1011.
- Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience*, 18, 34–48. doi:10.1016/j.dcn.2015.11.005
- Drummond, A., Bischoff-Grethe, D. F., Dinges, L., Ayalon, C. M., & Mednick & Meloy, M. J. (2005). The Neural Basis of the Psychomotor Vigilance Task. *Sleep*, 28(9), 1059–1068. doi: 10.1093/sleep/28.9.1059
- Ducrocq, E., Wilson, M., Vine, S., & Derakshan, N. (2016). Training attentional control improves cognitive and motor task performance. *Journal of Sport and Exercise Psychology*, 38(5), 521–533. doi:10.1123/jsep.2016-0052
- Etmer, 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. doi:10.1016/j.brainresrev.2006.01.002
- Faubert, J. (2013). Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes. *Scientific Reports*, 3, 1154–1156. doi:10.1038/srep01154
- Furley, P., & Memmert, D. (2011). Studying cognitive adaptations in the field of sport: Broad or narrow transfer? A comment on Allen, Fioratou, and McGeorge (2011). *Perceptual and Motor Skills*, 113(2), 481–488.
- García-Madruga, J. A., Gómez-Veiga, I., & Vila, J. (2016). Executive functions and the improvement of thinking abilities: The intervention in reading comprehension. *Frontiers in Psychology*, 7, 58. doi:10.3389/fpsyg.2016.00058
- Heppe, H., Kohler, A., Fleddermann, M.-T., & Zentgraf, K. (2016). The relationship between expertise in sports, visuospatial, and basic cognitive skills. *Frontiers in Psychology*, 7, 904. doi:10.3389/fpsyg.2016.00904
- 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. doi:10.1038/nrn2298
- Hoeger, W. W., & Hoeger, S. A. (2015). *Principles and labs for fitness and wellness*. Wadsworth, OH: Cengage Learning.
- Huijgen, B. C. H., Leemhuis, S., Kok, N. M., Verburgh, L., Oosterlaan, J., Elferink-Gemser, M. T., & Visscher, C. (2015). Cognitive functions in elite and sub-elite youth soccer players aged 13 to 17 years. *PloS One*, 10(12), e0144580. doi:10.1371/journal.pone.0144580
- Jacobson, J., & Mattheus, L. (2014). Athletics and executive functioning: How athletic participation and sport type correlate with cognitive performance. *Psychology of Sport and Exercise*, 15(5), 521–527. doi:10.1016/j.psychsport.2014.05.005
- Llorens, F., Sanabria, D., & Huertas, F. (2015). The influence of acute intense exercise on exogenous spatial attention depends on physical fitness level. *Experimental Psychology*, 62(1), 20–29. doi:10.1027/1618-3169/a000270
- Lum, J., Enns, J. T., & Pratt, J. (2002). Visual orienting in college athletes: Explorations of athlete type and gender. *Research Quarterly for Exercise and Sport*, 73(2), 156–167.
- Luque-Casado, A., Perakakis, P., Ciria, L. F., & Sanabria, D. (2016a). Transient autonomic responses during sustained attention in high and low fit young adults. *Scientific Reports*, 6, 27556. doi:10.1038/srep27556
- Luque-Casado, A., Perakakis, P., Hillman, C. H., Kao, S.-C., Llorens, F., Guerra, P., & Sanabria, D. (2016b). Differences in sustained attention capacity as a function of aerobic fitness.

- Medicine and Science in Sports and Exercise*, 48(5), 887–895. doi:10.1249/MSS.0000000000000857
- McMorris, T. (2016). *Exercise-cognition interaction: Neuroscience perspectives*. Amsterdam: Elsevier.
- Monk, T. H. (1989). A visual analogue scale technique to measure global vigor and affect. *Psychiatry Research*, 27(1), 89–99. doi:10.1016/0165-1781(89)90013-9
- Moreau, D., & Conway, A. R. (2013). Cognitive enhancement: A comparative review of computerized and athletic training programs. *International Review of Sport and Exercise Psychology*, 6(1), 155–183. doi:10.1080/1750984X.2012.758763
- Nougier, V., & Rossi, B. (1999). The development of expertise in the orienting of attention. *International Journal of Sport Psychology*, 30, 246–260.
- Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport and Exercise Psychology*, 34(6), 766–786. doi:10.1123/jsep.34.6.766
- Pesce, C., & Bösel, R. (2001). Focusing of visuospatial attention. Electrophysiological evidence from subjects with and without attentional expertise. *Journal of Psychophysiology*, 15(4), 256–274. doi:10.1027//0269-8803.15.4.256
- Pesce, C., Tessitore, A., Casella, R., Pirritano, M., & Capranica, L. (2007). Focusing of visual attention at rest and during physical exercise in soccer players. *Journal of Sports Sciences*, 25(11), 1259–1270. doi:10.1080/02640410601040085
- Remor, E. (2007). Propuesta de un cuestionario breve para la evaluación de la competitividad en el ámbito deportivo: Competitividad-10. *Revista de Psicología del Deporte*, 16(2), 167–183.
- Schmidt, E. A., Schrauf, M., Simon, M., Fritzsche, M., Buchner, A., & Kincses, W. E. (2009). Drivers' misjudgement of vigilance state during prolonged monotonous daytime driving. *Accident Analysis & Prevention*, 41(5), 1087–1093. doi:10.1016/j.aap.2009.06.007
- Singer, R. N. (2000). Performance and human factors: Considerations about cognition and attention for self-paced and externally-paced events. *Ergonomics*, 43(10), 1661–1680. doi:10.1080/001401300750004078
- Stillman, C. M., Cohen, J., Lehman, M. E., & Erickson, K. I. (2016). Mediators of physical activity on neurocognitive function: A review at multiple levels of analysis. *Frontiers in Human Neuroscience*, 10, 626. doi:10.3389/fnhum.2016.00626
- Taatgen, N. A. (2013). The nature and transfer of cognitive skills. *Psychological Review*, 120(3), 439–471.
- Taddei, F., Bultrini, A., Spinelli, D., & Di Russo, F. (2012). Neural correlates of attentional and executive processing in middle-age fencers. *Medicine & Science in Sports & Exercise*, 44(6), 1057–1066. doi:10.1249/mss.0b013e31824529c2
- Verburgh, L., Scherder, E. J. A., van Lange, P. A. M., & Oosterlaan, J. (2014). Executive functioning in highly talented soccer players. *PloS One*, 9(3), e91254. doi:10.1371/journal.pone.0091254
- Vestberg, T., Gustafson, R., Maurex, L., Ingvar, M., & Petrovic, P. (2012). Executive functions predict the success of top-soccer players. *PloS One*, 7(4), e34731.
- Voelcker-Rehage, C., & Niemann, C. (2013). Structural and functional brain changes related to different types of physical activity across the life span. *Neuroscience & Biobehavioral Reviews*, 37(9), 2268–2295. doi:10.1371/journal.pone.0034731
- Voss, M. W., Kramer, A. F., Basak, C., Prakash, R. S., & Roberts, B. (2010). Are expert athletes 'expert' in the cognitive laboratory? A meta-analytic review of cognition and sport expertise. *Applied Cognitive Psychology*, 24(6), 812–826. doi:10.1002/acp.1588
- Wang, C.-H., Chang, C.-C., Liang, Y.-M., Shih, C.-M., Chiu, W.-S., Tseng, P., ... Juan, C.-H. (2013). Open vs. closed skill sports and the modulation of inhibitory control. *PloS One*, 8(2), e55773. doi:10.1371/journal.pone.0055773
- Zheng, B., Tien, G., Atkins, S. M., Swindells, C., Tanin, H., Meneghetti, A., ... Pantan, O. N. M. (2011). Surgeon's vigilance in the operating room. *The American Journal of Surgery*, 201(5), 673–677. doi:10.1016/j.amjsurg.2011.01.016