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Original article

Sport participation and vigilance in children: Influence of different sport expertise

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Abstract

Purpose: The present study aimed to investigate the relationship between different types of sport expertise (externally-paced *vs.* self-paced sports) and vigilance performance in children by evaluating the cardiovascular fitness level of the participants.
Methods: Three groups of children (11.0 ± 0.2 years) differentiated in terms of their regular sport participation (football players, $n = 20$; track and field athletes, $n = 20$; non-athletic controls, $n = 20$) took part in the study. In one session, participants performed the Leger Multi-stage fitness test to estimate their aerobic fitness level. In another session, participants completed the Psychomotor Vigilance Task (PVT) to evaluate their vigilance performance under 2 conditions of velocity demands (normal *vs.* speed).
Results: The results revealed that both groups of sport practitioners had higher cardiovascular fitness than non-athlete controls. In contrast, no significant differences in the performance PVT were found between track and field athletes and controls. Crucially, football players showed better performance in the PVT than track and field athletes and controls. These between-group differences were not modulated by the speed demands of the task.
Conclusion: The major novel finding of this research points to a positive relationship between sport participation and vigilance performance during childhood. We discuss our results in terms of the different hypotheses put forward in the literature to explain the relationship between regular exercise and cognitive functioning: the "cardiovascular fitness" and the "cognitive component skills" hypotheses.

Keywords: Childhood; Cognition; Cognitive skills; Physical activity; Physical exercise; Sustained attention

1. Introduction

Vigilance or sustained attention is the capacity to maintain attention over time and to react efficiently to relevant stimuli.[1] The study of vigilance is highly important because optimal levels of this capacity are necessary in many daily life activities such as driving,[2] performing efficiently in certain work settings,[3,4] and attending to academic lessons. In fact, a positive relationship has been found between sustained attention and academic achievement in children.[5]

Individual differences in terms of regular practice of exercise have been related to vigilance across the lifespan.[6–10] These findings are in line with the positive relationship between exercise and cognitive processing reported in the exercise–cognition literature.[11,12] Nonetheless, just few studies have directly addressed the relationship between regular practice of exercise and sustained attention in children.

Some studies have focused on the role of cardiovascular fitness on the cognition–exercise relationship. For instance, Pontifex et al.[13] showed fewer errors of omission in a flanker task[14] in high-fitness 9–10 years old children than in their low-fitness counterparts, a result that was taken as a piece of evidence of superior sustained attention capacities in the high-fit group. The positive relationship between aerobic fitness and sustained attention in children has also been supported by a functional magnetic resonance imaging study.[15] Taken together, these results are consistent with the cardiovascular fitness hypothesis,[16,17] which suggests that cardiovascular fitness is the physiological mediator that explains the cognitive benefits of regular exercise.

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Researchers have also investigated the influence of different sport expertise on the relationship between regular exercise and vigilance performance in children. However, the empirical evidence is limited, to the best of our knowledge, to 1 study with adolescents,[6] and young adults (Lum et al.[7]). Ballester et al.[6] showed better performance in the Psychomotor Vigilance Task (PVT) of a group of football players compared with their age-matched controls. Importantly, vigilance performance did not correlate with the cardiovascular fitness level of the participants. Taken together, these results seem to be consistent with the cognitive component skills hypothesis[18,19] which considers "sport training as a medium for experience dependent brain plasticity, or cognitive training, that results in more efficient brain networks (both general and sport-specific)" (Voss et al.,[19] page 822). This rationale is in line with the "cognitive skill transfer"[20] and the "broad transfer"[21] hypotheses, which suggest that learning and practicing certain activities may lead to adaptations in basic cognitive abilities that in turn can transfer to different skills in other domains.

In sum, researchers have evaluated the relationship between sustained attention and regular practice of exercise in children while considering either aerobic fitness or sport expertise, but there is no investigation considering both factors in the same study. In the same vein, although vigilance performance has been related to gender,[22,23] no previous study has considered the potential role of gender in the association between sport participation and vigilance in children (Ballester et al.,[6] for evidence in adolescents). In line with previous direct evidence testing the influence of gender in the vigilance capacities of children from the age range of our participants,[23] we did not expect differences in cognitive performance as a function of gender.

The main purpose of the present study was to investigate the relationship between different types of regular sport participation and vigilance performance, while taking into account the cardiovascular fitness level of the participants. In order to do so, we compared performance in the PVT and cardiovascular fitness of a group of non-athlete controls with 2 groups of children enrolled in different sport types: externally-paced sports (i.e., football) and self-paced (i.e., athletics). Externally-paced sports are defined as those with a changing, unpredictable, and externally-paced environment (e.g., football, tennis, martial arts, *etc.*), while self-paced sports are defined as those in which the sporting environment is relatively consistent, predictable, and self-paced[24] (e.g., athletics, swimming, rowing, *etc.*).

Sport modality has been shown to be a potential moderator of the exercise−cognition relationship because different sport contexts impose distinctive perceptual-cognitive demands.[18,19] During externally−paced sports, athletes are required to react quickly and accurately in a highly unpredictable sport environment, while during self-paced sports athletes are typically exposed to a lesser degree of temporal pressure demands in the response to external stimulus. Thus, it would be expected that potential differences in vigilance performance between groups might be modulated by the speed response requirements of the task. To validate such hypothesis, here we have manipulated the velocity demands of the PVT (see Materials and methods below for details).

The "cardiovascular fitness" hypothesis[16,17] predicts that both groups of athletes, who were expected to show better cardiovascular fitness than controls, would outperform non-athlete children in vigilance performance. The "cognitive component skills" hypothesis,[19] however, predicts an advantage in vigilance performance for football players compared to track and field athletes and non-athletes. Concerning the velocity demands manipulation, due to the requirement for athletes of externally-paced sports to react quickly under temporal pressure to different external cues from a fast-changing and highly unpredictable environment, we hypothesized larger performance differences in the speed condition than in the normal PVT condition in favor of football players.

2. Materials and methods

2.1. Ethics statement

The study protocol and procedure were approved by the Ethical Committee of the Faculty of Physical Education & Sport Sciences, Catholic University of Valencia (2015/2016/22). The study was performed in full compliance with the Declaration of Helsinki 1964. All participants were given verbal and written information about the experiment. They were also informed about their right to leave the experiment at any time. All participants took part in the study with the written consent of their parents and club or school.

2.2. Participants

An *a priori* power analysis was conducted to determine the minimum sample size required for a power level of 0.80. This analysis was based on data from a similar study,[6] with 19 participants in each group that compared performance in the PVT of a group of adolescent football players and their age-matched non-athlete counterparts. Consequently, 60 children (Table 1) were recruited to participate in the present study. For the sports participation groups, 20 participants (8 females) from a Spanish 1st Division League junior team formed the externally-paced sport group, and 20 track and field athletes (12 females) from an athletic club formed the self-paced sport group. Participants of both groups were competing at the highest level for their age range in their respective sports modalities and were matched in terms of regular sport participation as they all attended specific training sessions 2 times per week and competition on weekends (4 h/week of deliberate sport practice according to the criteria established by Ericsson et al.[25]). All of them reported more than 4 years of systematic sport participation in their respective sport modality and no regular practice of other sports. For the control group, 20 participants (10 females) were selected from a local school who met the inclusion criteria of not reporting any sport experience and regular sport participation out of school (1 h or less per week). None of the participants had an individual education plan or accommodations to receive direct or indirect special education services (e.g., attention deficit disorder, cognitive, or physical disability).

Table 1
Mean (95%CI) of participants' demographic, fitness, PVT, and scores in K-BIT and BIS-11c.

	Football players ($n = 20$)	Track and field athletes ($n = 20$)	Non-athletes ($n = 20$)
Demographic characteristics			
Age (year)	11 (10.9, 11.1)	11 (10.9, 11.1)	11 (10.9, 11.1)
PA/week (h)	4 (3.9, 4.1)	4 (3.9, 4.1)	0.8 (0.7, 0.9)**,‡
Cardiovascular fitness measures			
Pre-testing HR (bpm)	68 (64, 72)	66 (62, 70)	76 (73, 80)*,‡
HR_{max} (bpm)	205 (201, 208)	201 (197, 204)	202 (198, 205)
TTE (s)	442 (387, 497)	372 (318, 427)	241 (186, 295)**,‡
HRR_{180} index (%)	43.7 (41.6, 46.0)	40 (37.8, 42.2)*	36.3 (34.1, 38.5)**,†
VO_{2max} (mL/kg/min)	50.5 (49.4, 51.5)	49.3 (48.7, 49.9)	47.6 (46.8, 48.5)**,†
PVT			
Mean RT (ms)	365 (334, 397)	415 (384, 446)*	440 (408, 471)*
K-BIT			
IQ composite (points)	97 (91, 102)	100 (95, 105)	97 (91, 102)
Impulsivity			
Impulsivity composite (points)	26 (23.1, 29.0)	26.7 (23.8, 29.6)	25 (22.1, 28.0)

* $p < 0.05$, **$p < 0.001$, compared with football group.
† $p < 0.05$, ‡$p < 0.001$, compared with track and field group.
Abbreviations: BIS-11 = Barrat Impulsiveness Scale; CI = Confidence interval; HR_{max} = maximum heart rate; HRR_{180} = hear rate recovery following 180 s after the physical test; IQ = intelligence quotient; K-BIT = Kaufman Brief Intelligence Test; PA = physical activity; PVT = Psychomotor Vigilance Task; RT = reaction time; TTE = time-to-exhaustion; VO_{2max} = maximal oxygen uptake.

2.3. *Apparatus, materials, and procedure*

Participants were evaluated in the same season and at the same time of the day on 2 separate occasions (vigilance task sessions and fitness assessment sessions were completed in a counterbalanced order between participants) with a minimum interval of 2 days and a maximum interval of 7 days. At the end of the last session, participants were debriefed on the purposes of the study and given an explanation of their cardiovascular fitness with easily understandable data.

2.3.1. *Vigilance task session*

The participants were fitted with a Polar RS800CX HR monitor (Polar Electro Ltd., Kempele, Finland). Subsequently, they rested for 5 min in a seated position to record the baseline pre-testing heart rate (HR). Successively, participants completed the PVT (see details below) using a laptop PC (HP Pavilion g series 15'6-inch, HP, Palo Alto, CA, USA) running the E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA) that controlled the presentation of stimuli, timing operation, and collection of responses. Participants performed the PVT sitting on a chair 60 cm from the computer monitor. The baseline HR and the PVT were completed in a dimly illuminated and noise-reduced room. Afterwards, participants completed 2 questionnaires. First, the Spanish validated version (BIS-11c)[26] of the revised form[27] of the Barrat Impulsiveness Scale (BIS) was administered to measure impulsiveness. We analyzed a composite scale comprised of the scores of the motor, planning, and cognitive impulsivity scales. Then, the Kaufman Brief Intelligence Test[28] (K-BIT) was completed. The K-BIT is an individually administered screening tool widely used to assess verbal and nonverbal intelligence within the age group tested in the present study.[13] Impulsivity and intelligence were measured to control for potential confounding factors that may influence the relationship between sport participation and vigilance performance during childhood.

In PVT, on each trial, a Gabor patch (4.20° × 4.20°) with a horizontal orientation appeared at the center of the screen in a gray 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 by pressing the space bar on the laptop PC with the index finger of their dominant hand. The PVT was divided into 2 different conditions (normal condition *vs.* speed condition).

The first condition started with a practice block of 1 min duration. Subsequently, another block of 1 min was performed to estimate the baseline mean reaction time (RT) of the participant before starting the experimental block. Each condition lasted for 9 min without interruption. The order of presentation of the 2 conditions was counterbalanced across participants. A 5 min break was allowed between the 2 conditions in which the participants watched a cartoon animation video. In the normal condition, participants were only instructed to respond to the target without anticipating their response. In the speed condition, participants were instructed to respond to the target as fast as possible. In the speed condition, if the response was slower than the individual baseline mean RT of the participant, the message "Quickly!" appeared on the screen and the next trial began. In both conditions, if a response had not been made within 5000 ms, the message "You did not answer" appeared on the screen and the next trial began. Each velocity condition lasted for 9 min without interruption resulting in an average of 83(9) trials for the normal condition and 87(9) trials for the velocity condition.

2.3.2. *Fitness assessment session*

Léger multi-stage fitness test was originally designed to determine the maximal aerobic power of schoolchildren and healthy adults.[29] This test or its adaptations is one of the most common assessment for measuring cardiorespiratory fitness in studies involving young participants.[30]

The participants were fitted with a Polar RS800CX HR monitor. Subsequently, participants in groups of 6 run back and forth on a 20 m course and had to reach the 20 m line at an initial speed of 8.5 km/h that increased progressively (0.5 km/h) in accordance with a pace dictated by a pre-recorded tape. The test finished when the participants acknowledged voluntary exhaustion or were not able to follow the pace during 2 consecutive acoustic signals. The maximal HR (HR_{max}) of each participant was annotated right after the end of the test. The time completed was used to define the time-to-exhaustion (TTE). The last stage number announced was also used to calculate maximal oxygen uptake (VO_{2max}) (Y, mL/kg/min) from the speed (X, km/h) corresponding to that stage (speed = 8.0 + 0.5 stage number) and age (A, year): $Y = 31.025 + 3.238X - 3.248A + 0.1536AX$.[27]

After completing the physical test, participants stayed in the upright seated position[31] (inactive recovery) to calculate the HR recovery (HRR) index, measured as the percentage of reduction of the HR with regard to the HR_{max} following 180 s of recovery (HRR_{180}). Post-exercise HRR has been reported to be an important index of exercise endurance capacity and individual cardiovascular fitness.[32]

2.4. Design and statistical analysis

Analyses of variance (ANOVAs) with the between participants factors of sex (male, female) and sport participation (football, athletics, non0-athlete controls) were used to analyze the physiological and behavioral data. For the RT data from the PVT, we had a factorial design with the between-group variables of sport participation and sex and the within-group variables of condition (normal, speed). Trials with RTs below 100 ms (1.0%) in the PVT were considered anticipations[33] and therefore discarded from the analysis. Holm-Bonferroni corrected *t* tests[34] were used to analyze further significant main effects and interactions. Standardized effect size was reported by means of the partial η^2 for *F*s and Cohen's *d* for *t* tests.

A multiple linear regression analysis was performed to further examine the relative influence of sport expertise and cardiovascular fitness on vigilance performance. Participants' overall mean RT in the PVT was included in the model as a dependent variable, while sport expertise and the main indicator of cardiovascular fitness (TTE) were included as independent variables. The 3-category sport expertise variable was transformed in 2 dummy variables, with the non-athlete group being the reference category: (1) athletes = 1 for the athletes group; 0 otherwise, (2) football = 1 for the football group; 0 otherwise. Gender was also introduced to control for the potential effect of this variable in the regression model. Statistical analyses were performed using IBM SPSS (Version 22.0; IBM Corp., Armonk, NY, USA).

3. Results

3.1. Physiological measures

3.1.1. Pre-testing HR

The analysis revealed a significant main effect of sport participation in pre-testing HR ($F(2, 54) = 8.93$, $p < 0.001$, $\eta^2_{partial} = 0.25$). No significant differences were found between football players and track and field athletes ($p = 0.463$). In contrast, both track and field athletes ($t(38) = 4.35$, $p < 0.001$, $d = 1.41$) and football players ($t(38) = 2.75$, $p = 0.018$, $d = 0.89$) showed lower pre-testing HR values than non-athletes (Table 1). Neither the main effect of gender ($F(1, 54) = 3.45$, $p = 0.069$, $\eta^2_{partial} = 0.06$), nor the interaction between sport participation and gender ($F(2, 54) = 2.96$, $p = 0.060$, $\eta^2_{partial} = 0.10$), reached statistical significance for pre-testing HR.

3.1.2. Léger multi-stage fitness test

The analyses with participants' TTE in the Léger multi-stage fitness test revealed a main effect of sport participation ($F(2, 54) = 12.76, p < 0.001, \eta^2_{partial} = 0.32$). No significant differences were found between football players and track and field athletes ($t(38) = 4.35$, $p = 0.082$, $d = 0.58$), while significant differences were found between football players and non-athletes ($t(38) = 4.77$, $p < 0.001$, $d = 1.55$), and between track and field athletes and non-athletes ($t(38) = 3.82$, $p < 0.001$, $d = 1.24$) (Table 1). Regarding gender, the analyses revealed that males showed greater TTE values than females ($F(1, 54) = 13.30$, $p < 0.001$, $\eta^2_{partial} = 0.20$). The interaction between sport participation and gender was not statistically significant for TTE ($F(2, 54) = 1.51, p = 0.23$).

A main effect of sport participation was also found for VO_{2max} ($F(2, 54) = 10.98$, $p < 0.001$, $\eta^2_{partial} = 0.29$). No significant differences were found between football players and track and field athletes ($t(38) = 2.00$, $p = 0.053$, $d = 0.65$). In contrast, significant differences were found between football players and controls ($t(38) = 4.88$, $p < 0.001$, $d = 1.46$), and between track and field athletes and controls ($t(38) = 3.89$, $p = 0.002$, $d = 1.10$) (Table 1). Regarding gender, the analyses revealed that males showed higher VO_{2max} than females ($F(1, 54) = 9.74$, $p = 0.003$, $\eta^2_{partial} = 0.15$). The interaction between sport participation and gender was not statistically significant ($F(2, 54) = 1.29, p = 0.28$).

No differences as a function of sports participation were shown in HR_{max} ($F(2, 54) = 1.20$, $p = 0.309$, $\eta^2_{partial} = 0.04$), which suggests that participants in the 3 groups gave a maximal effort in the physical test (Table 1). The main effect of gender and the interaction between sport participation and gender did not reach statistical significance (both $Fs < 1$).

Regarding HRR, the analyses revealed a main effect of sport participation in HRR_{180} ($F(2, 54) = 13.22$, $p < 0.001$, $\eta^2_{partial} = 0.33$). Football players showed better HRR than controls ($t(38) = 5.13$, $p < 0.001$, $d = 1.67$) and track and field athletes ($t(38) = 3.89$, $p = 0.029$, $d = 0.83$). The difference between track and field athletes and controls was also significant ($t(38) = 2.19$, $p = 0.035$, $d = 0.71$) (Table 1). The analysis also revealed a main effect of gender for HRR ($F(1, 54) = 12.26$, $p < 0.001$, $\eta^2_{partial} = 0.18$). This main effect was further explained by the interaction between sport participation and gender ($F(1, 54) = 3.97$, $p = 0.025$, $\eta^2_{partial} = 0.13$). Non-athletes showed similar HRR regardless of the gender ($p = 0.90$), while track and field athletes ($t(38) = 3.97$, $p < 0.001$, $d = 1.95$), and football players ($t(38) = 3.44$, $p = 0.003$, $d = 1.55$), showed significant differences in HRR between males and females.

3.2. K-BIT and impulsivity

The ANOVAs did not reveal any significant main effect: main effect of sport participation in intelligence quotient (IQ) ($F(2, 57) = 2.06$, $p = 0.14$) and impulsivity ($F < 1$); main effect of gender in IQ ($F(2, 57) = 1.36$, $p = 0.25$) and impulsivity ($F < 1$); interaction between sport participation and gender for IQ ($F(2, 57) = 1.77$, $p = 0.18$) and impulsivity ($F < 1$).

3.3. Vigilance measures

3.3.1. PVT

The analysis of the participants' RTs revealed a significant main effect of sport participation ($F(2, 57) = 4.72$, $p = 0.013$, $\eta^2 = 0.15$). Football players showed faster RTs than track and field athletes ($t(38) = 3.01$, $p = 0.014$, $d = 0.98$), and non-athletes ($t(38) = 2.98$, $p = 0.014$, $d = 0.97$). In contrast, no differences were found between track and field athletes and non-athletes ($p = 0.311$).

The analysis also revealed a significant main effect of condition on RT ($F(2, 54) = 34.89$, $p < 0.001$, $\eta^2_{partial} = 0.39$). Participants were faster in the speed condition (382 ms) than in the normal condition (432 ms). Regarding gender, the analysis did not reveal significant differences between males and females ($F(1, 54) = 2.42$, $p = 0.126$, $\eta^2_{partial} = 0.04$). None of the rest of the terms in the ANOVAs were significant (all Fs < 1) (Table 2).

3.4. Multiple regression

The Durbin-Watson index (2.0) and plot of residuals suggested independence and normality of the residuals, respectively. Tolerance values (between 0.501 and 0.782) indicated lack of multicollinearity in the regression model. Taken together, these data suggest that all relevant assumptions of the multiple linear regression analysis were met. The analysis revealed that the regression model significantly predicted 21.4% of the variance ($F(4, 55) = 3.74$, $r^2 = 0.214$, $r^2_{adjusted} = 0.157$, $p = 0.009$). Neither gender ($\beta = -0.14$, $t(55) = 1.05$, $p = 0.259$) nor TTE ($\beta = -0.12$, $t(55) = -0.75$, $p = 0.45$) were significant predictors of vigilance performance. Regarding sport expertise, only football emerged as significant predictor with respect to the baseline non-athletes group ($\beta = -0.36$, $t(55) = -2.16$, $p = 0.035$) of RT performance (Table 2). To further confirm these results, we conducted another regression analysis that included the predicted VO_{2max} as index of cardiovascular fitness. The results mimicked those reported below. The model explained 21.6% ($F(4, 55) = 3.79$, $p = 0.009$, $r^2 = 0.21$, $r^2_{adjusted} = 0.16$). Crucially, football was a significant predictor of RT, ($\beta = -0.361$, $t(55) = -2.18$, $p = 0.03$). However, VO_{2max} ($\beta = -0.13$, $t(55) = -0.84$, $p = 0.40$), gender ($\beta = -0.14$, $t(55) = -1.1$, $p = 0.27$) and athletes ($\beta = -0.11$, $t(55) = -0.72$, $p = 0.47$) did not significantly predict RT.

4. Discussion

The present study is the first direct attempt to compare the vigilance capacities of children from different sport modalities by assessing the influence of their cardiovascular fitness level.

Our results show that regular sport participation is positively related to physical fitness with a greater level of cardiovascular fitness in both groups of athletes compared with non-athletes. This difference in cardiovascular fitness between athletes and controls in the Léger multi-stage fitness test was supported by the between-group differences in pre-testing HR and HRR with greater values for both groups of sport practitioners than for controls, presumably as a result of regular endurance training. No differences in pre-testing HR were found between football players and track and field athletes. In contrast, football players showed slightly better results in the cardiovascular fitness test (better HRR; albeit marginally significant for TTE and VO_{2max}) compared to track and field athletes. These differences in favor of the football players, with respect to track and field athletes, may be influenced by the specific characteristics of the Léger test, which reproduces more closely the intermittent efforts with continuous accelerations and decelerations performed in football.

Regarding the main goal of our study, the analysis revealed no psychomotor vigilance performance advantage in track and field athletes, who showed similar RTs to non-athletes, despite the levels of physical activity and aerobic fitness being significantly different between the 2 groups. In contrast, football players showed better performance in the PVT than both track and field athletes and non-athletes. The aforementioned finding seem consistent with the main outcome of the study of Wang et al.[35] who showed in an inhibitory control task with young adults, faster stop-signal RTs for externally-paced athletes (tennis) compared with self-paced athletes (swimmers) and non-athletic controls. In the same vein, Cereatti et al.[36] compared adolescent externally-paced athletes (orienteers) with their age-matched counterparts, and showed better ability in the orienteers group to zoom the focus in the central visual field and to shift it to the peripheral visual field.

Previous research investigating the relationship between regular practice of exercise and cognitive processing during the childhood has pointed to cardiovascular fitness as an

Table 2
Participants' mean RT (95%CI) in the PVT as a function of sport participation, gender, and speed condition.

	Football players ($n = 20$)		Track and field athletes ($n = 20$)		Non-athletes ($n = 20$)		Total
	Female	Male	Female	Male	Female	Male	
RT normal condition (ms)	399 (334, 464)	382 (329, 435)	449 (397, 502)	421 (357, 486)	502 (449, 454)	429 (364, 493)	432 (408, 455)
RT speed condition (ms)	352 (311, 394)	339 (305, 373)	396 (361, 430)	389 (347, 431)	427 (393, 462)	386 (345, 428)	382 (366, 397)*

* $p < 0.001$, compared with normal condition.
Abbreviations: CI = confidence interval; PVT = Psychomotor Vigilance Task; RT = reaction time.

important mediator.[11] The observed superior aerobic fitness and PVT performance of football players with respect to non-athlete controls would support those previous findings. In the same vein, when comparing both groups of athletes, the significant difference in favor of the group with slightly better cardiovascular fitness (football players) might be seen as another argument to support the mediating role of cardiovascular fitness in the exercise−cognition relationship. However, 2 results appear to nuance the cardiovascular hypothesis: (1) the non-significant difference between males and females in the PVT, although they were considerably different in terms of fitness level, and (2) the fact that track and field athletes did not outperform non-athletes in the PVT although they had higher cardiovascular fitness. Moreover, the results of the multiple regression analyses revealed that cardiovascular fitness was not a significant predictor of the PVT performance, while football expertise significantly predicted the vigilance performance of our participants. Thus, one might argue that the observed superior vigilance performance of football players as compared to track and field athletes and non-athlete controls described here could be driven by other factors apart from cardiovascular fitness.

In recent years, some authors[37−40] have proposed to go beyond the mere relationship between cardiovascular fitness and cognitive function to avoid overlooking relevant aspects of exercise environment that may specifically contribute to the enhancement of cognitive functioning. This line of research suggests that the cognitive demands inherent to sensorimotor learning[41] and performing complex sport tasks[42] may be important factors responsible for the positive association between physical activity and cognition. Consistent with this argument is the hypothesis proposed by sport expertise researchers,[18,19] the “cognitive component skills”.

Our results, together with previous research, point to the exercise−vigilance relationship as a multifactorial process in which the combination of different variables such as cardiovascular fitness and sport expertise may positively influence cognitive functioning. Therefore, the demands of perceptual-cognitive skills required in an externally-paced sport[24] may have improved the vigilance performance of football players as compared to track and field athletes and non-athletes. It is important to emphasize here that the PVT is far more than a simple RT task. The PVT involves high focused attention demands due to the great temporal uncertainty of the target onset. Indeed, studies that have investigated the neural basis of the PVT have associated fast responses in this task with greater activation of cerebral areas within the cortical sustained attention network[43] and to electrophysiological indexes of top-down response preparation.[9,10]

The superior vigilance performance of football players may be driven by the fact that externally-paced athletes are continuously forcing their vigilance capacities through training and competition, as their sport demands sustained high levels of attention to respond efficiently to external cues (e.g., movements of the ball, their teammates, their opponents, *etc.*) that appear with a great degree of spatial and temporal uncertainty. Moreover, the between-group differences in RTs could be also explained by the fact that quick and accurate reactions are constantly needed in open and fast-paced sports with respect to sports in which the sport environment is highly consistent, predictable, and self-paced for players.[18] Hence, the requirement for athletes from externally-paced sports (football players) to react quickly to environmental cues in a changing and unpredictable environment together with their enhanced motor coordination patterns due to their superior sporting abilities might lead them to superior performance of interceptive actions, hand−eye coordination, and perception−action,[44] which could develop more flexible visual attention, action execution,[45,46] and in light of the present and previous research,[6,7] enhanced vigilance.

With regard to the influence of gender in vigilance performance, no significant differences were found between males and females. This results is consistent with the findings of Venker et al.,[23] who used the PVT to evaluate the vigilance capacities of children ranging 6−11 years old, which showed that the gender differences in favor of boys present at the age of 6 disappeared progressively until performance was approximately equal by age 11. Along the same lines, no gender or between-group differences were found for IQ or impulsivity.

Overall, the present study, together with previous research, suggests that the “cognitive component skills” hypothesis and the “cardiovascular fitness” hypothesis should not be considered mutually exclusive. Our results point to the sport training context as a stimulating environment, where both cardiovascular fitness and perceptual−cognitive skills are enhanced, which may in turn, influence conjointly cognitive functioning. Thus, further research in this field, comparing larger groups of participants from different sport types and with different levels of sport participation and cardiovascular fitness will be needed to clarify the specific, rather than combined, effect of each variable on vigilance performance.

It is worth noting, moreover, that any potential explanation of the between-group differences observed in the present study should take into consideration the issue of self-selection in the sports context,[19] which is inherently linked to any cross-sectional study related to this research topic. Did our football players start playing football because of their superior cardiovascular fitness and cognitive abilities to excel in this sport environment, or did they develop and reinforce their cognitive skills through sport-dependent learning? These questions cannot be unequivocally addressed without longitudinal studies that track athletes from different disciplines before starting and throughout their life sport experiences to investigate how the perceptual-cognitive abilities may be developed as a function of cardiovascular fitness and different sport-dependent practice.

5. Conclusion

Our novel findings have important theoretical and practical implications for the investigation of the relationship between exercise and cognitive processing during childhood. Our results suggest that vigilance performance might specially benefit from training in an externally-paced sport environment. Therefore, our findings, together with previous research,[41] suggest that a sport environment with both physical and cognitive demands may provide a stimulating context to enhance cognitive functioning during childhood. An important direction for further research is the investigation of exercise and sport environments that may provide clinical intervention for children with difficulties in vigilance performance, such as patients with autism or attention deficit hyperactivity disorder. This line of research, supported by our findings here, should encourage public health system administrators to implement policies aimed to promote sport participation during childhood, inside and outside the school context.

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Authors' contributions

RB was involved in the design of the study, collected the data, participated in the statistical analysis, and drafted the manuscript; FH coordinated and designed the study and supervised the statistical analysis and writing of the manuscript; EM participated in the statistical analysis; DS coordinated and designed the study and supervised the statistical analysis and writing of the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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