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Prospective associations between physical fitness and executive function in adolescents: The UP&DOWN study

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ABSTRACT

Introduction: The objective of the present work is to investigate the prospective associations between physical fitness components (cardiorespiratory fitness, motor fitness, and muscular strength) and two domains of executive function (working memory and inhibitory control) in adolescents.

Methods: A total of 422 Spanish adolescents (13.35 ± 1.54 years, at baseline) from the UP&DOWN study with assessments at baseline and at 2-year follow-up were included in the analysis. Physical fitness was assessed using the ALPHA Fitness Test Battery. Working memory was measured by the n-back task and inhibitory control by the go/no-go task. Relationships of physical fitness components with working memory and inhibitory control were examined using linear regression models, adjusted for confounders.

Results: Higher baseline levels of the three physical fitness components (cardiorespiratory fitness, motor fitness, and muscular strength) individually predicted better performance on the working memory (β_{ranged}, from .159 to .207; all $p < .012$) and inhibitory control (β_{ranged}, from 0.168 to 0.263; all $p < .004$) tasks at the 2-year follow-up. Muscular strength was the only component associated with inhibitory control independent of the other 2 physical fitness components ($\beta = 0.266$; $p = .005$).

Conclusions: All components of adolescents' physical fitness at baseline were individually associated with better working memory and inhibitory control at 2-year follow-up. Specifically, our results revealed that muscular strength was the component showing the strongest association with executive function, and even the only fitness component associated with inhibitory control independent of the other fitness components. These findings may have important public health and educational implication, since promoting exercise programs that improve physical fitness, and particularly, muscular strength, may positively influence cognitive health.

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1. Introduction

Physical fitness is an important marker of physical health throughout the lifespan (Ortega et al., 2018). Additionally, physical fitness is positively linked to structural and functional brain properties, such as gray matter volume and white matter microstructure (Esteban-Cornejo et al., 2019a; Ruotsalainen et al., 2020), as well as executive function in youth (Khan & Hillman, 2014; Mora - Gonzalez et al., 2020; Rodriguez-Ayllon et al., 2019). Two, related yet distinct, core executive function domains are working memory and inhibitory control (Miyake & Friedman, 2012). Working memory refers to an individual's ability to temporarily store information and manipulate it, and inhibitory control is the ability to ignore or to avoid responding to irrelevant information in the environment while reacting to relevant aspects/goal-directed stimuli (Diamond, 2013; Miyake & Friedman, 2012). Both domains are considered important prerequisites for successful learning, reasoning, and self-regulation during youth and have been further related to better life outcomes (Diamond, 2013). Additionally, these two executive function domains have demonstrated a direct and close relation to academic achievement in youth (Best, Miller, & Naglieri, 2011).

During late childhood and adolescence, the brain undergoes rapid development and thus is a sensitive period of maturation (Giedd et al., 1999; Johnson, Blum, & Giedd, 2009). Accordingly, health factors, such as physical fitness, maybe especially beneficial, influencing the development of cognitive processes including executive function (Chaddock et al., 2012a). Physical fitness is defined as a set of attributes related to an individual's ability to perform physical activities that require cardiorespiratory fitness, muscular strength, motor fitness (speed-agility), and flexibility (Ortega et al., 2018). In this respect, growing evidence has been accumulated over the last two decades demonstrating the importance of physical fitness for executive function in youth (Donnelly et al., 2016; Meeusen et al., 2018). Components of physical fitness are modifiable with regular participation in physical activity. Several mechanisms have been investigated through which physical activity (mainly via cardiorespiratory fitness changes) may be related to executive function. Specifically, three levels of mechanism (molecular/cellular, brain structure/function, and higher-order behaviors) have been documented (Stillman et al., 2016, 2020), and those mechanisms may differ depending on the assessed executive function domain and the improvement in each physical fitness component. For instance, cardiorespiratory and motor fitness influences on executive function domains could, at least in part, be explained by the neurotrophic hypothesis (Hillman, Erickson, & Kramer, 2008a, 2008b; Valkenborghs et al., 2019; Vazou, Pesce, Lakes, & Smiley-Oyen, 2019) and muscular strength to the muscle–brain crosstalk theory (Severinsen & Pedersen, 2020).

Collectively, the evidence among preadolescent children has progressed from observational studies to randomized controlled trials (de Greeff, Bosker, Oosterlaan, Visscher, & Hartman, 2018). For instance, the FITKids randomized controlled trial in which 221 children (7–9 years) participated in a 9-month afterschool physical activity program was one of the first intervention studies (Hillman et al., 2014). The authors found benefits following the intervention for inhibition and cognitive flexibility. As a result of this study and others, a growing body of randomized controlled trials and longitudinal studies has emerged in preadolescent children (Donnelly et al., 2016; Khan & Hillman, 2014; Pesce, 2012; Valkenborghs et al., 2019). However, similar advances in the field have not followed for adolescent populations, with most of the accumulated evidence stemming from observational/cross-sectional studies (Khan & Hillman, 2014; Xue, Yang, & Huang, 2019). Accordingly, further investigation of physical fitness and executive function in adolescents over time, which employs prospective/longitudinal or randomized controlled trial designs, is warranted.

To date, cardiorespiratory fitness is the most studied component of physical fitness and has been positively related to working memory and inhibitory control in preadolescent children (Donnelly et al., 2016; Hillman et al., 2008a, 2008b; Khan & Hillman, 2014; Mora - Gonzalez et al., 2019; Scudder et al., 2016) and adolescents (Hogan et al., 2013; Huang et al., 2015; Reigal et al., 2020; Stroth et al., 2009; Westfall et al., 2018). Importantly, all previous studies have used a cross-sectional design, and the only study using a longitudinal design found that cardiorespiratory fitness did not predict working memory from adolescence to adulthood (from age 13–42 years) (Ferro et al., 2016). Evidence of the associations between other physical fitness components (e.g. motor fitness and muscular strength) and executive function in youth is scarce, lacks consensus, and relies on cross-sectional evidence (Kao, Westfall, Parks, Pontifex, & Hillman, 2017; Shigeta et al., 2020). For example, we have previously found that higher levels of motor fitness were associated with better working memory and inhibitory control performance in children with overweight/obesity (Mora - Gonzalez et al., 2019, 2020), whereas two recent cross-sectional studies in adolescents did not replicate such associations (Cancela, Burgo, & Sande, 2019; Moradi et al., 2019). Similarly, muscular strength has been found to relate to working memory (Kao et al., 2017; Mora - Gonzalez et al., 2019) but not inhibitory control in children (Kao et al., 2017; Mora - Gonzalez et al., 2020; Mora-Gonzalez et al., 2019). In adolescents, the only existing study found no evidence of a cross-sectional association between muscular strength and working memory or inhibitory control (Kao et al., 2017; Shigeta et al., 2020).

In an attempt to better understand these relationships, this study aimed to examine prospective associations between several physical fitness components (cardiorespiratory fitness, motor fitness, and muscular strength) and executive function (working memory and inhibitory control) in adolescents. Given previous research on the association between cardiorespiratory fitness and executive function (Donnelly et al., 2016), we hypothesized a positive prospective association of cardiorespiratory fitness and motor fitness with executive function, whereas we were less certain of the association between muscular strength and executive function since this relationship is inconsistent across the literature.

2. Methods and materials

2.1. Study sample and design

Data were taken from the UP&DOWN study, which is a 2-year longitudinal study with a convenience sample of 2225 youth aged 6–18 years from Spanish schools. In total, 23 schools from Cádiz (1188 children aged 6–11 years) and 22 schools from Madrid (1037 adolescents aged 11–18 years) participated (Castro-Pi ñ ero et al., 2014). All high-schools ($n = 22$) belonging to the UP&DOWN study were invited to participate in the executive function assessment, and only those who agreed ($n = 14$) to participate were included in this sub-sample. Baseline data were collected from September 2011 to June 2012, and 2-year follow-up data were collected from September 2013 to June 2014. The executive function measures were recorded only at the 2-year follow-up in a sub-sample of adolescents ($n = 548$). Of the 548 participants initially enrolled in this study, 422 adolescents (13.35 ± 1.54 years old; 49.8% girls) had valid data in all relevant variables included in the main analyses (physical fitness components and confounders at baseline, and executive function at 2-year-follow-up), and were therefore included in analyses. No statistical differences between included and excluded participants (548 vs 422) were observed in the outcomes of interest ($p > .05$; data not shown).

Before participating in the UP&DOWN study, written informed consent was obtained from parents and participants. The Bioethics Committee of the National Research Council (Madrid, Spain), the Ethics Committee of the Hospital Puerta de Hierro (Madrid, Spain), and the Committee for Research Involving Human Subject at the University of Cádiz (Cádiz, Spain) approved the study protocols.

2.2. Physical fitness components

Physical fitness was measured using cardiorespiratory fitness, motor fitness, and muscular strength tests from the ALPHA Fitness Test Battery (Ruiz et al., 2011). For a detailed description of physical fitness measurements, see **Supplementary Material 1**. Briefly, cardiorespiratory fitness was assessed in group via the 20-m shuttle-run test and the total number of completed laps was registered. Motor fitness was assessed with the 4 × 10 m shuttle-run test and the completion time (seconds) was recorded and inverted by multiplying by −1. Muscular strength was evaluated via upper and lower limb muscular strength procedures. Upper limb muscular strength was assessed using maximum handgrip strength (isometric strength), and the maximum value of each hand was taken and averaged. Lower limb muscular strength was measured by the standing long jump and the longest attempt from 2 trials was recorded (centimeters) and multiplied by the body weight. A muscular strength z-score was calculated as the mean of the z-standardized scores from the absolute muscular strength tests (handgrip strength test and standing long jump). Scores for each physical fitness component at baseline were used as exposure variables.

2.3. Executive function

Executive function was assessed for the domains of working memory and inhibitory control. Both tests were performed in one 30-min session. We assessed working memory using a computerized n-back task. The specific visual n-back task consisted of a sequence of stimuli (i.e., numbers) presented on a laptop screen using 3 levels of difficulty (1-, 2-, and 3-back) in a counterbalanced order, with each block of difficulty composed of 25 trials. A black stimulus was displayed in a fixed central location on a white background with a fixed 2000 ms interstimulus interval (ISI). In brief, for each level, participants were instructed to respond as quickly and accurately as possible by clicking on a "yes" key when the current stimulus matched the one presented *n* steps earlier in the sequence (i.e., the target) or a "no" key when the current stimulus did not match the one presented *n* steps previously. Targets were presented with a 33.3% probability of "yes" across all conditions of the n-back task. For the 1-back task, participants had to compare the current number to the previous one; and they were instructed to press the "yes" key only when trial n matched trial n – 1; otherwise, they were instructed to press the "no" key. The 2-back and 3-back task procedures were similar, on 2-back trials participants had to compare the current trial to the one presented two stimuli before (n – 2), and on 3-back trials, the comparison was made between the current trial and the number presented three trials before (n – 3). The number of hits, misses, false alarms, correct rejections, and response latencies of hits was recorded. For this study, the average of the two last tasks (2- and 3-back) was used for analyses. The two higher difficulty levels were used because the 1-back task is typically considered too simple to be sensitive to differences in working memory functioning. Still, results observed when averaging the three tasks (instead of two) were qualitatively identical to the ones reported here.

The go/no-go task was assessed as a marker of inhibitory control. Each task (go and no-go) was divided into two blocks of 25 trials, which were separated by a brief break. The first two blocks constituted the "go" task and the second two blocks comprised the "no-go" task. The participant was instructed to perform a practice block of 25 trials before engaging in the test blocks. In go task (80% probability of a go trial), participants were instructed to press a key as quickly as possible whenever the "go" stimulus (80% probability) was presented (e.g., the letter D) and to withhold their response when the "no-go" stimulus (20% probability) was presented (e.g., the letter E). The designation of stimuli to the go and no-go conditions were counterbalanced across participants. The ISI was set at 900 ms, and each stimulus was presented during 1000 ms (Perales et al., 2014). The number of hits, misses, false alarms, correct rejections, and response latencies of hit trials was recorded.

For this investigation, the outcome of both cognitive tests was presented as a discrimination index (d'). This index was calculated for both domains separately as follows: z-score (hits rate) - z-score (false alarm rate) (Sorkin, 1999). Higher values of d' were indicative of an increased ability of the participant to discriminate between targets and nontargets, therefore indicating better working memory or inhibitory control performance.

2.4. Potential confounders

Information on sex, biological maturation, maternal education level, and body mass index (BMI) at baseline were used as potential confounders. Biological maturation was measured as peak height velocity (PHV) (Malina, Rogol, Cumming, Coelho e Silva, & Figueiredo, 2015), which is a maturity indicator and reflects the maximum velocity in stature growth during adolescence. Weight, height, and seated height were used to obtain PHV according to Moore's equations (Moore et al., 2015). Sitting height was calculated as the maximum distance from the vertex (highest point on the head) to the base of the sitting surface. The participant was seated on a measuring box or level platform (of known height) with their hands resting on their thighs. Years from PHV were calculated by subtracting the age of PHV from chronological age. Weight and height were measured with participants having bare feet and wearing light under-clothes. Height was rounded to the nearest 1 mm and weight to the nearest 0.05 kg using a standard beam balance (SECA 220; SECA, Hamburg, Germany) with a stadiometer (SECA 701; SECA, Hamburg, Germany). Then, BMI was calculated as weight divided by squared height (kg/m^2). Maternal educational level was reported as, no studies, elementary school, middle school, high school, or university. For analyses, maternal educational level responses were dichotomized as having a university level or not having a university level.

2.5. Statistical analyses

Descriptive characteristics of the study sample at both time points are presented as means and standard deviations (SD) or percentages. Sensitivity analyses showed no significant interactions of sex, age, or BMI with each physical fitness component (i.e., sex*physical fitness component; age*physical fitness component; BMI*physical fitness component) to executive function domains (all $p > .1$), therefore all analyses were performed for the whole sample. The normality and homoscedasticity were checked and assumed for analyses. Pearson correlation coefficients were obtained to test the relationship across all physical fitness components at baseline (see **Supplementary Table 1 (ST1)**) and between the d' of working memory and inhibitory control tests. We corrected for assessing multiple regressions by defining statistical significance as a Benjamini-Hochberg False Discovery Rate *Q* less than 0.10 (Benjamini & Hochberg, 1995). All statistical analyses were performed using Statistical Analysis IBM SPSS Statistics version 24.0 (Chicago, IL, USA) and the level of significance was set at $p < .05$.

To examine the prospective associations between physical fitness variables (cardiorespiratory fitness, motor fitness, and muscular strength) at baseline and executive function at the 2-year follow-up, a linear regression analysis using two different models was conducted. In model 1, analyses were adjusted for sex, PHV (years), maternal educational level (university level/below university level), and BMI (kg/cm^2) at baseline, and model 2 was adjusted for model 1, but simultaneously included the three physical fitness components at baseline.

3. Results

Table 1 shows the descriptive characteristics of the study sample by time point (baseline and 2-year follow-up) as means and SD or percentages.

ST1 shows pearson correlation coefficients between physical fitness components at baseline in adolescents. Physical fitness components at

Table 1
Descriptive characteristics of the study sample (n = 422).

Descriptive characteristics	Baseline	2-year follow-up
Girls (n = 210), %	49.8	49.8
Physical characteristics		
Age (years)	13.3 5 ± 1.54	15.35 ± 1.53
Weight (kg)	54.92 ± 12.65	61.31 ± 12.39
Height (cm)	160.21 ± 9.67	166.78 ± 8.71
Body mass index (kg/m^2)	21.19 ± 3.48	21.93 ± 3.41
Overweight and obesity, %	27.8	25.4
Peak height velocity (years)	12.82 ± 0.86	13.19 ± 0.91
Maternal educational university level, %	36.7	36.7
Grade point average (1-5)	3.44 ± 0.93	3.32 ± 1.01
Physical fitness components[a]		
Cardiorespiratory fitness (laps)	47.45 ± 22.90	–
Motor fitness (sec)	12.27 ± 1.11	–
Absolute lower limb muscular strength (cm × kg)	8669.54 ± 2897.91	–
Absolute upper limb muscular strength (kg)	25.53 ± 7.43	–
Muscular strength (z-score)[b]	−0.01 ± 1.0	–
Executive function domains		
Working memory		
Hits	–	5.04 ± 2.15
Misses	–	2.60 ± 1.63
False alarms	–	13.41 ± 3.29
Correct rejections	–	4.74 ± 3.26
Hit rates	–	0.70 ± 0.13
False alarm rates	–	0.22 ± 0.14
Discrimination index (d')	–	0.48 ± 0.20
Inhibitory control		
Hits	–	19.80 ± 0.60
Misses	–	0.20 ± 0.44
False alarms	–	2.01 ± 0.47
Correct rejections	–	2.97 ± 0.56
Hit rates	–	0.99 ± 0.03
False alarm rates	–	0.19 ± 0.19
Discrimination index (d')	–	0.79 ± 0.22

Values are expressed as means ± standard deviations unless otherwise indicated.
Working memory was assessed with the n-back task and inhibitory control with the go/no-go task.
Hit rates was computed as the ratio between the number of hits (correctly responded across trials) and the total number of hits plus misses (hits/hits + misses). False alarm rate was computed as the ratio between the number of false alarms (in-correctly responded across trials), and the total number of false alarms plus correct rejections (false alarms/false alarms + correct rejections). Discrimination index(d') was computed as the difference between the number of hits and the total number of false alarms [z-score (hits rate) - z-score (false alarm rate)].
Higher values of d' (d' range = 0–1) were indicative of an increased ability from the participant to discriminate between targets and nontargets, therefore indicating a better working memory or inhibitory control performance.

[a] The valid sample for physical fitness components was for cardiorespiratory fitness 382; motor fitness: 399; absolute lower limb muscular strength: 400 and absolute upper limb muscular strength: 411. Cardiorespiratory fitness was assessed by the 20-m shuttle-run test, motor fitness by the 4 × 10-m shuttle-run test, absolute lower limb muscular strength by standing long jump test × body weight, and absolute upper limb muscular strength by handgrip strength test.

[b] The muscular strength z-score was computed as the mean of the z-scores from absolute measurements of the handgrip strength and standing long jump tests (i.e., standing long jump × body weight).

Table 2
Prospective associations between physical fitness components at baseline with executive function at 2-year follow-up in adolescents.

Executive function at 2-year follow-up (outcome variable at follow-up)						
Exposure variable at baseline	Working memory (d')			Inhibitory control (d')		
	β	B (95% CI)	*p*	*B*	B (95% CI)	*p*
Cardiorespiratory fitness (laps)						
Model 1	**.159**	.033 (.007, .059)	**.012**	**.220**	.048 (.021, .075)	**.001**
Model 2	.013	.003 (−.032, .037)	.878	.061	.013 (−.022, .049)	.458
Motor fitness (sec)[a]						
Model 1	**.196**	.041 (.018, .065)	**.001**	**.168**	.037 (.012, .062)	**.004**
Model 2	.130	.026 (−.008, .062)	.126	-.015	-.004 (−.039, .033)	.863
Muscular strength (z-score)[b]						
Model 1	**.207**	.043 (.018, .069)	**.001**	**.263**	.058 (.031, .085)	**<.001**
Model 2	.092	.019 (−.020, .058)	.336	**.266**	.057 (.017, .098)	**.005**

(β) Values are standardized beta coefficients. Statistically significant values are shown in bold.
All significant associations remained significant after adjustment for multiple comparisons using the Benjamini and Hochberg method.
Cardiorespiratory fitness is indicated by the 20-m shuttle-run test and motor fitness by the 4 × 10-m shuttle-run test.
Working memory was assessed with the n-back task and inhibitory control with the go/no-go task.
Discrimination index (d') was computed as the difference between the number of hits and the total number of false alarms [z-score (hits rate) - z-score (false alarm rate)].
Higher values of d' were indicative of an increased ability from the participant to discriminate between targets and nontargets, therefore indicating a better working memory or inhibitory control performance.
The valid sample for physical fitness components was 382 for cardiorespiratory fitness, 399 for motor fitness, and 380 for muscular strength.
Model 1: analyses were adjusted for peak high velocity (years), maternal educational level (university level/below university level), and body mass index (kg/cm$^{2)}$ at baseline. Model 2: was adjusted for model 1 but including simultaneously all physical fitness components at baseline.

[a] The original score of the motor fitness test expressed in seconds was multiplied by −1 to invert the variable so that a higher score indicates higher fitness performance.

[b] The muscular strength z-score was computed as the mean of the z-scores from absolute measurements of the handgrip strength and standing long jump tests (i.e., standing long jump × body weight).

baseline were strongly correlated with each other (all p < .001). Motor fitness was positively related to cardiorespiratory fitness (r = 0.707) and muscular strength (r = 0.588), and muscular strength was positively associated with cardiorespiratory fitness (r = 0.487). The *d'* of working memory was positively associated with the *d'* of inhibitory control (r = 0.250, p < .001).

Table 2 shows the prospective associations between physical fitness components at baseline and executive function 2-year follow-up, adjusted for potential confounders. With regard to working memory, higher levels across all physical fitness components at baseline were related to higher *d'* (β_{ranged}, from .159 to .207; all p < .012) in model 1; but model 2, when all physical fitness components were included simultaneously, the association completely disappeared for cardiorespiratory fitness (β = 0.013, p = .878), and were attenuated but no significant for motor fitness (β = 0.130, p = .126) and muscular strength (β = 0.092, p = .336). Regarding inhibitory control, higher levels across all physical fitness components at baseline were related to higher *d'* (β_{ranged}, from 0.168 to 0.263; all p < .004) in model 1, however in model 2 only muscular strength at baseline was related to higher *d'* (β = 0.266, p = .005), but not cardiorespiratory (β = 0.061, p = .458) nor motor fitness (β = −0.015, p = .863).

4. Discussion

The objective of this study was to examine the association between a variety of physical fitness components (cardiorespiratory fitness, motor fitness, and muscular strength) with two of the core domains of executive function (working memory and inhibitory control) in adolescents over a 2-year follow-up. The results from this study address a gap in the literature and report outstanding findings: (i) higher levels of the three physical fitness components (cardiorespiratory fitness, motor fitness, and muscular strength) at baseline individually predicted better performance on working memory and inhibitory control tasks at the 2-year follow-up after controlling for confounders; (ii) muscular strength was the only component associated with inhibitory control independent of the other 2 physical fitness components, but none of the three physical fitness components were independent of each other associated with working memory; and (iii) muscular strength was the component showing the strongest association with both working memory and inhibitory control. This finding extends prior research and supports the hypothesis that higher levels of physical fitness may predict better executive function during adolescence, suggesting the potential benefits of physical fitness for cognitive and brain health, particularly to muscular strength.

Our finding, which prospectively associated higher baseline levels of physical fitness with better executive function, partially fits our *a priori* hypothesis. With regards to cardiorespiratory fitness, our findings differ from that of the only longitudinal study in adolescents available to date (Ferro et al., 2016), which did not find an association between cardiorespiratory fitness in adolescence and working memory in adulthood. Certainly, methodological differences across both studies could explain the discrepancy between the results (i.e. differences in the length of follow-up testing, cardiorespiratory fitness tests, and working memory tasks). Importantly, Ferro et al. (Ferro et al., 2016) used two-time points, one during adolescence and another during adulthood, whereas the present study was completed over 2-years during adolescence. Our findings are also meaningful given that we included, for the first time, the association of the inhibitory control domain with the various components of physical fitness during a key stage of cognitive development (i.e., adolescence).

The relationship between cardiorespiratory fitness and executive function observed in our study is consistent with former studies in children and adolescents. More specifically, the current study found that higher levels of cardiorespiratory fitness at baseline were individually related to better working memory and inhibitory control performance during the 2-year follow-up. Findings from our laboratory and others, which have employed structural/functional magnetic resonance image and neuroelectric approaches have also indicated a positive relationship of cardiorespiratory fitness with performance on executive function outcomes in children (Chaddock et al., 2010, 2012b; Esteban-Cornejo et al., 2019a; Hillman, Castelli, & Buck, 2005; Mora - Gonzalez et al., 2019, 2020; Weinstein et al., 2012). Several hypotheses have been proposed to explain fitness-related differences in brain structure. Specifically, a recent study suggested that white matter microstructure in specific tracts (e.g. superior corona radiata, the body of corpus callosum) moderated the relationship between cardiorespiratory fitness and working memory in adolescents (Ruotsalainen et al., 2020). Likewise, another investigation in children found that cardiorespiratory fitness was related to the thickness of the rostral anterior cingulate cortex (rACC thickness), and in turn, a greater rACC thickness was associated with lower intraindividual variability during the Stroop test that measures inhibitory control (Bento-Torres et al., 2019). Therefore, structural brain changes during adolescence might explain associations between physical fitness components and executive function.

Another interesting finding from our research was that higher baseline levels of motor fitness were individually linked to better working memory and inhibitory control at 2-year follow-up during adolescence. To the best of our knowledge, our results are consistent with the limited evidence available between specific field-based physical fitness tests and both executive function domains (Mora - Gonzalez et al., 2019, 2020; Mora-Gonzalez et al., 2019). Of note, speed and agility are not independent aspects of physical fitness due to their close relationship with other physical fitness components such as cardiorespiratory fitness or muscular strength, as shown in the present study. Indeed, the association of motor fitness with working memory and inhibitory control disappeared when considering the 3 physical fitness components simultaneously. Importantly, we used the 4 × 10 m shuttle-run test to assess motor fitness, but this test demands specific motor abilities such as speed and agility, but not balance. Other aspects of motor fitness (i.e. balance) have also been linked to working memory and inhibitory control during childhood (Haapala et al., 2019; Moradi et al., 2019; Scharfen & Memmert, 2019). The mechanisms are therefore far from being understood. However, it has been hypothesized that the execution of cognitively engaging exercise involving complex motor movements engages the prefrontal cortex, which in turn facilitates cognitive performance (Vazou et al., 2019); however, available evidence for such claims is limited at this time, and other forms of exercise, which are ‘less’ cognitively engaging (e.g., walking) have also demonstrated benefits for the prefrontal cortex (Colcombe et al., 2004). The past findings from our laboratory could shed light on the Best (Best, 2010) hypothesis and provide an explanation for the observational results of our current study by showing a positive association between motor fitness and brain structure (the white/gray matter volume and cortical thickness) and function n children with overweight/obesity (Esteban-Cornejo et al., 2019a, 2019b, 2021; Mora - Gonzalez et al., 2019, 2020).

Findings from the current study also suggest that higher baseline levels of muscular strength individually predicted better working memory and inhibitory control 2-year later in adolescents. However, muscular strength was not independently related to working memory but was the only component associated with inhibitory control independent of the other 2 physical fitness components Prior reports in adolescents (Shigeta et al., 2020) found that muscular strength was also individually associated with both working memory and inhibitory control, but these associations disappeared when controlling for cardiorespiratory fitness, suggesting that the variance accounted by muscular strength was not independent of cardiorespiratory fitness. However, our results were consistent with those of Kao et al. (Kao et al., 2017), who found that higher levels of muscular strength contributed to better working memory in preadolescent children, independently of cardiorespiratory fitness. Importantly, muscular strength showed the strongest association with both working memory and inhibitory control in the present study. Underlying these associations, previous studies in children with overweight/obesity found that muscular strength was associated with global white matter volume, and with regional white matter volume and integrity (Esteban-Cornejo et al., 2019a; Rodriguez-Ayllon et al., 2020). In addition, skeletal muscle has been recognized as a secretory organ that works in a hormone-like fashion and might exert specific endocrine effects on brain functioning (Pedersen & Febbraio, 2012). Specifically, it is plausible that certain myokines pass throughout the blood-brain barrier to enhance brain-derived neurotrophic factor production and promote neurogenesis, which in turn, may impact positively upon executive function (Pedersen, 2019). However, future studies including both behavioural and neuroimaging data are needed to test the potential mechanisms that drive the associations between physical fitness and executive function in youth.

Some limitations of the current study should be acknowledged. The lack of a baseline measure of executive function is an important limitation, as we could not adjust the association between physical fitness at baseline and executive function at 2-years follow-up for executive function values at baseline. Future observational studies using longer follow-ups and repeated measures of outcomes (i.e., executive function) may provide further insights on this association. Likewise, well-designed randomized controlled trials are needed to draw causality on the effects of changes in physical fitness components on executive functions, and their underlying mechanisms. To the best of our knowledge, this is the first prospective study to examine the relationship between different components of physical fitness with working memory and inhibitory control over a 2-year follow-up during adolescence. Other strengths include the longitudinal design, the relatively large sample size, the objective measures of physical fitness, the assessment of multiple executive function domains, and the adjustment for important confounders (e.g., BMI and PHV).

5. Conclusions

The results from the present study suggest that not only higher levels of cardiorespiratory fitness but also motor fitness and muscular strength are individually predictors of working memory and inhibitory control over a 2-year follow-up during adolescence. Our results also revealed that muscular strength was the physical fitness component with the strongest association with executive function, even was the only physical fitness component associated with inhibitory control independent of the other physical fitness components. Collectively, our findings may have public health and educational implication, since promoting exercise programs that improve physical fitness, and particularly muscular strength, may positively influence cognitive health. However, further longitudinal studies and randomized controlled trials are needed to shed light on the importance of physical activity and fitness for cognitive health among adolescents.

Authors' contributions

Dr Adrià Muntaner-Mas drafted the initial manuscript, carried out analyses, and reviewed and revised the manuscript. Drs José C. Perales, Jo Salmon, Charles H. Hillman, Jose Mora-Gonzalez, and Irene Esteban-Cornejo carried out initial analyses, and reviewed and revised the results section. Drs Irene Esteban-Cornejo and Verónica Cabanas-Sánchez designed the data collection instruments and collected data. Drs Oscar L Veiga, Jose Castro Piñero and Irene Esteban-Cornejo conceptualized and designed the study, coordinated and supervised data collection and reviewed and revised the manuscript. All reviewed and revised the final draft.

Declaration of competing interest

Declarations of interest: none.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2022.102203.

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