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Development and Aging

Sex differences on the relation among gross motor competence, cognition, and academic achievement in children

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An association between gross motor competence (GMC) and academic achievement (AA) has been described, but the potential mechanisms behind this association are still unknown. It is not known either whether these mechanisms are similar for boys and girls. The aim of this study was to analyse whether the association between GMC and AA is mediated by executive functions (EFs), and to investigate whether this mediation differs by sex. This cross-sectional study involved 451 children aged 8 to 10 (234 girls; mean age 9.95 ± 0.59). The Movement Assessment Battery for Children-Second Edition (MABC-2), NIH Toolbox, and grades in language and mathematics were used to test GMC, EFs, and AA, respectively. Multifactorial structural equation model (SEM) was used to evaluate a possible relation between variables, controlling for confounders. The differences by sex were examined using a multi-group SEM approach. The results showed that EFs acted as a full mediator of the relationship between GMC and AA in boys ($\beta = 0.14$, $p = 0.012$) but not in girls ($\beta = 0.10$, $p = 0.326$). These results show that the benefit of GMC on AA is mediated by EFs in boys but not in girls. Nevertheless, these conclusions should be carefully considered due to the cross-sectional nature of the study.

Key words: Academic achievement, children, cognition, mediation analysis, motor competence, structural equation model.

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BACKGROUND

Motor competence can be defined as an individual's level of execution in a wide range of motor tasks, as well as the movement coordination and control underlying a given motor outcome (D'Hondt *et al.*, 2013). In particular, gross motor competence (GMC), which involves the larger muscle groups, is a prerequisite for child physical activity participation and also for engagement in learning and social activities, including sports and games (Cameron, Cottone, Murrah & Grissmer, 2016; Loprinzi, Cardinal, Loprinzi & Lee, 2012; Piek, Baynam & Barrett, 2006). In addition, it has been associated with a broad range of health benefits in children and adolescents (Lubans, Morgan, Cliff, Barnett & Okely, 2010).

A growing body of literature indicates a positive association between GMC and cognitive functioning and academic performance (Haapala, 2013; Macdonald, Milne, Orr & Pope, 2018). More specifically, observational studies show that children with higher levels of motor competence exhibit higher order cognitive function (Geertsen *et al.*, 2016; van der Fels *et al.*, 2019), attention and working memory (Hudson, Ballou & Willoughby, 2021; Ludyga, Pühse, Gerber & Herrmann, 2019) as well as better academic achievement (AA) (de Bruijn *et al.*, 2019; Fernandes *et al.*, 2016; Lopes, Santos, Pereira & Lopes, 2013; Westendorp, Hartman, Houwen, Smith & Visscher, 2011). The effectiveness of motor competence interventions on improving cognitive functioning and academic performance is limited, but emerging evidence seems to indicate a positive impact (Ericsson, 2008; Ericsson & Karlsson, 2014; Mulvey, Taunton, Pennell & Brian, 2018). Research has also suggested that early motor development is a predictor of motor and cognitive performance in childhood (Piek, Dawson, Smith & Gasson, 2008).

Although research shows a positive relationship between GMC and AA, the nature and mechanisms of this association are uncertain and still under discussion (Cameron *et al.*, 2016). Some studies have suggested that the relationship between these two variables is mediated by executive functions (EFs) (Cadoret, Bigras, Duval, Lemay, Tremblay & Lemire, 2018; Rigoli, Piek, Kane & Oosterlaan, 2012; Schmidt *et al.*, 2017), which are predictors of academic success (Best, Miller & Naglieri, 2011; Lopes *et al.*, 2013). EFs comprise several different cognitive processes responsible for controlling and organizing goal-directed behaviour and enable individuals to mentally play with ideas, take the time to think before acting or stay focused, among others (Diamond, 2013; Zelazo & Carlson, 2012). An interaction between the movement systems and the cognitive system has been demonstrated (Cameron *et al.*, 2016; McClelland & Cameron, 2019). Furthermore, it is known that motor exercise leads to specific adaptation of the prefrontal cortex and the

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cerebellum, brain areas typically associated with cognitive operation (Diamond, 2013).

Sex differences have been reported in both self-perceived and measured GMC. Whereas boys generally display better object control skills than girls, and girls exhibit better balance than boys, evidence on sex differences in motor skills is inconclusive (Barnett *et al*., 2016). Concerning self-perceived motor competence, higher perception in boys has been evidenced (Jacobs, Lanza, Osgood, Eccles & Wigfield, 2002; Noordstar, van der Net, Jak, Helders & Jongmans, 2016). In the same vein, sex differences have also been described in cognitive functioning. For example, girls are less impulsive and make decisions conditioned by avoiding negative outcomes, while boys have faster reaction times and are less sensitive to negative outcomes in decision making (Cornblath *et al*., 2019; Grissom & Reyes, 2019). Regarding school performance, most studies have failed to find evidence of significant sex differences, although some studies show weak dissimilarities in favour of girls (Li, Zhang, Liu & Hao, 2018; Reilly, Neumann & Andrews, 2019; Voyer & Voyer, 2014). Thus, considering the above, the mediating role of EFs between GMC and AA will plausibly be different depending on sex.

Few studies have analysed the potential mediator effect of EFs in the relationship between GMC and AA in children (Cadoret *et al*., 2018; Rigoli *et al*., 2012; Schmidt *et al*., 2017). Only one of these controlled for potential confounding variables (Schmidt *et al*., 2017), and, to the best of our knowledge, no studies have examined these relationships by sex. Hence, a comprehensive view of the mediating role of cognition performance between GMC and AA is still lacking.

Therefore, the objective of the present study was to analyse whether the association between GMC (as a composite of aiming-catching, static balance, and dynamic balance) and AA (measured as language and mathematics grades) is mediated by EFs (cognitive flexibility, working memory and inhibitory control), after controlling for age and maternal education level, and to investigate whether this mediation is different by sex.

METHODS

Participants

This is a cross-sectional analysis of baseline data from a cluster-randomized controlled trial (NCT03236337) aiming to assess the effectiveness of a physical activity intervention (MOVI-daFIT! study) to reduce cardiometabolic risk and to improve cardiorespiratory fitness, executive functioning, and AA in schoolchildren. All the schools in the province of Cuenca (Castilla-La Mancha, Spain) with at least one full class of fourth and fifth graders were invited to participate (n = 19). Of those that accepted (n = 18), 10 were randomly selected. All the fourth and fifth grade children belonging to these schools were invited to participate (n = 923). In the end, 570 schoolchildren participated in this trial, 451 of whom were included in this cross-sectional analysis, as they had complete data in all study variables. Children included in the data analysis for this study did not differ in age, sex, or maternal education level from the entire population of children participating in the trial.

Procedure

The measurement procedures used in this study have been widely described elsewhere (Martínez-Vizcaíno *et al*., 2019). The study variables were measured in the schools during September–October 2017 by experienced researchers under standardized conditions. Data were evaluated in two sessions separated by one week. In the first session, sociodemographic information was collected (age, sex, and maternal education level), anthropometric data were measured (weight and height) and motor competence tests were performed (aiming-catching and balance skills). In the second one, children completed a cognitive evaluation.

Measures

Anthropometric and sociodemographic data. The age, sex and maternal education level were gathered through a questionnaire administered to the parents. Weight and height were measured twice under standardized conditions. The mean of both measurements of weight and height was used to calculate body mass index (kg/m^2) and tri-ponderal mass index (kg/m^3).

Data on maternal education level were gathered from parents using the validated scale proposed by the Spanish Society of Epidemiology (Domingo-Salvany, Regidor, Alonso & Alvarez-Dardet, 2000) to measure the maximum level of education achieved by the mother. This consists of one item with six response options, of which mothers mark only one: i) no literacy skills; ii) no studies; iii) elementary studies; iv) secondary studies; v) high school; and vi) university studies. In our study, these six categories were clustered into three: lower/lower middle (no literacy skills, no studies, and elementary studies), middle (secondary studies) and upper middle/upper (high school and university studies). Maternal education level was used as covariate in the mediation model (as an interval variable), because it has been shown to be a strong predictor of children's AA (Crede, Wirthwein, McElvany & Steinmayr, 2015; González *et al*., 2020).

Gross motor competence. The validated Spanish version of the Movement Assessment Battery for Children-Second Edition (MABC-2) was employed (Henderson, 1992). This battery evaluates motor competence and is useful to detect motor impairment in children aged 3–16 years old. The MABC-2 includes versions appropriate for three age ranges (4–6, 7–10 and 11–16 years). Each version consists of eight motor tasks, classified in three categories: manual dexterity (three items), aiming-catching (two items) and static and dynamic balance (three items). These three motor categories included in MABC-2 were re-categorized into fine motor skills (manual dexterity) and gross motor skills (aiming-catching and balance). Due to the large number of tests included in the randomized controlled trial and the time available, only GMC was evaluated.

The tasks performed were: i) Aiming-catching 1 (*catching*) – throwing a tennis ball at a wall and catching it using both hands after it bounces on the floor (8 years) and using both hands before it reaches the floor (9–10 years); ii) Aiming-catching 2 (*throwing*) – throwing a bean bag onto a mat with a target (8–10 years); iii) Balance 1 (*static*) – one-board balance (8–10 years); iv) Balance 2 (*dynamic*) – walking forward heel-to-toe along a line (8–10 years); v) Balance 3 (*dynamic*) – hopping forward on mats (8–10 years) (Wubbenhorst, 2019). Each test received a raw score (number of catches, number of hits on target, seconds on one leg, number of steps on the line and number of right jumps) where a higher score indicates better GMC.

Executive functions. Three EFs were evaluated by using the NIH Toolbox (NIH Toolbox in Spanish, v. 1.8) (Weintraub *et al*., 2013). All tests were performed individually in a quiet classroom using a tablet (iPad Pro; Apple, Inc., San Francisco, CA, USA). The evaluation tests included in the Toolbox for each cognitive domain are listed as follows:

- *Inhibitory Control* was evaluated using an adaptation (Zelazo, Anderson, Richler, Wallner-Allen & Beaumont, 2013) of the Flanker Task (FT). Participants had to indicate the left–right direction of a centrally showed stimulus while inhibiting their attention to the potentially incongruent stimuli around it. In some trials, the orientation of the flanking stimuli was congruent with the orientation of the central stimulus (> > > > > or < < < < <), while in other trials, this orientation was incongruent

(> > < > > or < < > < <). The NIH Toolbox contained a practice block of trials. If participants passed it, a 20-trial block was presented. These trials consisted of a succession of congruent and incongruent combination of arrows. Using a two-vector method that included both reaction time and accuracy, a final score was calculated for schoolchildren who reached a high level of accuracy (>80%), which was as follows: (0.25 × number of correct responses) + 5 – log10 [(congruent reaction time + incongruent reaction time/2)] (Zelazo *et al.*, 2013). A total score considering accuracy was determined for children who scored less than 80% (Table 1).

- *Cognitive flexibility* was evaluated with the Dimensional Change Card Sort test (DCCS) (Zelazo *et al.*, 2013). Participants were shown two target cards and asked to order a group of bivalent test cards, first according to one dimension and then according to the other dimension. After a four-trial practice, children were given a 30-trial block with both "shape" and "color" requirements. Using reaction time and accuracy percentage on preswitch and postswitch, a raw score was determined (Zelazo *et al.*, 2013). Using a two-vector method that integrated both accuracy and reaction time, a final score was calculated for children who reached a high level of accuracy (>80%) as follows: (0.167 × number of correct responses) + 5 – log10 [(congruent reaction time + incongruent reaction time/2)] (Zelazo *et al.*, 2013). For participants scoring <80%, a total outcome considering accuracy was determined (Table 1).
- *Working memory* was evaluated using the List Sorting Working Memory test (LSWM) (Tulsky, Carlozzi, Chevalier, Espy, Beaumont & Mungas, 2013). Children were given a group of pictures, and items were presented both auditorily and visually. Then, they were required to repeat the names of the items observed in order of size, from smallest to biggest. The number of items showed in each trial increased by one each series. This test was made up of two parts. In the first one, all the items belonged to the same category (animals or food items). In the second one, the items from both categories (food items and animals) were presented together, and children had to repeat the items by category and size. The List Sorting "Total Score" was composed of final scores based upon a sum of the total correct trials across the two lists (Tulsky *et al.*, 2013).

Academic achievement. Final grades in language and mathematics provided by the school's administration were used to determine AA. The children's final grades (range from 1 to 10 score, with 10 being the best grade) from the previous academic year were used (2016/17 season, third and fourth grades). In Spain, final grades represent the student's work across a complete academic year.

Data analysis

Quantitative variables (sample characteristics, GMC, EFs and AA) are expressed as means and standard deviations. Qualitative variables (maternal educational level) are expressed as counts and frequencies. The Kolmogorov–Smirnov test was used to evaluate the goodness of fit of quantitative variables to a normal distribution. All variables fitted to a normal distribution.

Intra-cluster correlation coefficients (ICC) were calculated as the ratio random effect proportion of the sum of the variances between-cluster component of the variance and the within-cluster component of the

Table 1. *Characteristics of the study sample, by sex*

	Total (n = 451)	Range Min–Max	Boys (n = 217)	Girls (n = 234)	p	ICC
Sample characteristics						
Age (years)	9.48 (0.63)	8.74–10.99	9.43 (0.66)	9.52 (0.59)	0.158	0.06
Weight (kg)	35.93 (9.07)	21.30–68.90	36.14 (9.06)	35.74 (9.10)	0.638	0.00
Height (cm)	140.46 (6.98)	122.5–159.5	140.77 (6.85)	140.18 (7.10)	0.371	0.01
Body mass index (kg/m^2)	18.05 (3.59)	11.40–34.28	18.09 (3.66)	18.02 (3.54)	0.829	0.00
Tri-ponderal mass index (kg/m^3)	12.84 (2.42)	8.34–26.50	12.85 (2.51)	12.84 (2.35)	0.987	0.01
Maternal education level [n (%)]						
Lower/lower middle	45 (9.98%)		23 (10.60%)	22 (9.40%)	0.672	
Middle	201 (44.57%)		95 (43.78%)	106 (45.30%)	0.746	
Upper middle/upper	205 (45.45%)		99 (45.62%)	106 (45.30%)	0.945	
Gross motor competence*						
Aiming and catching						
Catching (n)	7.47 (2.60)	0–10	8.33 (2.31)	6.67 (2.60)	**<0.001**	0.08
Throwing (n)	6.99 (1.97)	0–10	7.33 (1.87)	6.67 (2.00)	**<0.001**	0.12
Balance skills						
Static balance (s)	18.77 (9.00)	1–30	16.80 (8.86)	20.59 (8.77)	**<0.001**	0.04
Walking along a line (st)	13.81 (3.23)	0–15	13.17 (3.91)	14.41 (2.30)	**<0.001**	0.08
Jumping (j)	4.79 (0.48)	2.5–5	4.74 (0.51)	4.82 (0.45)	0.076	0.01
Executive functions						
Inhibitory control (FT)[¥]	19.62 (1.44)	7–20	19.56 (1.48)	19.68 (1.41)	0.407	0.03
Cognitive flexibility (DCCS)[§]	28.24 (2.96)	7–39	27.96 (2.94)	28.49 (2.97)	0.059	0.02
Working memory (LSWM)	14.43 (3.07)	1–23	14.69 (3.03)	14.18 (3.09)	0.079	0.04
Academic achievement (grades)						
Language	7.42 (1.66)	2–10	7.27 (1.72)	7.56 (1.60)	0.066	0.05
Mathematics	7.14 (1.80)	1–10	7.22 (1.77)	7.06 (1.84)	0.343	0.03

Notes: Values are mean ± standard deviation, except for maternal education level which are shown as percentages [n (%)]. DCCS = dimensional change card sort test; FT = flanker task; LSWM = list shorting working memory test; ICC = intra-cluster correlation coefficient.
In bold, statistical signification (p < 0.05).
*Raw test scores: n = number; s = seconds (more time indicates better score); st = steps; j = jumps.
[¥]Total score was calculated using a two-vector method that incorporates both accuracy and reaction time. Total score = (0.25 × number correct responses) + 5 – log10 [(congruent reaction time + incongruent reaction time/2)].
[§]Total score was calculated using a two-vector method that incorporates both accuracy and reaction time. Total score = (0.167 × number correct responses) + 5 – log10 [(congruent reaction time + incongruent reaction time/2)].

variance for each variable considering each school as a cluster (Donner & Klar, 2000).

The analysis of the relationships among variables was conducted in three steps. First, Pearson's correlation coefficients between all measured variables were calculated. Values below 0.1 were defined as *trivial*, *weak* in the range 0.1–0.29, *moderate* in the interval 0.3–0.49, and *large* when greater than 0.5 (Cohen, 1988). Second, a confirmatory factor analysis was performed to test whether the latent variables (GMC, EFs, and AA) were adequately described by the observed measurements for the total sample and by sex. Finally, a multifactorial structural equation model (SEM) was designed to evaluate the possible relationships between variables, with a direct path from GMC to AA and a direct path from GMC to EFs and from EFs to AA (Fig. 1). In this model, it was considered that GMC can indirectly affect AA via EFs. Furthermore, direct paths were drawn from maternal education level and age to all latent variables. To test the hypothesized mediating role of EFs, bias corrected bootstrap analyses [95% confidence interval] (Bollen & Stine, 1992) was performed, to reveal the indirect effects as significantly different from zero (Shrout & Bolger, 2002). Sex differences in the mediation model fitting were examined using a multi-group SEM approach.

To evaluate the fit of the model data, standardized indices were calculated and compared with the standardized fit criteria (Schermelleh-Engel, Moosbrugger & Müller, 2003): statistical χ^2, degrees of freedom (df), comparative fit index (CFI, with values equal to or better than 0.95), root mean square error of approximation (RMSEA, which should be 0.08 or less) and standardized root mean square residual (SRMR, $\leq$0.10). All trajectory coefficients (with an asterisk when significant) are presented as standardized estimates. The coefficient of determination (R^2) is shown for dependent latent variables (EFs and AA), which indicates the proportion of the variance in the dependent variables that is predictable from the independent variable.

In all cases, $p < 0.05$ was considered for significant differences (95% confidence interval). All calculations were performed using SPSS and AMOS v. 24 (SPSS, Inc., Chicago, IL, USA).

RESULTS

Descriptive statistics and correlations

The characteristics of the study sample by sex are presented in Table 1. Of the 451 schoolchildren involved in the study, 234 were girls (51.88%), and the mean age was 9.95 years (SD = ±0.59). Boys scored significantly higher on catching and throwing ($p < 0.001$) and girls on static and dynamic balance ($p < 0.001$). All ICC's were close to zero; thus, the within-cluster variance (school) was negligible in relation to total sample (Smeeth & Ng, 2002).

The bivariate correlation coefficients are presented in Table 2. The correlation coefficients between GMC and AA variables ranged from 0.107 to 0.212, with all of them being statistically significant ($p < 0.05$), except for aiming-catching and dynamic balance for boys. Aiming-catching was correlated with inhibitory control ($r = 0.093$; $p < 0.05$), while static balance was weakly correlated with inhibitory control (for total sample and girls; $p < 0.01$), cognitive flexibility (for total sample and boys; $p < 0.05$) and working memory (for boys; $p < 0.05$). In addition, weak to moderate correlations were found between AA and all EFs for the total sample and for both sexes (r values between 0.150–0.354; $p < 0.01$).

Confirmatory factor analysis

The model with all three latent variables by covariance provided a good fit to the data (Schermelleh-Engel *et al.*, 2003) for the total sample [χ^2 = 15.949; p (df) = 0.527 (17); χ^2/df = 0.938; CFI = 0.999; RMSEA = 0.001; SRMR = 0.023], as well as for boys [χ^2 = 19.788; p (df) = 0.285 (17); χ^2/df = 1.164; CFI = 0.993; RMSEA = 0.028; SRMR = 0.039] and girls [χ^2 = 16.177; p (df) = 0.511 (17); χ^2/df = 0.952; CFI = 0.999; RMSEA = 0.001; SRMR = 0.039], where multi-group analysis showed that the mediation model fitting was similar in both boys and girls [χ^2 differences = 17.458; p (df) = 0.233 (14)]. All measured variables loaded significantly ($p \leq 0.011$) on the respective latent variable, and the model explained small to large amounts of the item variance (R^2 ranged from 0.09 to 0.92).

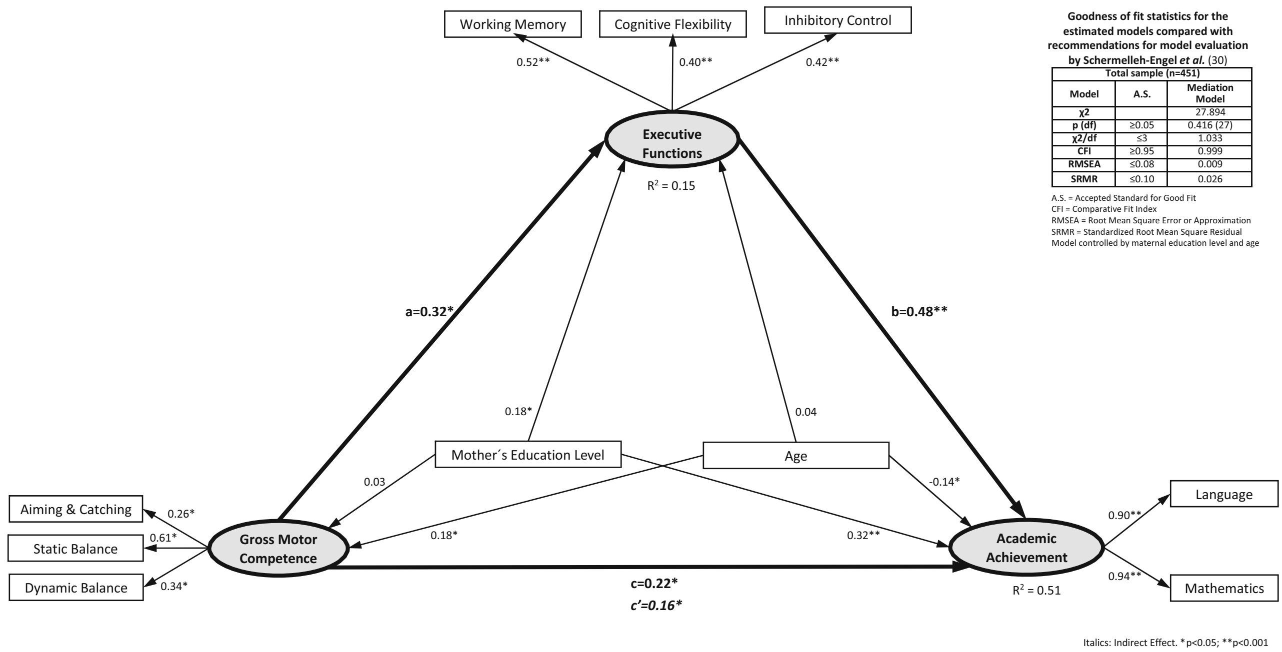

Fig. 1. Mediation model, with gross motor competence as the predictor, executive functions as mediator, and academic achievement as outcome variable (total sample). All the significance levels are included in each figure (lower right corner).

Table 2. *Bivariate correlation coefficients among gross motor competence, executive functions and academic achievement, by sex*

		Aiming and catching	Static balance	Dynamic balance	Inhibitory control	Cognitive flexibility	Working memory	Language
Static balance	Total	0.143**						
	Boys	0.176**						
	Girls	0.279**						
Dynamic balance	Total	0.110*	0.213**					
	Boys	0.228**	0.176**					
	Girls	0.146*	0.198**					
Inhibitory control	Total	0.093*	0.135**	0.076				
	Boys	0.132	0.087	0.071				
	Girls	0.092	0.172**	0.074				
Cognitive flexibility	Total	0.017	0.100*	0.040	0.161**			
	Boys	0.075	0.148*	0.027	0.314**			
	Girls	0.025	0.023	0.018	0.009			
Working memory	Total	0.084	0.057	0.004	0.208**	0.223**		
	Boys	0.072	0.152*	0.051	0.216**	0.255**		
	Girls	0.049	0.007	−0.022	0.209**	0.212**		
Language	Total	0.107*	0.212**	0.110*	0.245**	0.223**	0.279**	
	Boys	0.064	0.236**	0.058	0.277**	0.191**	0.223**	
	Girls	0.223**	0.161*	0.163*	0.206**	0.242**	0.354**	
Mathematics	Total	0.163**	0.184**	0.112*	0.245**	0.200**	0.296**	0.853**
	Boys	0.064	0.249**	0.101	0.286**	0.150**	0.274**	0.879**
	Girls	0.239**	0.152*	0.169**	0.211**	0.253**	0.310**	0.846**

*$p < 0.05$.
**$p < 0.001$.

Mediation model and sex analysis

The mediation model is shown in Fig. 1. Age was positively correlated with GMC ($\beta = 0.18$, $p < 0.05$) and negatively with AA ($\beta = -0.14$, $p < 0.05$), while maternal education level positively correlated with EFs ($\beta = 0.18$, $p < 0.05$) and AA ($\beta = 0.32$, $p < 0.001$). The paths from GMC to EFs (a; $\beta = 0.32$, $p = 0.020$, $R^2 = 0.15$) and from EFs to AA (b; $\beta = 0.48$, $p < 0.001$, $R^2 = 0.51$) were significant and the model provided a good fit to the data. The direct path from GMC to AA was significant (c; $\beta = 0.22$, $p = 0.022$). This path coefficient decreased, although maintaining its significance, when EFs were included as a mediator (c′; $\beta = 0.16$, $p = 0.009$) for the total sample. Among the variables included in EFs, working memory was the most important predictor ($\beta = 0.52$, $p < 0.001$), followed by inhibitory control ($\beta = 0.42$, $p < 0.001$).

In the analysis by sex, it was found that EFs totally mediated the association between GMC and AA (c′; $\beta = 0.14$, $p = 0.012$) in boys (Fig. 2), but in girls (Fig. 3), EFs did not mediate this association (c′; $\beta = 0.10$, $p = 0.326$).

DISCUSSION

Studies examining the potential mediator effect of EFs in the relationship between GMC and AA in children are scarce. Most do not control for confounders or effect modification, and none of them have examined this relationship by sex. Our results revealed that the model simultaneously fitted for both sexes, although the mediating role of EFs between GMC and AA is different for boys and girls. Thus, the relationship between GMC and AA is mediated by EFs in boys, but not in girls. However, the cross-sectional nature of this research precludes from draw solid conclusions and temporal inferences.

The positive association between GMC and AA reported in this study is in line with previous reports in children and adolescents (Cadoret *et al.*, 2018; Geertsen *et al.*, 2016; Jenni, Chaouch, Caflisch & Rousson, 2013; Kovač & Strel, 2000; Planinsec, 2002; Rigoli *et al.*, 2012; Roebers & Kauer, 2009; Schmidt *et al.*, 2017). Although this relationship was not strong, it suggests that proficiency in GMC relates to better academic performance in mathematics and language. Nevertheless, this direct association was found only in girls. In the literature, this association by sex is unclear; Aadland, Moe, Aadland, Anderssen, Resaland and Ommundsen (2017) found that gross motor skills are related to academic performance only in girls, as well as Sigmundsson, Englund and Haga (2017), who found a positive association between motor competence and reading in girls (9 and 12 years), but a negative one in boys (9 and 12 years). By contrast, Jaakkola, Hillman, Kalaja and Liukkonen (2015) reported very weak to weak correlations between grades in Finnish language and total scores in fundamental movement skills for boys in grades 7–9, but found non-significant associations for girls.

Regarding the mediating role of the EFs in the relationship between GMC and AA, our results support those of previous studies (Cadoret *et al.*, 2018; Rigoli *et al.*, 2012; Schmidt *et al.*, 2017), for the total sample, confirming that the positive relationship between GMC and AA was partially explained by EFs, even after controlling for confounders. However, for a meaningful comparison, some differences, as well as similarities, with those studies must be underlined. Rigoli *et al.* (2012) do not use the EF construct, but just one of its domains (working memory). Regarding the components of GMC, there is evidence that AA in mathematics and reading is positively and significantly associated with aiming-catching, but not with balance (Rigoli

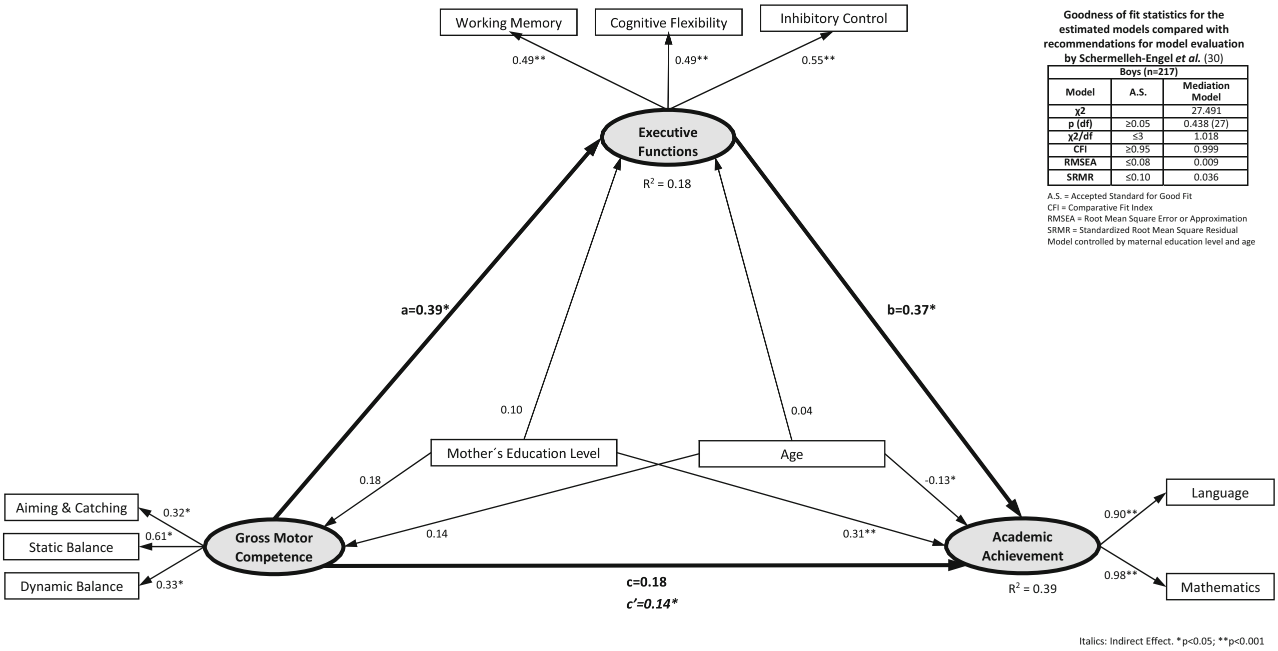

Fig. 2. Mediation model, with gross motor competence as the predictor, executive functions as mediator, and academic achievement as outcome variable (boys). All the significance levels are included in each figure (lower right corner).

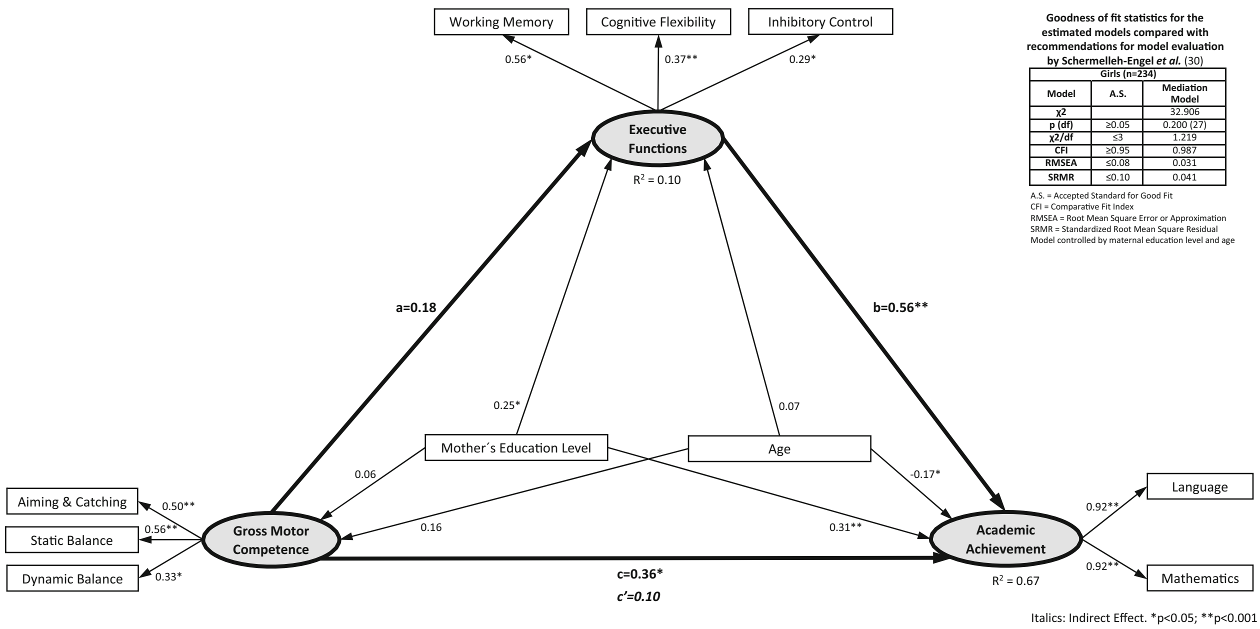

Fig. 3. Mediation model, with gross motor competence as the predictor, executive functions as mediator, and academic achievement as outcome variable (girls). All the significance levels are included in each figure (lower right corner).

et al., 2012), which does not coincide with our results, where AA significantly and positively associates with both aiming-catching and balance, for the total sample. The results reported by Schmidt *et al.* (2017) are similar to ours, but, in their case, coordination is determined exclusively by the sideways jumping test (a subtest of the *Körperkoordinationtest für Kinder*), instead of using a full motor competence construct. It is worth noting that none of studies mentioned above found evidence of a significant direct association between motor competence and AA, which could explain the total mediation of EFs in this relationship, whereas our study reveals a significant direct association.

The interaction between brain motor areas (motor cortex) and other structures of the central nervous system (Piek *et al.*, 2006) could explain the mechanisms underlying the positive relationship between motor skills and AA. Specifically, the activation of the lateral zone of the cerebellum, in charge of the muscular contractions required in rapid skill movements, and the prefrontal cortex, linked to EFs, has been related to the association between complex motor and cognitive processes (Ansari & Dhital, 2006; Diamond, 2000). Executive functions have been connected to both mathematics and language AA (Ansari & Dhital, 2006).

In addition, our findings suggest that the partial mediation of EFs could be explained by sex asymmetries, given that evidence of full mediation of EFs was found in boys, but the opposite result was found in girls, where the association between GMC and AA was totally explained by the direct path GMC-AA. In pursuit of possible explanations to account for the sex differences found in this work, the literature shows there are potential biological mechanisms that contribute to sex differences. Thus, sex differences in key neurotransmitter systems, specifically within brain regions that are essential to EFs (prefrontal cortex, striatum), have been reported. The sex differences in action planning suggest that different circuit and molecular mechanisms are used by males and females to solve the same cognitive problems. Consequently, even though the overall ability may be the same, the strategies utilized are unlikely to be supported by identical neurobiological mechanisms (Grissom & Reyes, 2019).

These findings suggest that it would be useful to develop motor activities and games requiring cognitive processes. This is especially important in boys, given that the association between GMC and AA could be best understood through an indirect impact via EFs. By contrast, only a direct association was found between GMC and AA in girls, suggesting that presumably, in girls, this association might be explained by other cognitive processes or other psychological, physical, and genetic factors not measured in this study. Despite this, the cross-sectional design used in this study precludes causality inferences, and there is need for intervention studies examining the mediating role of EF on effects of school-based GMC interventions on academic performance. Therefore, more research is needed to confirm these findings.

Limitations

The current study has some limitations to be described, as follows: i) The study used a cross-sectional design; thus, our findings should be interpreted with caution since temporal ambiguity is a limitation of this design. Nevertheless, the temporality proposed in our model is consistently backed considering the current knowledge about the relationships between GMC, EFs and AA (Piek *et al*., 2008). ii) Our sample included only Spanish children from fourth and fifth grades, so caution is necessary when extrapolating these results to another population or age range. iii) Even though the analyses in this study controlled for some potential confounders, neither visual acuity nor adiposity was controlled for, both of which are known to be health conditions affecting the ability to perform motor skill tests (Bakke & Cavalcante, 2019; Cheng *et al*., 2016; Houwen, Visscher, Hartman & Lemmink, 2007).

Despite these limitations, our study had several strengths, such as the relatively large sample size and the validated measurement tests used to assess both GMC and EFs. Furthermore, the mediating role of EFs in the relationship between GMC and AA by sex has been examined for the first time.

Conclusions

Our results reveal that the relationship between GMC and AA is mediated by EFs in boys but not in girls. Moreover, they suggest that training gross motor tasks involving cognitive processes could improve AA, particularly in boys. Thus, to promote physical activities, especially gross motor skills involving EFs in boys, should be a priority for educational policies in early ages. Nevertheless, these conclusions should be carefully considered due to the cross-sectional nature of the study, which prevents from inferring causality and directionality.

Two implications for school health can be drawn from the present article. i) The present study supports that motor tasks have an influence in AA across EFs, especially in boys. Since motor skills are known to be a determinant factor of physical activity and fitness, the promotion of physical activity and games that involve both motor competence and cognitive demand should be a priority for teachers in order to improve children's physical and mental health. ii) Using a wide range of motor-cognitive strategies could provide opportunities for boys and girls to improve their motor competence, EFs and therefore AA. As motor strategy is not supported by the same neurobiological mechanisms by sex, different mental processes will be used for boys and girls to solve the same cognitive tasks.

All procedures performed in this study followed the Declaration of Helsinki and its ethical standards for experiments involving humans. The study was approved by the management team of each school and by the Clinical Research Ethics Committee of Virgen de la Luz Hospital in Cuenca, Spain. (REG: 2016/PI021). After obtaining these approvals, we set up a meeting with all the children's parents in order to explain the goals of the study, where they also signed an informed consent form prior to participating in the study. Before data collection, all the children were asked whether they wished to participate and were informed they could drop out at any time during the study. All data were treated confidentially.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author, MSL. The data are not publicly available due to containing information that could compromise the privacy of research participants.

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