

The mediation role of executive functions as predictors between physical activity and academic performance in high school students

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ABSTRACT

Several studies have highlighted the intricate interplay between physical activity, executive functions, and academic performance. However, the nuanced relationships among these variables necessitate further investigation into the roles of physical activity and executive functions as predictors or mediators of academic success. A study was conducted with a convenience sample comprising 172 Spanish high school students. This study assessed physical activity levels, executive functions (specifically focusing on cognitive components such as attention and inhibition, as well as the affective component of emotional regulation), and academic performance. The findings revealed several key insights: firstly, both physical activity and cognitive executive functions (specifically attention and inhibition) emerged as significant predictors of academic performance. However, emotional regulation did not show a significant predictive relationship. Secondly, cognitive executive functions (attention and inhibition) were found to partially mediate the association between physical activity and academic performance. These results suggest that interventions targeting improvements in both physical activity levels and cognitive executive functions, particularly attention and inhibition, may yield positive outcomes in terms of academic performance among students in compulsory secondary education.

1. Introduction

Academic performance (AP) has been defined as a means of estimating, through grades, the level of skills achieved by an individual at the end of an educational process (García-Gil et al., 2022). The AP attained by students in Spain is of concern for policymakers, since, according to the most recent Programme for International Student Assessment (PISA) reports (OECD, 2023), it is progressively declining. This may have implications for the future of citizens and the country's progress. Clearly, AP is also a source of concern for teachers, families, and students (Escarbajal Frutos et al., 2019). In order to improve students' AP, first it is necessary to determine the factors influencing it and then intervene accordingly. Therefore, this study addressed the variables of physical activity and executive functions (specifically, attention, inhibition, and emotional regulation), given their potential relationship with AP. It is worth noting that there are many other lines of research that address the relationships between AP in schoolchildren. Some of the

variables that have been explored in recent years include demographic factors, socioeconomic status, psychological well-being, social networks, emotional attachment, fear, and social trust (Ding et al., 2024; Pang and Huang, 2024; Pang and Zhang, 2024; Pang and Yanyinxue, 2023; Sun et al., 2024). Given the large number of variables and the limitations this presents for a single study, some have been considered that may have mediational relationships between them and can be directly addressed in students.

2. State of the art

In this section, the three main variables of the study (PA, EF, RA) will be defined, and their relationships will be systematically analysed, presenting each variable and its direct relationship with the other variables. After that, the mediational relationships between the three variables will be examined.

Firstly, physical activity (PA) has been defined as a bodily movement

Abbreviations: AP, Academic Performance; EF, Executive Functions; PA, Physical Activity; PAQ-A, Physical Activity Questionnaire for Adolescents; SENA, Sistema de Evaluación de Niños y Adolescentes (Child and Adolescent Evaluation System).

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produced by skeletal muscles that requires energy expenditure (World Health Organization, 2020). Numerous studies have found a positive relationship between PA and AP (De Greeff et al., 2018; Gallardo et al., 2023; Ogrodnik et al., 2020; Wang & Guo, 2022). For example, Yang et al. (2023) found improvements in AP using a daily, 60-minute physical exercise intervention with adolescent students. Research examining systematic reviews and meta-analyses on the relevance of PA on AP affirmed that interventions aimed at improving AP through PA are effective (Barbosa et al., 2020). Moreover, Gallardo et al. (2023) found that adolescents with higher levels of PA in their daily lives had significantly higher AP than those with lower PA levels.

Regarding the second variable of interest, whose relationships with AP are addressed in this study, executive functions (EF) may be defined as higher-level cognitive (attention, inhibition, etc.) and affective (emotional regulation) processes enabling the coordination of actions, thoughts, and emotions, which empower individuals to resolve new or complex situations arising in their daily lives (Diamond, 2020). While no total consensus exists in the literature with regard to the specific processes making up EF, this study, following the proposal of Anderson (2002), addresses the following: attention, inhibition, and emotional regulation. Generally speaking, attention is the allocation of information processing to a stimulus (Zelazo et al., 2012). It involves the ability to stay focused on relevant stimuli for an extended period (Diamond et al., 2019). Inhibition involves controlling behaviors, as well as suppressing automatic thoughts and impulsive responses to choose the most appropriate ones (Diamond, 2013; Friedman & Miyake, 2004). Emotional regulation is a series of extrinsic and intrinsic processes that monitor, evaluate, and modify the occurrence, intensity, and duration of our emotional reactions (Thompson, 1994).

Recent research has found a positive relationship between EF and AP. For example, Zorza et al. (2017) found that EF independently predicted AP in a sample of 244 adolescents. Escolano-Pérez & Bestué, 2021 also found a predictive effect of EF on AP in a sample of adolescents, considering them both collectively and individually with regard to their components. Likewise, Samuels et al. (2023) found that EF, whether assessed by teachers or self-reported by adolescent students, independently contributed to the AP of students with and without disabilities. In line with these results, Gamino et al. (2022) found that students receiving an intervention that improved their EF achieved higher AP in mathematics, language, and social sciences than those who did not receive the intervention and therefore maintained lower levels of EF. All of this suggests that, in adolescents, EF may have a direct positive relationship with AP.

Based on the above, it may be concluded that numerous studies have highlighted the direct relationship between the variables of interest in this study (PA and EF) and AP (Arabi et al., 2023; Christiansen et al., 2019; Gamino et al., 2022; Park et al., 2023; Van Dijk et al., 2014; Visier Alfonso et al., 2022; Zorza et al., 2017). However, the relationships existing between all of these variables appear to be complex, with some studies suggesting a positive relationship between PA and EF (Gil-Madrona et al., 2019; Haverkamp et al., 2020; Mezcua-Hidalgo et al., 2019). This suggests that EF, in addition to having a direct effect on AP, may also play a mediating role in the relationships between PA and AP. Supporting the positive relationship between PA and EF, some studies have shown improvements in EF through interventions increasing PA in children and youth (Arabi et al., 2023; Christiansen et al., 2019; Dong et al., 2022).

As mentioned earlier, understanding that PA is a potential predictor of AP and EF, and that EF are predictors of AP (Gamino et al., 2022; Zorza et al., 2017), makes it necessary to analyze the relationship between PA and AP with the mediating effect of EF. Very few studies have addressed this issue, and they tend to focus on the age range corresponding to primary education (6–12 years old) (Aadland et al., 2017; Becker et al., 2014; Gandotra et al., 2022). To the best of our knowledge, only two studies have examined this issue in students in compulsory secondary education (12–16 years old). One of these studies (Park et al.,

2023) has revealed the mediating effect of the executive function of inhibition on the PA-AP relationship. The other (Van Dijk et al., 2014) has shown that, in addition to a predictive effect of both PA and EF on AP, EF (specifically, attention and inhibition) also has a mediating effect on the PA-AP relationship. Thus, these findings regarding the mediating effect of inhibition on the PA-AP relationship are consistent with the results of Park et al. (2023). Although these studies point in the same direction, the scarcity of research addressing this issue, especially in adolescent students, demands further works to determine the effect of these variables (PA and EF) on AP. Furthermore, it should be noted that neither of the two mentioned studies (Park et al., 2023; Van Dijk et al., 2014) considered the affective components of EF, which constitutes a partial view of EF. This further underscores the need for studies on the relationships between these variables, adopting a current theoretical perspective that includes affective components as part of EF. Improved understanding of how the AP of adolescent students is affected by this set of variables may permit the design of more effective educational interventions.

3. The current study

Therefore, the objectives of this study were: (1) To analyze the contribution of PA level and each of the three previously mentioned EF components (attention, inhibition, and emotional regulation) to the AP of a sample of Spanish compulsory secondary education students; (2) To determine the mediating effect of the level of each of these EF components (attention, inhibition, and emotional regulation) on the predictive ability of PA in the AP of these students.

The following hypotheses were proposed: (1) The level of PA and each of the EF components studied (attention, inhibition, and emotional regulation) will be predictors of AP; (2) There will be a mediating effect of each EF component (attention, inhibition, and emotional regulation) on the predictive relationship between PA and AP.

4. Methods

4.1. Design

A non-experimental study was carried out. It followed a retrospective, single-group, cross-sectional ex post facto design with an explanatory scope since all of the variables were measured at a single point in time, once the phenomenon had already occurred. The objective was to develop a model on the relationships existing between a set of variables (Quintanilla Cobián et al., 2020), specifically: PA, EF (attention, inhibition, and emotional regulation), and AP.

4.2. Participants

The sample consisted of 172 Spanish compulsory secondary education students, in all four grade levels of this educational stage in Spain, corresponding to ages between 13 and 16 years. Student distribution by gender and grade is detailed in Table 1. Regarding the International Standard Classification of Education (ISCED), the four years of compulsory secondary education (ESO) in Spain, from 1st to 4th year, are classified under ISCED level 2, representing lower secondary

Table 1
Sample distribution by gender and grade: frequency (n) and percentage (%).

—	Age	Gender		Female		Total	
		Male					
		n	%	n	%	n	%
	13	26	15.1	22	12.8	48	27.9
	14	24	14	19	11	43	25
	15	22	12.8	14	8.1	36	20.9
	16	23	13.3	22	12.8	45	26.2
Total		95	55.2	77	44.8	172	100

education as per the international standards of the ISCED framework. To facilitate the reader's understanding, the corresponding age for the academic suitability rate of each school year will be used. The sample subgroups by gender were similar sizes (girls: $n = 77$ (44.8 %); boys: $n = 95$ (55.2 %); $z = 1.83$, $p = 0.06$), and there were no significant differences with respect to school grade level [Class 1: $n = 48$ (27.9 %), Class 2: $n = 43$ (25 %), Class 3: $n = 36$ (20.9 %), Class 4: $n = 45$ (26.2 %); $\chi^2(3) = 0.90$, $p = 0.82$]. The gender distribution in each school grade was balanced, with no statistically significant differences: Class 1 (45.8 % girls; $z = 0.19$, $p = 0.85$), Class 2 (44.2 % girls; $z = -0.49$, $p = 0.62$), Class 3 (38.8 % girls; $z = -1.56$, $p = 0.07$), and Class 4 (52.1 % girls; $z = -1.35$, $p = 0.18$).

Participants attended a privately funded educational institution in a city in the northeast of Spain. Convenience sampling was used. Inclusion criteria for the study were: (a) being enrolled in one of the four grades of compulsory secondary education in Spain; (b) having an adequate level of spoken and written Spanish; and (c) providing signed informed consent from parents/legal guardians. The sole exclusion criterion was being a student having special educational needs. This implies having a disability, a developmental language and communication disorder, attention or learning disorder, high intellectual abilities, lack of proficiency in the language, or personal conditions that prevent regular attendance at the educational institution (Official Gazette of Aragón, 2017).

The study was conducted in compliance with the 1975 Declaration of Helsinki — revised in 2013 — and Organic Law 3/2018, of 5 December, on the Protection of Personal Data and Guarantee of Digital Rights. This research was approved by the Research Ethics Committee of the Autonomous Community of Aragón (PI24/055).

4.3. Instruments

To assess PA level, the validated Spanish version of the Physical Activity Questionnaire for Adolescents (PAQ-A) was used (Martínez-Gómez et al., 2009). This questionnaire consists of 10 items evaluating various aspects of the participant's PA over the past seven days (e.g., item 4: "Over the past 7 days, immediately after school until 6 pm, how many days did you play a game, engage in sports, or dance in which you were very active?"). Each item is to be answered on a five-point Likert scale, with 1 = None (or depending on the item, none of the days of the week) and 5 = 6 or more times (or depending on the item, every day of the week). The final score is obtained by calculating the mean of the scores obtained on the first nine items. The last item is not scored since it gathers information regarding whether the student has experienced any illness or disabling situation (in terms of PA) during the past week. The internal consistency of the instrument was $\alpha = 0.775$, considered to be adequate (Cronbach, 2004), and similar to that obtained by the original authors of the Spanish version (Martínez-Gómez et al., 2009).

To assess the level of EF, the SENA (Sistema de Evaluación de Niños y Adolescentes – Child and Adolescent Evaluation System-) questionnaire was used (Fernández-Pinto et al., 2015). More precisely, the version for adolescents to be answered by the tutor or another teacher or professional who knew the students well was used. Specifically, the scales of Attention Problems, Hyperactivity/Impulsivity, and Emotional Regulation Problems were used. The first scale consists of ten items and evaluates symptoms related to distractibility and inattention, with a focus on deficits in attentional control. This allows for the identification of difficulties in directing and sustaining attention on tasks (e.g. item 4: "I get distracted and make mistakes without realising it"). Its internal consistency was $\alpha = 0.888$. Another scale, with ten items, measures hyperactive and impulsive behaviors, characterized by excessive and contextually inappropriate motor activity, assessing deficits in inhibitory control (e.g. item 3: "I find it difficult to wait for my turn"). This scale showed internal consistency of $\alpha = 0.867$. The Emotional Regulation Problems scale, with an internal consistency of $\alpha = 0.879$, includes seven items that assess challenges in understanding, managing,

and expressing emotions (e.g., item 2: "Some things bother me and I don't know why"). For all three scales, higher scores indicate greater difficulties in the respective executive functions. Responses to each item are scored on a five-point Likert scale, from "never" to "always." It is noteworthy that this questionnaire assesses deficits in EF, such that higher scores indicate a lower level of EF. This questionnaire has shown good reliability, having a Cronbach's alpha coefficient of 0.88 in the original validation sample. In this study, a value of 0.82 was found.

A brief ad hoc questionnaire was completed by the students to indicate their grade (first, second, third, or fourth year of compulsory secondary education) and gender (male, female, or other).

To determine the participants' AP, their last term grades were considered for the mandatory curricular subjects of all four years of compulsory secondary education: Language, Mathematics, Geography and History, Physical Education, and Foreign Language (English). The grades were measured last in order to construct a predictive model using the variables measured initially. Moreover, it is important to highlight that the final term's grade encompasses all preceding ones, as it forms part of a continuous assessment process. Following the educational assessment regulations in Spain, each grade ranged from 0 to 10, with 0 being the lowest and 10 the highest. A grade of ≥ 5 indicated passing the subject.

4.4. Procedure

The research team held informative meetings with the school's management team. Subsequently, an informative letter and the informed consent form requesting the legal guardian's signature to authorize the minor's participation were distributed to all compulsory secondary education students (inclusion criterion "a").

Once the signed consents were received (inclusion criterion "c"), another meeting was held with the management team, where they reported on the fulfillment of inclusion criterion "b" (adequate level of spoken and written Spanish) and the non-fulfillment of the exclusion criterion in potential participants (i.e., not having special educational needs). This determined the study sample.

The researchers visited the educational institution on the agreed days and times to administer the questionnaires. For each grade and class, a single session was conducted with a member of the research team and the class tutor present. The order of questionnaire administration was as follows: ad-hoc questionnaire to determine gender and grade, followed by the PAQ-A, with no break between completion of the same. Approximately 15 min were given to complete these questionnaires. In addition, the school counselor completed the SENA scales (Attention Problems, Hyperactivity/Impulsivity, and Emotional Regulation Problems) for each participant, spending approximately 20 min per student. Fifteen days were provided to complete all of the scales for all students. After that, to determine the students' AP, the school's management team was asked to provide the grades received by participants on the last assessed term for the subjects that are mandatory in all four years of compulsory secondary education: Language, Mathematics, Geography and History, Physical Education, and English. AP was calculated (the arithmetic mean of the subjects) based on these grades.

4.5. Data analysis

To address the first objective focused on the contribution of PA level and each of the EF studied (attention, inhibition, and emotional regulation) on AP, these variables were introduced into a Multiple Linear Regression model (Holmes & Rinaman, 2014). Thus, the dependent or criterion variable was AP, and the independent or predictor variables were the levels of PA and EF (attention, inhibition, and emotional regulation). The stepwise process was utilized, establishing the critical probability value for the variable to enter the model at 0.05 (Muñoz Cantero et al., 2018). Prior to this process, the assumptions of Multiple Linear Regression analysis were checked: Linearity, Independence of

errors, Homoscedasticity, Normality, and No Collinearity (Vilà et al., 2019). All analyses were performed using SPSS v.26 statistical software.

As for the second objective, focused on analyzing the mediating effect of each EF on the PA-AP relationship, it was initially planned to test three different mediation models (according to hypothesis 1, positing that all three EFs –attention, inhibition, and emotional regulation– would predict AP). In these models, PA level was planned to be assumed as the predictor variable (X), AP as the criterion variable (Y), and each different EF as the mediator variable (M) in each model: attention, inhibition, and emotional regulation. Ultimately, however, given the results obtained in the previously calculated Multiple Linear Regression model, only two models were tested: one related to attention and one related to inhibition. The hypothesis of mediation was tested using the bootstrap method with a bias correction of 5,000 samples to calculate a 95 % confidence interval. For analysis, the PROCESS command (Hayes, 2013) in the SPSS v.26 statistical software was used.

5. Results

5.1. Objective 1: multiple linear regression

All assumptions of the Multiple Linear Regression analysis were met. Regarding the regression results, as seen in Table 2, Model 1 explained up to 15 % of the variance in AP ($F(1, 170) = 90.083, p = 0.000$), supported exclusively by PA ($p = 0.000$). In the second regression model, attention deficit was included as the second predictor variable ($p = 0.000$), explaining up to 26.1 % of the variance in AP ($F(2, 169) = 83.004, p = 0.000$). The last model included a third predictor variable, inhibition deficit ($p = 0.000$), which explained up to 28.6 % of the variance in AP ($F(3, 168) = 61.901, p = 0.000$). In all models, emotional regulation deficit was excluded and, therefore, it was not a predictor variable of AP in this research.

5.2. Objective 2: Mediation models

5.2.1. Attention

Regarding the mediation models, the first model, focusing on attention deficit as a mediating variable (Figure 1), had a good fit ($F(2, 169) = 99.26, p = 0.000$) and explained 37.3 % of the variance in AP. The results revealed a significant negative relationship between PA level and attention deficit ($b = -0.19, p = 0.000$), indicating that higher levels of PA are associated with lower attention deficits. In addition, PA is positively related to AP ($b = 0.58, p = 0.000$), suggesting that higher levels of PA are associated with higher AP. In turn, attention deficit levels are negatively related to AP ($b = -0.65, p = 0.000$), such that higher attention deficits are associated with lower AP. In the case of the Direct Effect, when attention deficit is present, the relationship between PA and AP is significant and positive ($b = 0.46, p = 0.000$). The Indirect Effect (10,000 bootstrap samples) is significant and positive ($b = 0.12$) since the 95 % CI values [0.06, 0.19] do not include 0 as a possible value.

Table 2
Multiple linear regression models on academic performance.

Model	Adj. R^2	ΔR^2	B	SE	β	95 % CI	t	p
Model 1 Physical Activity	0.150	0.150	0.679	0.072	0.072	0[.53, 0.82]	9.491	0.000***
Model 2 Physical Activity Attention Deficit	0.26	0.111	0.571 -0.594	0.069 0.079	0.328 -0.317	0[.43, 0.70] [-0.73, -0.49]	8.312 -8.034	0.000*** 0.000***
Model 3 Physical Activity Attention Deficit Inhibition Deficit	0.286	0.025	0.546 -0.712 -0.289	0.067 0.086 0.070	0.313 -0.380 -0.174	0[.40, 0.67] [-0.74, -0.40] [-0.43, -0.14]	8.017 -9.011 -3.840	0.000*** 0.000*** 0.000***

Note: *** = $p < 0.001$; Adj. R^2 = adjusted R-squared; ΔR^2 = Increment in R^2 ; B = unstandardized beta; SE = standard error for the unstandardized beta; β = standardized beta or standardized regression coefficient; CI = confidence interval; t = t-statistic value; p = p-value of t-statistic.

Furthermore, it is observed that mediation exists, since the value of the standardized regression coefficient of $\hat{c} < c$ ($b = 0.46, b = 0.58$). Regarding the type of mediation, the presence of both an Indirect Effect and a Direct Effect ($p = 0.000$) indicates partial mediation. On the other hand, Figure 1 reveals that PA level explains 26 % of the variance in AP when attention deficit is not present in the relationship, while this percentage increases to 37.3 % when these difficulties are present.

5.2.2. Inhibition

The second model, focused on inhibitory deficits as a mediating variable (Figure 2), obtained a good fit ($F(2, 169) = 68.47, p = 0.000$) and explained 21.4 % of the variance in AP. The results revealed a significant negative relationship between PA level and inhibitory deficits ($b = -0.11, p < 0.05$), indicating that higher PA levels are associated with fewer inhibitory difficulties. In addition, PA level is positively related to AP ($b = 0.68, p = 0.000$), indicating that higher PA levels are associated with higher AP. Furthermore, inhibitory deficits are negatively related to AP ($b = -0.42, p = 0.000$), indicating that greater inhibitory difficulties are associated with lower AP. In the case of the Direct Effect, when inhibitory deficits exist, the relationship between PA and AP is significant and positive ($b = 0.63, p = 0.000$). The Indirect Effect (10,000 bootstrap samples) is significant and positive ($b = 0.04$), since the 95 % CI values [0.004, 0.93] do not include 0 as a possible value. It has also been observed that mediation exists, according to the value of the standardized regression coefficient $\hat{c}' < c$ ($b = 0.63, b = 0.68$). As for the type of mediation, the presence of both an Indirect and Direct Effect ($p = 0.000$) indicates partial mediation. Furthermore, Figure 2 shows that the PA level explains 15.2 % of the variance in AP when inhibitory difficulties are not present in the relationship, while this percentage of explained variance increases to 21.4 % when these deficits exist.

6. Discussion

This study examined the relationships between PA, EF (specifically, its components of attention, inhibition, and emotional regulation), and AP in Spanish secondary education students. Specifically, we analyzed whether PA and EF predicted AP and whether EF played a mediating role in the PA-AP relationship. The following hypotheses were proposed: (1) The level of PA and each of the EF components studied (attention, inhibition, and emotional regulation) will be predictors of AP; (2) There will be a mediating effect of each EF component (attention, inhibition, and emotional regulation) on the predictive relationship between PA and AP.

The results showed that the level of PA and difficulties in attention and inhibition (but not difficulties in emotional regulation) are both important for predicting student AP in our sample. Furthermore, difficulties in attention and inhibition are also significant for the relationship between PA and AP. Therefore, the results suggest that PA may have positive effects on the students' AP, as well as on reducing their

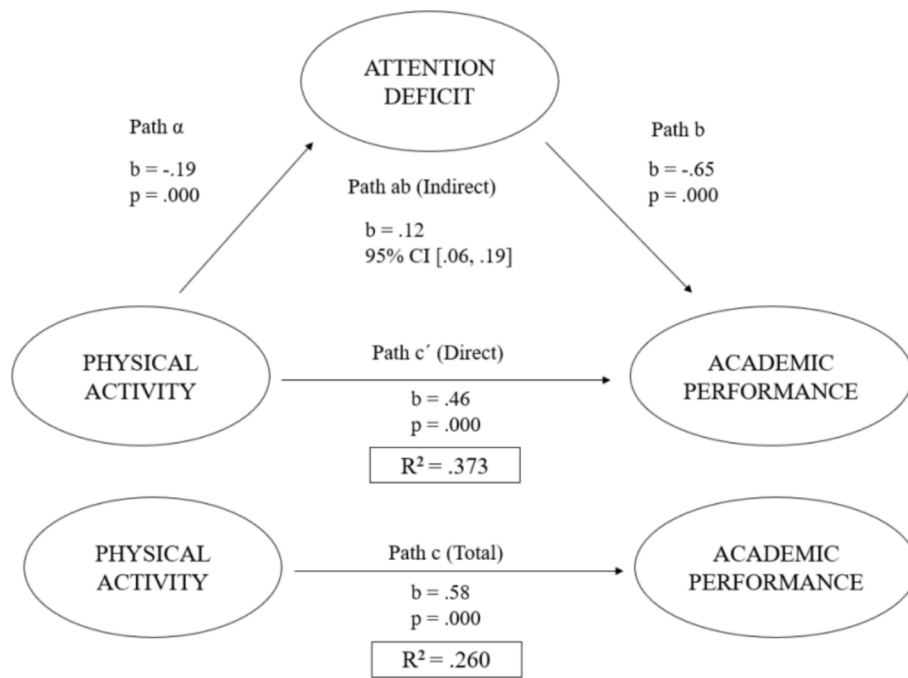


Figure 1. Summary of mediation analysis. Mediating variable: attention deficits. *Note:* b = Unstandardized regression coefficient; p = Significance; CI = Confidence Interval; R^2 = Coefficient of determination.

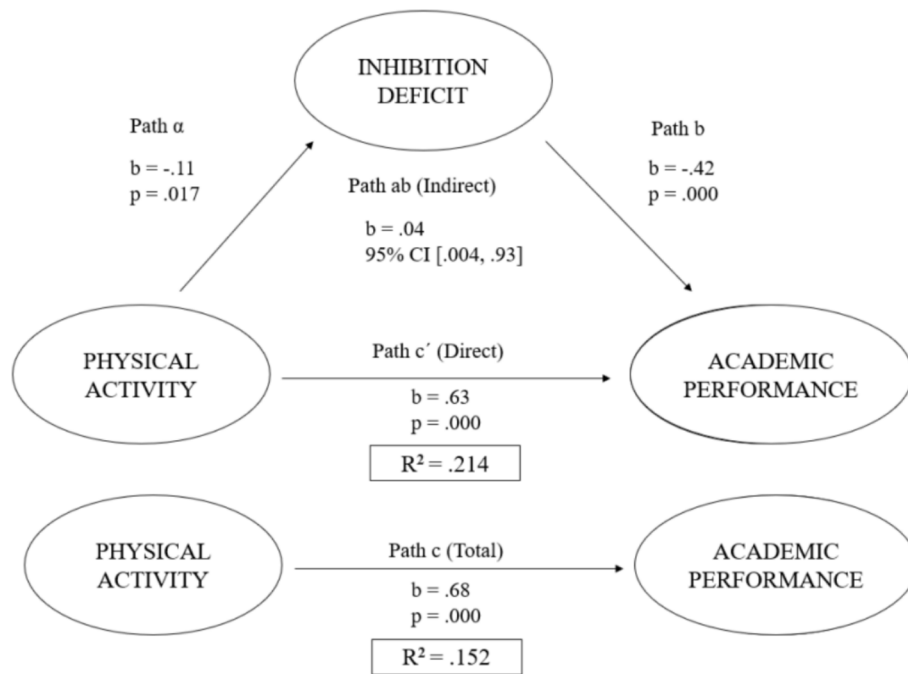


Figure 2. Summary of mediation analysis. Mediating variable: inhibitory deficits. *Note:* b = Unstandardized regression coefficient; p = Significance; CI = Confidence Interval; R^2 = Coefficient of determination.

difficulties in attention and inhibition. Furthermore, through the reduction of difficulties in attention and inhibition, these EF may further improve AP both directly and indirectly.

These results partially support the hypotheses: 1) regarding hypothesis 1, it has been confirmed that PA and the executive components of attention and inhibition predict AP, but the same cannot be confirmed for emotional regulation; 2) as for hypothesis 2, similar to the results found for hypothesis 1, it may be confirmed that these two executive components (attention and inhibition) have a mediating effect between

PA and AP. However, the mediating effect of emotional regulation in the PA-AP relationship was not confirmed.

Some findings of this study are consistent with those of previous studies, while others are not. Specifically, regarding the relationship between PA and AP, numerous recent studies have confirmed this relationship (De Greeff et al., 2018; Gallardo et al., 2023; Ogrodnik et al., 2020; Wang & Guo, 2022).

As for the relationship between EF and AP, our results agree with some aspects in the same direction as other studies, while differing in

other aspects. For example, similar to our results, the *meta-analysis* conducted by Verburgh et al. (2014) showed that EF (considered both as a general index and individually considering its cognitive components of planning, working memory, and inhibition) were positively related to AP. Another more recent *meta-analysis* (Schmidt-Kassow & Kaiser, 2023) found that EF, especially attention and inhibition, were positively related to AP in children and adolescents, consistent with the results of our study. However, regarding the relationship between the affective EF of emotional regulation and AP, our results differ from those of Zorza et al. (2017). These authors found a predictive effect between emotional regulation and AP, while in our study, this type of relationship was not confirmed. Nevertheless, these results are in line with the theoretical model proposed by Abín et al. (2020), who indicated that academic (mathematical) performance was predicted by cognitive variables, but not by emotional (and motivational) ones.

Regarding the detected relationship between PA and EF, a *meta-analysis* (Álvarez-Bueno et al., 2017) found that PA is positively related to the following EF in children and adolescents: attention, inhibition, and emotional regulation. While the results regarding attention and inhibition are consistent with our study, the same cannot be said for emotional regulation. This discrepancy regarding the PA-emotional regulation relationship, as well as the previously mentioned one regarding the emotional regulation-AP relationship, highlights that the results of our study on emotional regulation go in the other direction as compared to the consulted literature. This demands additional study of this variable. It is possible that the theoretical perspective from which this variable is considered in the research, the instruments used for its assessment, the age and gender of each study sample, among other aspects, may contribute to these discrepancies. For example, all of the studies included in the aforementioned *meta-analysis* by Álvarez-Bueno et al. (2017) were carried out with children and adolescents, but they were a maximum of 13 years of age. The sample in our study, however, ranged from 13 to 16 years of age. In this age range, specifically between the ages of 14 and 16, gender identification processes intensify. These processes lead to more stereotyped cultural behaviors in which girls are encouraged to display greater frequency and intensity of emotions and concern for others, whereas boys are encouraged to inhibit any type of emotion (Zimmermann & Iwanski, 2014). Therefore, gender differences in emotional regulation that solidify between 14–16 years old could help explain the discrepancies between our results and those obtained in other studies having younger samples. However, as mentioned earlier, further research is necessary to clarify these discrepancies.

Regarding the mediating role of EF in the PA-AP relationship, one recent study (Muntaner-Mas et al., 2022), in contrast to our work, found that cognitive EF (attention, inhibition, and cognitive flexibility, the latter not addressed in our study) did not partially mediate the relationship between PA-AP in 9 to 13-year-olds. Although the different ages of the study participants may have contributed to the discrepancy between the results, further studies should examine the relationships between these variables to gain additional knowledge about them and have more evidence that helps clarify these discrepancies. From a macro perspective, the systematic review by Visier-Alfonso et al. (2022) on mediating variables between PA and AP, conducted with a sample of over 75,000 participants (4–16 years of age), reveals that PA can affect AP through certain cognitive domains but not through others. However, almost all of the studies included in the systematic review showing cognitive variables to be mediators in the PA-AP relationship were conducted on samples of children aged 12 and under. Only one study was conducted with adolescents (Van Dijk et al., 2014). In this study, the authors found a mediating effect of cognitive EF (attention and inhibition) on the PA-AP relationship. These results were consistent with those obtained in our study. In addition to this study carried out on adolescents (Van Dijk et al., 2014), another was published after the systematic review (therefore, it was not included in the same). This work (Park et al., 2023) only addressed the inhibitory function as a mediator, revealing a mediating effect of inhibition in the PA-AP relationship, like

the study by Van Dijk et al. (2014) and our study.

In this sense, our study provides information to determine which specific cognitive EF mediate the relationship between PA and AP. From a neurophysiological perspective, physical activity directly affects the brain and its cognitive capacity. One of the main proposed mechanisms is that physical activity increases cerebral blood flow, which enhances oxygenation and the supply of nutrients to brain cells. This increase in blood flow stimulates the release of neurotrophic factors, such as Brain-Derived Neurotrophic Factor (BDNF), which promotes neurogenesis, synaptic plasticity, and the strengthening of neuronal connections (Caamaño-Navarrete et al., 2024). BDNF plays a significant role in learning, memory, and other executive functions. Studies such as that of Padmapriya et al. (2024) have found that individuals who regularly engage in physical activity have higher levels of BDNF, which may explain the beneficial effects of physical activity on executive functions. Furthermore, it has been observed that physical activity can increase the size of the hippocampus, a brain region involved in memory and learning, which supports the idea that physical activity has a positive effect on executive functions (Singh et al., 2019). For example, inhibitory control is involved in tasks that require concentration, self-control, and the ability to ignore distracting elements (Caamaño-Navarrete et al., 2024). This inhibitory control improves in adolescents and adults who engage in regular physical activity (Caamaño-Navarrete et al., 2024), suggesting that physical activity may be linked to the optimisation of the ability to regulate behaviour and certain emotional responses in challenging situations or when faced with distracting elements.

For this reason, our results and those obtained in previous works by other authors constitute a small compilation of results affirming the existence of a mediating effect of, at least, some cognitive EF in the PA-AP relationship. In the three studies carried out with adolescent participants (Park et al. (2023), Van Dijk et al. (2014), and ours) this mediating effect has been found for inhibitory function. And in both our study and that by Van Dijk et al. (2014), a mediating effect for attention was also found. However, regarding affective EF, and more specifically, emotional regulation, no results were found for adolescent samples (only from children) to be compared with this research. Therefore, caution should be exercised when generalizing these results. It would be interesting to conduct this type of research on different samples of adolescent students to delve deeper into the existence of this mediating effect. It is true that the existence of a mediating effect for emotional regulation is not possible in our results since this variable, independently, does not display a relationship with AP or with PA. These results, specifically those referring to the absence of a relationship between emotional regulation and AP, are similar to those of García Arias (2012) who did not find a relationship between affective EF and AP in a sample of 9-year-olds. Authors such as Mulder et al. (2014) have supported this idea by concluding that while cognitive EF predicted both academic skills and behavior problems a year later, affective EF only predicted behavior problems. However, these results should be viewed with caution since their sample consisted of very young children, and the age difference between those participants and those in this study could imply differences not only in the development of EF and their underlying processes (Hartung et al., 2020), but also in the processes, skills, and competencies involved in AP at each educational stage, and therefore also in the relationships between both aspects (EF and AP). There have also been results that are contrary in this regard to ours and those of García Arias (2012) and Mulder et al. (2014). For example, Perpiñá et al. (2023) found that emotional regulation positively contributed to AP (especially in Mathematics) in students aged 9 to 11. Given these discrepancies between results, further research continues to be needed to investigate the relationships involving affective EF.

In summary, certain findings from this study are in line with those found in some past studies, while others are not. Consistent with other works, a positive relationship has been found between PA and AP and between PA and cognitive EF (attention and inhibition), as well as a positive relationship between these cognitive EF and AP. These results

suggest that PA may have positive effects on the development of these cognitive EF, which, in turn, may have positive effects on AP. However, at least in the studied sample, the same does not occur with emotional regulation (affective EF). These results demonstrate the absence of a relationship between PA and emotional regulation, and between the latter and AP, are contrary to the results from other works in the literature. Therefore, further studies are clearly necessary.

From an academic perspective, students who engage in physical activity tend to demonstrate better academic performance in tasks involving executive functions such as planning, problem-solving, and inhibitory control. Specifically, motor coordination and cardiorespiratory fitness have been directly associated with higher grades in subjects such as language and mathematics (Tanineh & Halaweh, 2023). This study highlights that both fine and gross motor coordination are related to attention capacity and information processing, which are key to academic success. Additionally, studies have shown that children who participate in physical activity tend to achieve better academic outcomes, likely due to improvements in attention and working memory, facilitating better information processing in the school environment (Tanineh & Halaweh, 2023).

This study has certain limitations and strengths. As for limitations, firstly, the sample was not very heterogeneous (students from a single educational center) and it was not randomly selected, compromising the generalizability of the results. In this sense, it has been found that PA of greater intensity produces more substantial and lasting neurobiological changes which, consequently, lead to more significant improvements in AP (Berrios-Aguayo et al., 2022; Van der Niet et al., 2015). Berrios-Aguayo et al. (2022) found that variables such as frequency, intensity, and type of PA are also significant moderators of the PA-EF association. For example, 150 min per week of moderate PA requiring cognitive effort (such as cooperative and adversary sports where there are numerous changing stimuli) is the most beneficial for cognitive development (Chacón-Cuberos et al., 2020).

Another limitation of our study is that it only assessed some of the potential variables related to AP. Many variables, both family-related (such as the socioeconomic and educational level of parents) and educational (for example: teacher-student relationship) and other personal variables not examined in this work (such as the course or the gender), may play a significant role in AP (Escolano-Pérez & Martín-Bozas, 2023; Board, 2021). However, it is worth noting that our study considered specific personal variables that, through educational interventions, may be modified and, therefore, improved.

Other potential limitations include the use of student grades as an indicator of AP. The fact that student grades were reported by the school's management team is an advantage as compared to studies in which grades are self-reported by students, given the lower reliability of the latter (Faught et al., 2017). However, some authors have noted that limitations still exist due to potential teacher differences in the grading process, including the level of rigor and the difficulty of tests (Escolano-Pérez & Bestué, 2021). However, other authors have emphasized the utility of this method (Li et al., 2020; Paloş et al., 2019) and its greater ecological validity in countries such as Spain, where official student assessment is conducted through this method (Castejón, 2014). Thus, it should be noted that the assessment of PA level was conducted through self-reporting. This type of measure may have the following widely recognized limitations: social desirability, response biases, lack of motivation to answer, etc. (Dalton & Ortegren, 2011). However, the instrument used (PAQ-A) has appropriate psychometric characteristics, and its results have been correlated with measures from accelerometers (Martínez-Gómez et al., 2009).

The final limitation presented in the article is the limited number of variables studied. Although the focus has been on personal variables that can be intervened upon and have interconnected relationships, relevant variables in the literature, such as socioeconomic status, psychological well-being, fear, and social networks, have not been considered (Ding et al., 2024; Pang and Quang, 2024; Pang and Zhang, 2024; Pang and

Yanyinxue, 2023; Sun et al., 2024).

As for the study's strengths, only a few investigations have examined this relationship of variables in adolescent participants. Specifically, only two studies have been found that focused on these variables in samples aged 12 to 16 (Park et al., 2023; Van Dijk et al., 2014). Therefore, this study offers knowledge on the complex relationships existing between PA, EF, and AP in adolescents. The adolescence is a stage in which numerous changes take place having significant short, medium, and long-term consequences. This makes it an area of great interest and complexity, and one that is key to enhancing personal development.

Another strength of this work is the inclusion of variables that are not always present in research of this kind: 1) the inclusion of affective EF, of an emotional nature, which is not common in this type of research, since oftentimes, EF is only considered from the perspective of its purely cognitive components; 2) the use of different subjects to determine the total AP of students, also uncommon, as most studies limit AP exclusively to instrumental subjects (Mathematics and Language). However, as a future prospect, it may be interesting to examine how PA and each EF component affect each subject in the school curriculum, addressing them individually.

On the other hand, it is worth noting that this research has important educational and social implications. Designing and implementing educational interventions based on variables such as levels of PA, attention, and inhibition may be necessary if the goal is to improve the AP of compulsory secondary education students. At the same time, we should be conscious of the fact that these adolescents are the future citizens and leaders of the country, and their levels of AP largely determine the future economic and social progress of the nation (Escolano-Pérez & Bestué, 2021; Ferrão, 2022).

7. Future perspectives

In the future, it may be interesting to include participants from public, private, and concerted centers, as well as from urban and rural areas of different populations, through random sampling. In addition, students having special educational needs were not included in this research, so it would also be interesting to include these students in the sample of future investigations, as they are a fundamental part of educational reality (James et al., 2023). On the other hand, it would be interesting to differentiate between the PA variable based on type, frequency, and intensity. Some studies have considered the relationship between PA (differentiated based on these criteria) and AP (Nakagawa et al., 2020). Regarding PA, it would be interesting to consider the type, frequency, and/or intensity of PA performed by students and analyze its possible relationships with each of the EF assessed and with AP. In addition to the variables, it may be interesting for future research to address new personal variables that have not been assessed here but which are also sensitive to the effects of an intervention (such as other executive components such as flexibility or planning; motivational aspects; etc.).

It would be interesting for future studies to complement the assessment of student AP through the use of standardized batteries (Escolano-Pérez & Bestué, 2021) and compare the relationships established in each case (AP assessed through grades; AP assessed through standardized tests) with the variables of interest (PA and EF).

8. Conclusions

In this study, it was found that PA and cognitive EF (specifically attention and inhibition) significantly contribute to the prediction of AP in secondary education students. However, the affective EF of emotional regulation was not found to be a predictor of AP. Furthermore, it was observed that attention and inhibition, but not emotional regulation, act as mediating variables in the relationship between PA and AP. These findings suggest that promoting PA and developing cognitive EF

(specifically attention and inhibition) may be effective for enhancing AP in compulsory secondary education students. Therefore, it would be interesting to implement focused educational interventions that target PA and the cognitive EF of attention and inhibition in students. Thus, from the perspective of the potentialities of transfer, these results also encourage the promotion of increased PA among adolescents through various educational and welfare policies. In this way, the creation of more sports facilities and the expansion of extracurricular sports activities would directly contribute to promoting PA, and consequently, enhancing cognitive EF and AP.

CRedit authorship contribution statement

Fernando Martín-Bozas: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elena Escolano-Pérez:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Marta Bestué-Laguna:** Writing – review & editing, Resources, Investigation, Funding acquisition, Data curation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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