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“Move” Their Brain: Motor Competence Mediates the Relationship of Physical Activity and Executive Functions in Children

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Abstract: The inconsistent conclusions regarding the effects of physical activity (PA) on children’s executive functions (EFs) call for an investigation of the mediators that may explain this relationship during development. This study attempted to examine the potential mediating role of children’s weight status and motor competence (MC) in the PA-EFs relationship. In this regard, 115 children (M_{age} = 10.3 ± 1.2 years, 42.61% boys) practicing sports were cross-sectionally assessed for their PA (pedometers); BMI (body mass and height); MC (Bruininks–Oseretsky Test of Motor Proficiency); EFs (via computerized tests). The associations among the variables were examined using structural equation modelling. Based on the significant correlation between them (PA was not related to EFs, and BMI was not related to other variables), a serial path model was considered for investigation (PA→MC→EFs). The model fitted well with the data ($\chi2[5] = 7.244$, $p = 0.203$; CFI= 0.991; RMSEA = 0.071 [0.000, 175], $p = 0.315$). The unstandardized path coefficients were significant ($p < 0.05$) (PA predicts MC/MC predicts EFs). All (but one) direct and all indirect effects were significant ($p < 0.05$), confirming that MC is an intervening variable in the PA-EFs relationship. Given that the cognitive/coordinative challenges related to PA are important to EFs development, children should be encouraged to participate in PA, especially sports, in programs targeting their motor skills.

Keywords: cognition; working memory; cognitive flexibility; active behaviour; motor development; childhood; SEM; cross-sectional study

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1. Introduction

Physical activity (PA) and cognition research was ‘adult-born’, with studies concerning adults dating back several decades. More recently, in the last two decades, the research focus has shifted towards childhood [1], a developmental period during which the positive effect of PA on cognitive performance may be stronger, as already suggested by early evidence syntheses (e.g., [2]). Indeed, a rising number of studies with children and adolescents have confirmed that PA is beneficial for the development of cognition [3–5] and brain structure [6].

Cognition refers to mental structures, operations, and processes facilitating perception, intellect, memory, and action [7]. Cognitive development and maturation occur throughout childhood with the myelination of axons in the dorsal prefrontal and parietal cortex. However, axonal myelination elicits increases in the white matter, while decreases in the grey matter are accelerated during adolescence [8,9]. The main bulk of research in the

PA-cognition field concerns learning, executive functions (EFs), and academic achievement [10]. EFs consist of mental skills and top-down processes essential for the execution of daily tasks including reasoning and problem-solving. Particularly, EFs are goal-directed behaviours exerting control on actions and thoughts necessary in unprecedented and challenging situations [11,12]. They are important for cognitive, physical, and psychosocial development and health and success in school [13,14] and life [12,15].

The multicomponent construct of human EFs integrates three core sub-components: (a) working memory, which is the ability to hold information in mind and manipulate it; (b) inhibitory control, which refers to the ability to inhibit spontaneous thoughts and reactions; and (c) cognitive flexibility, which is the ability to switch behaviour in changing tasks and situations [12,16]. Diamond [12] also identifies as higher-level EFs other complex processes, such as planning, decisions making, and problem solving.

Given the relevance of EFs to children's development, researchers and policymakers have been targeting whole-child approaches that combine physical, cognitive, and/or psychosocial aspects to foster EF development [15]. To this vein, the relationship between PA and several aspects of cognition, including EFs and/or academic achievement (see, for reviews, [3,4,10,17], or specifically EFs (see, for reviews, [11,18,19]), in childhood has been systematically examined. The above literature reported positive effects of chronic (i.e., multiple bouts [3,5,18]), acute (i.e., single bouts [20]), or both acute and chronic PA on EFs [11,19].

However, also contrasting conclusions of no effects have been reached in reviews [21] and meta-reviews [22], which call for a more nuanced investigation of the moderators and mediators that may constrain and explain the PA-cognition relation during development and be responsible for the observed inconsistencies across evidence synthesis outcomes. Lubans et al. [23,24] suggested a range of neurobiological, psychosocial, and behavioural mechanisms to mediate the PA effects on cognition: alterations in the structural and functional brain composition due to physical fitness (e.g., increased cerebral blood flow and oxygenation, neurogenesis; e.g., [6]), changes in mood and emotions (e.g., [25]), sleep quality (e.g., [26]), and self-regulation skills (e.g., [1]), respectively, may enhance cognitive function.

Apart from fitness, other individual characteristics, such as age, sex, and weight status, could act as mediators or moderators of PA effects on cognition, as they impact the PA time, type, context, frequency, and intensity which, in turn, influence cognitive function [5,23]. Possible stronger positive effects of PA interventions on EF performance were found for obese/overweight population (i.e., higher Body Mass Index [BMI] [5,27]), suggesting an amplifying moderation of the PA-cognition relation by adiposity. Lastly, reviews have also confirmed that fitness or adiposity may mediate the relationship between PA and cognition [28].

For example, several cross-sectional studies highlight the significant association between children's BMI and either PA [29–32] or EFs [33–36]. In these studies, it is manifested that overweight and obese children not only tend to participate less in PA but also present lower levels of EFs in comparison with their normal-weight peers. Physical fitness and its improvement have also been found associated with EFs in children (EFs and mathematics [37], executive control and brain function [38], and working memory [39],) and in adolescents (EFs, problem-solving, and fluid reasoning, [40]).

Motor competence (MC) could also act as a mediator in the relationship of PA with cognition. The fact that MC is thought to contribute to goal-directed human movements [41] could offer ground for connecting PA with the cognitive domain, particularly with EFs [42–45]. Lemes et al. [40] concluded that the synergistic physiological integration among all fitness components would enhance adolescents' EFs. Interestingly, according to Schmidt et al. [46], EFs seem to be a significant mediator (indirect effects) between primary school children's motor abilities and academic achievement. Neuroimaging studies have shown that during a cognitive task the activation in cerebellum and prefrontal cortex is increased in both of them [47,48]. In line with this research, Ludyga et al. [49] linked MC and working memory in children 10–12 years.

There is large piecemeal evidence [42,50] or full mediational but cross-sectional evidence [46] supporting the important role of MC for the PA-cognition relationship in children. Nevertheless, to our knowledge, only two interventional studies addressed mediation of PA effects on EFs and non-executive cognition through MC with a true statistical mediation approach [51,52]. Pesce et al. [51] found that gross motor skills (specifically object control skills) mediated the executive function outcomes (specifically: inhibition) of an enriched PA program for primary school children. Similarly, Sanchez-Lopez et al. [52] found that the cognitive non-executive outcomes (specifically: intelligence and spatial cognition) of an enriched and multicomponent after-school recreation PA program tailored for primary school children were partially mediated by MC. However, MC (named 'motor fitness' by Sánchez-López et al. [52]) was assessed only by shuttle run, thus limiting the MC assessment to children's speed and agility skills.

To conclude, there is convincing evidence for the positive health effects of PA and physical fitness in obese/overweight children and adolescents [53,54] and also emerging evidence for positive cognitive effects of PA in this population [55]. However, the relationship between PA and MC in children and adolescents has not been yet well established [56], while research on PA, MC, and weight status and whether they mediate EFs, is scarce. This could be attributed to the observed change in consistency and strength of this relationship over the developmental age. EFs develop at early years (3–6) and continue to grow throughout childhood, adolescence, and young adulthood [15]. In pursuit of other possible mediators of the PA-EFs relationship in childhood, the purpose of the present study is to consider the distinctive mediating role that children's weight status and MC may hold.

2. Materials and Methods

2.1. Participants

Participants of the present study were 115 typically developing children (M_{age} = 10.3 ± 1.2 years, 42.61% boys), recruited from sport clubs across various locations in Athens, Greece, following convenient sampling procedures. Accordingly, the administrators of sport clubs (e.g., offering programs of track and field, gymnastics, volleyball, football, and tennis) were called to support this research by allowing their members to volitionary participate in its procedures. Each member of the sport clubs was eligible to participate if the following criteria were met: (a) they were between 8 to 12 years of age, (b) they regularly participated in the sport of their choice (at a non-elite level) three or more times per week, (c) their parent/guardian submitted a written consent allowing their participation, and (d) they verbally consented to participate. The methods and procedures of the study were accepted by the Ethics committee of the School of Physical Education and Sport Science, National and Kapodistrian University of Athens, Greece (1206/15 July 2020).

2.2. Measures

2.2.1. Physical Activity

Participants' PA was recorded as the number of their daily steps by Walking Style Pro HJ-720IT-E2 (HJ-720) Omron pedometers. It is well known that the gold standard for energy expenditure is the doubly labelled water method; nevertheless, is difficult to apply in a daily life study like the present one [57]. In several studies of this kind, questionnaires or diaries have been utilized; however, they appear to have a lot of weaknesses (e.g., over-reporting PA, inaccuracies, etc.) [58]. That is why wearable monitoring devices (like accelerometers and pedometers) are preferable when objective and valid information about PA is to be gathered [59]. In this study, it was decided to use pedometers, because they are inexpensive and provide information easy to understand by general public [60]. Focusing on the Walking Style Pro HJ-720IT-E2 (HJ-720) Omron pedometers, they have been found to be valid measures of children's daily PA [61]. To obtain PA data, participants were asked to wear the pedometers on their right hip, during all day (outside time spent in water activities, bathing, and/or sleeping), for seven consecutive days. Minimum three days of at least ten hours of wear time and recorded steps between the range of 1000 and 30,000 steps were required for valid data [62].

2.2.2. Motor Competence

MC was assessed with the short form of the Bruininks–Oseretsky Test of Motor Proficiency-Second Edition (BOT-2SF [63]), a test battery assessing both gross and fine motor skills for individuals 4–21 years of age. Its technical adequacy is well supported [63,64]; its valid and reliable use in Greek population has also been established [65]. According to the BOT-2SF manual, participants are assessed individually across a range of 14 items: drawing lines through crooked paths; folding paper; copying a square; copying a star; transferring pennies; jumping in place—same sides synchronised; tapping feet and fingers—same sides synchronised; walking forward on a line; standing on one leg on a balance beam-eyes open; one-legged stationary hop; dropping and catching a ball; dribbling a ball; knee push-ups; sit-ups. The test administration time varies between 15 and 20 min.

Children's performance on the 14 BOT-2SF items are recorded as raw performance scores (e.g., number of correct executions of the skill) and are converted into point scores, according to the battery scoring system. By adding the 14-point scores together, a total point score (range: 0–88) is provided and can be converted into a standard score first and then into percentile ranks and/or descriptive performance categories. In the present study, participants' total point scores were used for data analysis.

2.2.3. Executive Functions (EFs)

In this study, computerized cognitive flexibility and working memory tests were selected prioritizing their validity for children from the Greek context. Cognitive flexibility was assessed through the testing task "How many—What number" [66], which has been previously used with Greek children [67]. This task has been widely used in several studies [67,68] to measure the ability of children to respond according to different rules presented to them on the device's screen. The assessment procedure requires the use of four types of stimulus cards, which show either one (1, 3) or three (111, 333) digits. These cards are arranged into simple and complex blocks. The two simple blocks include four practice- and 24 main assessment trials with only non-switch trials, whereas the two complex ones consist of eight practice- and 72 main assessment trials with both switch and non-switch trials. During their assessment for the first and the second simple blocks, participants are requested to identify "what number" and "how many digits" are presented on the screen, respectively. In both instances, they respond by pressing either 1 or 3 on the keyboard. During their assessment for the complex blocks, participants are asked to alternate, by pressing either 1 or 3 on the keyboard, between the given rules, which change every second trial.

Mean reaction times (SwitchRT, NSwitchRT) for correct responses only and accuracy rates (SwitchAcc, NSwitchAcc) for both switch and non-switch trials of complex blocks were used for analysis. An index of switch costs (calculated by the subtraction of mean reaction time for the non-switch trials from the mean reaction time for the switch trials in the complex blocks) was also analysed to estimate the switch costs exclusive of overall RT. For the assessment of cognitive flexibility variables, the E-Prime Software 2.0 (Psychology Software Tools, Pittsburgh, PA, USA) was utilized.

For assessing working memory, the task "Digits Backwards", from the Working Memory Test Battery for Children [69] was used. Its reliability and technical adequacy in children are supported for both its original [70,71] and Greek version [72–74]. This test assesses whether the examinee can recall a sequence of digits (presented at a rate of one digit per second) in reverse order. The participant receives one point for each correct response and zero points for each wrong one, respectively. The test is terminated when the participant makes three unsuccessful recalls of sequences of digits of the same length. The number of correct responses (WMcorrect) is recorded.

2.3. Procedure

This study was cross-sectional and was conducted in May and June 2021. Data were collected by trained assessors within two meetings during participants' regular training in their sport club's facilities, adjusted for the optimal administration of both motor and cognitive measures. At the beginning of the first meeting, participants' body mass (Kg) and height (cm) were measured. These measurements were then used to calculate their BMI (kg/m^2). Subsequently, the BOT-2SF items were administered, according to guidelines included in the test's manual. At the end of the meeting, which usually lasted approximately 25 min per child, a pedometer was assigned to each participant, along with written instructions about its use. During the second meeting, arranged after an interval of seven days, participants returned their pedometers, and they were assessed for EFs via the computerized tasks described above, administered in counterbalanced order across participants. This meeting lasted approximately 20 min per child.

2.4. Preliminary Analyses

As a first step to data analysis, data cleaning procedures were conducted. The data of 90 children ($M_{age} = 10.3 \pm 1.1$ years, 42.2% boys), who completed all measures, were included in the analysis. Interestingly, the highest percentage of missing data was due to invalid pedometer data. According to boxplots and Kolmogorov–Smirnov tests results, all key study variables (PA, MC, BMI, and EFs; working memory and cognitive flexibility variables) were normally distributed. The single outlier detected in switch costs distribution ($z > 3.29$) was retained in the sample, as it was considered representative of the population under examination. Onwards, descriptive statistics were computed for all participants as well as bivariate correlations (Pearson's correlation coefficients) and gender differences for all key study variables.

2.5. Data Analysis

A hypothesized structural equation model (path model) was conducted to investigate associations among the study variables. The specification of the model was based on the significant bivariate correlations (Table 1). As it is shown in Table 1, BMI was the only variable that did not significantly correlate with the others; therefore, it was not included in the model. Due to the non-significant relationships between PA and EFs and to the significant relationships of MC with both PA and EFs, it was conceptualized in the model that PA (predictor variable) indirectly predicts EFs (outcome variable) through MC (intervening variable). Particularly, it was hypothesized that PA positively predicts MC, which in turn predicts working memory and each cognitive flexibility variable (PA→MC→EFs) except switch costs, which was not related to the hypothetical intermediate variable of the serial modelling path (i.e., MC) and was excluded. Because of the negative associations of MC with RT variables indicating a negative relation between PA level and reaction speed in cognitive flexibility tasks (SwitchRT and NSwitchRT), the respective estimates of path coefficients were expected to be negative (−). The above indirect effect was not examined separately in boys and girls, due to absence of significant differences between genders in most of the study key variables ($p > 0.05$).

Since the study variables were continuous and normally distributed, the maximum likelihood estimation method was used for the analysis. Model fit was assessed by the commonly accepted model fit indicators: Model chi-square (χ^2), Normed-fit index (NFI), Comparative fit index (CFI), Tucker–Lewis Index (TLI), and Root mean square error of approximation (RMSEA). A nonsignificant Chi-square value ($p > 0.05$) signifies a good overall model fit. According to conventional cutoffs for the above fit indices, for NFI and CFI, values close to 0.95 indicate a well-fitting model [75]; for RMSEA, values close to 0.06 [75] or 0.07 [76] are indicative of reasonable model fit.

Table 1. Bivariate correlations of the study variables.

	PA	MC	BMI	SwitchAcc	SwitchRT	NSwitchAcc	NSwitchRT	Switchcosts	WMcorrect
PA	1000								
MC	0.211 *	1.000							
BMI	0.000	−0.068	1.000						
SwitchAcc	−0.095	0.324 **	−0.044	1.000					
SwitchRT	−0.098	−0.270 *	0.062	0.410 **	1.000				
NSwitchAcc	−0.053	0.381 **	−0.034	0.763 **	0.328 **	1.000			
NSwitchRT	−0.071	−0.208 *	0.045	0.257 *	0.802 **	0.206 *	1.000		
Switch costs	−0.039	−0.087	0.024	0.227 *	0.273 **	0.084	0.356 **	1.000	
WMcorrect	−0.125	0.347 **	−0.067	0.160	−0.201	0.257 *	−0.278 **	0.133	1.000

PA: physical activity, MC: motor competence, BMI: body mass index, SwitchAcc: accuracy in switch trials, SwitchRT: reaction time in switch trials, NSwitchAcc: accuracy in non-switch trials, NSwitchRT: reaction time in non-switch trials, switch costs: SwitchRT-NSwitchRT, WMcorrect: correct responses in the task Digits Backwards, * $p < 0.05$, ** $p < 0.001$.

The strength of associations in the model was determined by the estimation of standardized path coefficients. The bias corrected bootstrap method was used to test the significance of direct and indirect effects. The IBM SPSS Statistics (Armonk, NY, USA; version 25.0) was used to calculate descriptive data, Pearson correlation coefficients, and gender differences. Path analysis was conducted using IBM SPSS Amos (Armonk, NY, USA, version 25.0). The significance level was set at $p < 0.05$.

3. Results

Descriptive statistics for all participants are provided in Table 2. The main analysis revealed that the estimated model fitted reasonably well with the data (χ2[5] = 7.244, $p = 0.203$; NFI = 0.972; TLI = 0.961; CFI = 0.991, RMSEA = 0.071 [0.000, 175], $p = 0.315$). All unstandardized path coefficients proved to be significant at $p < 0.05$, indicating that (a) PA significantly predicts MC and (b) MC predicts all the EFs variables in the model. Based on the standardized path coefficients, it was shown that the associations between the variables were low to medium (Figure 1). According to squared multiple correlations (Figure 1), PA explained 4.5% of variance in MC, whereas MC accounted for 4.3–14.5% of variance in EFs.

Table 2. Descriptive statistics (M ± SD) for all study variables.

Variables	M ± SD
PA	12,461 ± 3449
MC	73.0 ± 4.7
BMI	18.3 ± 3.1
EFs	
WMcorrect	14.29 ± 4.065
SwitchAcc	0.858333 ± 0.1044384
SwitchRT	2042.828508 ± 610.5183967
NSwitchAcc	0.875926 ± 0.0893287
NSwitchRT	1976.520956 ± 628.4286279
Switch costs	66.307552 ± 390.6293040

PA: physical activity, MC: motor competence, BMI: body mass index, EF: executive functions, M = Mean, SD = Standard Deviation.

Except for the effect of MC on NSwitchRT, all other direct effects in the model (Table 3) were significant ($p < 0.05$). Similarly, all the indirect effects of PA on EFs through MC (Table 3) were significant, confirming the hypothesis that MC is an intervening variable in these relationships.

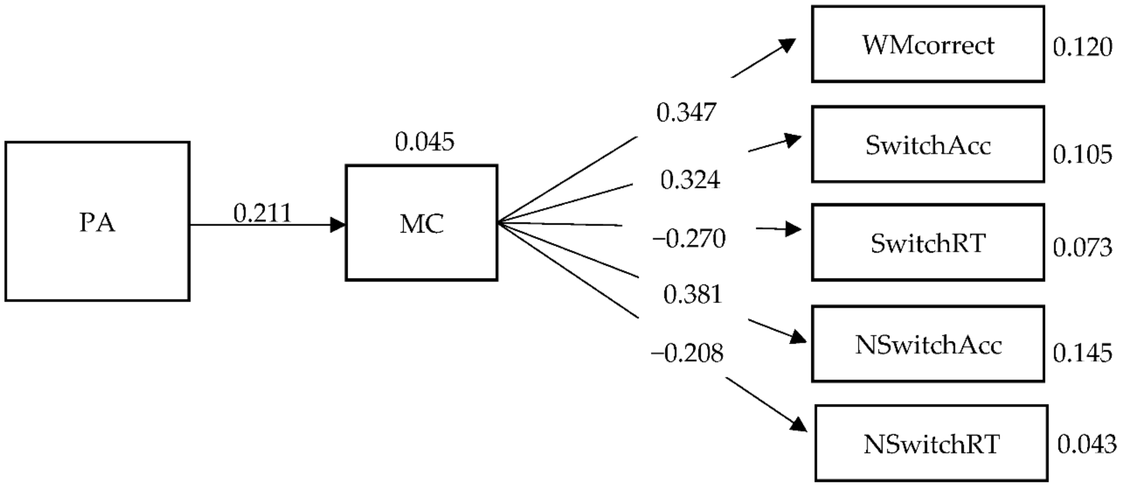

Figure 1. Standardized path coefficients and squared multiple correlations. PA: physical activity, MC: motor competence, WMcorrect = working memory.

Table 3. Standardized directs and indirect effects.

	Direct Effect	Confidence Intervals (95%)	*p*		Indirect Effect	Confidence Intervals (95%)	*p*
PA→MC	0.095	0.060, 0.374	0.016				
MC→WMcorrect	0.093	0.188, 0.501	0.011	PA→MC→WMcorrect	0.033	0.023, 0.141	0.010
MC→SwitchAcc	0.144	0.047, 0.552	0.032	PA→MC→SwitchAcc	0.040	0.017, 0.168	0.014
MC→SwitchRT	0.111	−0.475, −0.092	0.019	PA→MC→SwitchRT	0.036	−0.131, −0.011	0.022
MC→NSwitchAcc	0.137	0.112, 0.575	0.035	PA→MC→NswitchAcc	0.042	0.023, 0.173	0.020
MC→NSwitchRT	0.108	−0.401, −0.040	0.069	PA→MC→NswitchRT	0.032	−0.125, −0.008	0.040

Bootstrap samples = 200.

4. Discussion

Due to current research interest in human cognition and its relation to PA participation in children, this study intended to investigate hypothetical serial paths of relationships between PA participation and EFs. It was revealed that, although PA does not directly lead to the enhancement of working memory and cognitive flexibility measures, a serial path links PA to MC and this latter to EFs. In contrast to the association of MC with both PA levels and EFs and its important role in the serial path linking PA, MC, and EFs, in this study, BMI was not related to EFs.

The absence of associations between BMI, PA, and EFs is contrary to our hypothesis. Although evidence exists on the PA-BMI relationship in children [29,31,32], the relationship between BMI and EFs still remains to be explored [34,36]. Notably, children in this study were active members of sport clubs. This fact may have influenced their weight status which was normal for most of them. Other studies have shown that children participating in sports usually have normal weight status [77]. For instance, the effects of a 14-week intervention of short active breaks on EFs were moderated by socioeconomic and weight status [78]. In particular, overweight or obese adolescents (senior high school students) had the largest improvements in working memory performance, but no effects were found on normal weight adolescents.

In fact, the current results reaffirmed the hypothesis that PA participation contributes to the refinement of children's motor skills, with a significant direct effect of PA detected on MC. However, in this study, we did not find a direct link between PA and working memory. Previous studies supporting the relationship between PA and working memory have reported inconclusive findings: some have shown a positive association [79–82], while others did not [83–85].

In the systematic review and meta-analysis of Alvarez-Bueno et al. [3], small effects of PA on working memory were shown (ES = 0.14), while significant publication bias was reported in the subgroup analyses of working memory. It was also suggested that different types of PA may provoke different PA effects, based on the cognitive demand required. However, several researchers, who compared EFs of children participating in different types of sports identified a lack of differences in their working memory skills; a finding that was attributed to the similarity of training content among sports in childhood [86,87]. Importantly, the absence of association between PA and working memory in the present study could be due to the fact that only active participants were involved, possibly reaching their highest potential. Controlling for individual differences such as fitness-related factors and/or intelligence (e.g., [79]) or children's level of engagement in each sport [88] may shed light on this relationship.

Interestingly, looking at the nuances of the pattern of effects of MC on cognition during development, both overall MC and different facets of it seem differentially related to different EFs [89]. As regards the range of executive and non-executive functions that have been found linked to MC during development, previous research with preadolescent children has found a connection between MC and working memory [45,89–91] and inhibition [91], as well as non-executive cognitive functions such as episodic memory, attention, and information processing speed [45,91]. Attempting to comprehend how MC and EFs are related, their relationship could be explained by the fact that mechanisms underlying motor skills and working memory share common neural substrates [90]. Interestingly, both MC and working memory follow a similar developmental trajectory [89], suggesting that their acquisition and level of maturation are interrelated [92]. Regarding our key finding about the significant mediating role of MC in the PA-cognitive flexibility relationship, it is in line with the findings of current research showing that speed-agility can be a potential predictor of non-verbal and verbal ability, abstract reasoning, spatial ability, numerical ability [93], and better memory [94], while motor coordination was associated with intelligence [95], concentration, and attention [96].

Cognitive flexibility is generally measured by reaction time and accuracy (e.g., [66]). Speed-agility, motor skill and coordination alter the brain's processing speed and efficiency of neuronal activity [97], which are essential processes for cognitive flexibility, inhibition, and working memory [98]. Concomitantly, speed and accuracy are important elements for the execution of motor tasks [99]. As such, common underlying mechanisms during the process of skills acquisition can be found in both cognitive performance and sports/exercise [100]. For instance, participation in organized PA and sport is a demanding undertaking that requires quick reactions during constantly changing situations. These contexts are thought to be relevant for developing skill-related fitness, such as speed and agility [101].

For example, a 10-week active recess program in 8–12 years old children, including moderate-to-vigorous PA in the form of small-side games (e.g., football, basketball) three times per week, found improvements on creativity, cognitive flexibility (TMT-B), and school aptitudes [102]. The PA tasks involved peer cooperation, strategy coordination, and continuing changing task demands. The significant relationship between PA and cognitive flexibility in children has also been indicated in recent studies [103,104]. Specifically, in the cross-sectional study of Mazzocante et al. [103], it was observed that 6–7-year-old children participating in sports presented higher level of cognitive flexibility (TMT-A and TMT-B) in comparison with children not participating in sports. Furthermore, the results of the longitudinal study of McNeill et al. [104] showed that the shifting performance of preschoolers after one year of sport participation was associated with the level of their engagement with both moderate-to-vigorous and vigorous PA.

The overall findings of this study highlight the importance of reinforcing active behaviour in children, since engagement with PA, and especially sports, is the suggested pathway to develop their motor skills and consequently extend their possibilities to boost EFs. Given that today's children's MC level is reported to be low [105], it is imperative for teachers and parents to encourage children to participate in age-appropriate sport programs with the aim of making improvements in that field.

Most importantly, targeting the overall physical literacy of children would enable them to be more competent and confident in being physically active and engage in a wide range of PA offering them pleasure and an enhanced sense of self from their movements and sensorimotor experiences [106]. According to the physical literacy model for cognitive development in early childhood of Cairney et al. [106], participation in cognitively challenging PA and games, putting emphasis on MC refinement, may also promote and signify gains in various aspects of EFs. Cognitive enrichment of PA involves physical activity tasks with a gradual progression of motor coordination and cognitive demands (cognitive stimulation hypothesis [107]).

Providing quality PA with a wider focus on learning and motor skill development instead of mere health-related physical fitness outcomes would place EFs as a mechanism linking PA-academic related outcomes (e.g., academic achievement [46]). Notably, there is yet sound evidence that PA which incorporates both motor and cognitive tasks (e.g., physically active learning, active breaks, and cognitively engaging PA) has prominent effects on children's and adolescents' cognitive outcomes (e.g., memory, academic achievement, and on-task behaviour [108–110]).

Although the present study's findings come to fill a gap in the literature, shedding light on the mechanism underlying the PA-EFs relationship, it presents certain limitations. First of all, its findings should be interpreted with caution, due to its cross-sectional design, which does not establish causality between the examined variables. Experimental studies such as controlled randomized trials, using large samples allocated to groups at random, are a more reliable and powerful design for examining causality as well as identifying possible mediators. In addition, the limited number of participants based on a convenient sample diminishes the generalizability of the results derived from the structural equation modelling technique and increases the risk of potential biases towards finding positive outcomes.

In addition, participants were members of sports clubs located in several suburbs in Athens, representative of diverse socio-economic backgrounds. However, such information was not directly included. Future studies should also consider including socio-economic status as a covariate variable. Lastly, participants' physical activity levels were objectively measured with the use of pedometers. These tools provide only quantitative information on the amount of physical activity but not on the type. A recent review highlighted the determinant role of contextual factors such as physical activity type (e.g., running vs. bicycling), setting (e.g., school, gym), and delivery mode (e.g., group or individual) that may also mediate the relationship of PA-cognition effects [4]. Future research should examine these factors on their effects on children's executive function skills.

Since this study only confirmed the mediating role of MC in the relationship of interest, future research should focus on exploring other potential mediators and/or moderators (e.g., age, sex, and weight status). For instance, a cross-sectional study in Spanish primary school children showed that, when adjusting for weight status and sex, PA was associated with physical fitness, and this latter to EFs [111]. Moreover, PA-EFs relationship was shown to be mediated by physical fitness [40,111].

5. Conclusions

This study attempted to explore hypothetical paths of causal relationships between PA and certain EFs in childhood. Structural equation modelling revealed that, even though PA does not directly predict working memory and measures of cognitive flexibility, there is a significant indirect effect of PA on these EFs through MC. Given the absence of a relationship between BMI and EFs in this study, it is assumed that the cognitive and coordinative challenges related to PA are more important for the enhancement of working memory and cognitive flexibility. Therefore, all children should be encouraged to participate in PA, especially in programs that place emphasis on refining children's various motor skills.

Although the current findings offer a new insight into MC as a mechanism underlying the PA-EFs relationship, future studies can further our understanding by considering the role of the PA context. Indeed, PA contexts, such as the social, natural, or built environment, may act as triggers of different mechanisms through which PA affects cognition [4]. Future studies with a stronger ecological validity focus should verify whether the mediating role of MC, broadly found in this study for a large array of EF performances, is more differentiated when accounting for the PA context in which children develop their MC.

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