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The relationship between motor coordination and executive functions in 4th grade children

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The relationship between motor coordination and executive functions in 4th grade children

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In the last decades, there has been a declining trend in different components of children's motor capabilities and an increasing concern with cognitive skills, but the relationship between motor and cognitive domains remains uncertain. In this study, we aimed to (1) analyse the relationship between motor coordination (MC) and executive functioning, (2) verify the role of processing speed in this relationship and (3) examine the interaction between MC and task complexity. Ninety-six healthy 9- to 11-year-old were evaluated using the Körperkoordination Test für Kinder and the planning scale of the Cognitive Assessment System. The results showed moderate associations between the global composite of MC and executive functioning; however, it seems that processing speed plays an important role in this association. The results also show that children with high MC have better cognitive performances particularly in tasks with higher complexity.

Keywords: Motor coordination; Executive functions; Processing speed; Children; Task complexity.

The nature of early experiences affects our lifelong development. In the last decades, profound changes resulted in adverse consequences for the holistic development of children, leading to a decrease in children's physical activity

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(Dollman, Norton, Norton, & Cleland, 2005). This decrease in children's physical activity has a negative impact on cardiovascular fitness (Tomkinson & Olds, 2007) and motor coordination (MC; Vandorpe et al., 2011). Cardiovascular fitness, as paramount to physical activity, has been widely studied, but MC has only recently been included in this type of research (Lopes, Stodden, Bianchi, Maia, & Rodrigues, 2012).

MC has been pointed out as a predictor for physical activity (Lopes, Rodrigues, Maia, & Malina, 2011), correlating it positively with physical activity, cardiorespiratory fitness and perceived physical competence, and inversely with weight status (Lubans, Morgan, Cliff, Barnett, & Okely, 2010). Stodden et al. (2008) suggested a model linking MC to healthy lifestyles, proposing that low levels of MC during childhood could compromise the adoption of active and healthier lifestyles. Several physiological mechanisms could explain the relationship between physical activity and cognition, such as increased cerebral blood flow, alterations in brain neurotransmitters, structural changes in the central nervous system, modified arousal levels (Sibley & Etnier, 2003) and the increased production of brain-derived neurotrophic factor (Zoladz & Pilc, 2010).

Recently, a growing body of research has been attempting to understand the relationship between motor skills and cognitive abilities, more precisely between executive functions (EFs) and motor skills in typical and atypical children. EFs is an umbrella term for a complex set of cognitive processes that underlie flexible goal-directed responses to novel or difficult situations (Hughes & Graham, 2002). EFs include a large range of top-down control and monitoring processes, such as attentional control, planning and regulation of action (Lee, Bull, & Ho, 2013). Miyake et al. (2000) proposed an EF model with three central components: inhibition, shifting and updating. Inhibiting control involves the ability to control one's attention, behaviour, thoughts and/or emotions to override a competing or prepotent response or process, and to do what's more appropriate or needed (Diamond, 2013). Shifting requires the ability to change between sets of mental operations (Lee et al., 2013). Updating refers to the ability or capacity to refresh and preserve information in working memory in the presence of novel information (Lee et al., 2013). The structure of EFs is age dependent. It has been suggested one-factor structure for preschool children (Wiebe, Espy, & Charak, 2008) and for children up to around the age of 9 (Brydges, Reid, Fox, & Anderson, 2012; Wiebe et al., 2008; Willoughby & Blair, 2012), but a recent study (Lee et al., 2013) considered a two-factor structure, combining inhibition and shifting on one factor, was the best model for 5- to 13-year-old children. A three-factor structure was established for adults (Miyake et al., 2000) and for 13- to 15-year-old adolescents (Lee et al., 2013). Independently of the model considered, EFs are essential skills for mental and physical health; success in school and life; and cognitive, social and psychological development (Diamond, 2013).

Despite sharing the same origin, cognitive functions and motor development were traditionally studied as an independent phenomena (Diamond, 2013). Piaget (1952) argued that these two domains were somehow related, but irrefutable scientific evidence was missing. Modern neuroimaging techniques show that important regions to motor and cognitive performances such as dorsolateral prefrontal cortex and cerebellum have closely coupled activation, therefore confirming the mutual association between these two domains (Diamond, 2000; Schall et al., 2003; Wagner, Koch, Reichenbach, Sauer, & Schlösser, 2006). Even though this association has been previously studied (e.g., Asonitou, Koutsouki, Kourtessis, & Charitou, 2012; Davis, Pitchford, & Limback, 2011), to our knowledge the evidence of a directional relationship has seldom been explored and is not yet confirmed (Wassenberg et al., 2005). Studies that investigated the strength and nature of the motor-cognition association using typical children resulted on mixed conclusions. Davis, Pitchford, and Limback (2011) found moderate correlations between global measures of cognitive functions and motor performance. However, several authors only found moderate to weak associations for specific measures, for example between total motor score with visual motor integration, word order (Wassenberg et al., 2005) and trail-making task (Piek et al., 2004). Rigoli, Piek, Kane, and Oosterlaan (2012) also discovered different specific relationships, such as between balance and inhibition. Davis, Pitchford, and Limback (2011) argued that the use of comprehensive standardized tests with global scores was fundamental to the success of the relationships.

Despite the links established between MC and cognitive abilities, the relation between postural motor tests (i.e., depending mostly on balance skills) and specific cognitive measures is uncertain. For example, Davis, Pitchford, and Limback (2011) found the relationships to be moderate, while no associations were discovered in other studies (Jenni, Chaouch, Caflisch, & Rousson, 2013; Livesey, Keen, Rouse, & White, 2006). It has also been proposed that cognitive processing speed plays an important role in the associations between cognitive and motor domains (Davis, Pitchford, & Limback, 2011; Roebers & Kauer, 2009), but the extension of this role remains unclear and a trail-making task has been suggested for clarification (Davis, Pitchford, & Limback, 2011). To our knowledge, few studies have specifically examined the relationship between MC and cognitive abilities, and even fewer used a standardized quantitative test of MC and a standardized cognitive test. Therefore, the aims of this study were: (1) to analyse the relationship between MC (global and specific measures) and executive functioning; (2) to verify the role of processing speed in the relationship between motor and EF variables and (3) to examine the interaction between MC and task complexity, comparing the cognitive performance in tasks with different cognitive complexity in two groups with differentiated MC. We hypothesized that there would be a positive significant association between MC and cognitive abilities, with cognitive processing speed playing an important role in this association. We also predicted that children with high MC would perform better in cognitive complex tasks than children with poor MC.

METHODS

Participants

Ninety-six children (53 boys) between 9 and 11 years of age ($M = 9.99$, SD = .34) participated in the study. According to the social stratification of Graffar (1956), 49.2% of the participants belonged to the upper class (class 1), 23.1% to upper-middle class (class 2) and 27.7% belonged to middle class (class 3). All students attended the 4th grade for the first time and had no cognitive impairment or learning disabilities according to school records.

Procedures

After the study's approval given by the Ethics Committee of the Faculty and by the board of the schools, written informed consent was obtained from parents and verbal assent from the children. Socioeconomic status was evaluated using the Graffar scale.

Children's MC was assessed with the Körperkoordination Test für Kinder (KTK; Kiphard & Schilling, 1974), and children's cognitive abilities were evaluated using the Cognitive Assessment System (CAS; Naglieri & Das, 1997).

Instruments

Motor coordination. KTK (Kiphard & Schilling, 1974) is a widely used, valid and reliable instrument to assess the general MC of children with a test–retest reliability coefficient of .97 (Lopes et al., 2012) consisting of four subtests:

1. Balance: walking backwards three times along each of three balance beams with 3 m in length but of decreasing widths (6, 4.5 and 3 cm).
2. Shifting platforms: moving sideways for 20 s using two wooden platforms (25 cm × 25 cm × 2 cm).
3. Hopping on one leg over an obstacle: hopping over a stack of foam blocks 5 cm high. After a successful attempt with each foot, the height is increased by one foam block.
4. Jumping laterally: jumping sideways with 2 ft together over a wooden beam as fast as possible for 15 s.

Scores in each subtest are transformed using gender- and age-specific reference values, and the sum of standardized scores provides an overall motor quotient, used as the global indicator of MC.

Cognitive abilities

The CAS (Naglieri & Das, 1997) is based on the work of (Luria, 1973) and is a standardized test defined on the basis of four interrelated cognitive processes: planning, attention, simultaneous and successive. For this study, we used only the planning scale because it reflects the EF (Davis, Tomporowski, et al., 2011; Naglieri & Rojahn, 2001). This scale has high internal reliability coefficients (.88) and provides information about programming, regulation, and verification of behaviour (Naglieri & Rojahn, 2001). It includes three subtests: matching numbers, planned codes and planned connections.

(1) Matching numbers: three items, each one with eight lines and six rows of numbers. The child should find and underline two similar numbers in each line. The complexity of the test increases every four lines, with the introduction of a digit. The final score results on the combination of time and correct number of answers for each item.
(2) Planned codes: two items, each one with seven lines and eight rows of letters. This subtest consists in writing under each letter the respective code as quickly as possible. The final score results on the combination of time and correct number of answers for each item.
(3) Planned connections: the child must connect the presented numbers in sequential order. The amount of numbers increases in each item. For the last two items, the child should connect numbers and letters in sequential order, alternating between numbers and letters (1-A-2-B, etc.). The subtest score is based on the total amount of time (seconds) used to complete the items.

The planning scale total score results of the sum of the standardized scores of the subtests.

To study the interaction between MC and task complexity, a novel easy planning task (connect 10 numbers in a sequential order) and a difficult planning task (connecting 13 numbers and 13 letters in a sequential order) were used. These two planned connections tasks were chosen because of their difference in the difficulty level and because EF is held to be necessary particularly in novel and complex tasks (Diamond, 2000; Hughes & Graham, 2002).

Data analysis

Descriptive statistics (means and standard deviations) were calculated to characterize MC and cognitive abilities for the whole sample and by gender. Pearson's correlation coefficients were used to investigate the correlation between motor and cognitive variables. As suggested in previous studies (Davis, Pitchford, & Limback, 2011; Roebers & Kauer, 2009), partial correlations controlling for planning connections were assessed in order to control for processing speed. Independent samples *t* tests were performed to determine gender differences in MC and in the planning scale. A 2 × 2 mixed ANOVA was computed to examine the interaction between task difficulty (within-subjects variable) and MC level (between-subjects variable) in the planned connections tests. Children were divided in two groups according to the median of the results in the KTK battery: high MC ($M = 117.40$ points, SD = 5.95) and low MC ($M = 98.96$ points, SD = 8.27).

RESULTS

Descriptive statistics and gender differences

The descriptive statistics and gender differences, for the motor and cognitive variables, are presented in Table 1. MC results were within the normal range for both genders according to the normative values of the KTK test battery (Kiphard & Schilling, 1974). Boys outperformed girls in all motor variables except for the balance subtest. There were no systematic differences between girls and boys for the cognitive abilities; so, further analyses were performed for the whole sample.

Correlations between MC and EF

Table 2 presents the correlations (above diagonal) and partial correlations controlled for planned connections (below diagonal) among all variables. Almost all motor subtests were significantly related among each other and with MC, presenting values between $r = .30$ and $r = .84$. However, the balance subtest

TABLE 1
Descriptive statistics (mean ± SD) and gender differences (*t* test results) for the total scores and subtests of motor and cognitive variables

	Total ($n = 96$); $M \pm SD$	*Girls* ($n = 43$); $M \pm SD$	*Boys* ($n = 53$); $M \pm SD$	*t*	*p*
Balance	97.2 ± 12.4	98.1 ± 12.2	96.4 ± 16.6	−.69	.491
Hopping on one leg over an obstacle	75.0 ± 15.2	67.3 ± 15.9	81.2 ± 11.4	5.00	.000
Jumping laterally	97.0 ± 17.2	88.3 ± 14.8	104.1 ± 15.8	5.05	.000
Shifting platforms	86.3 ± 15.0	81.4 ± 10.5	90.3 ± 16.9	2.99	.004
MC	108.2 ± 11.7	102.9 ± 10.6	112.5 ± 10.8	4.38	.000
Matching numbers	10.5 ± 2.8	9.9 ± 2.6	10.9 ± 2.8	1.76	.082
Planning codes	10.3 ± 2.2	10.4 ± 2.2	10.2 ± 2.3	−.53	.597
Planning connections	9.9 ± 2.3	9.3 ± 2.0	10.5 ± 2.5	2.53	.013
Planning score	30.7 ± 5.7	29.6 ± 5.3	31.5 ± 5.9	1.67	.098

Notes: MC, motor coordination [MC categories: “not possible” (MQ < 56), “severe motor disorder” (MQ 56–70), “moderate motor disorder” (MQ 71–85), “normal” (MQ 86–115), “good” (MQ 116–130) and “high” (MQ 131–145)].

TABLE 2
Pearson's correlations (above principal diagonal) and partial correlations controlling for planning connections (below principal diagonal) between motor and cognitive variables

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
1 Balance	–	.32**	.32**	.17	.56**	.18	.04	.07	.13
2 Hopping on one leg over an obstacle	.31**	–	.58***	.47***	.81***	.15	.13	.25*	.23*
3 Jumping laterally	.21**	.55***	–	.52***	.84***	.24*	.26**	.30**	.35**
4 Shifting platforms	.16	.41***	.45***	–	.74***	.20	.21*	.47**	.37**
5 MC	.58***	.79***	.83***	.69***	–	.25*	.22*	.37**	.37**
6 Matching numbers	.17	.07	.15	.05	.15	–	.37***	.29**	.76***
7 Planning codes	.02	−.03	.13	−.06	.02	.22*	–	.52***	.79***
8 Planning connections	–	–	–	–	–	–	–	–	.76***
9 Planning scale	.12	.06	.17	.026	.14	.84***	.64***	–	–

Note: *$p < .05$; **$p < .01$; ***$p < .001$.

presented the weakest association with all MC variables and did not present any correlation with the shifting platforms subtest.

Regarding the cognitive variables, planning scale presented the higher correlation values with all cognitive tasks ($r = .76$ to .79). Planned codes and planned connections were more closely interrelated ($r = .52$) than matching numbers and planned codes ($r = .37$), or matching numbers and planned connections ($r = .29$).

Concerning the associations between motor and cognitive variables, general MC and the jumping laterally subtest presented moderate associations with all cognitive variables. Shifting platforms only did not presented association with the matching numbers subtest, and the hopping on leg over an obstacle test was only correlated with the planned connections and the planning scale.

The effect of processing speed

The planned connections test measures processing speed, which has been suggested to contribute significantly to the strength of the relationships between these two different domains (Davis, Pitchford, & Limback, 2011). We found that all associations among cognitive and motor variables disappeared when controlling for planned connections, suggesting that processing speed is an influent factor in this relationship (see below diagonal in Table 2).

Complexity of the task and MC

The ANOVA revealed a main effect of task difficulty ($F(1,94) = 635.29$, $p < .001$, $\eta_p^2 = .871$) and MC level ($F(1,94) = 9.341$, $p = .003$, $\eta_p^2 = .088$) in the planned connections performance. The interaction between task difficulty and MC level was also significant ($F(1,94) = 6.597$, $p = .012$, $\eta_p^2 = .033$). These results indicate that children with higher MC outperformed children with lower MC in the easy (high MC: $M = 11.63$ s, SD = 3.05; low MC: $M = 13.31$ s, SD = 2.75) and in the difficult (high MC: $M = 82.50$ s, SD = 29.78; low MC: $M = 100.27$ s, SD = 32.28) planning tasks, but the difference was higher in the more complex task.

DISCUSSION

The first goal of this study was to analyse the relationship between MC and EF. We found moderate associations between MC and the CAS planning scale (.37). These results are in the line with previous studies (Asonitou et al., 2012), yet they were weaker than the results reported by Davis, Pitchford, and Limback (2011). Both studies used a standardized quantitative and qualitative measure for motor proficiency and standardized cognitive tests. Asonitou et al. (2012) evaluated preschool children and found an association of .27, whereas Davis, Pitchford, and Limback (2011) discovered correlations of .51 in 4- to 11-year-old children. To our knowledge, our study is the first that analysed the relationship between MC and the planning scale using a standardized quantitative test of overall MC for children.

More studies have investigated this association, but no global or standardized motor or cognitive measures were used. For example, Roebers and Kauer (2009) evaluated 7-year-old using five cognitive tasks and four motor tests and found height correlations among them ranging from .20 to .33. Wassenberg et al. (2005) also reported associations among quantitative and qualitative aspects of motor performance and several aspects of cognition in preschool children.

Regarding our motor subtests, we found that jumping laterally presented better associations with the planning scale than the other subtests, being this result consistent with previous findings (Roebers & Kauer, 2009). In contrast, no associations were established between balance and any of the cognitive subtasks, which is in accordance with some studies (Jenni, Chaouch, Caflisch, & Rousson, 2013; Livesey et al., 2006) but contradicted by others (Asonitou et al., 2012; Davis, Pitchford, & Limback, 2011; Rigoli et al., 2012). This apparent inconsistency in results may arise from differences in the measures used to evaluate cognitive and motor abilities. Some movement patterns are more complex than others (e.g., jumping laterally implies more coordination and movement speed than balance), and the more complex the movement, the greater the activation of large networks in cortical, cerebellar and brainstem regions (Deliagina, Orlovsky, Zelenin, & Beloozerova, 2006). Cortical and cerebellar areas are vital to important cognitive functions, for example EFs and learning (Davis, Pitchford, & Limback, 2011). On the other hand, the cerebellum (Morton & Bastian, 2004) and the basal ganglia–brainstem pathways are important for postural control (Takakusaki, Saitoh, Harada, & Kashiwayanagi, 2004). The fact that balance is not controlled by a high order of cognitive processing might explain the weaker correlations found between balance tasks and cognitive functions. Other possible explanation is that the balance subtest is relatively easy and well-known to children because it is often used in physical education classes. The greater familiarity with balance tasks might lead to an automatic response without much emphasis on cognitive functions (Davis, Pitchford, & Limback, 2011). In sum, it's well known that measures of EF suffer from task impurity problems (Miyake et al., 2000; Rabbitt, 1997), and the motor tasks used probably have the same problem.

Our second goal was to verify the role of processing speed in the relationship between motor and cognitive variables. Similar to our results, it has been previously suggested that associations between cognitive and motor domains are dependent of cognitive measures emphasizing processing speed (Roebers & Kauer, 2009). However, Davis, Pitchford, and Limback (2011) did not find the same results in a subsequent study. Both studies used different and not very sensitive measures to evaluate processing speed, for example Roebers and Kauer (2009) used the pegboard task, whereas Davis, Pitchford, and Limback (2011) applied the visual processing tasks from the Kaufman Assessment Battery for Children—2nd edition (KABC-II; Kaufman, 2004). It is possible that this discrepancy is due to the instruments used, and it has been argued that more explicit, sensitive measures such as the trail-making task should be used (Davis, Pitchford, & Limback, 2011). In our study, a trail-making task was used and our findings are in line with previous studies (Roebers & Kauer, 2009), suggesting that processing speed contributes to the strength of the associations. Nevertheless, more research is necessary to better understand the role of the processing speed in the relationship between motor and cognitive domains.

Regarding our study's third goal, results indicate that typically developing children with higher MC performed better on cognitive tasks, particularly in those with high complexity. The participation of EFs, the cerebellum and the prefrontal cortex is strongest in novel tasks and in tasks with a high complex level (Diamond, 2000; Hughes & Graham, 2002). The results in the easy novel task and in the complex task underline the positive correlation between coordinative skills and motor function. To our knowledge, there is no data available concerning this matter, therefore it is impossible to compare our results; however, Pontifex et al. (2011) showed that aerobic fit participants had better accuracy in a cognitive task with increased cognitive demanding, and that these participants displayed augmented allocation of attentional resources with the increase of task complexity.

The association between MC and physical fitness in children has been established previously (Barnett, Van Beurden, Morgan, Brooks, & Beard, 2008), with high MC children displaying better physical fitness. Several studies tried to understand the relations between EF and physical fitness using neuroimaging methods (Chaddock et al., 2010) and electroencephalographic activity (Hillman, Buck, Themanson, Pontifex, & Castelli, 2009). Neuroimaging methods showed that children with high aerobic fitness display larger volume of specific regions of the basal ganglia, specifically the dorsal striatum (Chaddock et al., 2010), an important sub-region for EF (Aron, Poldrack, & Wise, 2009). Electroencephalographic activity further showed that high-fit children had increased allocation of attentional resources (i.e., larger P3 amplitude) (Hillman et al., 2009) and processed environmental information more efficiently (i.e., smaller P3 latency) allowing a greater cognitive performance (Pontifex et al., 2011). In addition, it has been shown that exercise increases cerebral blood flow (Rooks, Thom, McCully, & Dishman, 2010), and associations between aerobic fitness, vascular function and cognition have been reported (Brown et al., 2008). We suggest that similar mechanisms should be present in children with high MC due to the strong association between motor and physical fitness.

Although presenting only behavioural measures, our study indicates that motor and cognitive abilities are correlated, which might support the general idea they share common neural structures. It has been shown that cerebellum and prefrontal cortex show similar activations during motor and cognitive tasks (Diamond, 2000). Diamond (2000) and Chaddock et al. (2010) also emphasized the importance of basal ganglia and certain neurotransmitters, like dopamine, in both motor and cognitive tasks.

Further research using neuroimaging and electroencephalographic activity could help to identify the possible differences in the brain structure and function of high and low MC participants. Longitudinal studies, with larger sample sizes, will be important to better understand the association between cognitive abilities and MC along the lifespan. The use of latent variables and structural equation modelling will allow to further analyse the possible directional relation between MC and EF, with processing speed as mediator.

Finally, studies quantifying changes in cognition resulting from the implementation of MC programmes with different characteristics (e.g., duration, intensity) and targeted to different stages of childhood and adolescence should be conducted. This study presents some limitations. The upper social classes are over-represented in our sample, and socioeconomic status is known to influence the studied variables. Also, the trail-making task used to assess processing speed measure is also a measure of shifting; therefore, a pure reaction time task (Anderson, 1986) should also be used in the future. Controlling for confounding variables (e.g., attention see Rigoli et al., 2012; Wassenberg et al., 2005) is also recommended.

CONCLUSIONS

Our investigation suggests that motor and EFs appear to be related, with moderate to weak associations. This relation seems to be underpinned by cognitive abilities that depend on processing speed skills. In addition, it was found that participants with high levels of MC have better performances in planning tasks than participants with low levels of MC, especially in tasks with higher cognitive demands. Thereby, the detrimental trends in coordination (Vandorpe et al., 2011) and cardiovascular fitness (Tomkinson & Olds, 2007) that exists in modern societies might result on huge health damages not only at a physical level (Ekelund et al., 2007), but also in the cognitive domain. It seems that the development of motor and cognitive opportunities should coexist within the same school system, because this is the only way to prepare our children for present and future challenges.

This study used quantitative measures of motor skills and tried to clarify the relationship between motor and cognitive variables. The full understanding of the neural mechanisms underlying this association remains a challenge that should be addressed in the future.

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