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Relationship between executive functions, mathematical skills and fitness/physical activity in elementary school children: a systematic review

Alejandro González-Andrade[1], Javier Tubío[1], Aitor Álvarez-Bardón[1], Sandra Santiago-Ramajo[1]

[1] Department of Education,
Universidad Internacional de La Rioja (UNIR), Logroño

Spain

Correspondence: Javier Tubío. Avda. de La Paz, 137. 26006 Logroño (Spain). E-mail: javiertubio@unir.net

Abstract

Executive functions (EF) play a fundamental role in the acquisition of learning, especially in mathematics. The literature seems to indicate that fitness and physical activity (PA) have an important impact on cognition, including EF. Although the relationship between these variables seems evident, few studies have investigated the mediation role of EF between fitness/PA and mathematical skills (MS). The purpose of this systematic review was analysing the relationship between EF, fitness/PA and mathematical skills (MS) in children aged 6 to 12 aged. The systematic review (CRD42021237840) used information from Pubmed, WOS and ERIC published between 2010 and 2021. Eligibility criteria were: scientific articles, in English, children aged 5-16 years, assessment of EF using standardised tests and inclusion of the three variables (fitness/PA, EF and MS). For assess risk of bias was used the Medical Education Research Study Quality Instrument (MERSQI). From the selected articles were extracted the following data: country, age, type of study, characteristics of the sample, evaluation instruments, physical activity program and results. From the 387 initial records, 21 studies with a total of 8601 participants have been selected to be included in the systematic review. Only one of the studies analysed shows a clear causal relationship between the three variables, while five show a linear relationship. EF could act as a mediator between fitness and MS but not between PA and MS, although long-term randomised and controlled intervention studies are needed.

Keywords: Fitness, physical activity, mathematics, executive functions.

Resumen

Las funciones ejecutivas (FE) juegan un papel fundamental en la adquisición del aprendizaje, especialmente del matemático. La literatura parece indicar que el fitness y la actividad físisca (AF) tienen un importante impacto en la cognición, incluidas las FE. Aunque la relación entre estas variables parece evidente, pocos estudios han investigado el papel mediador de las FE entre fitness/AF y las habilidades matemáticas. El objetivo de esta revisión sistemática era analizar la relación entre las FE, fitness/AF y las habilidades matemáticas en niños de 6 a 12 años. La revisión sistemática (CRD42021237840) usó información de Pubmed, WOS y ERIC publicada entre 2010 y 2021. Los criterios de elegibilidad fueron: estudios científicos, en inglés, niños de 5 a 16 años, evaluación de las FE usando pruebas estandarizadas e inclusión de las tres variables (fitness/actividad física, FE y habilidades matemáticas). Para evaluar el riesgo de sesgo se usó el instrumento Medical Education Research Study Quality Instrument (MERSQI). De los artículos seleccionados se extrajeron los siguientes datos: país, edad, tipo de estudio, características de la muestra, instrumentos de evaluación, programa de actividad física o fitness y resultados. De 387 registros iniciales, 21 estudios con un total de 8601 participantes fueron seleccionados para ser incluidos en la revisión sistemática. Solo uno de los estudios analizados mostró una clara relación causal entre las tres variables, mientras que cinco mostraron relación lineal. Las FE podrían actuar como un mediador entre fitness y las habilidades matemáticas, pero no entre AF y las habilidades matemáticas, sin embargo, para arrojar más luz sobre esta cuestión, es necesario que se lleven a cabo más estudios aleatorios a largo plazo y de intervención controlados.

Palabras Clave: Fitness, actividad física, habilidades matemáticas, funciones ejecutivas.

Introduction

In the last decades neuroscience has been making important contributions to the world of education from the perspective of empirical, scientific, and demonstrable facts (Dekker et al., 2012). In this sense, one of the lines of research that is awakening the most interest is that which explores the relationships between physical activity, cognitive functions and academic performance as shown in some recently published reviews (Daly-Smith et al., 2018; Donnelly et al., 2016; Sember et al., 2020; Singh et al., 2019; Xu et al., 2019).

Executive functions (EF) are defined as "the cognitive processes necessary for goal-directed cognition and behaviour" (Best, 2010, p. 331) and, although numerous constituent processes have been proposed, inhibition, working memory and mental flexibility are considered to have the most empirical support (Miyake et al., 2000). These EF emerge at preschool age and continue to develop throughout middle childhood and adolescence and play an important role in academic success (Garon et al., 2008).

Evidence seems to point to the important role of these EF on academic performance (Bull et al., 2008; St Clair-Thompson & Gathercole, 2006). Indeed, their importance for mathematical skills (MS) in children and adolescents is well documented (Best, 2010; Cantin et al., 2016; Gathercole et al., 2004; Jacob & Parkinson, 2015; Martínez-López et al., 2020; Vazou & Skrade, 2017) and it is these MS that provide a foundation for further academic development (Duncan et al., 2007) to the point of being a predictor of future academic and career success (Butterworth, 2005; Parsons & Bynner, 2005). There are many ways in which EF influence MS. For example, working memory helps retain relevant information, store, and retrieve partial results while solving an arithmetic problem. Inhibition may suppress inadequate strategies or irrelevant information to the solution. Mental flexibility can help switch between operations, solution strategies, and between the steps of a problem that requires performing multiple steps (Bull & Lee, 2014).

Physical activity (PA) is often defined as any bodily movement produced by skeletal muscles that results in energy expenditure while physical exercise is defined as the practice of PA in a systematic and relatively stable way (United States Department of Health and Human Services, 2018) (for example, running). “Physical fitness is a physiologic attribute determining a person’s ability to perform muscle-powered work” (United States Department of Health and

Human Services, 2018, p. C-18) and is an important factor in the ability to perform routine daily activities (for example, the weight). The factors responsible for the effects of PA on the central nervous system and cognition would be mediated mainly by growth factors such as insulin-like growth factor (IGF1), brain-derived neurotrophic factor (BDNF) and vascular endothelial growth factor (VEGF), which produce a series of changes related to synaptic efficiency and the generation of new neurons that we know as synaptic plasticity (Trejo & Sanfeliu, 2020). Namely, PA generates several functional and structural adaptations at the brain level such as stimulation of neurogenesis, increased complexity of dendritic arborization, increased number of synapses, increased cerebral blood flow, increased availability and functionality of neuro-transmitters or increased neuroprotective factors (Gradari et al., 2016; Nokia et al., 2016; Oka-moto et al., 2015). And several of these findings have been replicated in children (Bidzan-Bluma & Lipowska, 2018; Donnelly et al., 2016). For example, children with high levels of PA show greater hippocampal grey matter volume and higher grey matter thickness in the frontal cortex, greater white matter integrity and better cerebral circulation and synaptic plasticity (Chaddock-Heyman et al., 2013, 2020; Hillman et al., 2009), which could lead to higher cog-nitive and academic performance (Chaddock et al., 2010; Chaddock-Heyman et al., 2015). In fact, inactivity in children has been found to have negative effects not only on their mental and physical health but also on cognitive and academic performance (Singh et al., 2019) and many studies pointing to an effect of PA on EF because the structures mentioned above are especially linked with them (Berse et al., 2015; Blair & Razza, 2007; Chaddock-Heyman et al., 2013; Davis & Cooper, 2011; Haapala, 2013; van Waelvelde et al., 2020; Vazou & Smiley-Oyen, 2014; Verburgh et al., 2014).

The most recent studies (from the last 10 years) seem to point out that fitness and PA are related to improvements in EF and MS in children (Kvalø et al., 2019; Oberer et al., 2018; Schmidt et al., 2017) but the type of relationship is not completely clear, so it would be neces-sary to deepen how is this relationship between the different variables and if the type of design used in the study can influence the results (causal or bidirectional). In addition, it would be interesting to investigate whether EF can act as a mediator between fitness/PA and MS. Medi-ational analyses allow us to know who the effect of one variable (x) is produced on the other (y), considering an intermediate variable (mediator) (Rockwood & Hayes, 2020). In this way we can get a more complete explanatory model that will help us to better understand the whole process. In this case, it is proposed that the influence of fitness/PA on MS takes place through EF. This would help us to better understand the indirect effect of fitness/PA through EF. There is a need to systematically review the most recent studies (from the last 10 years) to know the congruence of the results according to the type of study (causal or bidirectional) and whether EF can be a mediator between fitness/PA and MS.

Therefore, the general objective of this systematic review is to explore how is the relationship between fitness/PA, EF and MS in elementary school children (aged 6-12 years). The specific objectives are a) explore the results based on the research design used (causal or bidirectional) and b) review the role of EF as a mediator between fitness/PA and MS.

Method

The systematic review was registered in PROSPERO on 07 April 2021 (registration number CRD42021237840). Available from: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42021237840. No amendment was necessary.

We conducted a systematic review of the research that has studied the relationship between fitness/PA, EF, and MS in children. We followed the recommendations of the PRISMA guide (Page et al., 2021) and other related systematic reviews (Suárez-Manzano et al., 2018; Van Waelvelde et al., 2020) for this purpose. The search strategies, filters applied, and articles identified are detailed in Table 1.

Table 1. *Search strategies for the different databases*

Database	Filters	Results	Search strategy
Pubmed	- Publication date from 01-01-2010 to 31-01-2022 - Search in Title/Summary	57	(“Physical exercise” OR “Physical fitness” OR “Physical activity” OR “Physical education” OR Exercise OR Fitness OR Sports OR Training) **AND** (“executive function”) **AND** (Children OR Childhood OR Schooler OR Preadolescent) **AND** (mathematic OR math OR arithmetic OR calculation OR problems solving in math OR educational status OR educational performance OR academic performance OR academic achievement)
ProQuest ERIC	- Publication date from 01-01-2010 to 31-01-2022 - Scientific journals - Search in any field except full text	23	
Web of Science	- Publication date from 01-01-2010 to 31-01-2022 - Excluded: Book Chapter, Editorial material, Meeting abstract - Search in Topic	307	

On January 31 of 2022 a search was made in articles published in the Pubmed, WOS and ERIC databases since 2010. The search terms used were: 1) Physical activity (physical exercise, physical fitness, PA, physical education, exercise, fitness); 2) Executive function; 3) Children (Childhood, schooler, preadolescent); 4) Mathematic (math, arithmetic, calculation, problem solving in math, educational status, educational performance, academic performance, academic achievement).

The resulting articles from these searches were reviewed to check if they met the following inclusion criteria: 1) scientific articles published in peer-reviewed scientific journals; 2) the articles were published in English; 3) they included children aged 6-12 years; 4) they performed an assessment of EF using standardised tests; 5) the study included the three variables: fitness or PA, EF and MS. The following were excluded: 1) articles whose study population included children with attention deficit hyperactivity disorder, brain damage, intellectual disability, or any other developmental disorder; and 2) reviews and meta-analyses.

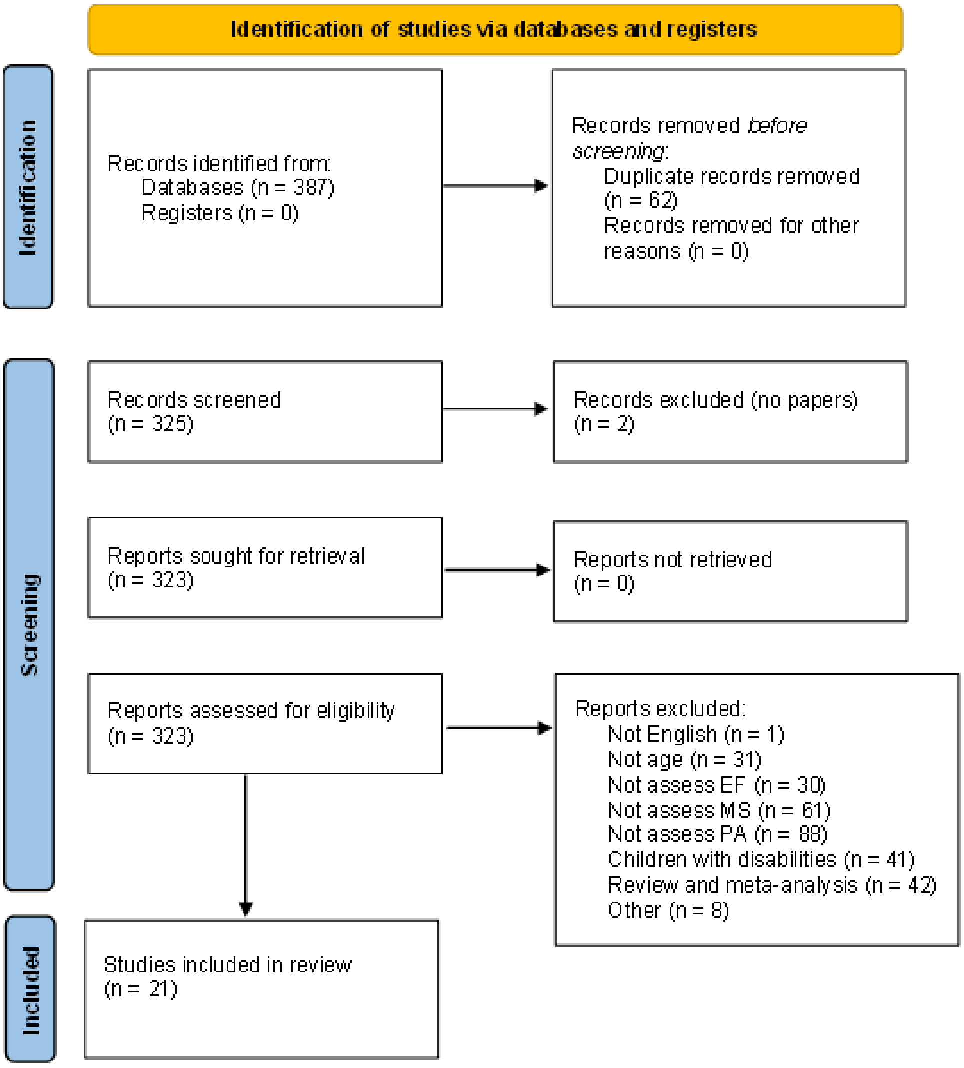

Figure 1 . Flow chart for study selection

Three independent reviewers (AGA, JT and SSR) read the title and author to exclude duplicated articles. These reviewers subsequently checked the abstract and method of the remaining articles for inclusion criteria. Cases of disagreement were pooled and decided by vote. The results of the search are shown in Figure 1.

The twenty-one selected papers were evaluated for their methodological quality according to the Medical Education Research Study Quality Instrument (MERSQI) (Reed et al., 2007), an instrument with high reliability for educational studies (Cook & Reed, 2015). This instrument measures the following domains: Study design (maximum 3 points), Sampling (institutions and response rate) (maximum 3 points), Type of data (maximum 3 points), Validity of evaluation instrument (maximum 3 points), Data analysis (sophistication and appropriate) (maximum 3 points) and Outcomes (maximum 3 points). The review of the methodological quality of the studies was performed independently by two of the authors (JT and AGA) and in case of disagreement, it was agreed and voted with a third author (SSR).

To obtain the results of the selected articles, JT, AGA, SSR and AAB reviewed the articles extracting the following data: country, age of the sample, type of study (application of PA programme, ex post facto study with correlational analysis or ex post facto study with mediation analysis, characteristics of the sample, evaluation instruments, PA programme (in cases where there are interventions) and main results. All this information was included in a table for syntheses the results. This review protocol has not been previously published.

Results

From the 387 initial records, 21 studies with a total of 8601 participants have been selected to be included in the systematic review.

The evaluation of the methodological quality of the studies using the MERSQI scale showed that the studies had a quality of between 13.5 and 17 points out of a maximum of 18 (Table 2). In general, the studies had the highest methodological quality in the categories of sampling, type of subjects, validity of the instruments and analysis of the data applied. Scores were lower in the study design and outcomes categories. Table 3 shows the main results of the studies included in the review.

Table 2. *Methodological quality of studies*

Study	Study design	Sampling	Type of data	Validity of evaluation instrument	Data analysis	Outcomes	Total
Aadland et al., 2017a	1	2.5	3	3	3	1.5	14
Aadland et al., 2017b	1	3	3	3	3	1.5	14.5
Aadland et al., 2018	3	2	3	3	3	1.5	15.5
Beck et al., 2016	2	3	3	1	3	1.5	13.5
Becker et al., 2018	1	2	3	3	3	2	14
Chaddock-Heyman et al., 2020	3	1	3	3	3	2	15
Davis and Cooper, 2011	1	2	3	3	3	1.5	13.5
Davis et al., 2011	3	2	3	3	3	2	16
Gerber et al., 2021	2	3	3	3	3	2	16

Have et al., 2018	3	3	3	3	3	2	17
Hecht & Garber, 2021	2	2	3	3	3	2	15
Howie et al., 2015	3	2	3	3	3	2	16
Kvalo et al., 2019	1	3	3	3	3	2	15
Layne et al., 2020	2	1	3	3	3	2	14
Migueles et al., 2020	2	3	3	3	3	2	16
Morris et al., 2019	3	2.5	3	3	3	2	16.5
Muntaner-Mas et al., 2020	1	2	3	3	3	1.5	13.5
Nuñez et al., 2019	1	2	3	3	3	2	14
Oberer et al., 2018	1.5	3	3	3	3	2	15.5
Schmidt et al., 2017	1	2	3	3	3	2	14
Visier-Alfonso et al., 2020	1	3	3	3	3	2	15

Study design

Of the twenty-one studies reviewed, eight have an interventional design with at least one experimental group (application of PA programme) and one control group (Aadland et al., 2018; Beck et al., 2016; Chaddock-Heyman et al., 2020; Davis et al., 2011; Have et al., 2018; Hecht & Garber, 2021; Layne et al., 2020; Morris et al., 2019) and one has an intrasubject quasi-experimental design (Howie et al., 2015).

The remaining twelve studies have an ex post facto design, where they explore the relationship between the variables of interest. Of these studies, six analysed the bidirectional relationship between the three variables (Aadland et al., 2017a; Becker et al., 2018; Davis et al., 2011; Gerber et al., 2021; Migueles et al., 2020; Muntaner-Mas et al., 2020). The other six studies have also carried out mediation analysis (Aadland et al., 2017b; Kvalø et al., 2019; Núñez et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020) to determine whether EF is a mediator between the effect of fitness/PA on MS.

Characteristics of the sample

Of the twenty-one studies, thirteen were conducted in European countries (four in Spain, four in Norway, two in Denmark, two in Switzerland and one in UK), seven in the USA and one in Africa.

Regarding the ages of the participants in the different studies, they vary between 5 and 16 years old. Several of the studies work with age-specific samples, such as the study by Beck et al. (2016) in which all the children are 7 years old or those by Aadland et al. (2018, 2017a, 2017b) and Hecht & Garber (2021) in which all the children are 10 years old. In the remaining studies we find samples with specific age ranges. The two studies with the widest range are the study by Núñez et al. (2019), with participants varying from 10 to 16 years old, and the study by Gerber et al. (2021), with participants varying from 6 to 12 years. Two of the studies analysed works with subjects aged between 7 and 11 years and another three with subjects aged between 9 and 10 years (Chaddock-Heyman et al., 2020; Layne et al., 2020; Morris et al., 2019). In the rest of the research, the ages analysed vary slightly as in the studies of Have et al. (2018) with children aged 6-7 years, that of Kvalø et al. (2019) with children aged 9 and 10 years or the studies by Howie et al. (2015), Visier-Alfonso et al. (2020) and Migueles et al., (2020) with somewhat more age dispersion of the subjects, which are between 9-12 years, 7-11 years and 8-11 years, respectively. Finally, Becker et al. (2018) did not present an age range, but the mean age was at 14.19 (*SD*= 2.37).

In terms of sample size, the largest sample is the study by Gerber et al. (2021) with 1277 children, followed by Aadland et al. (2017b, 2018) with 1129 children, followed by Aadland et al (2017a) with 697 subjects, followed by Becker et al. (2018) with 660 subjects, Visier-Alfonso et al. (2020) with 563 subjects, Have et al. (2018), Núñez et al. (2019) and Kvalø et al. (2019) with samples of 505, 490 and 378 subjects, respectively, and the study by Morris et al. (2019) with a sample of 158 experimental subjects and 145 controls. The smallest sample is the study by Layne et al. (2020) with only 19 experimental subjects and 21 controls.

Of note are two studies that divide participants into two different experimental groups, in addition to a control group. The study by Beck et al. (2016) on the one hand, whose experimental groups perform fine or gross motor PA; and the study by Davis et al. (2011), in which one group performs acute intensity PA and the other, low intensity. It is also worth noting that the participants in some of the studies were overweight children (Davis & Cooper, 2011; Davis et al., 2011; Migueles et al., 2020).

Assessment instruments

Regarding the assessment instruments used in the studies, it is worth noting the heterogeneity both between tasks used and between the executive processes assessed. Firstly, and with regard to the assessment of EF, it is observed that some tasks are repeated in several studies, such as the Stroop task (Aadland et al., 2017a, 2007b, 2018; Kvalø et al., 2019; Migueles et al., 2020; Muntaner-Mas et al., 2020), the Trail Making Test (TMT) (Aadland et al., 2017a, 2017b, 2018; Howie et al., 2015; Kvalø et al., 2019; Migueles et al, 2020; Morris et al., 2019; Muntaner-Mas et al., 2020), the WISC direct and inverse digit task (Layne et al., 2020; Muntaner-Mas et al., 2020; Visier-Alfonso et al., 2020) or the flanker task (Beck et al., 2016; Gerber et al., 2021; Have et al., 2018; Hecht & Garber, 2021; Morris et al., 2019; Núñez et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). However, many other tasks differ across studies. Regarding the assessment of MS, all but four studies used standardised tests adapted to the characteristics of the population studied (Aadland et al., 2017a, 2017b, 2018; Davis et al., 2011; Hecht & Garber, 2021; Kvalø et al., 2019; Muntaner-Mas et al., 2020; Núñez et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). Another relevant aspect is that all assessed MS with a single measure, except for Oberer et al. (2018) that distinguished between addition/subtraction and sequencing.

Physical Activity Programme

In this regard, the main point of note is that not all the studies analysed explored the results of a PA programme. Twelve of the studies applied an ex post facto design (Aadland et al., 2017a; 2017b; Becker et al., 2018; Davis and Cooper, 2011; Gerber et al., 2021; Kvalø et al., 2019; Migueles et al., 2020; Muntaner-Mas et al., 2020; Núñez et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020), where one studies measured PA by questionnaire (Becker et al., 2018) three by accelerometer (Aadland et al., 2017a; 2017b; Migueles et al., 2020; Muntaner-Mas et al., 2020) and six measured fitness evaluating with shuttle run, blood oxygenation, heart rate, anthropometric measurement or others (Davis & Cooper, 2011; Gerber et al., 2021; Kvalo et al., 2019; Núñez et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). Finally, there is two study that measured both PA and fitness (Aadland et al., 2017a; 2017b).

The remaining nine studies either explored the effects of PA acutely (Howie et al., 2015; Morris et al., 2019) or conducted an intervention programme in PA of between 4 weeks and 9 months duration, with three studies conducting longer intervention programmes of 7-9 months (Aadland et al., 2018; Have et al., 2018; Chaddock-Heyman et al., 2020; Davis et al., 2011).

The studies that conducted an intervention programme also varied in the type of PA used and its intensity; while some combined moderate-intensity PA with an evocation of mathematical concepts (Aadland et al., 2018; Beck et al., 2016; Have et al., 2018) or learning emotional intelligence and executive function skills (Hecht & Garber, 2021), others were high intensity and focused only on sports practice (Chaddock-Heyman et al., 2020; Davis et al., 2011; Howie et al., 2015; Layne et al., 2020; Morris et al., 2019).

General results

Of the eight intervention studies reviewed, only one has found improvements in both EF and MS after implementation of the PA programme (Davis et al., 2011). Of the remaining intervention studies, three have found improvements in MS but not in EF (Beck et al., 2016; Have et al., 2016; Howie et al., 2015) and one study has found the reverse results, i.e., improvements only in EF and not in MS (Layne et al., 2020). Finally, four studies claim not to find improvements in any of the afore-mentioned variables (Aadland et al., 2018; Chaddock-Heyman et al., 2020; Hecht & Garber, 2021; Morris et al., 2019).

With respect to correlation studies, two of them confirm the relationship between PA, EF and MS (Becker et al., 2018; Migueles et al., 2020) and three between fitness, EF and MS (Aadland et al., 2017a; Davis & Cooper, 2011; Gerber et al., 2021; Muntaner-Mas et al., 2020).

Finally, regarding the six studies that proposed mediation analyses, all but one (Nuñez et al., 2019) of them found significant results of the mediating role of EF between fitness and MS (Aadland et al., 2017b; Kvalø et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). Núñez et al. (2019) concluded that there was no inhibition effect on mathematics but did find a significant relationship between fitness and MS, but not on EF.

Table 3. *Characteristics of the studies analyzed*

Type of study: Application of a physical activity programme

Authors	Country	Age	Sample by Groups	Assessment instruments	Physical Activity Programme	Results
Aadland et al., 2018	Norway	10 years	All children with low scores in numeracy at baseline. Experimental group: 596 children Control group: 533 children	EF: Stroop Golden colour-word test, verbal fluency, Trail Making Test and working memory (direct and inverse digits of WISC-IV). MS: Norwegian standardised test designed by Norwegian Directorate for Education and Training: numeracy	Intervention programme with the following characteristics: One school year (10 months). Three types of exercises for a total of 165 min/week. Physically active lessons (3x30 min / week) outdoors. Breaks with PA between classes (5min/day). Homework with PA (10min/day). 25% of the activity was high intensity	Neither executive function, behavioral self-regulation, nor school related well-being mediated the effect of intervention. The children included in the present study scored significantly lower on all mediators at baseline. They found an effect of the intervention on executive function.
Beck et al., 2016	Denmark	7 years	Experimental group 1 (gross motor skills): 59 children Experimental group 2 (fine motor skills): 49 children Control group: 57 children	EF: Eriksen Flanker Task (inhibition) MS: Standardized test developed by experts in Denmark: arithmetic y geometry	Intervention programme with three groups: • Gross motor skills: gross movements that supported mathematical concepts. • Fine motor skills: tasks with Lego blocks related to mathematical principles. • 6-week intervention, 3 times a week, 60 min. each time	Gross motor enrichment produces greater improvements in mathematical performance than fine motor enrichment. The effects on mathematical performance were maintained 8 weeks after the cessation of the intervention in PA. No improvements are found in EF.
Chaddock-Heyman et al., 2020	U.S.A.	8-9 years	Experimental group: 78 children Control group: 72 children	EF: Woodcock-Johnson Battery measures flexibility, planning and interference control. MS: Kaufman Test of Educational Achievement: math concepts and application (comparing numbers, rounding numbers, algebra, calculus, and trigonometry). Math computations: addition, subtraction, multiplication and division, and fractions.	Intervention programme with the following characteristics: 9 months. 2 h after each class day. Non-competitive. 50% of moderate-vigorous activity. 30-35 minutes sustained	The PA group did not show greater gains in EF or MS than the control group. Children in the PA program had greater brain network modularity.

					and then another 90 minutes intermittent. Aerobic fitness testing by VO2 and respiratory ex-change ratio assessed every 20 s	
Davis et al., 2011	U.S.A.	7-11 years	Experimental group 1 (low intensity PA): 55 overweight children Experimental group 2 (acute intensity PA): 56 overweight children Control group: 60 overweight children	EF: Cognitive Assessment System (planning, atten-tion, simultaneous, and successive). MS: Woodcock-Johnson Tests of Achievement III (mathematics in general)	Intervention programme with three groups: 13 weeks. After-class PA programmes with two ses-sions of 20 minutes (acute intensity), one ses-sion of 20 minutes and an-other 20 sedentary (low in-tensity). Vigorous move-ments with emphasis on intensity, not on competi-tion	Improvements in EF (planning) and MS found in both in the low and high intensity condition of PA.
Hecht & Garber, 2021	U.S.A.	10 years	Experimental group: 48 chil-dren Control group: 35 children	EF: NIH Toolbox: Flanker Inhibitory Control and Attention Test (Inhibitory control), List Sorting Working Memory Test (Working Memory) and Di-mensional Change Card Sort Test (Flexibility). MS: Standardized test (STAR Math test) PA: accelerometry ActiGraph during school hours for week (5 days) at week 1 (T1), week 6 (T2), and week 12 (T3; 15 days total).	Intervention programme with the following charac-teristics: 12 weeks. Chil-dren learn to develop their emotional intelligence and executive function skill along with PA.	The PA group did not show significant im-provements in executive functions com-pared to the control group. There were also no significant differences in mathematics performance after the PA programme.
Have et al., 2018	Denmark	6-7 years	Experimental group: 294 children Control group: 211 children	EF: Modified Eriksen Flanker Task (inhibition) MS: Standardized test developed by the Danish na-tional test (Hoegrefe Forlag): calculus and math in terms of the understanding of quantity and numbers, relations, addition, subtraction and geometry	Intervention programme with the following charac-teristics: 9 months. Mathe-matics classes with PA. 6 45-minute mathematics classes with PA a week Maximum 20 minutes of sedentary activity.	Children in PA programme improve in MS but not in FE.
Howie et al., 2015	U.S.A.	9-12 years	Single group of 96 children	EF: Trail Making Test (flexibility), digits (working memory) MS: Timed Math Test: math fluency (resolve an arithmetical problem in 1 minute).	Intrasubject intervention programme with the fol-lowing characteristics: 4 conditions: 10 minutes of sedentary activity, 5 min, 10 min, 20 min break from active classes. Moderate-	Improvements are found in mathematics (10-20 minutes rest condition with PA) but not in EF.

					vigorous activity. Participants took their pulse to achieve rates of 150 beats. Mathematics and FE assessments were conducted before and after each experimental condition (acute effects in a single session)	
Layne et al., 2020	U.S.A.	8-9 years	Experimental group: 19 children Control group: 21 children	EF: Go-No Go task (inhibitory control). MS: Maths tests prepared by the teacher on previously learned material	Intra-subject intervention programme with the following characteristics: 4 weeks. Daily 10-minute sessions before math class. Use of Kinect video game with movements such as jumping or running (Fit-Nexx 1.0). Moderate-high intensity	Children in PA programme improve in EF (reaction time and inhibitory control) but not in MS.
Morris et al., 2019	UK	8-9 years	Experimental group: 158 children Control group: 145 children	EF: Trail Making Test (flexibility); Digit Recall (working memory) Eriksen Flanker Task (inhibition); Animal Stroop task (inhibitory control) MS: Math fluency (MASSAT): addition, subtraction, speed and accuracy.	Intervention programme called The Daily Mile is widely used: Acute intervention consisting of running approximately one mile for 15 minutes before class (acute effects in a single session). Accelerometer and anthropometric measurements	No improvements found in MS and FE in children from acute intervention.

Type of Study: Ex post facto study (correlational analysis)

Authors	Country	Age	Sample by Groups	Assessment instruments		Results
Aadland et al., 2017a	Norway	$M =$ 10.2 (SD = 0.3)	Single group of 697 children	EF: interference (Stroop Golden colour-word test), flexibility (verbal fluency and Trail Making Test), and working memory (WISC-IV direct and inverse digits). MS: Norwegian standardised test designed by the Norwegian Directorate for Education and Training: numeracy	Non-intervention	Significant relationships were found between sedentary time, aerobic fitness and motor skills with executive functions and academic performance, but no relationships were found between these variables and variables with moderate to vigorous PA

				PA and fitness: PA and sedentary time followed for 7 days (ActiGraph GT3X+), and aerobic fitness was measured with Shuttel Run test		
Becker et al., 2018	U.S.A.	$M =$ 14.79 (SD = 2.37)	Single group of 660 children	EF: Tower of Hanoi task (planning) MS: Woodcock–Johnson Battery–Revised PA: Participation in sport was measured by asking parents over the past year. Sports were classified as being open or closed skilled and Each sport was assigned a MET intensity value.	Non-intervention	Significant curvilinear relationship between sport metabolic intensity and EF which case the relationship was positive up to intensities of 25 METs and then became negative Open-skilled sports would be associated with higher math scores. Relation between MS, open-skilled sports and EF.
Davis and Cooper, 2011	U.S.A.	7-11 years	Single group of 170 overweight children	EF: Cognitive Assessment System. (planning). MS: Woodcock-Johnson Tests of Achievement III (mathematics in general) Fitness: is assessed with a treadmill running test. They also measured blood oxygenation and heart rate. They took anthropometric measurements of weight, height, circumference	Non-intervention	There is a relationship between physical fitness and FE and MS. Namely, planning and attention scales, MS and fitness were positively related and negatively related with fatness.
Gerber et al., 2021	South Africa	6-12 years	Single group of 1277 children from low- and middle-income countries.	EF: Flanker Task (inhibitory control) (computer-based version administered via E-Prime) MS: school grades (end of year) Fitness: Cardiorespiratory fitness was assessed by the 20-meter shuttle-run test and upper body strength was determined with the grip strength test. Body weight via electronic scale.	Non-intervention	Higher cardiorespiratory fitness was associated with higher grades in mathematics skills but neither grip strength nor body mass index was associated with mathematical performance. Higher cardiorespiratory fitness was associated with higher performance in Flanker Task in girls but not in boys. Higher grip strength was associated with higher performance in Flanker Task in boys but not in girls.
Migueles et al., 2020	Spain	8-11 years	Single group of 95 overweight children	EF: Flexibility (design fluency test y Trail Making Test); Inhibition (modified version of Stroop); Working Memory (Delayed non match to sample) MS: English version of the Woodcock-Johnson Tests of Achievement III Fitness: Accelerometer activity level assessment: inter-daily stability (IS); intra-daily variability (IV)	Non-intervention	Positive relationship between IS and working memory and between IV and mathematical performance. Lower IV is associated with higher mathematical performance. And higher IS and lower IV is associated with better EF. Relationship of rest-activity pattern with academic performance and executive functioning. Stable and less fragmented rest-activity patterns, and PA earlier in the day, are associated with better academic performance and executive functioning
				Type of Study: Ex post facto study (mediation analysis)		

Authors	Country	Age	Sample by Groups	Assessment instruments		Results
Aadland et al., 2017b	Norway	10 years	Single group monitored up to 7 months: 1129 children	EF: interference (Stroop Golden colour-word test), flexibility (verbal fluency and Trail Making Test), and working memory (WISC-IV direct and inverse digits). MS: Norwegian standardised test designed by the Norwegian Directorate for Education and Training: numeracy Fitness: PA and sedentary time followed for 7 days (ActiGraph GT3X+), and aerobic fitness was measured with Shuttel Run test	Non-intervention	The executive function did not mediate the prospective relations between PA and academic performance but a small mediating effect of the executive functions between aerobic fitness (Shuttel Run test) and numeracy.
Kvalo et al., 2019	Norway	9-10 years	Single group of 378 children	EF: Stroop Golden colour-word test (interference), Verbal semantic fluency (naming animals in 60), Backward Digit Span (WAIS-IV) (working memory) and Trail Making Test (flexibility) MS: The standardized national test of the Ministry of Education and Research: numbers, measurement and statistics (mathematics and reading) Fitness: The aerobic fitness of the children is measured through a 10-minute running test called Interval Running Test: they run between two lines 20 metres apart for 10 minutes and the distance run is the result of the test. Weight, height, waist circumference and body mass index were also measured.	Non-intervention	Mediation analyses showed a significant indirect relationship of aerobic fitness on MS while no significant direct relationship of aerobic fitness on MS was found.
Muntaner-Mas et al., 2020	Spain	9-13 years	Single group of 130 children	EF: Trail Making Test (flexibility); Stroop Golden colour-word test (inhibition) MS: Academic performance mathematics subject grade 0-10. Fitness: Different heart rate measurements were taken in physical education classes using PA watches indicating high intensity (Polar H10 Sensor)	Non-intervention	A relationship is found between maximum heart rate (fitness) and academic performance in mathematics. A relationship is found between minimum heart rate (fitness) and some EF: flexibility (visual scanning and sequencing) and inhibition (colour naming).
Nuñez et al., 2019	Spain	10-16 years	Single group of 490 children	EF: Eriksen Flanker Task (inhibition), MS: Woodcock-Muñoz Battery III: Math fluency (Woodcock-Muñoz Battery-III): calculation: addition, subtraction, and multiplication in 3 minutes. Speed. Fitness: Shuttle Run Test: this consists of running a distance of 20 m when a signal sounds with increasing frequency. It ends when the subject stops due to exhaustion.	Non-intervention	The sample is divided into three clusters according to fitness level. Only in cluster high was a relationship found between fitness level and mathematics, but not in the other two clusters. No effect of inhibition on mathematics was found either. In addition, the high fitness group showed differences with respect to the low fitness group in inhibition and mathematics. Inhibition

						does not mediate the relationship between cardiorespiratory fitness and math fluency.
Oberer et al., 2018	Switzer-land	5-7 years	Single group of 134 chil-dren	EF: Eriksen Flanker Task: inhibition and flexibility to change; Backward Colour Recall Test: verbal up-date MS: Sequences and Addition/Subtraction (Heidel-berger Rechentest) Fitness: Physical fitness was measured with 6-mi-nute run, Jumping Sideways task to measure agility, and standing long jump task to measure strength.	Non-intervention	EF and physical fitness are predictors of academic performance when entered inde-pendently but when entered in the same model, only EF remain significant. The re-lationship of physical fitness with aca-demic performance appears to be mediated by EF.
Schmidt et al., 2017	Switzer-land	10-12 years	Single group of 236 chil-dren	EF: E-Prime Software; Update: Non-spatial n-back task; Inhibition: Child adapted Eriksen Flanker Task; Change (flexibility): Flanker Task (blocks) MS: Deutscher Mathematiktest 5+ (arithmetic, ge-ometry and solving written mathematical problems) Fitness: Aerobic fitness was measured with: 20m Shuttler Run Test (endurance), Standing Long Jump Test (strength); Jumping sideways test (coordina-tion). The general levels of PA were measured with Physical Activity Questionary-Children.	Non-intervention	The path from motor ability to academic achievement (without EF as mediator) was significant that decreased to non-signifi-cant when EF was included as a mediator. The path from motor ability to EF as well as from EF to MS were significant. Executive functions are found to mediate between physical fitness and mathematics.
Visier-Alfonso et al., 2020	Spain	8-11 years	Single group of 563 chil-dren	EF: Inhibition (Eriksen Flanker Test; Cognitive flex-ibility (Dimension Change Card Sort); Working memory: List Sorting Working Memory Test. MS: Academic performance: Mathematics subject score 0-10. Fitness: cardiorespiratory fitness and VO2 were measured during the Shuttle Run Test (running 20 metres at different speeds). Anthropometric measures were also used (Weight, height, and BDI).	Non-intervention	A relationship is found between physical fitness, mathematics, and EF. Performance functions (inhibition and flexibility) are a mediator between cardiorespiratory fitness and mathematics. In the first step, cardi-orespiratory fitness was positively related to the executive function domains. In the second step, the regression coefficients of cardiorespiratory fitness were positively associated with academic achievement in all mediation models. In the last regression model, the executive function domains were positively related to the dependent variable (p <0.001), and the relationship between cardiorespiratory fitness and aca-demic achievement became weaker (alt-hough significant) when the executive function domains were included in the model.

Note: EF=Executive functions; MS: Mathematical skills; PA: Physical activity; WISC-IV: Wechsler Intelligence Scale for Children; MET: metabolic equivalent of task; IS: Inter-daily stability; IV: Intra-daily variability.

Discussion

The objective of this review is to explore how is the relationship between the variables of interest. The search for information yielded 21 articles on the relationship between the variables of fitness/PA, EF, and MS in primary school children (5-16 years). Of the nine causal relationship studies (applying an intervention programme in PA), only three studies have not found improvements in either EF or MS (Chaddock-Heyman et al., 2020; Hecht & Garber, 2021; Morris et al., 2019). The remaining six have found improvements in both variables (Davis et al., 2011), only in MS (Beck et al., 2016; Have et al., 2016; Howie et al., 2015) or only in EF (Aadland et al., 2018; Layne et al., 2020). All bidirectional correlation studies have found significant relationship between fitness, EF and MS (Aadland et al., 2017a; Davis & Cooper, 2011; Muntaner-Mas et al., 2020) or between PA, EF and MS (Becker et al., 2018; Migueles et al., 2020). Five of the six studies that have analysed the mediation role of EF find significant results between fitness/PA and MS confirming the mediating effect of EF (Aadland et al., 2017b; Kvalø et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). Only one study that studied the mediational effect of EF between fitness/PA and MS found no statistically significant mediation (Núñez et al., 2019).

The first objective of the study is to explore the results based on the research design used (causal or bidirectional relationship). For this reason, the characteristics of the studies will be analysed in detail to identify a common pattern that will shed some light on the true relationship between the variables studied. From the nine intervention studies, only one study found an effect from PA both on EF and MS (Davis et al., 2011). Therefore, it seems that intervention studies fail to demonstrate the causal relationships between variables. These results indicate that there are currently some differences between the findings of the intervention studies (causal relationship) and the results of the correlation studies (bidirectional relationship).

Regarding sample size, of the three intervention studies that found no significant improvements, two had a small sample size (Chaddock-Heyman et al., 2020 with an experimental group of 78 children and Hecht & Garber, 2021 with 48 children) while the other used a slightly larger sample (experimental group of 158 children) (Morris et al., 2019). The study by Davis et al. (2011) that found effects on both variables also had a small sample size of 55 subjects in the acute PA group, which is where the effects were observed. In other words, it seems that the sample size would not influence the results. As for correlational studies, the five studies used samples ranging from 95 (Migueles et al., 2020) to 1227 participants (Gerber et al., 2021). Regarding mediation studies, sample sizes ranged from 134 (Oberer et al., 2018) to 1129 participants (Aadland et al., 2017b), and all but one of them found significant results of the mediating role of EFs. The study that found mediation with MS, but not with EF had a smaller sample size had a sample size of 490 (Núñez et al., 2019). It appears that sample size does not affect the results of ex post facto designs either.

To finish analysing the characteristics of the sample, it should be noted that the study by Davis et al. (2011) uses a sample of overweight children, while the studies that have not found improvements use a sample of children of normal weight (Chaddock-Heyman et al., 2020; Hecht & Garber, 2021; Morris et al., 2019). In correlational studies, two of the studies that find a relationship between the three variables also use a sample of overweight children (Davis & Cooper, 2011; Migueles et al., 2020). These characteristics could, possibly, influence the relationship between the study variables, with overweight children tending to benefit more from PA. Indeed, some studies suggest that overweight children tend to benefit more from PA (Must & Tybor, 2005) or physically active lessons (Grieco et al., 2009; Vazou & Smiley-Oyen, 2014), and even that overweight children have a lower level of academic achievement (Sallis et al., 1999). In relation to this aspect, studies have shown that children with obesity have lower scores in mathematics and geometry, showing greater difficulties in learning these academic skills (Heshmat et al., 2014).

Another aspect of note regarding the assessment of EF in the different studies, is that while the study by Davis et al. (2011) assesses only one component of EF, planning, the three studies that found no effect from the PA programme (Chaddock-Heyman et al., 2020; Hecht & Garber, 2021; Morris et al., 2019) measured different processes of EF such as flexibility, planning, working memory, inhibition, problem solving and interference control. In the case of mediation study Muntaner-Mas et al. (2020) included the measurement of a single component (interference) while the other studies measure several components such as interference, fluency, flexibility and working memory (Aadland et al., 2017; Kvalø et al., 2019; Schmidt et al., 2017; Visier-Alfonso et al., 2020) and all of them found a mediational role of EF. Regarding to correlational studies, two studies included the measurement of a single component (Davis & Cooper, 2011: planning and Gerber et al., 2021: inhibition). This aspect should be emphasized since perhaps the effect of fitness/PA on EF may be specific to a particular component being measured, and improvements may be found in some concrete components, such as working memory, and not in others. It would even be useful to explore whether certain components of EF could be mediators between fitness/PA and MS in a specific way in order to propose specific intervention programmes that work on each of these components. Along these lines, Nieto-López et al. (2020) have found that pre-schoolers in higher cardiorespiratory categories have better inhibitory control than do their peers with lower fitness levels but did not show greater cognitive flexibility. In fact, other studies agree in finding such an effect of PA on the inhibitory component, but not on cognitive flexibility (Tomporowski et al., 2008; Vazou & Smiley-Oyen, 2014), which they explain by an improvement in alertness through an increase in blood flow and circulating catecholamine (Tomporowski et al., 2008; Verburgh et al., 2014).

Regarding the measurement of MS only three studies used academic performance; two are correlation studies and the other a mediation study (Muntaner-Mas et al., 2020; Visier-Alfonso et al., 2020). All studies found significant results in line with the rest of the studies, so the use of these measures does not seem to have had any effect. It is striking that only one study (Oberer et al., 2018) has conducted a detailed assessment of the different components of MS with the rest of the studies obtaining a single measure. MS can be differentiated into several processes such as numeracy, quantification, calculation, arithmetic or problem solving. It would be important to carry out further research on this aspect because specific relationships could be found between each of the components of the MS and the different processes of EF (for example, finding more effect on arithmetic problem solving versus numeration).

Regarding the intervention studies that found some improvement on MS (Beck et al., 2016; Have et al., 2018; Howie et al., 2015), EF (Aadland et al., 2018; Layne et al., 2020) or both (Davis et al., 2011), three of them used PA programmes that included sessions teaching MS and concepts (Aadland et al., 2018; Beck et al., 2016; Have et al., 2018). In fact, the three studies that found no effect from the intervention programme on either MS or EF did not incorporate review of mathematical concepts and skills (Chaddock-Heyman et al., 2020; Morris et al., 2019). Along these lines, some studies argue that PA designed as cognitively demanding or enriched, provides greater cognitive benefits (Best, 2010; Pesce et al., 2009) especially on processes such as executive attention (Tomporowski et al., 2010). This approach and the need to increase the time of moderate to vigorous PA during school time has led several studies to the approach known as Physical Activity in Academic Lessons, which has been shown to be particularly beneficial for improving mathematics and reading (Martínez-López et al., 2020). It seems, therefore, that PA acts directly on EF and other cognitive processes, according to Howie

& Pate's model (2012), and these, in turn, on MS. The impact of these results may help us to propose PA based on the components of EF (working memory, inhibition, planning...) and which could possibly provide a greater mediation between the variables.

Regarding the duration of the PA programme, we found a disparity of results. Among the three studies with longer programmes (between 9 and 10 months), there is one that found no improvement in either variable (Chaddock-Heyman et al., 2020), one that only found improvements in EF (Aadland et al., 2018) and another that only found improvements in MS (Have et al., 2018). In the four studies using shorter programmes (between 4 and 13 weeks), there is also no clear consensus on the results, with two of them finding improvements in EF (Davis et al., 2011; Layne et al., 2020), one in MS (Beck et al., 2016) and the other found no effect (Hecht & Garber, 2021). There are two studies that measure the acute effects of PA in a single session (Howie et al., 2015; Morris et al., 2019) with no improvements in EF, although one of them did find improvements in MS (Howie et al., 2015). Therefore, it seems that, in these cases, the duration of the intervention programme does not translate into a greater effect. This is in contradiction with the findings of other studies indicating that high intensity PA would only have temporary effects (Chang et al., 2012).

Regarding the PA levels of the studies, it is difficult to compare the intensity between studies, as almost all the selected studies include moderate or acute intensity PA, although it is not entirely clear, in some cases, how they make this categorisation of intensity since practically no study offers a single operational definition of this variable or its categorisation. Only Becker et al. (2018) explored PA intensity as a mediating variable for the effect of PA on executive functioning and found a significant curvilinear relationship. This biphasic relationship has also been found in animal studies, both in the rate of neurogenesis and in spatial memory capacity, in response to different intensities of PA. Neurogenesis levels and spatial memory capacity were lower in both sedentary animals and those performing high PA intensities and were maximal for the group performing intermediate levels of PA (Gradari et al., 2016; Inoue et al., 2015; Okamoto et al., 2015).

In this regard, in recent years the importance of the hormesis concept where we find an inverted U-shaped relationship between PA intensity and cognitive benefits (Gradari et al., 2016) is re-emerging (Trejo & Sanfeliu, 2020). Above a certain amount of PA, the effects would become negative as they would imply a high level of oxidative stress, so that the effects on cognitive functioning would also be reduced (oxidative stress, elevated cortisol...). This specific limit would be different for each person, which would mean that the same intervention programme would not have the same effects on all children, as this maximum point (peak of the curve) depends on physical conditions and a series of other individual factors. Therefore, in order to seek optimal benefit from PA, its intensity should be personalised for each child. However, more studies are needed to further investigate which factors determine the ideal amount of PA (Gradari et al., 2016).

The second specific aim of the study has been to review the mediating effect that EF might exert between fitness/PA and MS. In this case, five of six ex post facto studies support this hypothesis (Aadland et al., 2017b; Kvalø et al., 2019; Oberer et al., 2018; Schmidt et al., 2017; Visier-Alfonso et al., 2020). However, it should be noted here that the mediational relationship of EFs that these studies showed was between aerobic fitness and MS, not with PA. In fact, Aadland et al. (2017b) found a mediational effect of EFs only in case of fitness, but not in PA. These results may indicate that the decisive variable is the physical fitness of the child and not PA. Fitness is influenced by PA (Dencker et al., 2006; Pozuelo-Carrascosa et al., 2018), in addition to other factors (Morrow et al., 2013). This coincides with the conclusion of Chaddock et al. (2011), which confirms that poor physical fitness produces effects on the brain structures and functions of children that can have repercussions on school performance.

We can extract from the results derived from the mediational analyses that there seems to be a mediational effect of EF on the relationship between fitness and MS. This leads us to see the importance of these cognitive processes, since there may be children who have a high physical fitness and low scores in the EF, and this leads to the fact that physical fitness does not have a positive impact on MS. There is a need to develop programs to stimulate fitness and EF to improve MS.

Despite these patterns that seem to be beginning to emerge in the studies explored, it should be borne in mind that due to the variability in the characteristics of the studies and the different results obtained in each of them, it is very difficult to reach an unequivocal conclusion from this literature review. Furthermore, it should be noted that there are few standardised tools for assessing MS, especially those that assess the complexity of mathematical competence and its different components (numerical representation, counting, calculation, arithmetic, problem solving, etc.). For this reason, there is a need for more longitudinal studies to test the effect of

PA in the long term (even up to the age of 16) on MS, considering EF as a mediating variable. In these studies, it would be useful to study the differential effect of the different components of EF and MS, as well as the characteristics of the sample (e.g., with overweight children) and the adjustment of the appropriate level of intensity for each pupil considering the concepts of hormesis. These studies could provide information on how to achieve a greater effect of school-based PA on EF and thus on MS learning. It would also help to establish the appropriate number of hours in school curricula and to specify what type of sport, at what ages and with what timing PA would help students, not only in terms of health but also in terms of school development and learning.

Based on the results obtained from this systematic review we can conclude that it seems likely that EF could act as a mediator between fitness and MS, given that some components of EF to a higher level appear to be related to an increase in MS in children aged 6 to 12 years, although there is a lack of causal studies to corroborate this. These results may be affected by the type of study design used (correlational vs. experimental), the intensity of the PA (the hormesis concept), the characteristics of the sample (overweight children seem to derive greater benefits from EF) and the component analysed in both EF and MS.

Availability of data

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of interest

There are no relevant financial or non-financial competing interests to report.

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