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THE NEUROPHYSIOLOGICAL EFFECTS OF PHYSICAL ACTIVITY IN CHILDREN: SYSTEMATIC REVIEW NEUROFISIOLÓGICOS DE LA ACTIVIDAD FÍSICA EN LOS NIÑOS: REVISIÓN SITEMÁTICA

LOS EFECTOS NEUROFISIOLÓGICOS DE LA ACTIVIDAD FÍSICA EN LOS NIÑOS: REVISIÓN SITEMÁTICA

Enrique Jiménez Vaquerizo [1A-F]
[1] Facultad de Educación del Campus de Segovia- Universidad de Valladolid (UVA), España

Responsabilidades. (A Diseño de la investigación; B Recolector de datos; C Redactor del trabajo; D Tratamiento estadístico; E Apoyo económico; F Idea original y coordinador de toda la investigación)

Responsabilities. (A Research design; B Data collector; C Editor of the paper; D Statistical processing; E Financial support; F Original idea and coordinator of the whole research)

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Correspondence:
Enrique Jiménez Vaquerizo. vakerizo.sportsalud@gmail.com

ABSTRACT

The practice of regular physical activity provides several benefits related mainly to the improvement of health and quality of life, as well as the control of risk factors for diseases, a topic widely recognized today. However, recent studies have shown that the relationship between physical activity and cognition is allowing great advances and positive results. In the present work and through a systematic review, the current evidence that establishes the causality of neurophysiological changes in the brain structure of healthy children and with pathologies is compiled. A total of 23 studies were selected and analyzed through which it was possible to conclude that there is a beneficial association between long-term physical activity and changes in neurophysiological functions.

KEY WORDS: physical activity, children, neuroscience, neuronal function, plasticity and benefits

RESUMEN

La práctica de actividad física regular proporciona varios beneficios relacionados principalmente con la mejora de la salud y la calidad de vida, así como con el control de los factores de riesgo de enfermedades, un tema ampliamente reconocido en la actualidad. Sin embargo, estudios recientes han demostrado que la relación entre actividad física y cognición está permitiendo grandes avances y resultados positivos. En el presente trabajo y mediante una revisión sistemática, se recopila la evidencia actual que estable la causalidad sobre los cambios neurofisiológicos en la estructura cerebral de niños sanos y con patologías. Un total de 23 estudios fueron seleccionados y analizados mediante los que se pudo concluir que existe una asociación beneficiosa entre la actividad física a largo plazo y los cambios en las funciones neurofisiológicas.

PALABRAS CLAVE: actividad física, niños, plasticidad, neuroimagen, plasticidad, desarrollo y beneficios

INTRODUCTION

Physical activity has been associated with a variety of physical, behavioural, cognitive and academic benefits (1,2). A growing body of literature indicates that the majority of the paediatric population does not even approach the 60 minutes of moderate intense physical activity per day recommended for children (3). Furthermore, the prevalence of a sedentary lifestyle among children is rapidly increasing (4). The apparent lack of physical activity among children is of particular concern in light of the existing evidence on the beneficial effects of physical activity on brain development (5). The beneficial effects of physical activity on the brain are thought to have longer-lasting effects in childhood compared to adulthood, suggesting that physical activity in childhood also contributes to brain functioning in adulthood (6).

In line with this idea, physical activity is also suggested as a potential treatment to improve brain development in paediatric clinical populations, such as children with depression or attention deficit hyperactivity disorder (ADHD) (7). For example, exercise intervention studies indicated beneficial effects on behavioural and cognitive symptoms of ADHD (8,9). In addition, altered brain functions and cognitive dysfunction have been found in obese children compared to leaner children (10).

Recent studies have shown that exercise also has beneficial effects on cognition in this population (11). However, to date it remains largely unknown which underlying neural mechanisms give rise to the beneficial effects of physical activity in children. Fundamental neuroscience findings have identified several pathways through which physical activity may act on brain structure and neurophysiological functioning. A single session of physical activity (or short-term physical activity) has been shown to directly improve cerebral blood flow (12) and trigger the positive regulation of neurotransmitters that facilitate cognitive processes (e.g., epinephrine, dopamine) (13).

These immediate effects resulting from a single session of physical activity are often referred to as acute effects. Longer periods of continuous physical activity (long-term physical activity) are thought to trigger additional pathways that exert beneficial effects on brain development. Long-term physical activity has been shown to elevate levels of neurotropic factors (e.g. brain-derived neurotrophic factor and nerve growth factor), which are known to stimulate neural blood vessel formation and neurogenesis (13,14).

These prolonged effects of long-term physical activity are often referred to as chronic effects. The observed acute and chronic effects indicate that physical activity is potent in changing brain structure and neurophysiological functioning through differential mechanisms. Consistent with this evidence, previous studies in children have revealed associations between physical fitness - which is considered an indirect measure of long-term physical activity (15) - and brain structure as well as neurophysiological function. With respect to brain structure, for example, cross-sectional magnetic resonance imaging (MRI) studies in children aged 9-10 years have shown that greater aerobic fitness is associated with larger brain volumes, including basal ganglia and bilateral hippocampal volumes (16).

With respect to neurophysiological functioning, several cross-sectional electroencephalography (EEG) studies in children aged 9-10 years have shown that greater aerobic fitness is associated with greater allocation of attentional resources (as measured by the P3 component of the event-related potential) in tasks measuring interference control (17), cognitive flexibility (18), language processing and mathematical processing (19). Although these cross-sectional studies indicate an association between physical fitness and neural mechanisms and support the idea that long-term physical activity has beneficial effects on children's brains, they do not provide causal evidence. In contrast, intervention effectiveness studies, such as randomised controlled trials (RCTs) and crossover trials, do allow causal effects to be assessed.

The present study aims to provide an overview of all available RCTs and cross-over trials testing the causal effects of physical activity on brain structure and neurophysiological functioning in children. Previous reviews of studies on this topic did not use a systematic approach (20), o conclusions were based (in part) on studies using study designs that cannot provide evidence of causality (association studies or quasi-experimental designs) or did not attempt to quantify effects (21,22). The mechanisms underlying the effects of physical activity on neuroimaging measures may be influenced by health status. On this basis, a distinction will be made in the present review between studies in clinical and healthy samples of children.

Changes in brain structure and neurophysiological functioning parallel to changes in cognitive functioning potentially provide more information on the mechanisms underlying the effects of physical activity. Therefore, results presented in studies using correlation/regression analyses or coincident positive effects of physical effects on neuroimaging and behaviour will allow us to determine whether the reported changes in brain structure and neurophysiological functioning are accompanied by beneficial effects of physical activity on cognitive functioning.

MATERIAL AND METHODS

A systematic literature search was conducted following the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The focus in the literature search was on randomised controlled trials (RCTs). Only papers written in English and Spanish were reviewed.

Inclusion criteria were as follows: 1) RCT studies or crossover design, 2) papers examining the effects of moderate to vigorous physical activity on brain structure and/or neurophysiological functioning 3) research involving children with an average age between 5-12 years 4) papers with a no intervention control group (RCT) or control condition (crossover trials).

The search strategy was applied in the electronic databases PubMed, Embase, SportDiscus, Scopus and Cochrane by combining search terms (MeSH terms and thesaurus) related to physical exercise and children, and Brain Imaging or electroencephalography and their equivalents (in Spanish and English) and combined with the Boolean operators AND and OR.

The initial search retrieved 2,275 unique articles, of which only 222 were analysed after applying search limits (study type, date and full text). After reading these 222, a total of 37 articles were considered relevant based on title and abstract selection. These 37 articles were assessed for eligibility based on full text, after which 25 articles met all inclusion criteria. Two studies were excluded due to contaminating factors such as lack of sufficient intensity of physical activity intervention, relaxation (23) or assessment of neurophysiological functioning in relation to food stimulus processing (24). Finally, a total of 23 articles were included in the review (see Figure 1).

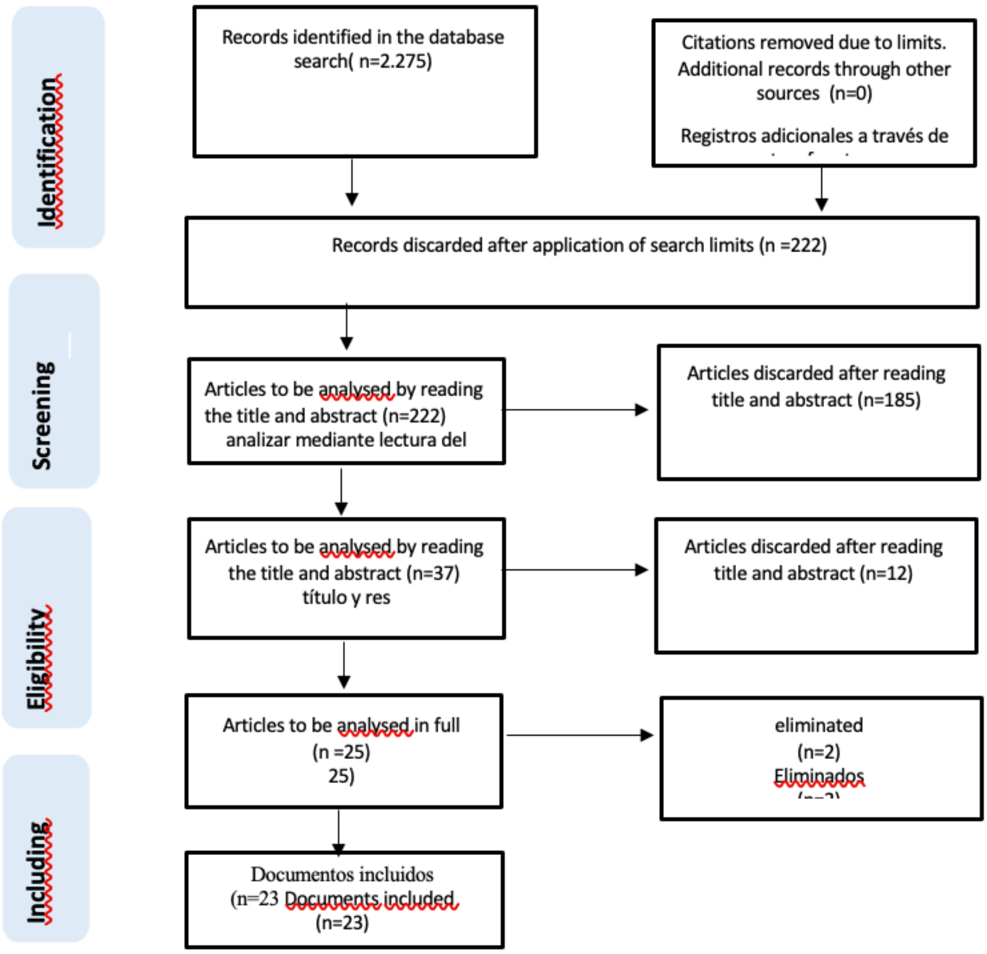

Figure 1. Flowchart (flow diagram)
Source: Own elaboration based on PRISMA template.

RESULTS

The following data were extracted from the included articles: a) sample characteristics (for each study group: sample size, mean age and sex distribution; b) intervention or control characteristics (type, intensity and frequency of physical activity or control sessions); c) outcome measures (imaging modality and cognitive tests assessed, if available).

The quality of included studies was performed using the Cochrane Collaboration's tool for risk of bias in randomised trials. This tool examines selection bias (random sequence generation and allocation concealment), conduct bias (blinding of participants and staff), detection bias (blinding of outcome assessment), attrition bias (participants lost during the study) and reporting bias (selective outcome reporting of pre-specified outcome) measures in methods sections or clinical trial registries). In addition, all studies were assessed for sampling bias (representativeness of the sample for the target paediatric population). For each of these categories of bias, studies were classified as low, unclear or high risk of bias.

The overall risk of bias of the included studies varied, but was generally low. However, in only five studies were outcome assessors blinded (25-29) and in seven studies, the included population was not a representative sample of the general healthy or clinical paediatric population (30-36).

Acute effects of physical activity

No studies addressed the acute effects of physical activity on brain structure. One study addressed the acute effects of physical activity on cerebral blood flow (37). The results did not indicate acute effects of physical activity on cerebral blood flow in the frontoparietal, executive control and motor networks. Crossover studies addressed acute effects on neurophysiological functioning, of which seven included healthy children (EEG; k = 6; MRI; k = 1). All studies in healthy children showed acute effects induced by physical activity on neurophysiological functioning. Results indicated improved neurophysiological functioning during rest (36) and goal-directed behaviour (36,38), increased allocation of attentional resources during task performance (30, 39, 40) and improved conflict processing (30).

Two studies reported accompanying beneficial effects on measures of cognitive performance (39,40) or academic functioning (39). Four studies addressed the acute effects of short-term physical activity on neurophysiological functioning in clinical samples (i.e., ADHD; EEG k = 4) and all of these studies indicated beneficial effects induced by physical activity. Results indicate an increased allocation of attentional resources towards the target stimulus (18, 36), reduced processing time (18), improved performance of anticipatory attention and motor preparation (31) and an improved theta/beta ratio in resting EEG (32). Two studies reported co-existing beneficial cognitive effects and beneficial effects on academic performance (31, 18).

Chronic effects of physical activity

Four studies (MRI k = 4) described chronic effects on brain structure in which one study included a healthy population and three studies included a clinical population (obesity k = 2; deafness k = 1). All studies used Diffusion Tensor Imaging, which is an MRI-based measure of white matter integrity (WMI). The study evaluating healthy children observed increased WMI in the knee of the corpus collosum after long-term physical activity compared to the control group (25). The two studies evaluating obese children observed a higher WMI after long-term physical activity compared to a control group. Neither study reported concomitant objective cognitive measures. In contrast, a study in deaf children found a decrease in WMI after long-term physical activity (41). The study also observed accompanying effects on measures of cognitive performance, of which some effects were beneficial, while others were detrimental. Ten studies described chronic effects on neurophysiological functioning, of which six focused on healthy children (EEG; k = 5; MRI: k = 1). Five studies in healthy children showed physical activity-induced effects on neurophysiological functioning. Results indicated improved resting-state attention (42) and altered brain activation in the right anterior PFC (43), improved error detection (27), increased efficiency of attention and motor processes (44), increased allocation of attentional resources during goal-directed behaviour and reduced processing time (28).

In addition, the observed changes in neurophysiological functioning were accompanied by improved cognitive performance on tasks in all studies (27,28,42-44). Four studies described chronic effects on neurophysiological functioning in clinical samples (EEG; k = 1; MRI; k = 3). One study investigated the chronic effects of physical activity in children with ADHD and found improved alertness after long-term physical activity as measured by EEG. This result was not accompanied by an improvement in cognitive task performance (45). All three studies investigating the chronic effects of long-term physical activity in obese children indicated changes in neurophysiological functioning as measured by functional magnetic resonance imaging. The results indicate altered brain activity during direct target behaviour (26,35) and resting state (33). None of these studies observed accompanying beneficial effects on cognitive task performance.

A synthesis of the studies and the most relevant items is presented in table 1 below:

Table 1. Summary of studies

Author/ Nº	Type of study	Sample	Intervention/ control	Outcome measure	Results
ChaddockHeyman et al. (25)	ECA/pre-post	n=143 (healthy) Average age:8.7	Physical activity programme Vs Waiting list (600 min. x sem/ 36 sem)	Brain structure (DTI)	Decrease in activation in the condition of AF*
Davies et al., (26)	ECA/pre-post	n=19 (obese) Average age: no data	Aerobic Physical Activity Programme Vs No Activity (200 min x sem/13 sem)	Brain function (IRM)	Increased activation in bilateral CBP under the condition of AF* Decreased activation in bilateral PPC in the condition of AF*
Drollette et al. (27)	ECA/pre-post	n=308 (healthy) Average age: 8.8.	Physical activity programme Vs Waiting list (600 min. x sem/ 36 sem)	Brain function (EEG)	Increased RER amplitudes in the control condition *

Author/ Nº	Type of study	Sample	Intervention/ control	Outcome measure	Results
Hillman et al. (28)	ECA/pre-post	n= 221 (healthy) Average age:8.8	Physical activity programme Vs Waiting list (600 min. x sem/ 36 sem)	Brain function (EEG)	Greater improvement in the d condition of AF
Ludyga et al. (2019) (29)	ECA/pre-post	n=37 (healthy) Average age:9.3	Aerobic training group Vs Co-ordinating training group Vs No activity (135 min. x sem/ 10 sem)	Brain function (EEG)	No significant differences
Chu et al. (2017) (30)	Transversal/post-intervención	n=20 (healthy) Average age:10.5	Treadmill Running Session Vs Reading (30 min)	Brain function (EEG)	Higher amplitudes of P3 after the AF Smaller SP amplitudes of conflict after the AF* ;RT slightly shorter after the AF(p = 0,057)
Chuang et al (31)	Transversal/post-intervención	n=19 (TDAH) Average age:9.4	Running on a treadmill Vs Watching videos (30 min.)	Brain function (EEG)	Smaller CNV 2 frontal amplitudes for No Go stimuli after the No Go condition of AF RT shorter after the AF
Huang et al. (32)	ECA/pre-post	n= 24 (TEA) Average age: no data	Running on a treadmill Vs Watching videos (30 min.)	Brain function (EEG)	No significant differences
Krafft et al. (33)	ECA/pre-post	n= 22 (Obese) Average age:9.4	Physical activity programme Vs Sedentary control group (200 min. x sem/ 32 sem)	Brain function (resting-state MRI))	Decrease of synchrony in the AF condition; Decrease of synchrony in the AF condition; Increase of synchrony in the AF condition
Kraft et al., (34)	ECA/pre-post	n= 43 (Obese) Average age:9.8	Physical activity programme Vs Sedentary control group (200 min. x sem/ 32 sem)	Brain function (IRM)	Decreased activation in the AF condition in: bilateral precentral gyrus, MFG, paracentral lobe, postcentral gyrus, SPL, IPL y ACC; > Increased activation in the condition of AF en: SFG bilateral, MFG, MFG, cingulate gyrus and ACC
Krafft et al (35)	ECA/pre-post	n= 18 (Obese) Average age:9.8	Physical activity programme Vs Sedentary control group (200 min. x sem/ 32 sem)	Brain structure WMI (MRI)	An improvement in executive function was observed in the condition of AF; an increase in WMI was observed in the condition of AF; decrease of WMI was observed in the condition of AF.
Hung et al.,(36)	Transversal/post-intervención	n= 34 (TEA) Average age:10.2	Running on a treadmill Vs Watching videos (30 min.)	Brain function (EEG)	Higher P3 amplitudes during trials that required the involvement of working memory following the AF
Pontifex et al. (37)	Transversal/post-intervención	n= 41 (healthy) Average age:10.2	Treadmill running Vs Treadmill running at minimum intensity (20 min.)	Cerebral blood flow (IRM)	No significant differences
Chen et al. (38)	Transversal/post-intervención	n=9 (healthy) Average age:10	Cycle ergometer Vs Sedentary rest session (35 min.)	Brain function (IRM)	Increased activation after the training session of AF
Hillman et al. (39)	Transversal/post-intervención	n=20 (healthy) Average age:9.6	Treadmill Run Vs Rest Session (20 min.)	Brain function (EEG)	Increased P3 amplitudes after the AF session; Improvement after the training session AF

Author/ Nº	Type of study	Sample	Intervention/ control	Outcome measure	Results
Lind et al (40)	Transversal/post-intervención	n=33 (healthy) Average age:11.8	Football Vs walking football (20 min.)	Brain function (EEG)	Greater amplitudes of P3 in Fz in children performing football compared to the walking football group and the control group* RT shorter football condition compared to walking football group
Xiong et al., (41)	ECA/pre-post	n=18 (deaf children) Average age:	Aerobic exercise Vs no intervention (180 min. x sem/ 11 sem)	Brain structure WMI (MRI)	Improved performance in the condition of AF
Kim & So (42)	ECA/pre-post	n= 26 (healthy) Average age:8.75	Combined Exercise Training (CET) Sedentary Control Group (180 min. x sem/ 16 sem)	Brain function (EEG)	Higher amplitudes in the condition of AF; Further improvement in the condition of AF
Chaddock-Heyman et al (43)	ECA/pre-post	n= 23(healthy) Average age:8.9	Physical activity programme Vs Waiting list (600 min. x sem/ 36 sem)	Brain function (IRM)	Decrease in activation in the condition of AF * ; ns* ; Improvement of the condition within the AF during neutral and incongruent tests > Improvement of the condition within the AF during the neutral test
Kamijeo et al (44)	ECA/pre-post	n= 26(healthy) Average age:8.9	Physical Activity Programme Vs Waiting List (600 min. x sem/ 36 sem)	Brain function (EEG)	Higher amplitudes of P3 in the condition of AF *
Lee et al (45)	ECA/pre-post	n=12 (TEA) Average age:8.8	Combined exercise group No-exercise control group (600 min. x sem/ 12 sem)	Brain function (EEG)	Higher beta-wave amplitudes in the condition of AF *
St-Louis Deschenes et al (46)	Transversal/post-intervención	n=32 (healthy) Average age:10.4	Cycle ergometer Sedentary session on Ergometer (30. min)	Brain function (EEG)	Increased P3b amplitudes after the AF
Wollseiffen et al. (47)	Transversal/post-intervención	n=16 (healthy) Average age:9.1	Aerobic exercise Art class (45 min.)	Brain function (EEG)	Decrease in cortical current density activity after the AF session*

DISCUSSION

Based on 23 studies with RCT or crossover designs representing 973 unique children, the results provide evidence of physical activity-induced changes in neuroimaging measures and, in particular, small beneficial effects of physical activity on neurophysiological functioning in children. These findings underline the importance of physical activity for brain development in children. The current study differentiates between acute effects resulting from a single episode of physical activity (or short-term physical activity) and chronic effects resulting from longer periods of continuous physical activity (long-term physical activity).

The analysis revealed support for both acute and chronic effects on neurophysiological functioning, while no evidence was found for effects on brain structure. This observed discrepancy is mainly explained by a very limited number of studies (n=4) assessing the effects of physical activity on brain structure, which also assessed heterogeneous samples of healthy, obese and deaf children.

It is not known whether these groups respond comparably to physical activity. If sample-specific mechanisms may contribute to the effects of physical activity, this may have contributed to the heterogeneity in the pooled effect size. Analyses targeting specific neuroimaging measures showed that the acute effects of physical activity might be driven primarily by changes in attentional resource allocation (P3 amplitude), rather than changes in processing time (P3 latency). This is in line with the results of a recent systematic review indicating that physical activity and cardiorespiratory fitness are associated with P3b modulation during cognitive control and attention tasks (46). Although this hypothesis awaits replication in future research, a specific effect of physical activity on attentional resource allocation would be highly relevant when physical activity is considered as an intervention to promote cognitive functioning in diverse populations with poor attentional skills, such as typically developing children in school groups or clinicians such as children with ADHD.

The current review made a distinction between studies in clinical and healthy samples of children. Although no evidence was found for differences between healthy and clinical populations in the magnitude of the effect of physical activity, there is a possibility that the dominant mechanisms of action underlying the effects of physical activity on brain structure and neurophysiological function depend (in part) on the health status and pathophysiology of the disorders studied. For example, it is suggested that physical activity may be a particularly powerful treatment for ADHD because it is supposed to up-regulate dopamine and noradrenaline, two neurotransmitters that are implicated in the pathophysiology of the disorder.

Interestingly, it is also suggested that the up-regulation of dopamine and noradrenaline underlies the beneficial effects of stimulant medications used to treat ADHD and alleviate ADHD symptoms (8). It is also suggested that vasoactive effects on cerebral arteries and neurotoxicity due to hyperinsulinaemia play a crucial role in the altered brain structure and function in obese individuals and may be counteracted by physical activity (11). The present study does not allow conclusions on the effects of physical activity in clinical populations because of the heterogeneous paediatric populations studied (ADHD, obese and deaf children) and because the acute effect studies focused exclusively on children with ADHD while the chronic effect studies were mainly focused on obese children. To provide a better understanding of the potential of physical activity programmes as a treatment approach in clinical populations, future studies should elucidate whether the effects of physical activity interact with health status and, more specifically, with the underlying pathophysiological processes that are supposed to be targeted by physical activity.

The results of the systematic review provide an overview of all findings on cognitive functioning in parallel to the observed changes in neural mechanisms. Almost all studies included in the review reported on cognitive performance together with neuroimaging measures (85%). The results showed that in half of the studies a concurrent improvement in at least one measure of cognitive or academic performance was observed. More specifically, 55% of studies observing acute effects of physical activity on neurophysiological function and 42% of studies observing chronic effects on neurophysiological function reported concurrent improvement.

These percentages are in line with the results of recent systematic reviews on the effects of physical activity on cognition and academic performance in children, where small to moderate effects were found (1, 47). Another interesting finding is that only three studies reported significant associations between imagery and cognitive measures (34, 35, 41).

One possible explanation for the fact that neurophysiological effects do not consistently parallel behavioural improvement is the typical use of small study sample sizes in neuroimaging research, which limits the statistical power to reveal relevant associations. Otherwise, the relationship between neurophysiological and behavioural effects of physical activity may be non-linear or a behavioural response to physical activity may not be detected until the neurophysiological response has reached a certain threshold level.

The main limitations of the present review are that the majority of studies (81%) did not adopt adequate procedures for blinding of intervention implementation and outcome assessment and almost half of the studies (42%) included a sample that was not representative of the target population. Even so, the overall risk of bias was low among the included studies.

CONCLUSIONS

The current systematic review shows that long-term physical activity produces beneficial changes in neurophysiological function. In addition, short-term physical activity may induce changes in neurophysiological functioning, although this evidence showed limited robustness.

In addition, there is preliminary evidence that physical activity may be a useful intervention to promote neurophysiological functioning (and cognitive functioning) in various paediatric populations.

Taken together, the findings reviewed converge across multiple domains to suggest potentially deleterious effects of physical inactivity and poor aerobic fitness on brain structures and functions that underlie aspects of school performance in school. The data speak to the importance of physical activity and aerobic fitness in maximising brain health and cognitive function during development. Given that physical activity behaviours are often established during pre-adolescent childhood, creating and maintaining physical activity opportunities within the school, where children spend most of their day, may provide a means to increase and/or maintain health and effective functioning across the lifespan. Indeed, as reviewed above, the level of aerobic fitness at one point in time may predict cognition in the future. In summary, the existing literature highlights the interaction between physical fitness, brain and cognitive skills that underlie aspects of academic performance.

However, more research is needed to gain insights into the effects of physical activity in such specific populations.

High-quality intervention studies should include both neuroimaging techniques and behavioural outcomes. Given the signs of limited robustness of the available evidence, future studies should also consider pre-registration to limit the influence of publication bias in this field.

Despite this, the usefulness of the present study is that it presents an overview of the best available evidence on the causal effects of physical activity on brain structure and neurophysiological functioning in children and highlights the importance of physical activity for brain development during childhood.

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