The role of cognitive elements plays in physical activity interventions among individuals with attention-deficit/hyperactivity disorder: A systematic review of brain evidence

Yuan Fang, PhD[1], Fenghua Sun, PhD[1*], Zixin Wang, PhD[2], Yaxi Yang, MEd[3], Man Lau, BChinMed[1], Kunyi Huang, MSc, MEd[1], Michael Kin-Chung Yeung, PhD[4], Simon B. Cooper, PhD[5], Yajun Chen, PhD[6]

[1] Department of Health and Physical Education, The Education University of Hong Kong, Hong Kong SAR, China;
[2] Centre for Health Behaviours Research, JC School of Public Health and Primary Care, The Chinese University of Hong Kong, Hong Kong SAR, China;
[3] Center for Language and Brain, Shenzhen Institute of Neuroscience, Shenzhen, China;
[4] Department of Psychology, The Education University of Hong Kong, Hong Kong SAR, China;
[5] Department of Sport Sciences, Sport, Health and Performance Enhancement (SHAPE) Research Centre, Nottingham Trent University, Nottingham, UK;
[6] Department of Maternal and Child Health, School of Public Health, Sun Yat-sen University, Guangzhou, Guangdong, China.

* Correspondence author: **Dr. Fenghua Sun**

Email: fhsun@eduhk.hk

Address: Rm D4-2/F-25, The Education University of Hong Kong, No. 10 Lo Ping Road, Tai Po, New Territories, Hong Kong SAR, China

Author Note

No.	Name	Degree	Email	ORCID
1st	Yuan FANG	PhD	lunajoef@gmail.com	0000-0003-1154-5076
2nd & Cor.	Fenghua SUN	PhD	fhsun@eduhk.hk	0000-0001-5251-4087
3rd	Zixin WANG	PhD	wangzx@cuhk.edu.hk	0000-0002-1158-2304
4th	Yaxi YANG	MEd	yassee_yang@outlook.com	0000-0002-9652-855X
5th	Man LAU	BChinMed	alma.chinmed@gmail.com	0000-0002-7452-9690
6th	Kunyi HUANG	MSc, MEd	kunyihuang88@gmail.com	0009-0000-7390-6717
7th	Michael Kin-Chung YEUNG	PhD	michaelyeung@eduhk.hk	0000-0001-6699-6080
8th	Simon B. COOPER	PhD	simon.cooper@ntu.ac.uk	0000-0001-5219-5020
9th	Yajun CHEN	PhD	chenyj68@mail.sysu.edu.cn	0000-0003-3132-2945

YF and FS contributed to the study design and professional consultation. YF, YY, ML, and KH conducted the data collection and analysis. YF, FS and ZW wrote the manuscript. YF, ZW, FS, MKCY, SBC, and YC reviewed the manuscript critically. All authors significantly contributed to the intellectual content of the manuscript.

All authors declared no conflict of interest.

This study was substantially supported by an internal fund from Committee on Research and Development, Education University of Hong Kong and a matching fund from Department of Health and Physical Education, Education University of Hong Kong (Project No. RG 58/2023-2024R).

This review was registered in PROSPERO (Ref No.: CRD 42024560284).

Data availability statement: The data that support the findings of this study are available from the corresponding author (Dr. Fenghua SUN) upon request.

Ethic statement: Since this review was conducted and analyzed based on published data, Internal Review Board (IRB) approval was not required.

Word count: abstract: 237 words; main text: 4,916 words.

Abstract

Physical activity (PA) with cognitive elements has received significant attention in recent years because it has been shown to have a large effect on increasing executive function in individuals with attention-deficit/hyperactivity disorder (ADHD). However, the mechanisms underpinning these effects are poorly understood. Therefore, this study systematically reviewed and summarized the brain outcomes of individuals with ADHD who completed either traditional intervention—PA alone, cognitive training (CT)-alone—or their combination in two forms—dual task of CT and PA (CT-PA) and cognitive-engaged PA (CE-PA). An extensive search on 13 online databases was conducted to identify eligible studies. Assessment indicated a relatively high quality demonstrated by 27 included studies. A total of 632 children/adolescents and 80 adults with diverse ADHD subtypes, symptom severity, and/or medication status participated in the reviewed interventions. Included interventions also varied largely in modality and volume. Nonetheless, changes in brain structure and function appeared to occur following these interventions in individuals with ADHD, including a prevalent increase in brain activity across the frontal lobe, a positive effect on brain volume (including in the frontal cortex and cerebellum), and an enhancement of particular brain networks related to inhibitory control, attention, and processing. With these tending, it elicits a rehabilitation towards normalization. The limited data preliminarily indicated a possible synergetic effect of CT/CE-PA; However, further research is warranted to obtain a comprehensive appraisal and establish a mechanistic model in terms of brain activity, morphology, and network connectivity.

Keywords

ADHD, brain, cognitive training, executive function, physical activity

Introduction

Attention-deficit/hyperactivity disorder (ADHD), characterized by a persistent pattern of inattention and/or hyperactivity-impulsivity (Wolraich et al., 2019), is one of the most common neurodevelopmental disorders from childhood that interferes with functioning or development (Huss et al., 2017; Nunez-Jaramillo et al., 2021). Individuals with ADHD often exhibit problems with higher-order cognitive abilities (e.g., executive function, EF). These include deficits in inhibitory control, working memory, cognitive flexibility, and attention functions (Huss et al., 2017; Liang et al., 2021). The executive dysfunction is highly related to the behavioral problems of individuals with ADHD, such as internalizing and externalizing behaviors, aggressive and/or disruptive behaviors (Tzang & Chang, 2009). They jeopardize the well-being of affected individuals and their families.

Investigations of the neural differences between individuals with ADHD and healthy controls have mainly used neuroimaging, including electroencephalography (EEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and diffusion weighted imaging (DWI). These original studies have been systematically summarized, and revealing the potential mechanism related to ADHD deficits in inhibitory control. The evidence indicates abnormalities emerging with ADHD in terms of brain activity, morphology, and connectivity. Hypoactivity (e.g., during a Go/No-go task) is frequently found across (1) the frontal cortex, including the left and right prefrontal cortex (PFC) (Arnsten, 2009; Gossé et al., 2021), inferior PFC (Arnsten, 2009; Dickstein et al., 2006), dorsolateral PFC (dlPFC) (Dickstein et al., 2006; Hart et al., 2013; Kim et al., 2023), right lateral PFC (Gossé et al., 2021), orbital and ventromedial prefrontal area (Lukito et al., 2020), left frontopolar cortex (Gossé et al., 2021), right inferior frontal cortex (Hart et al., 2013), right inferior frontal gyrus (IFG, Gossé et al., 2021), right middle frontal gyrus (MFG, Gossé et al., 2021), and supplementary motor area (SMA, Hart et al., 2013; Kim et al., 2023); (2) the anterior and posterior cingulate (Hart et al., 2013) and right anterior insula (Dickstein et al., 2006; Lukito et al., 2020); (3) the medial wall regions (Dickstein et al., 2006); (4) the precentral gyrus (Dickstein et al., 2006); and (5) the limbic areas, such as striato-thalamic areas (Dickstein et al., 2006; Faraone, 2018; Hart et al., 2013; Kim et al., 2023). Problematic morphology includes a decreased volume in ventromedial orbitofrontal gray matter (Faraone, 2018; Nakato et al., 2011), abnormal structure of PFC circuits (Arnsten, 2009), and reduced fractional anisotropy of white matter alterations in the splenium and body of the corpus callosum, extending to the cingulum (Arnsten, 2009; Parlatini et al., 2023). Impaired connectivity is also noted in the default mode network (DMN, Kim et al., 2023), right and left hemispheric dorsal, ventral, and medial fronto-cingulo-striato-thalamic and fronto-parieto-cerebellar networks (Kim et al., 2023; Lukito et al., 2020; Parlatini et al., 2023; Rubia, 2018), and domain-dissociated right hemispheric fronto-basal ganglia networks (Kim et al., 2023; Parlatini et al., 2023; Rubia, 2018).

In terms of the EF-specific brain abnormality, the integrity of frontal-striatal-thalamic-cortical (FSTC) circuitry, which is deemed to associate with EFs, is supposed to be malfunctioned for individuals with ADHD to perform EF tasks (Roth & Saykin, 2004). A compensatory recruitment of other frontal and nonfrontal circuitry is also possibility involved (Roth & Saykin, 2004). Furthermore, a case-control study indicated that people with impairment in the left/right lateral and dorsomedial frontal lobes (but not ventromedial frontal lobes) had worse inhibitory control than their healthy counterparts (Yeung et al., 2021). This suggests that multiple prefrontal regions play the necessary but distinct roles in the task performance (Yeung et al., 2021). In addition, repeated trainings on working memory may reduce the brain activation in frontoparietal and striatal networks with increased neural circuitry efficiency and improved functional connectivity (Brooks et al., 2020).

Currently, ADHD management focuses primarily on medications (Cerrillo-Urbina et al., 2015; Den Heijer et al., 2017; Jeyanthi et al., 2019; Neudecker et al., 2019; Ng et al., 2017). However, such medications (e.g., methylphenidate, MPH) have notable side effects, such as decreased appetite, nausea, headache, insomnia, nasopharyngitis, dizziness, abdominal pain, irritability, and somnolence (Cerrillo-Urbina et al., 2018; Storebø et al., 2018). Therefore, formulating new effective and sustainable management strategies well be advantageous for individuals with ADHD. According to a recent meta-analysis (Qiu et al., 2023), the overall effect size (Hedge's *g*) of non-pharmaceutical ADHD interventions on the combined EFs is 0.672. Among traditional intervention types, the two with largest average effect sizes are physical activity (PA, *g*: 1.108) and cognitive training (CT, *g*: 0.724). Consistently, PA and CT also presented the significant effect on reducing problematic behaviors of children with ADHD (i.e., PA, *g*: 0.56-0.66, Cerrillo-Urbina et al., 2015; CT, *g*: 0.28-0.40, Pauli-Pott et al., 2021). Thus, PA and CT may have great potential therapeutic benefit for individuals with ADHD.

To achieve potential synergetic effects in the population affected by ADHD, researchers have proposed PA with cognitive elements, such as the dual task of CT and PA (CT-PA, i.e., CT and PA tasks are distinct in planning, goal-setting, and execution but performed simultaneously as a dual task (Dhir et al., 2021; Nejati & Derakhshan, 2021)) or cognitive-engaged PA (CE-PA, i.e., PA task is performed with cognitive involvement, Best, 2010; Nejati & Derakhshan, 2021). CT/CE-PA is believed to possess the advantages of both CT and PA-alone interventions. Based on a recent meta-analytic result (Fang et al., 2024), compared to controls, CT/CE-PA exhibits a significant large effect on improving overall EFs (*g*: 1.10), and task accuracy of inhibitory control (*g*: 0.99), working memory (*g*: 0.82), and cognitive flexibility (*g*: 1.70) in children and adolescents with ADHD.

However, to date, the brain-mediated mechanisms that underpin these effects have received less attention. Thus, the current systematic review may help reveal the brain mechanism responsible for the large effect exhibited by CT/CE-PA, and further inform researchers to improve this new form of effective intervention that can specifically target the underlying mechanisms of improving inhibitory control in individuals with ADHD. Therefore, the current study aimed to systematically search and review studies that investigated the effect of brain outcomes following interventions (i.e., PA, CT, and their combination) among individuals with ADHD, and synthesize and compare the brain outcomes following the different intervention designs.

Methods

Search strategy

The current review was registered in PROSPERO. Relevant journal articles were identified by searching 13 electronic databases covering the published periods of 1929–2024 (i.e., the search was completed on June 20, 2024, **Figure 1**). The Boolean operator was used in the search strategy with “OR” and/or “AND” used to link search terms. The complete and detailed search strategies are shown in Supplemental Material **Table S1**.

Inclusion and exclusion criteria

Inclusion criteria for the review were that included studies had to (1) involve an acute/chronic intervention with clearly described content, (2) apply an intervention design with PA alone, CT alone, CT-PA, or CE-PA to achieve effectiveness comparison; (3) have the intervention be evaluated with individuals diagnosed with ADHD; (4) be published in English journals; and (5) use human neuroscience techniques to evaluate the effectiveness of interventions.

An article was excluded if (1) participants did not have a clinical diagnosis of ADHD; (2) participants were family members, friends, teachers, or clinicians of individuals with ADHD only; (3) it focused on other comorbidities, such as Tourette syndrome, cerebral palsy, concussion, autism spectrum disorder (ASD), intellectual disability (ID), overweight/obesity, or fragile X syndrome; (4) the intervention lacked a CT or PA component; (5) the intervention involved multiple components but contained a small proportion of CT and/or PA (e.g., intervention volume <50%); (6) it focused on animal models; (7) it reported the development/validation of a scale/tool; (8) it focused on modelling or projection; or (9) it is a study protocol, review, editorial, commentary, discursive paper, conference abstract, or unpublished dissertation.

Screening process

The screening process is outlined in **Figure 1**. Two authors screened the articles, wherein a consensus by comparison or discussion was made between the authors. After the initial execution of the search strategy and the exclusion by the automated tool (e.g., article type, language use) for each type of interventions, articles were screened for relevance through titles and abstract review. The remaining papers on interventions were read in full to identify if they met the inclusion criteria. Finally, 12, 9, 1, and 5 articles that included interventions focusing on PA alone, CT alone, CT-PA, and CE-PA, respectively, were identified and included for further analysis.

Assessment for study quality

Risk of bias from the included articles was assessed using a structured questionnaire and its criteria, with detailed descriptions of the ratings (Hawker et al., 2002). The eligible studies were listed under a structured framework, the results of which are shown in **Table S2**. The assessment was determined for each item by two authors, reaching a consensus by comparison or discussion as necessary.

Data extraction

Relevant information from the included articles was analyzed and summarized using a standardized table with categorized themes of key information (**Table 1**). This table includes the published year, country/district, study design, background information of the sample, intervention protocol (i.e., modality, duration, and content), and cerebral/brain activity/response results. Two authors independently completed the review process and data extraction, with a consensus regarding final study inclusion, analyses and summary achieved via discussion.

Results

Overview of included studies

The PRISMA flow diagram describing the search process is presented in **Figure 1**. A total of 27 papers published between 2010 and 2023 were included in this review (**Table 1**). Of the included studies, 632 children/adolescents with ADHD (5–18 years old; 486 boys, 117 girls, and 29 participants for whom sex was not reported) and 80 adults with ADHD (mean age: 28.6–31.4 years old; no disclosure of sex) participated in the reviewed interventions. Six studies did not report the medication status of the participants; sixteen studies involved participants who were totally (three studies) or partially (thirteen studies) on ADHD medication during the intervention, and five studies included drug-naïve participants. The studies were conducted in 13 countries/districts, i.e., Taiwan China (seven studies), Germany (three studies), mainland China (three studies), South Korea (three studies), Israel (two studies), Spain (two studies), USA (two studies), and one study each in Australia, Brazil, Finland, Iran, Mexico, and Switzerland. The included interventions were evaluated using 13 randomized controlled trials (RCTs), 11 quasi-experiments, and 3 pre-/post-tests. Lastly, study settings involved the home (three studies), school (two studies), clinic (two studies), and laboratory (twenty-one studies).

Study quality

According to the assessment of study quality (**Table S2**), the included studies received total scores ranging from 23 to 32, exceeding the average score of the assessment tool (i.e., 22.5, Hawker et al., 2002). This indicated the relatively high quality of the included studies. Potential bias was mainly due to the use of a non-experiment design and small sample size, which may negatively influence the accuracy of the results and generalization of findings.

Design of included interventions

As shown in **Table 1**, four types of intervention design were employed in the 27 included studies, i.e., PA-alone (twelve studies), CT-alone (nine studies), dual task training of CT and PA (one study), and cognitive-engaged PA (five studies).

Among the 12 studies focused on PA alone, 8 used a single bout of 20–30 min PA and 4 evaluated the chronic practice of PA. Apart from one dose-response study (Tsai et al., 2021), 11 studies employed structured PA at a moderate level (MPA). Closed-skill sports were used in seven studies (e.g., rope skipping, treadmill running, cycling), and mixed types of sports were used in the other five studies (e.g., a combination of jump rope and ball sport or an aquatic exercise consisting of swimming and coordination skills). Of the studies employing chronic PA, intervention dosage ranged from 6 to 12 weeks, one to three sessions per week, and 30–90 min per session. A sedentary control group (e.g., video-watching, educational talks, inactive control) was prevalently used in these studies, except in one study that compared the effect of different session durations (30 min vs. 60 min, Yu et al., 2020).

Of the studies that focused on CT alone, all nine CTs were practiced in a chronic manner with the assistance of computerized devices. The CT training included N-back, stop-signal training (SST), reading, training of working memory and inhibitory control. The dosage of involved CTs ranged from 10 days to 12 weeks, three to seven sessions per week, and 15 to 45 min per session. All CT-alone studies used an experimental study design (true or quasi) to compare the intervention and control groups. Among them, one study compared the effect between high- and low-intensity CT (Johnstone et al., 2010), one compared the effect between adaptive and non-adaptive CT (Meyer et al., 2020), and one did not report a control design (Horowitz-Kraus et al., 2019). Of the remaining, a waitlist control, sham control, education training of social skills or school content, or video games were used as the control/comparison condition.

Our review identified only one CT-PA study (Van Riper et al., 2023), which utilized a single bout of a 25-min dual task of EF training (working memory and inhibitory control) during moderate-intensity exercise. The dual task effect was compared with the isolated PA component at the same dosage.

Meanwhile, five CE-PAs were included in our review, they all involved chronic practice. The modalities included exergaming (two studies, Ji et al., 2023; Smith et al., 2019), horseback riding (two studies, Lee et al., 2015; Yoo et al., 2016), and judo training (one study, Ludyga et al., 2022). The practice of CE-PAs lasted from 4 to 32 weeks, one to three sessions per week, and 50 to 90 min per session. Participants of two PA-active control groups experienced bicycle exercise or physical rehabilitation, two studies used inactive controls, and one study did not disclose the control design.

Results of brain outcomes

As shown in **Figure 2** and summarized in **Table S3**, brain outcomes are categorized into activity, morphology, and connectivity. Among the included studies, 15 used EEG to obtain brain activity data (8 PA alone, 4 CT alone, and 3 CE-PA), 11 employed fMRI (4 PA alone, 5 CT alone, 2 CE-PA), and 1 investigated the effect of CT-PA using fNIRS.

Brain activity

PA-alone interventions. Compared with the control/comparison group, participants with ADHD who attended PA-alone interventions showed a significant larger power or amplitude of various waves/signals in their EEG data. These were mainly found in the frontal and central lobes of the brain (Chuang et al., 2015; Hung et al., 2016; Lee et al., 2017; Ludyga et al., 2017; Yu et al., 2020). Furthermore, the theta/beta ratio (i.e., a prominent biomarker of ADHD) in the midline or frontocentral lobe tended to decrease more in the PA compared with the control condition (Huang et al., 2018; Huang et al., 2017). In the dose-response study (Tsai et al., 2021), the alpha power increased following low- or moderate-intensity PA but decreased following vigorous-intensity PA. According to fMRI results, regional homogeneity (ReHO, i.e., the summarized local functional connectivity between a given node and its nearest neighboring nodes, Jiang & Zuo, 2016) in children with ADHD was elevated in the left middle and right superior frontal gyri, whereas degree centrality (DC, i.e., a topologic indicator of functional importance degree in the whole brain functional network, Wang et al., 2023) increased in the right posterior cingulate cortex, following an eight-week rope skipping exercise program(Jiang et al., 2022). However, mixed findings of beta values were found in different brain areas and/or between different studies. In particular, after a six-week aquatic intervention (Choi et al., 2015), the mean beta value of the right frontal lobe in the intervention group increased compared with that in the control group (i.e., educational talks). In the right temporal lobe, the mean beta value decreased in the intervention group but remained unchanged in the control group. In another study, compared with healthy controls, adults with ADHD showed more increased beta values in the parietal, temporal, and occipital regions during correct inhibition in the PA condition compared with the movie-watching condition (Mehren, Özyurt, Thiel, et al., 2019). Moreover, adults with ADHD who engaged in a higher level of cardiorespiratory fitness recorded decreased beta values in their premotor areas during congruent trials and in the premotor and medial frontal cortex during incongruent trials when they were in the PA condition compared with the movie-watching condition (Mehren, Özyurt, Lam, et al., 2019).

CT-alone interventions. EEG results indicated the intervention effects of CTs on participants with ADHD. First, periodic beta bandwidth in the frontal-central lobe was lower compared with controls (Dakwar-Kawar et al., 2023). Second, resting-state theta power in the left (eyes closed condition) and right parietal electrodes (eyes open condition) were greater compared with controls, but no difference was found between groups (either condition) in the frontal electrodes (Meyer et al., 2020). Additionally, resting-state theta power was reduced in the central region after training (Johnstone et al., 2010). Third, resting-state delta power after training was greater in the central regions compared with the frontal and posterior regions (Johnstone et al., 2010). Fourth, increased sensory motor activity in the central midline was recorded in the intervention group (Rajabi et al., 2019). Fifth, N200 latency was significantly prolonged in the experimental group compared with the control group during the correct inhibition trial (Meyer et al., 2020). Sixth, the theta/beta ratio was reduced in the central midline of the intervention group (Rajabi et al., 2019). Seventh, N1 amplitude increased in both high and low-intensity conditions, especially in the left hemisphere (Johnstone et al., 2010). Lastly, N2 amplitude increased in event-related potential (ERP) during both Go and No-go trials under the low-intensity condition (Johnstone et al., 2010).

For fMRI findings, compared with the control group, participants in the CT intervention exhibited a significant increase in blood-oxygen-level-dependent imaging (BOLD) signals in the orbitofrontal, superior frontal, middle temporal, and inferior frontal cortex during the selective attention task, and in the cerebellum during the response inhibition task (Hoekzema et al., 2010). In another study with an inactive control (de Oliveira Rosa et al., 2020), children with ADHD who completed a CT intervention exhibited a significant increase in BOLD signals with increasing sustained attention delays in the bilateral precuneus, right insula, bilateral associative visual cortex and angular gyrus, right middle temporal, precentral, postcentral, superior frontal and middle frontal gyri. They also recorded a significant decrease in BOLD signals with increasing working memory load in the right insula, right putamen, left thalamus and left pallidum during a working memory task (de Oliveira Rosa et al., 2020). Cognitive training in participants with ADHD was associated with changes in activation in task-relevant parietal and striato-limbic regions of sustained attention and working memory. Furthermore, significant interaction effects of time × group on changes in brain activity were found in the dlPFC, superior and inferior parietal cortex, precuneus, and SMA/anterior cingulate cortex (ACC) of adults with ADHD who completed a three-week CT and were compared with active controls (Salmi et al., 2020).

Dual task of CT-PA. The only eligible study using a dual task as an intervention investigated the brain activity of participants through cerebral oxygenated hemoglobin (HbO) concentration via fNIRS (Van Riper et al., 2023). During the dual-task exercise, participants with ADHD exhibited significant lower brain activity in the inferior/superior parietal gyrus for the inhibition control task, and significant higher brain activity in the middle and inferior frontal gyri and the temporoparietal junction for the working memory task, compared with the control condition (i.e., 25-min structured moderate-intensity cycling exercise alone).

CE-PAs. Three studies utilized EEG to detect brain activity, and the results showed that the N2 amplitude in the midfrontal line was significantly greater (both Go and No-go trial) in the exergaming group compared with the PA-active controls (Ji et al., 2023). However, another exergaming study reported no difference in N2 amplitude between groups (either Go or No-go trial) in the frontocentral lobe (Smith et al., 2019). The same study found that integrated body brain and social (IBBS) intervention group exhibited P3 latency in the posterior parietal lobe significantly earlier compared with the control group. In another study, children with ADHD showed increased negativity of the contralateral delay activity (CDA) in the parieto-occipital and parietal lobes on the high load condition following judo training (Ludyga et al., 2022). Furthermore, children with ADHD who completed a 12-week equine-assisted training program demonstrated a significant reduction of ReHO in the right precuneus and right pars orbitalis clusters (Yoo et al., 2016).

Brain morphology

Two studies reported on morphological changes. Children with ADHD who attended a two-week intensive clinical CT intervention (Hoekzema et al., 2011) exhibited significantly larger focal volumetric gray matter in the bilateral middle frontal cortex and right inferior-posterior cerebellum compared with the control group. In another study (Lee et al., 2015), the decrease area of the activated insula and increase area of the cerebellum in a hippotherapy group (CE-PA) was significantly larger compared with the physical rehabilitation controls, although the blood brain-derived neurotrophic factor (BDNF) level showed no significant between-group difference.

Brain network connectivity

Two included studies that employed CT showed a positive improvement in the connectivity of brain networks. The frontal midline brain area (Fz) of an experimental group (high-frequency transcranial random noise stimulation applied with CT) showed a higher cortical excitation/inhibition (E/I) balance, paralleled by cognitive improvement, when compared with sham controls (Dakwar-Kawar et al., 2023). In another study (Horowitz-Kraus et al., 2019), reading training showed a positive effect on brain networks related to attention/dorsal attention, visual processing, and EF among children with ADHD.

Discussion

Overview and strengths of this study

A growing body of integrated interventions has emerged for ADHD treatment, among which PA with CT components has received much attention. The current work serves as the first-ever systematic review to summarize and compare the existing brain evidence of PA-alone, CT-alone, and PA-with-CT-component (i.e., CT-PA or CE-PA) interventions in response to the acknowledged moderate-to-large effect of these interventions on improving inhibitory control in individuals with ADHD (Qiu et al., 2023). Whether the relations between different intervention designs enhance the effectiveness and brain outcomes may influence the development of motor-cognitive theory and future practice for ADHD treatment.

As shown in **Figure 2**, first, PA-alone interventions exhibited an overall significant increase in brain activity in all four cortices of participants with ADHD. Second, CT-alone interventions significantly positively changed the activity, morphology, and connectivity in particular brain areas/networks (i.e., the frontal, temporal, and parietal lobes, basal ganglion, limbic system, and cerebellum). Third, the preliminary results showed that the dual task of CT-PA significantly modified brain activity in the frontal and parietal lobes, as well as the temporoparietal junction. Lastly, the limited evidence of CE-PA showed a general increase in EEG activity over the frontal, parietal, and occipital lobes, and an increase in the area of cerebellum. It also showed a decrease in ReHO related to the right precuneus and right pars orbitals clusters, as well as a reduced activated insular area.

Implications on the brain mechanism: towards normalization

Brain impairments in individuals with ADHD generally include a prevalent hypoactivity in the prefrontal-to-frontal cerebral area that is essential for higher-order cognitive functions (e.g., attention, voluntary behaviors, problem-solving, decision-making, planning and coordinating movements, Dickstein et al., 2006; Faraone, 2018; Kim et al., 2023), as well as a smaller volume in key structures (e.g., gray matter), which reflects a potential lower level of available neurons and substantially hampers information processing (Lukito et al., 2020). These deficits are further associated with insufficient connectivity in brain networks that are in charge of passing information and signals between functional areas in different layers of the brain (De La Fuente et al., 2013; Faraone, 2018).

The present systematic review of the literature highlighted the positive effects of different interventions (PA, CT, and their combination) on brain activity (see Figure 2 and Supplemental Material Table S3). First, a significant effect on increasing brain activity was evident in participants who completed any of the reviewed interventions, especially in the cerebral frontal lobe. Second, the hyperactivity in the theta/alpha ratio (measured by EEG), a prominent biomarker of ADHD, was reduced following both PA- and CT-alone interventions. Third, given the limited results in the temporal and occipital lobes, increased activity was observed in PA-alone, CT-alone, or CT-PA dual-task interventions. Fourth, positive changes in the cerebellum were detected following CT-alone and CE-PA interventions in terms of increased activity or volume. Fifth, mixed results were obtained in the parietal lobe following interventions with a CT element (especially CT alone), and in the limbic system following CT-alone interventions. Therefore, participants with ADHD undergoing the reviewed interventions generally experienced a rehabilitation of their brain activity toward normalization, offsetting some of the negative changes in brain activity commonly seen in ADHD.

Existing evidence preliminarily supports to combine PA and CT in the form of CE-PA

This systematic review sought to examine whether a combination of PA and CT provides synergistic benefits that exceed the benefits of either intervention alone. Although the information provided for the CT-PA and CE-PA interventions is limited, it preliminarily indicates that CE-PA may integrate advantageous features from both PA-alone and CT-alone interventions compared with the dual task of CT-PA. For CT-PA, the limited evidence obtained via fNIRS shows that the effects seemed to be a simple combination of the PA- and CT-alone interventions—increased brain activity in the frontal and temporal lobes but a trend of decline in the parietal lobe (Van Riper et al., 2023). Based on a previous meta-analysis (Dhir et al., 2021), CT-PA is less effective at enhancing inhibitory control in individuals with ADHD ($p = 0.242$) compared with its effect on older adults (g: 0.455, $p < 0.001$). In line with this, a recent RCT showed that a 12-week CT-PA intervention of children with ADHD had no significant Time × Group interaction effect on improving either inhibitory control or working memory (Liang et al., 2022). This implies that individuals with ADHD may require new strategy and/or design to show significant EF improvements owing to brain pathology.

Regarding CE-PA, in addition to the positive effect commonly found in the frontal lobe, improved brain activity is maintained in the occipital lobe and cerebellum as observed in PA- and CT-alone interventions. Contrary to the mixed results of CT-alone interventions, a more apparent increase in brain activity in the parietal lobe can be observed following CE-PA. This implies a potential interaction effect obtained through the combination of PA and CT elements in this area. As such, the effect of CE-PA may be partially explained by cognitive stimulation theory—CE-PA may enhance cognitive performance by training the brain areas that regulate higher order cognition (Pesce, 2012; Tomporowski et al., 2008). This is consistent with the three theoretical pathways which has been suggested by Best (2010): (1) CE-PA has the cognitive demands for goal-directed activity during exercise, (2) children is required to use the cognitive function to complete the complex motor tasks throughout CE-PA, and (3) CE-PA may induce the physiological rehabilitation associated with the brain activation/morphology, and/or functional connectivity.

Limitations

This study is the first to systematically review the brain evidence of interventions in individuals with ADHD. However, it has several limitations that should be noted when interpreting the results. First, the heterogeneity of the included studies was relatively large because of the diversity in participants' ADHD severity and type, intervention designs, and outcome evaluations. This hampered the quantitative integration and comparison between individual studies, which may limit the generalizability of our findings. Second, the results of this review should be interpreted with caution given the limitations reported by 25 of the 27 included studies with regard to study design, unbalanced background information on the participants, intervention design, and bias reporting. A small sample size (12 studies), lack of active/inactive controls (4 studies), absence of long-term effects (5 studies), and improper task selection (4 studies) were acknowledged as the main limitations of the study design. Regarding the background information of participants, the unbalanced distribution or unclear information on sex (6 studies), medication use (9 studies), and/or ADHD subtype and symptom severity (11 studies) predominantly contributed to the large heterogeneity among the included studies. This may reduce the generalization of study findings to the wider population of people with ADHD. Furthermore, not all included studies clarified the dose-effect relation in intervention design. Notably, PA dosage (i.e., intensity, period, modality, Choi et al., 2015; Hung et al., 2016; Smith et al., 2019) and CT load (Horowitz-Kraus et al., 2019; Salmi et al., 2020) should be considered. Finally, the studies selected for review were limited because only those with specific terms mentioned in the title/abstract were screened for analysis, and those in a non-English language or published in forms such as government reports, textbooks, or unpublished dissertations were not included.

Conclusion

This study systematically reviewed and summarized the brain outcomes of individuals with ADHD who participated in four types of interventions (two traditional designs: PA- and CT-alone, two variations of their combination: CT-PA and CE-PA) that previously exhibited moderate-to-large effect on improving EFs. Evidence embedded in these four intervention types shared a common essence of mechanism—a rehabilitation process toward normalization. This process includes three components: increase in brain activity prevalently in the cerebral frontal lobe, positive effect on brain morphology (e.g., enlarging focal volumetric gray matter in the frontal cortex and cerebellum), and enhancement of particular brain networks related to inhibitory control, attention, and processing. Moreover, the limited evidence preliminarily presented a possible synergetic effect of CT/CE-PA over PA or CT alone. Considering the limited existing evidence, research efforts are warranted to collect more comprehensive brain evidence in extended brain areas for appraising the intervention effects of CT/CE-PA. Relevant findings will benefit future intervention design and the establishment of a tailored model to maximize the adaptations in brain outcomes.

References

Arnsten, A. F. (2009). The emerging neurobiology of attention deficit hyperactivity disorder: The key role of the prefrontal association cortex. *The Journal of Pediatrics*, *154*(5), I-S43. https://doi.org/10.1016/j.jpeds.2009.01.018

Best, J. R. (2010). Effects of physical activity on children's executive function: Contributions of experimental research on aerobic exercise. *Developmental Review*, *30*(4), 331-551. https://doi.org/10.1016/j.dr.2010.08.001

Brooks, S. J., Mackenzie-Phelan, R., Tully, J., & Schioth, H. B. (2020). Review of the neural processes of working memory training: Controlling the impulse to throw the baby out with the bathwater. *Frontiers in Psychiatry*, 11, 512761. https://doi.org/10.3389/fpsyt.2020.512761

Cerrillo-Urbina, A. J., Garcia-Hermoso, A., Pardo-Guijarro, M. J., Sanchez-Lopez, M., Santos-Gomez, J. L., & Martinez-Vizcaino, V. (2018). The effects of long-acting stimulant and nonstimulant medications in children and adolescents with attention-deficit/hyperactivity disorder: A meta-analysis of randomized controlled trials. *Journal of Child and Adolescent Psychopharmacology*, *28*(8), 494-507. https://doi.org/10.1089/cap.2017.0151

Cerrillo-Urbina, A. J., García-Hermoso, A., Sánchez-López, M., Pardo-Guijarro, M. J., Santos Gómez, J. L., & Martínez-Vizcaíno, V. (2015). The effects of physical exercise in children with attention deficit hyperactivity disorder: A systematic review and meta-analysis of randomized control trials. *Child: Care Health Development*, *41*(6), 779-788. https://doi.org/10.1111/cch.12255

Choi, J. W., Han, D. H., Kang, K. D., Jung, H. Y., & Renshaw, P. F. (2015). Aerobic exercise and attention deficit hyperactivity disorder: brain research. *Medicine and Science in Sports and Exercise*, *47*(1), 33-39. https://doi.org/10.1249/MSS.0000000000000373

Chuang, L. Y., Tsai, Y. J., Chang, Y. K., Huang, C. J., & Hung, T. M. (2015). Effects of acute aerobic exercise on response preparation in a Go/No Go Task in children with ADHD: An ERP study. *Journal of Sport and Health Science*, *4*(1), 82-88. https://doi.org/10.1016/j.jshs.2014.11.002

Dakwar-Kawar, O., Mairon, N., Hochman, S., Berger, I., Cohen Kadosh, R., & Nahum, M. (2023). Transcranial random noise stimulation combined with cognitive training for treating ADHD: A randomized, sham-controlled clinical trial. *Translational Psychiatry*, *13*(1). https://doi.org/10.1038/s41398-023-02547-7

De La Fuente, A., Xia, S., Branch, C., & Li, X. (2013). A review of attention-deficit/hyperactivity disorder from the perspective of brain networks. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00192

de Oliveira Rosa, V., Rosa Franco, A., Abrahao Salum Junior, G., Moreira-Maia, C. R., Wagner, F., Simioni, A., . . . Paim Rohde, L. A. (2020). Effects of computerized cognitive training as add-on treatment to stimulants in ADHD: A pilot fMRI study. *Brain Imaging and Behavior*, *14*(5), 1933-1944. https://doi.org/10.1007/s11682-019-00137-0

Den Heijer, A. E., Groen, Y., Tucha, L., Fuermaier, A. B., Koerts, J., Lange, K. W., . . . Tucha, O. (2017). Sweat it out? The effects of physical exercise on cognition and behavior in children and adults with ADHD: A systematic literature review. *Journal of Neural Transmission (Vienna)*, *124*(Suppl 1), 3-26. https://doi.org/10.1007/s00702-016-1593-7

Dhir, S., Teo, W. P., Chamberlain, S. R., Tyler, K., Yucel, M., & Segrave, R. A. (2021). The effects of combined physical and cognitive training on inhibitory control: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews*, *128*, 735-748. https://doi.org/10.1016/j.neubiorev.2021.07.008

Dickstein, S. G., Bannon, K., Castellanos, F. X., & Milham, M. P. (2006). The neural correlates of attention deficit hyperactivity disorder: An ALE meta-analysis. *Journal of Child Psychology and Psychiatry*, *47*(10), 1051-1062. https://doi.org/10.1111/j.1469-7610.2006.01671.x

Fang, Y., Sun, F., Wang, Z., Yang, Y., Lau, M., Huang, K., Yeung, M. K., Kranz, G. S., & Chan, C. C. H. (2024). Cognitively combined/engaged physical activity for the executive function, symptomology, and motor competence of children and adolescents with attention-deficit/hyperactivity disorder: A systematic review and meta-analysis. *Research in Developmental Disability*, 155, 104880. https://doi.org/10.1016/j.ridd.2024.104880

Faraone, S. V. (2018). The pharmacology of amphetamine and methylphenidate: Relevance to the neurobiology of attention-deficit/hyperactivity disorder and other psychiatric comorbidities. *Neuroscience and Biobehavioral Reviews*, *87*, 255-270. https://doi.org/10.1016/j.neubiorev.2018.02.001

Gossé, L. K., Bell, S. W., & Hosseini, S. M. H. (2021). Functional near-infrared spectroscopy in developmental psychiatry: A review of attention deficit hyperactivity disorder. *European Archives of Psychiatry and Clinical Neuroscience*, *272*(2), 273-290. https://doi.org/10.1007/s00406-021-01288-2

Hart, H., Radua, J., & Nakao, T. (2013). Meta-analysis of functional magnetic resonance imaging studies of inhibition and attention in attention-deficit/hyperactivity disorder. *JAMA Psychiatry*, *70*(2), 185-198. https://doi.org/10.1001/jamapsychiatry.2013.277

Hawker, S., Payne, S., Kerr, C., Hardey, M., & Powell, J. (2002). Appraising the evidence: reviewing disparate data systematically. *Qualitative Health Research*, *12*(9), 1284-1299. https://doi.org/10.1177/1049732302238251

Hoekzema, E., Carmona, S., Ramos-Quiroga, J. A., Barba, E., Bielsa, A., Tremols, V., . . . Vilarroya, O. (2011). Training-induced neuroanatomical plasticity in ADHD: A tensor-based morphometric study. *Human Brain Mapping*, *32*(10), 1741-1749. https://doi.org/10.1002/hbm.21143

Hoekzema, E., Carmona, S., Tremols, V., Gispert, J. D., Guitart, M., Fauquet, J., . . . Vilarroya, O. (2010). Enhanced neural activity in frontal and cerebellar circuits after cognitive training in children with attention-deficit/hyperactivity disorder. *Human Brain Mapping, 31*(12), 1942-1950. https://doi.org/10.1002/hbm.20988

Horowitz-Kraus, T., Hershey, A., Kay, B., & DiFrancesco, M. (2019). Differential effect of reading training on functional connectivity in children with reading difficulties with and without ADHD comorbidity. *Journal of Neurolinguistics*, *49*, 93-108. https://doi.org/10.1016/j.jneuroling.2018.09.002

Huang, C.-J., Huang, C.-W., Hung, C.-L., Tsai, Y.-J., Chang, Y.-K., Wu, C.-T., & Hung, T.-M. (2018). Effects of acute exercise on resting EEG in children with attention-deficit/hyperactivity disorder. *Child Psychiatry & Human Development*, *49*(6), 993-1002. https://doi.org/10.1007/s10578-018-0813-9

Huang, C. J., Huang, C. W., Tsai, Y. J., Tsai, C. L., Chang, Y. K., & Hung, T. M. (2017). A preliminary examination of aerobic exercise: Effects on resting EEG in children with ADHD. *Journal of Attention Disorders, 21*(11), 898-903. https://doi.org/10.1177/1087054714554611

Hung, C. L., Huang, C. J., Tsai, Y. J., Chang, Y. K., & Hung, T. M. (2016). Neuroelectric and behavioral effects of acute exercise on task switching in children with attention-deficit/hyperactivity disorder. *Frontiers in Psychology*, *7,* 11, Article 1589. https://doi.org/10.3389/fpsyg.2016.01589

Huss, M., Duhan, P., Gandhi, P., Chen, C.-W., Spannhuth, C., & Kumar, V. (2017). Methylphenidate dose optimization for ADHD treatment: Review of safety, efficacy, and clinical necessity. *Neuropsychiatric Disease and Treatment, Volume 13*, 1741-1751. https://doi.org/10.2147/ndt.S130444

Jeyanthi, S., Arumugam, N., & Parasher, R. K. (2019). Effect of physical exercises on attention, motor skill and physical fitness in children with attention deficit hyperactivity disorder: A systematic review. *ADHD Attention Deficit and Hyperactivity Disorders*, *11*(2), 125-137. https://doi.org/10.1007/s12402-018-0270-0

Ji, H. Q., Wu, S., Won, J., Weng, S., Lee, S., Seo, S., & Park, J.-J. (2023). The effects of exergaming on attention in children with attention deficit/hyperactivity disorder: Randomized controlled trial. *JMIR Serious Games*, *11*, e40438. https://doi.org/10.2196/40438

Jiang, K., Xu, Y., Li, Y., Li, L., Yang, M., & Xue, P. (2022). How aerobic exercise improves executive function in ADHD children: A resting-state fMRI study. *International Journal of Developmental Neuroscience*, *82*(4), 295-302. https://doi.org/10.1002/jdn.10177

Jiang, L., & Zuo, X. N. (2016). Regional homogeneity: A multimodal, multiscale neuroimaging marker of the human connectome. *Neuroscientist*, 22(5), 486-505. https://doi.org/10.1177/1073858415595004

Johnstone, S. J., Roodenrys, S., Phillips, E., Watt, A. J., & Mantz, S. (2010). A pilot study of combined working memory and inhibition training for children with AD/HD. *ADHD Attention Deficit and Hyperactivity Disorders*, *2*(1), 31-42. https://doi.org/10.1007/s12402-009-0017-z

Kim, S. J., Tanglay, O., Chong, E. H. N., Young, I. M., Fonseka, R. D., Taylor, H., . . . Sughrue, M. E. (2023). Functional connectivity in ADHD children doing Go/No-Go tasks: An fMRI systematic review and meta-analysis. *Translational Neuroscience*, *14*(1). https://doi.org/10.1515/tnsci-2022-0299

Lee, N., Park, S., & Kim, J. (2015). Effects of hippotherapy on brain function, BDNF level, and physical fitness in children with ADHD. *Journal of Exercise Nutrition & Biochemistry, 19*(2), 115-121. https://doi.org/10.5717/jenb.2015.15061209

Lee, S. K., Song, J., & Park, J.-H. (2017). Effects of combination exercises on electroencephalography and frontal lobe executive function measures in children with ADHD: A pilot study. *Biomedical Research, 2017*, S455-S460.

Liang, X., Li, R., Wong, S. H. S., Sum, R. K. W., & Sit, C. H. P. (2021). The impact of exercise interventions concerning executive functions of children and adolescents with attention-deficit/hyperactive disorder: A systematic review and meta-analysis. *International Journal of Behavioral Nutrition & Physical Activity, 18*(1), 1-17. https://doi.org/10.1186/s12966-021-01135-6

Liang, X., Qiu, H., Wang, P., & Sit, C. H. P. (2022). The impacts of a combined exercise on executive function in children with ADHD: A randomized controlled trial. *Scandinavian Journal of Medicine & Science in Sports*, 32(8), 1297-1312. https://doi.org/10.1111/sms.14192

Ludyga, S., Brand, S., Gerber, M., Weber, P., Brotzmann, M., Habibifar, F., & Pühse, U. (2017). An event-related potential investigation of the acute effects of aerobic and coordinative exercise on inhibitory control in children with ADHD. *Developmental Cognitive Neuroscience*, *28*, 21-28. https://doi.org/10.1016/j.dcn.2017.10.007

Ludyga, S., Mücke, M., Leuenberger, R., Bruggisser, F., Pühse, U., Gerber, M., . . . Weber, P. (2022). Behavioral and neurocognitive effects of judo training on working memory capacity in children with ADHD: A randomized controlled trial. *NeuroImage: Clinical, 36,* Article 103156. https://doi.org/10.1016/j.nicl.2022.103156

Lukito, S., Norman, L., Carlisi, C., Radua, J., Hart, H., Simonoff, E., & Rubia, K. (2020). Comparative meta-analyses of brain structural and functional abnormalities during cognitive control in attention-deficit/hyperactivity disorder and autism spectrum disorder. *Psychological Medicine*, *50*(6), 894-919. https://doi.org/10.1017/S0033291720000574

Mehren, A., Özyurt, J., Lam, A. P., Brandes, M., Muller, H. H. O., Thiel, C. M., & Philipsen, A. (2019). Acute effects of aerobic exercise on executive function and attention in adult patients with ADHD. *Frontiers in Psychiatry, 10*, 132. https://doi.org/10.3389/fpsyt.2019.00132

Mehren, A., Özyurt, J., Thiel, C. M., Brandes, M., Lam, A. P., & Philipsen, A. (2019). Effects of acute aerobic exercise on response inhibition in adult patients with ADHD. *Scientific Reports, 9*(1), 19884. https://doi.org/10.1038/s41598-019-56332-y

Meyer, K. N., Santillana, R., Miller, B., Clapp, W., Way, M., Bridgman-Goines, K., & Sheridan, M. A. (2020). Computer-based inhibitory control training in children with Attention-Deficit/Hyperactivity Disorder (ADHD): Evidence for behavioral and neural impact. *PLoS One*, *15*(11), e0241352. https://doi.org/10.1371/journal.pone.0241352

Nakao, T., Radua, J., Rubia, K., & Mataix-Cols, D. (2011). Gray matter volume abnormalities in ADHD: Voxel-based meta-analysis exploring the effects of age and stimulant medication. *American Journal of Psychiatry*, 168, 1154–1163.

Nejati, V., & Derakhshan, Z. (2021). The effect of physical activity with and without cognitive demand on the improvement of executive functions and behavioral symptoms in children with ADHD. Expert Review of Neurotherapeutics, 21(5), 607-614. https://doi.org/10.1080/14737175.2021.1912600

Neudecker, C., Mewes, N., Reimers, A. K., & Woll, A. (2019). Exercise interventions in children and adolescents with ADHD: A systematic review. *Journal of Attention Disorders*, *23*(4), 307-324. https://doi.org/10.1177/1087054715584053

Ng, Q. X., Ho, C. Y. X., Chan, H. W., Yong, B. Z. J., & Yeo, W.-S. (2017). Managing childhood and adolescent attention-deficit/hyperactivity disorder (ADHD) with exercise: A systematic review. *Complementary Therapies in Medicine*, *34*, 123-128. https://doi.org/10.1016/j.ctim.2017.08.018

Nunez-Jaramillo, L., Herrera-Solis, A., & Herrera-Morales, W. V. (2021). ADHD: Reviewing the causes and evaluating solutions. *Journal of Personalized Medicine*, *11*(3). https://doi.org/10.3390/jpm11030166

Parlatini, V., Itahashi, T., Lee, Y., Liu, S., Nguyen, T. T., Aoki, Y. Y., . . . Cortese, S. (2023). White matter alterations in Attention-Deficit/Hyperactivity Disorder (ADHD): A systematic review of 129 diffusion imaging studies with meta-analysis. *Moleular Psychiatry*, *28*(10), 4098-4123. https://doi.org/10.1038/s41380-023-02173-1

Pauli-Pott, U., Mann, C., & Becker, K. (2021). Do cognitive interventions for preschoolers improve executive functions and reduce ADHD and externalizing symptoms? A meta-analysis of randomized controlled trials. *European Child & Adolescent Psychiatry*, 30(10), 1503-1521. https://doi.org/10.1007/s00787-020-01627-z

Pesce, C. (2012). Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *Journal of Sport & Exercise Psychology*, *34*, 766-786.

Qiu, H., Liang, X., Wang, P., Zhang, H., & Shum, D. H. K. (2023). Efficacy of non-pharmacological interventions on executive functions in children and adolescents with

ADHD: A systematic review and meta-analysis. *Asian Journal of Psychiatry*, *87*, Article 103692. https://doi.org/10.1016/j.ajp.2023.103692

Rajabi, S., Pakize, A., & Moradi, N. (2019). Effect of combined neurofeedback and game-based cognitive training on the treatment of ADHD: A randomized controlled study. *Applied Neuropsychology: Child*, 1-13. https://doi.org/10.1080/21622965.2018.1556101

Roth, R. M., & Saykin, A. J. (2004). Executive dysfunction in attention-deficit/hyperactivity disorder: Cognitive and neuroimaging findings. *The Psychiatric Clinics of North America*, *27*(1), 83-96, ix. https://doi.org/10.1016/S0193-953X(03)00112-6

Rubia, K. (2018). Cognitive neuroscience of attention deficit hyperactivity disorder (ADHD) and its clinical translation. *Frontiers in Human Neuroscience*, *12*, 100. https://doi.org/10.3389/fnhum.2018.00100

Salmi, J., Soveri, A., Salmela, V., Alho, K., Leppamaki, S., Tani, P., . . . Laine, M. (2020). Working memory training restores aberrant brain activity in adult attention-deficit hyperactivity disorder. *Human Brain Mapping*, *41*(17), 4876-4891. https://doi.org/10.1002/hbm.25164

Smith, S. D., Crowley, M. J., Ferrey, A., Ramsey, K., Wexler, B. E., Leckman, J. F., & Sukhodolsky, D. G. (2019). Effects of Integrated Brain, Body, and Social (IBBS) intervention on ERP measures of attentional control in children with ADHD. *Psychiatry Research*, *278*, 248-257. https://doi.org/10.1016/j.psychres.2019.06.021

Storebø, O. J., Pedersen, N., Ramstad, E., Kielsholm, M. L., Nielsen, S. S., Krogh, H. B., . . . Gluud, C. (2018). Methylphenidate for attention deficit hyperactivity disorder (ADHD) in children and adolescents - Assessment of adverse events in non-randomised studies. *The*

Cochrane Database of Systematic Reviews, *5*, CD012069. https://doi.org/10.1002/14651858.CD012069.pub2

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review*, *20*(2), 111-131. https://doi.org/10.1007/s10648-007-9057-0

Tsai, Y.-J., Hsieh, S.-S., Huang, C.-J., & Hung, T.-M. (2021). Dose-response effects of acute aerobic exercise intensity on inhibitory control in children with attention deficit/hyperactivity disorder. *Frontiers in Human Neuroscience*, *15*. https://doi.org/10.3389/fnhum.2021.617596

Tzang, R.-F., & Chang, Y.-C. (2009). Behavior problems and subtypes of attention-deficit hyperactivity disorder with comorbidities. *The Kaohsiung Journal of Medical Sciences*, 25(10), 530-536. https://doi.org/https://doi.org/10.1016/S1607-551X(09)70545-5

Van Riper, S. M., Tempest, G. D., Piccirilli, A., Ma, Q., & Reiss, A. L. (2023). Aerobic exercise, cognitive performance, and brain activity in adolescents with attention-deficit/hyperactivity disorder. *Medicine and Science in Sports and Exercise*, *55*(8), 1445-1455. https://doi.org/10.1249/MSS.0000000000003159

Wang, Y., Wang, R., Wang, Y., Guo, L., Zhan, Y., Duan, F., . . . Tang, Z. (2023). The alterations of brain network degree centrality in patients with neovascular glaucoma: a resting-state fMRI study. *Neurological Sciences*, 44(8), 2915-2922. https://doi.org/10.1007/s10072-023-06664-5

Wolraich, M. L., Hagan, J. F., Jr., Allan, C., Chan, E., Davison, D., Earls, M., . . . Subcommittee on Children Adolescents with Attention-Deficit/Hyperactive Disorder (2019). Clinical practice guideline for the diagnosis, evaluation, and treatment of attention-deficit/hyperactivity disorder in children and adolescents. *Pediatrics*, *144*(4). https://doi.org/10.1542/peds.2019-2528

Yeung, M. K., Tsuchida, A., & Fellows, L. K. (2021). Causal Prefrontal Contributions to Stop-Signal Task Performance in Humans. *Journal of Cognitive Neuroscience*, 33(9), 1784-1797. https://doi.org/10.1162/jocn_a_01652

Yoo, J. H., Oh, Y., Jang, B., Song, J., Kim, J., Kim, S., . . . Joung, Y.-S. (2016). The effects of equine-assisted activities and therapy on resting-state brain function in attention-deficit/hyperactivity disorder: A pilot study. *Clinical Psychopharmacology & Neuroscience*, *14*(4), 357-364. https://doi.org/10.9758/cpn.2016.14.4.357

Yu, C.-L., Hsieh, S.-S., Chueh, T.-Y., Huang, C.-J., Hillman, C. H., & Hung, T.-M. (2020). The effects of acute aerobic exercise on inhibitory control and resting state heart rate variability in children with ADHD. *Scientific Reports*, *10*(1), N.PAG-N.PAG. https://doi.org/10.1038/s41598-020-76859-9