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To what extent does exercise dosage affect working memory in children and adolescents?

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Abstract. Working Memory (WM) denotes the mental capacity that allows people to store, process, and manipulate information for a short time, which is essential as a component of executive function. In consequence, the healthy development in children and adolescents, and improvement of working memory, should be given weight, and a proper dosage of exercise is a promising solution to it. In order to give evidence-based physical activity recommendations for schools, this study researches the extent to which working memory is affected in children and adolescents, focusing on working memory and assessment methods, the most effective exercise types and amounts, and the physical changes in the nervous system related to exercise. The findings of this study indicate that working memory is enhanced by the motor skills involved across different types of sports, which can stimulate the prefrontal cortex. A regimen of high-intensity exercise for 10- 20 minutes per session, for 2-5 days per week, for at least a month, is linked to better working memory, while the dosage for moderate-intensity exercise remains inconclusive. It is also found that cognitive deficits like anxiety and individual variables like age and fitness level are potential factors that may impact cognitive performance. Given these influences, more research is needed to get a better understanding of their connection with working memory and, finally, to provide recommendations for future school physical education.

Keywords: working memory, children and adolescents, exercise dosage, High-Intensity Interval Training (HIIT)

1. Introduction

Impairments in Working Memory (WM) expose people to a wide array of psychological disorders, such as Alzheimer's disease and Attention-Deficit/Hyperactivity Disorder (ADHD), and the public ought to pay greater attention to mental health issues like these. To illustrate, according to the CDC, a national survey of parents using 2022 data reported that 7.1 million children (11.4 %), which means approximately 1 in 9 children, have ever been diagnosed with ADHD. On the other hand, executive function governs the organization of thoughts and purposeful activities, and it comprises a set of mental skills that enable goal-directed behaviour, where working memory plays an imperative role. Adolescents and children with poorer working memory often struggle with academic achievement, daily functioning, and social interactions—all areas that rely heavily on efficient working memory processes. Thus, measures should be taken to provide interventions to enhance working memory in modern students.

Cognitive performance can be influenced by multiple lifestyle-related factors. In fact, leading a sedentary lifestyle has been shown to be likely negatively effect cognitive development in early childhood [1]. Excessive screen time and computer games can significantly weaken attention functioning in school-aged children [2]. These findings further highlight the importance of cultivating an active lifestyle and encouraging regular physical exercise to support healthy cognitive development from an early age.

Greater basal ganglia and hippocampus capacities, which are tightly connected to cognitive control and memory, have been found in more fit children [2]. In addition, these children appear to have better academic achievement at school [3]. In addition, the benefits exercise could bring are especially important in children and adolescents, as their brains are still in a phase of development. Moreover, cognitive development during early stages can improve well-being and mental health later in adulthood [4]. As reported by the World Health Organization (WHO), physical activities are instrumental in motor and cognitive development in children and adolescents; hence, 60 minutes of exercise every day is recommended for this age group. Nevertheless, most young people do not meet the recommended activity levels: based on the collected data from 298 school-based surveys of 1.6 million students aged 11–17 years, there are 81% of physically inactive adolescents do not meet the WHO guidelines [5]. Therefore, as a promising method to both physically boost cardiometabolic and bone health and mentally improve cognitive outcomes, scientific exercise programs should be incorporated into school education for the overall well-being of students, which is the foremost purpose and meaning of this research.

There is, however, a considerable volume of existing research concerning the correlation between exercise and cognitive functions; most studies focus on older adults rather than younger populations, and the findings specific to working memory are still limited. This research attempts to obtain a deeper understanding of dose-response benefits of exercise, seeking to provide clearer guidelines for maximizing working memory gains through physical activities.

This study's primary objective is to explore the extent to which working memory is affected in children and adolescents. This study aims to achieve this through the following specific aims:

(1) Define working memory and review common measurement tasks;

(2) Investigate whether exercise can enhance working memory;

(3) Evaluate the influences of different types of exercise to try to determine the most effective mode;

(4) Analyse and try to identify the optimal dosage of workouts for students;

(5) Explore the physical variations within psychological networks;

(6) Recommend evidence-based appropriate exercise program to contemporary children and adolescents.

2. Research review

2.1. Working memory

2.1.1. What is working memory

Working Memory (WM) is a cognitive capability that enables us to hold a certain amount of information, process it, and be ready to manipulate it. It is associated with various cognitive activities in our lives, such as reasoning & problem-solving tasks, verbal comprehension in language learning, mathematical skills, and decision-making [6]. It involves concentrating on a certain task despite distractions and interferences. Working memory is different from both short-term and long-term memory [7]. To illustrate, dialling a telephone number that you were just told and recalling where you might have just placed your pen are common situations where we rely on our working memory. The next question therefore is why working memory is important in day-to-day life.

2.1.2. Why is working memory important

Working memory is closely related to daily life and learning, from remembering to bring essentials like keys and phones when going out to taking notes and following tutors' instructions in school settings.

Alloway and Copello have shown that working memory can affect certain particular learning skills [7]. First, working memory is crucial for reading ability, as a positive relationship between working memory capacities and reading skills has been found. It is shown that children who have difficulty reading typically exhibit substantial decrements on working memory tasks. Similarly, another study aligns with this opinion [6]. Their study has demonstrated that children with poorer performance on reading and vocabulary have language disorders, which are attributed to working memory deficits. Likewise, another investigation found that children who cannot easily comprehend like their peers also have difficulty performing updating tasks [8]. Moreover, working memory has been shown that it is also imperative for acquiring a second language, so the evidence that it is important for overall learning is quite solid.

Second, working memory—especially visuo-spatial memory—is closely related to mathematics performance [8], because children with poor working memory often demonstrate lower computational skills (mental math) and have problems with arithmetic word [7]. These represent merely a subset of its roles. Generally, working memory, which serves as a mental workspace, is indispensable in our lives.

Overall, therefore working memory can be regarded as a crucial scaffold to our cognitive functions, enabling individuals to temporarily store information and supporting relatively difficult cognitive activities, such as linguistic understanding and logical deduction. Consequently, enhancing and maintaining working memory is key for both healthy individuals and patients with cognitive impairments. Emerging research increasingly suggests that exercise is a promising avenue for improving working memory.

2.1.3. How to measure working memory

Accurately measuring working is of course very important, and there are many tests designed to assess working memory. For example, the N-back task, the digit span test, and the operation span task are all such ways to measure it. They can each help spot problems that may affect normal daily life, particularly for people suffering from cognitive deficits such as ADHD, dementia, or traumatic brain injury.

•The N-back task: This presents a series of letters on a computer screen, and then participants are required to decide whether the current stimulus (involving faces, shapes, letters, etc.) corresponds to one shown n steps back in a sequence earlier, and the difficulty increases as n increases [9].

•The digit span test—such as digit span forward, digit span backward, and letter digit span, which involves remembering and repeating sequences of numbers forward or backward [10].

•The Sternberg task [1]: This task assesses working memory maintenance. Participants encode an array of 5 letters (3 white, 2 green consonants, ignoring green ones). After an interval, judge via button press whether a probe letter was present in the encoded array. It includes a practice round and two blocks of trials, with randomized trial order and equal probability of probe presence/absence. The mean reaction time (correct trials) and accuracy are measured.

•Letter Digit Span (LDS) task [11]: This task measures frontal lobe-mediated working memory. It presents mixed numbers and letters auditorily, and participants respond by writing numbers from least to greatest and letters alphabetically. It includes practice trials, 4 trials per string length (2–7 items, 24 total), and is scored by correct responses.

There are differences in working memory loads between different tasks. The research conducted by Scharinger et al. [12] compared the cognitive demands in N-back tasks, complex operation span task (Ospan), and simple digit span task (Dspan) by EEG frequency band power and P300 amplitude. It was found that both the N-back and Ospan tasks showed a sustained decrease in alpha brain activity that lasted longer with higher working memory loads. In contrast, the Dspan task did not exhibit this longer-lasting effect of alpha ERD. The authors suggest that increases in alpha ERD reflect greater working memory processing requirements, indicating that N-back and Ospan are more demanding than Dspan. Theta power (ERS) was most marked in the N-back task, most likely (but not confirmed) because it places higher demands on executive functions. Therefore, it could be concluded that the N-back task could be the task that has the highest working memory load among the three, followed by Ospan and then Dspan, which could be attributed to the requirements in the N-back task being more complex, including not only working memory maintenance, but also the updating of new information, while processing and inhibiting stimuli, and shifting attention.

This perspective is further supported by Kane et al., as it is said that N-back requires greater cognitive effort, involving constant updating, dynamic decision-making, and rapid adjustments during play. Conversely, digit span does not require such cognitive complexity, so it might not be very reliable. In addition, the demands in the Sternberg task are quite similar to N-back tasks according to the task description. Therefore, these two tests, which can handle higher cognitive loads and examine more aspects of working memory, could be more effective in detecting the cognitive benefits of sports.

2.2. Does exercise enhance working memory

Having shown working memory's role in general cognition and explored the various ways it can be tested for, it is important for this study to turn to the relationship between working memory and exercise. The question of whether exercise can enhance working memory has been studied across various investigations, with most of the research showing positive results. However, differences in intervention effects may exist among multiple types of exercise [13], such as aerobic exercise, cognitive exercise, and skill-based exercises. Moreover, the evidence varies in its reliability and amount of confidence.

2.2.1. High-Intensity Interval Training (HIIT)

Some research has studied the impact of High-Intensity Interval Training (HIIT). A systematic review analysing 23 articles found that HIIT can enhance working memory in healthy children and adolescents [14]. Moreover, as such a comprehensive review, this is evidence that is worth paying attention to/ The type of HIIT intervention consisted of aerobic exercises (e.g., shuttle runs, jumping jacks, and skipping) and combined cardiorespiratory, motor, and coordinative training. The durations of chronic interventions in the included studies range from 4 to 24 weeks, and the frequencies of sessions range from 2 to 5 times a week, with 2 studies implementing only a single bout. Session lengths varied between 8 min and 20 min. The positive findings in the included studies could be owed to the fact that appropriate intensities of exercise can increase oxygenation in the prefrontal cortex [15], which is a brain region associated with executive functions. More oxygen can lead to increasing levels of chemicals such as H_2O_2 and TNF-α in the brain, which facilitate the process of generating Brain-Derived Neurotrophic Factor (BDNF) [14], therefore allowing the brain to be more responsive and better at working memory tasks.

Likewise, Deng et al. have noted that there is a small but significant positive impact of exercise on visuospatial working memory in healthy individuals [16]. The type of physical activities comprised aerobic exercises (e.g., cycling, walking, Tai Chi), resistance training, HIIT, balance training, etc, and the durations as well as the frequencies of which spanned from a single 15-minute session to 60-minute sessions weekly for 40 weeks. All these studies could provide empirical evidence supporting that exercise can enhance brain function, specifically regarding improving working memory. Nevertheless, it is undeniable that the intervention characteristic is another major moderator in the studies, which will be shown in the next section and should limit our certainty. As for the relationship between acute, chronic exercise and working memory, it becomes rather complex.

2.2.2. Acute and chronic exercise

Meanwhile, the duration of physical activity interventions, like a single acute session and long-term chronic participation, also affects their impact on working memory. Most studies align with the stance that long-term exercise, rather than acute exercise, yields more significant benefits for the working memory in children and adolescents.

To illustrate this, both Deng et al. [16] and Rathore and Lom [17] have found that chronic physical activities significantly improve working memory, while acute physical activities show non-significant benefits. These perspectives might suggest that working memory might be more sensitive to sustained exercise instead of short-term sessions. However, Rathore and Lom have also mentioned that the diversity of working memory instruments applied, unequal sample sizes between studies, and the sample age groups could contribute to the differences in the outcomes [17], so the viewpoint that acute exercise cannot exert significant benefits on working memory remains complex, but it is found that interventions lying primarily between 4 and 12 weeks can provide robust cognitive improvements since the all chronic PA studies out of the total eight chronic PA and seven acute PA studies captured in this review were within this range.

Furthermore, the different components of working memory could lead to differentiations in the study results. A systematic review has shown that, in terms of maintaining information, studies focusing on long-term exercise report more progress in the capability to manage information compared to those focusing on acute exercise. In contrast, findings on the manipulation of verbal information show an equal rate of positive and null outcomes in the same review [13]. The difference could be ascribed to the different maturity and sensitivity of working memory components. The maintenance segment matures later, relying more on rental lobe functions-which still develop in adolescence.

However, some other studies claim that acute exercise can improve working memory equally well. The aggregated results in a systematic review indicate that acute exercises have a substantial positive effect on working memory, while chronic exercises are effective in shortening response times [18]. This study, whose effect size meta-analysis (36 randomised controlled trials) includes 14 acute and 22 chronic, demonstrates that both chronic (30-90 minutes' session in 2-5 times weekly for 8-20 weeks) and acute exercises (moderate-intensity aerobic exercises like jogging or power cycling, with 10-40 min session length) can improve working memory performance in children and adolescents. Nonetheless, these conclusions need to be substantiated by more high-quality research, due to the limited quantity and quality of the studies included.

Overall, therefore numerous forms of sports have been shown to enhance working memory in healthy children and adolescents, although some research shows conflicting results.

2.3. Which form of exercise is most beneficial

It is reasonably safe to conclude that exercise can enhance working memory to some extent, while the differences existing between studies could be owing to the specific exercise forms. Exercise type is a major moderator of exercise-induced working memory benefits.

Ludyga, Gerber, and Kamijo compared the influences of mixed exercise, endurance exercise, and coordinated exercise on working memory [13]. Coordinated exercise was found to be the most beneficial for working memory and the visuo-spatial information manipulation among the three, even without extra cognitive demands. This is probably due to the motor skills targeted in this form of exercise. This is followed by a mixed program, which has been found not to consistently increase benefits despite the additional cognitive challenges involved. In contrast, long-term endurance exercise usually does not improve working memory unless it reaches a certain vigorous intensity, although there are some cases where endurance sports can enhance verbal working memory. This may imply that the exercise effects are also dependent on intensity, duration, as well as cognitive load and demands.

Another study further supports this point of view [19]. Another review suggests that cognitive-aerobic exercise is the most effective means to enhance working memory in children with ADHD, as this form of physical activity consistently requires children to concentrate, process information while engaging in aerobic activity, and the rules and goals during the intervention can keep the prefrontal cortex in an active state. The dosage of cognitive-aerobic exercise in the included studies is 45-60 minutes per session, 3 times a week, ranging from 5 to 12 weeks. This is followed by ball games, with two 70-minute lessons weekly for 12 weeks. Skills of planning strategies and adapting to changing situations are necessary in team ball games such as basketball and soccer contribute to better working memory.

However, the effects of mind-body exercises and virtual sports-based interactive games are relatively moderate, clustering between one 15-minute intervention and eight weeks' 45-minute lessons with a frequency of three times a week. It is undeniable that exercises with dual demands of body and mind, like yoga and Tai Chi, and exergaming, can effectively help with emotional control and simple social tasks for children, while the direct effects for working memory are less obvious because of the low degree of cognition task stimulation.

On the other hand, simple aerobic exercise, from a single 10-minute session to five 90-minute interventions per week for 10 weeks, such as running and skipping, has the weakest effects. This could be attributed to the lack of demands for memory and multitasking; therefore, they cannot activate the executive function brain areas.

All these findings of the aforementioned sports can reflect that the exercise type might not be the primary reason for the variations in effects. Instead, the requirements related to these sports are. In consequence, we should prioritise the types of sports with high cognitive load when attempting to improve working memory, and other factors, such as intensity and dosage, also play a role.

2.4. What is the optimal dosage of exercise

The previous section offers evidence that the format of exercise has to be taken into account when analysing the effects. Meanwhile, the dosage of physical activity can not be overlooked, on account of intervention frequency and total intervention time are also key factors to improve working memory [19].

Wilhite et al. hold the standpoint that exercises should be moderate [3]. Children exercising for 1–2 hours each week achieved better academic performance in comparison with those playing no sport or over 3 hours each week. In consequence, an inverted-U shape association between sport participation and academic performance could be uncovered in this review. There are reasonable causes for this, for example, students who devote too much time to exercise could have worse concentration due to the physical fatigue, while those who play sports for 1–2 hours per week still have enough recreation, sleeping, and studying time.

Similar results were found in a moderator analysis as well [18]. A study indicated that session durations of ≤ 30 min can enhance working memory responses, with effects being markedly better compared to sessions lasting > 30 min. This is because excessive exercise time is likely to cause fatigue and cannot induce an appropriate arousal state. In addition, a duration of less than 12 weeks and a frequency of 1-3 times a week could greatly benefit working memory performance; chronic exercise over 4 times weekly and for more than 12 weeks did not show a substantial benefit. The reason for this finding remains unclear since the experiments did not follow the subjects in the long term. Therefore, concerning chronic exercise, no definitive claims about duration and frequency were made.

Nevertheless, Deng et al. recommend another dose of physical activity [16]. For children, the intensity of physical activities should be low to moderate, achieving 40 to 75 percent of the maximum heart rate, as this could have better effects than vigorous interventions. And the frequency of exercise is three to four sessions per week, depending on individuals' bodily functions, with a more than 30 minutes and a longer period of at least 30 days; otherwise, no significant effect can be observed. Furthermore, it is also noticed that the effects after 90 days are found to be marginally better than those of 30-89 days in the study. The theory that can explain the findings is that intervention or practice, as prolonged for at least several weeks, is required in order to induce sufficient white matter plasticity changes, which are related to exercise, thereby causing significant improvements in working memory.

In summary, choosing the proper frequency, intensity, and duration of exercise can help to optimize improvements in working memory. The literature review has shown the importance of moving beyond a simplistic approach to just cataloguing the benefits of exercise, and instead to comprehending precisely why effects may vary between age groups, intensities and different cognitive demands. The following discussion section will attempt to begin this process.

3. Discussion

To achieve a true research breakthrough, this discussion will now interpret the findings of the literature review. It will examine the potential mechanisms that may account for variation—including dosage-related variation—in working memory outcomes across exercise modes and populations.

3.1. Motor skills

It is widely recognized that the type of sport one engages in can significantly influence the exercise-induced benefits at different dosage levels, particularly in relation to cognitive functioning in children and adolescents.

A systematic review by Heilmann, Weinberg, and Wollny highlights superior performance in executive function tests from individuals participating in Open-Skilled Exercises (OSE) than those engaging in Closed-Skilled Exercises (CSE) [20]. However, this might be overestimated due to some limits in the study, such as lacking reporting data in specific sports programs and an insufficient number of longitudinal studies on children and adolescents. Moreover, Wu et al. noted that while the performance of non-athletes is not as high as the performance of OSE athletes, there is still a marginal difference in working memory performance between the OSE and CSE groups in their research [21]. Therefore, the combination of a lack of research on CSE and limited amount of clarity about the subjects involved in studies is likely to contribute to both uncertainty and unpredictability surrounding OSE-related results.

Working memory may be particularly important in CSE, even though OSE may still have more advantages when it comes to enhancing executive function. Indeed, as Heilmann, Weinberg, and Wollny have shown, OSE needs a higher level of cognitive engagement during participation [20]. For instance, when compared against running—a narrowly and clearly defined form of CSE—skiing requires greater cognitive flexibility owing to its open nature. Specifically, owing to taking place outdoors in natural conditions, skiing demands more of its participants because there are often unpredictable changes, including because of changes in weather and terrain. Similar situations and conditions exist in team sports like football and tennis, as well as solo combat sports, which require constant attention to an opponent's changing game strategy. Such situations in OSE can enhance cognitive functions such as inhibition, attention, and self-regulation [22], as well as working memory, all of which can be beneficial for effective decision-making and performance in unpredictable sporting environments. The perspective that open motor skills could benefit working memory aligns with the conclusion in Liu et al. [18].

However, a counterpoint to this is that CSE could also induce working memory benefits, improving information processing and storage, as long as a particular type of sport requires one to learn a certain amount of new information, and put it into action while digesting it in a relatively short time interval. This notion is consistent with an fNIRS study [22]. Nonetheless, it is also essential to recognize that these results are based on young adult participants; further study is needed to determine if these conclusions are reliable for children and adolescents as well. Therefore, at the moment it is not yet established whether CSE is applicable to all.

Moreover, similar results have been found in the comparison between coordinative exercise and endurance exercise. Ludyga, Gerber, and Kamijo have demonstrated that coordinative exercise, regardless of extra cognitive demands, could always improve working memory, especially the manipulation of visuo-/spatial information [13]. Beyond visuo-/spatial working memory, the merits for concentration resources allocation, better reaction, better strategies for the task preparation process, and updating of information have also been found in other studies [1, 8]. Considering the limitations of these studies, including the lack of analysis on the possible influence of aerobic fitness, unknown social interactions and daily activities, as well as limited sample size, existing results need to be considered with caution. Coordinative exercise could efficiently enhance working memory due to its targeted motor skills. Participating in coordinative exercises implies the learning and application of particular movements over sustained training periods, which requires participants to absorb new information, retain it, and be ready to apply it.

It is interesting to note that swimming is not regarded as a coordinative exercise in the article by Ludyga, Gerber, and Kamijo [13]. This seems to indicate that, when compared with coordinative exercise, forms of CSE like swimming (also an endurance sport) are less conducive to improving working memory. Yet at the same time, novice swimmers do still need to master the relevant technique of a swimming stroke when they start to learn, try to meet the performance standard, and refine their skills in order to achieve higher proficiency. The storage and manipulation of information are indispensable throughout the process of acquiring motor skills such as this, as individuals must therefore be able to remember and effectively implement the guidance that their coaches provide.

Consequently, CSE like swimming and cycling could perhaps, to some extent, enhance working memory. Although in swimming, conditions are known and remain relatively constant, the effort to learn a new set of skills during the initial stages relies heavily on working memory. This controlled environment could, in fact, foster cognitive skills such as information storage and processing, allowing the focus to shift towards refining techniques across different strokes. Therefore, the true influential factors of the effects on working memory can be inferred to be the motor skills involved, rather than the exercise paradigms, given appropriate exercise dosage. In fact, this finding is substantiated by the conclusion that motor skill learning plays a crucial role in effectively enhancing working memory, particularly in the context of psychological mechanisms [13], which gives more confidence that the true source of the exercise benefits for working memory depend less on the label of open/closed skill, but rather on the motor learning demands that are involved in the sport itself.

3.2. Psychobiological mechanisms

Exercise at certain dosage levels can enhance cognition by affecting the human psychological network, and there is much research evidence to support this. In a randomized controlled trial, involving 57 children aged 8-12 years diagnosed with ADHD, an increased negativity of the CDA amplitude was observed after judo training when performing high-load cognitive tasks, which means it could make the memory-keeping processes work better, as people could remember more items in visuospatial working memory.

Moreover, exercise has been shown to induce physical changes in the central nervous system when sustained over time. As explained in the study, exercise can increase hippocampal and basal ganglia volume, white matter integrity, as well as cerebral blood flow, changing the release of neurotransmitters and physically altering the central nervous system. These neuroplastic effects are similarly echoed in the discovery that the left dorsolateral prefrontal cortex can be activated by acute exercise specifically, due to increased cerebral blood flow [9]. Aerobic and resistance training also appear to contribute to better functioning of Brain-Derived Neurotrophic Factor (BDNF). This protein is of great importance in helping the brain develop, recover from injury, and maintain its health. Indeed, it also ensures that nerve cells function properly and that cellular balance is preserved [13]. Complementary results have been found in the research of Ludyga et al. [1], showing that a short combined aerobic and coordinative exercise can increase initial Contingent Negative Variation (iCNV) amplitudes in the prefrontal cortex, implying that prefrontal cortex development can be facilitated by mixed exercise, and guides better-developed and proactive control, based on the knowledge that CNV is a sign of frontal lobe development, which increases from childhood to adolescence. Lastly, research has suggested that eight weeks of coordinative exercise training is able to increase haemoglobin concentration in the prefrontal cortex. The possible theory of this phenomenon is that all kinds of systems in the human body become more effective when completing a workload after exercise; overall, exercise can help allocate attention resources better, react faster, and activate the prefrontal cortex according to the increased oxy-Hb signal in the prefrontal cortex [8].

When we take this evidence together, we can see how exercise could stimulate the prefrontal cortex through various ways, and that this in turn can enhance working memory. Yet at the same time, it should also be noted that these effects could be influenced by mental challenges, and researchers should certainly pay more attention to this in future.

3.2.1. Mental health challenges

Based on the psychobiological mechanisms, it is acknowledged that it is the salutary physical changes brought by exercise that can improve working memory. Notwithstanding, it is still important to consider as moderating factors the role of adverse mental health challenges, such as anxiety, depression, and stress. These could interfere with normal functions of the brain, consequently disrupting participants' performance in the experiment.

First of all, anxiety can negatively affect working memory. According to a meta-analysis of 177 samples by Moran [23] and an investigation by Lukasik et al. [24], anxiety is linked to poorer working memory capacity. However, many studies omitted anxiety's possible impact, which could, in fact, make the real relationship between working memory and exercise unclear. Hence, subjects' anxiety levels need to be measured and controlled during interventions and testing in future research.

Anxiety is not the only psychological moderator. In addition, as suggested by Songco et al. [25], depression significantly burdens executive functions, particularly affecting working memory when negative distractor images are present as opposed to neutral images. Moreover, individuals with current or past depression performed worse than healthy subjects. This supports prior findings [26] that depressive moods can induce cognitive deficits, underscoring the need to account for depression in future research.

Besides anxiety and depression, Wunsch et al. [27] reported that acute psychosocial stress can impair working memory performance. The underlying reason is that these negative effects of stress on cognitive performance, including working memory, are supposed to be regulated by stress-related activity of the Hypothalamic Pituitary Adrenal (HPA) axis. This is because high amounts of glucocorticoid receptors can be found in areas associated with working memory, such as the prefrontal cortex, aspects of working memory relying on prefrontal cortex function are negatively influenced by increased levels of glucocorticoids during acute stress. Nevertheless, the experiment with a large sample of 503 participants exhibited no significant correlation between working memory and stress [24]. These conflicting results, together with the relatively small number of existing studies on this issue, highlight the need for further investigations to be pursued in this area in future.

In conclusion, there has so far been a shortage of studies focused on the relationship between working memory and mental health challenges. Despite this research gap, mental health-related challenges can all be potential variables that could influence the working memory improvements that exercise can induce. Knowing this, it is not enough to simply say that future studies should take these factors into account when researching the relationship between exercise and cognition. Instead, we should actively pursue and prioritise more specialised studies that deeply focus on understanding the link between working memory and cognitive deficits.

These would significantly contribute to advancing the research field surrounding exercise and cognition. While it may be argued that this is not necessary since the neurophysiological benefits of exercise are sufficient to override these mental health-related factors, ignoring these variables introduces the risk of masking meaningful cognitive processes, so it's still certainly worth trying to better understand these through future research.

3.3. Additional benefits

3.3.1. Neurodiversity

Over and above the common sports-induced merits of working memory enhancements that we know about, physical activity is also expected to generate extra advantages for our brain, including supporting people with neurodivergent conditions. This makes it a potentially effective approach to treating cognitive deficits.

First, in terms of Attention Deficit Hyperactivity Disorder (ADHD), it is believed that physical activity could contribute to the treatment of this cognitive disorders. A randomized controlled trial focused on 8–12-year-old children with ADHD and demonstrated that an improvement in participants' capability to remember more items in their visuospatial working memory and memory retention processes could be observed after they completed judo training [28]. Though this study may suggest that physical activities like judo can provide a cost-effective way for the treatment in children with ADHD, without relying on medication, it is worth noting that the results may not be generalized to all children with ADHD. This is because it claims only those receiving treatment with psychostimulants were included. Similarly, Song et al. have suggested that cognitive-aerobic exercise demonstrates the most significant benefits in improving the working memory of children with ADHD, while simple aerobic exercise has the least effect on enhancement [19]. This could further substantiate that a type of exercise (motor skills) that requires children to continuously process information, stay concentrated, and manage cognitively complex tasks during the exercise (therefore activating the executive function areas in the prefrontal cortex) could bring more benefits for working memory.

Regarding dyslexia, intensive, adaptive computerized working memory training can enhance dyslexic children's performance across multiple aspects, such as verbal and visuospatial working memory, central executive function, and literacy skills (accuracy and reaction time in visual rhyming tasks). Although working memory deficits, which could be improved by specific training, are closely related to dyslexia, there is a lack of research on the impact of physical exercise on dyslexia. Hence, claims about the effectiveness of exercise for treating dyslexia remain partly unanswered. However, there are contradicting results. Though there were effects in visuo-spatial Corsi block span tasks in the experiment, no long-term working memory improvements in children, both with or without dyslexia, were discovered.

Similar benefits are also expected in alleviating the symptoms of Autism Spectrum Disorder (ASD). There is a small to moderate effect on ASD children's overall executive function by exercise [29]. The underlying theory is that cortical pyramidal neuron spine density is revealed to be higher in patients with ASD than in healthy individuals, which could result in abnormal disruption in neural circuits, leading to cognitive impairments [30], and exercise was found to improve executive functions is that physical activity can facilitate synaptic function through the BDNF/TrkB signaling pathway [30]. Among various interventions, it was observed that Ping Pong was the most effective intervention in aiding children with ASD, followed by Mini Basketball, with Fixed Bicycle ranking the last, as it involves less cognitive engagement. Additionally, exercise may benefit cognition by increasing co-activation between the cerebellum and dorsolateral prefrontal cortex, as suggested by Mostofsky and Simmonds, cited in Liang et al. [29].

While these results are promising, further research is needed to gain a more comprehensive understanding and confirm the mechanisms behind the cognitive benefits of exercise for neurodiverse populations. Indeed, others might argue that these seeming additional benefits might actually stem from increased levels of engagement, or familiarity with the task—not the benefits of the exercise itself—even if the recurring frequency of the research results indicates that the benefits of exercise for people with neurodivergent conditions may be promising.

3.3.2. Reaction time

In addition to this, sports have also been shown to positively influence reaction time in several included studies. In particular, this is due to the effect of promoting more efficient information processing and faster response times among. For instance, Lai et al. found that preschoolers involved in tennis training exhibited shorter reaction times, suggesting that early participation in sports yields beneficial effects [8]. Furthermore, Ludyga et al. reported similar advantages from short bouts of aerobic and coordinative exercises, although the sample size of only 36 students in this study may limit the generalizability of the findings [1].

Nonetheless, another factor to consider is that an improved reaction time may be influenced by more than just exercise alone. Specifically, age-related factors may also be at play. For instance, Chen et al. have observed a significant improvement in reaction times following the intervention of working memory tests [9]. In their study, fifth-grade students demonstrated shorter reaction times compared to their third-grade counterparts, although at the same time, there was no change in the accuracy of response. Given these findings—which have not been validated elsewhere—further research is still needed to confirm the strength of correlation between working memory, exercise, and reaction time, particularly for children and adolescents.

Overall, the evidence suggests that exercise can both enhance working memory performance and help address mental health challenges by stimulating the neural systems that support executive control processes. However, before looking more specifically at the issue of exercise dosage, it is crucial to recognise that the true extent of these benefits is not uniform and may vary according to factors including the specific exercise type, cognitive demands, and participant characteristics. For this reason, therefore, dosage is a key variable to consider when developing exercise programmes that seek to maximise cognitive benefits.

3.4. Dosage

Motor skills are not the only impact factors in the influence on working memory; the intensity and duration of exercises also play a role, since these could affect brain structure and relevant neurological development. Therefore, the dosage of sports cannot be neglected when considering the benefits it could bring for cognition.

Comparing the included studies, exercises with high-intensity training (≥ 85% HRmax) for at least 10-20min per session, 2-5 times a week for at least 30 days could bring exercise-induced cognitive benefits.

The literature seems to suggest a widely acknowledged inverted-U, dose-dependent relationship between exercise and cognitive function [3, 9]. Specifically, these two studies identified a nonlinear association between acute bouts of exercise and cognitive outcomes, as well as between exercise and academic performance, respectively. Although neither investigation directly explored the link between exercise dosage and working memory, collectively their findings could be supportive of the stance that exercise should be moderate. This highlights the importance of trying to exercise within an optimal range (i.e. dosage) in order to maximize cognitive performance. The literature is quite clear, that it is much more optimal than either blindly pursuing an exercise regime that strives for extremely high intensity levels—or of following a lifestyle that includes insufficient levels of physical exercise.

Other included findings, such as those reported by Budde et al. [11], further support the existence of an inverted-U-shaped relationship between sport intensity and cognitive performance. Data from the single group analysis can partly support this notion, as significant enhancements in working memory were mainly found in the low-intensity acute exercise group instead of the high-intensity one. The explanation of this pattern may be attributed to similar inverted U-shaped interactions between neuroendocrine factors - specifically, testosterone (T) and cortisol (C) - and cognitive functioning. Although direct correlations between working memory enhancements and T and C concentrations have not been established, the results reported that T levels can affect the prefrontal cortex functions, and when surpassing a certain threshold, their effect on working memory may become detrimental. In consequence, based on the influence that has been found on cognition by steroid hormones, it is advisable to limit high-intensity physical activity bouts to durations of no more than 20 minutes. In addition, a study by Chang et al. [15], moderate-intensity aerobic exercise is the most efficient way to improve cognitive function, and this could be the result of increased IGF-1 concentration and brain blood flow. Conversely, high-intensity aerobic exercise is the least effective way. The underlying reason is that a heart rate of 80% of VO2max can activate the sympathetic nervous system, thereby actually slowing down executive functions. These findings should be carefully taken into consideration and used to inform the design of school exercise programmes, particularly to avoid and minimise any potential biologically-driven effects.

When it comes to intense exercise, a growing body of research has studied the cognitive effects of High-Intensity Interval Training (HIIT) in particular. Evidence suggests that positive outcomes are most associated with exercise durations that typically range from 8 to 16 minutes per session, conducted 3-5 times per week over periods of between 4 and 24 weeks. For example, in an experiment led by Tottori et al. [10], working memory in children aged 8–12 was significantly improved by a 4-week HIIT intervention with three times weekly 8–10-minute sessions, despite limitations like unequal gender distribution and a modest sample size (58 participants). Similarly, a 6-week program of 10-minute HIIT sessions, five times a week, also led to improvements in working memory for children aged 7–13. However, since session duration was not experimentally manipulated in that study, the optimal HIIT dose could not be determined [31]. Additionally, working memory improvements were observed after a single 16-minute HIIT bout [32]. These findings could link to the theory that that executive functions is positively associated with aerobic fitness [10], and HIIT is particularly effective in enhancing both aerobic and anaerobic capacities, so are other high-intensity exercises, this could be linked to the finding that an elevation of BDNF levels were observed after a 12-week vigorously intense endurance exercise. Thus, high intensity is a good choice for improving working memory. Also, compared to traditional forms of aerobic exercise such as jogging, it appears capable of inducing cognitive benefits within a shorter time frame. Another reason for recommending that high-intensity training should be shorter is the aforementioned steroid hormone concentrations. Sports of this intensity can rapidly elevate testosterone levels - often reaching approximately 50% VO2max [11] - with peak concentrations occurring at the end of a 20-minute session. Therefore, it is likely to be true that shorter periods of vigorous exercise are optimal for cognitive enhancement. Considering this, incorporating high-intensity activities like skipping, shuttle runs, vertical jumps, jumping jacks, and other similar exercises into school physical education curricula may offer a practical way to support students' mental and physical development, while also coincidentally promoting group exercise.

Meanwhile, the cognitive effects of moderate to vigorous intensity exercise remain complicated. Some studies indicate that even a single session of moderate-intensity sports can yield significant benefits for working memory. For instance, Chen et al. have found that 30 minutes of group jogging with an intensity of 40%-65% HRmax can enhance working memory performance in children in third grade and preadolescents in fifth grade [9]; likewise, a single 20-minute session of acute aerobic exercise on a treadmill can enhance working memory in preadolescents. Additionally, Cooper et al. [33] have found that task scanning speed can be improved following a single 60-minute session of basketball at 60%-70% HRmax in adolescents aged 12.3 ± 0.7 years. However, the finding that a single session can improve working memory performance is inconsistent with many current studies, since most research suggests that low to moderate intensity exercise must be performed 3-4 times per week, for at least 30 minutes per session, over a period of at least 30 days, to be effective, while this study has some notable limitations, with the disproportional distribution of sample ages and the sole focus on visuo-spatial working memory [16]. Overall, given the limited number of studies included, the findings regarding moderate-intensity exercise should be interpreted with caution.

At the same time, a possible challenge to the overall widely acknowledged dose-dependent relationship between all exercise and cognitive function could be that the effect of dosage is actually only a reflection of the various differences in study design across these different studies. The relationship would therefore only be determined by how exercise intensity was measured or how long interventions last in each case, rather than any true biological thresholds. According to this challenge, improvements in working memory only appear to show up because of limits in the testing or because of the short duration of the studies. However, on balance because similar dosage patterns have been reported across multiple research projects, it still remains reasonable to conclude that the dosage of exercise is likely to influence working memory in a meaningful way, even if the exact optimal level is not yet fully clear.

Overall, while exercise dosage is undoubtedly a critical component to consider when assessing the impact of exercise on working memory, individual differences are equally significant. Their role should not be overlooked, and instead, a comprehensive understanding of the role played by both dosage and individual factors is needed. Even if the observed dosage effects turn out to partially reflect the participant's existing fitness level, motivation, or cognitive abilities, this only emphasises the importance of reaching a comprehensive understanding. All these factors can markedly shape cognitive outcomes, with dosage possibly an important determinant.

3.5. Individual characteristics

In fact, having briefly touched on certain individual characteristics, it is worth studying individual characteristics more deeply. Improvements in cognition have been shown to be highly affected by the experiment subjects [34]. Therefore, individual differences should certainly be taken into account when designing and adjusting exercise programs.

First, age plays a significant moderating role in the effects of physical activity on cognitive outcomes. For example, Chen et al. reported that a significant reduction in response times during working memory tests following a single bout of 30 min jogging intervention [9]: fifth-grade students exhibited shorter reaction times compared to third-grade students, although no differences in response accuracy were found. However, the experiment measured the heart rates of only six participants rather than all subjects during exercise, and the instructors were not blinded to the intervention. Although these factors may introduce uncertainty to the findings, the results still suggest that individuals at distinct phases of working memory development may gain differently from the same activities. Furthermore, Egger, Conzelmann, and Schmidt [35] have found that acute cognitively engaging exercises generate no positive effects for younger children, and children between the ages of 7 and 9 are likely to experience an immediate drop in cognitive performance after participating in physically and mentally demanding activity breaks that last 20 minutes. This effect is expected across a wide range of typically developing kids in this age group, which could be attributed to the high level of self-control required when engaging in long-duration cognitively challenging exercise, leading to the impairment of self-regulation later in the tests. Additional research is needed to verify whether older children truly gain greater benefits than younger children from identical physical activities.

In addition to age, fitness level can also influence cognitive gains associated with exercise. Conzelmann et al. [36] have shown significant improvements in children with higher fitness who participate in physical activities. Also, only those with higher fitness appear to benefit from acute exercise. The underlying reason is probably that children with higher fitness reached the optimal heart rate while the identical activities were excessively demanding for their less fit peers. Similarly, another investigation conducted by Chaire, Becke, and Düzel [37] found that the participants with improvements in aerobic fitness demonstrate greater accuracy in the visual-attention-search task, as greater amplitude of frontal alpha power was observed; in addition, a positive correlation between alpha power and reaction time was discovered. Still, it is worth noting that the results in this study were based on forty young adults, with only 18 subjects comprising the exercise group, and the lifestyle variations besides experimental interventions remained unknown. While a research article targeting 39 young people aged 11–13 years can support the viewpoint, with the outcome that 60-minute games-based activity is particularly advantageous for fitter adolescents but possibly deleterious for those with lower fitness levels, as high-intensity exercise for 60 minutes is too physically demanding for them [33]. This could, again, be explained by the inverted U-shaped relationship between the intensity of sports and the magnitude of the cognitive benefits.

Moreover, the cognitive ability they possess before the intervention is another mediator. To illustrate, Children who performed better academically were the only ones to see benefits from acute physical activity interventions, regardless of whether these included cognitive engagement, as well as from sedentary activities that involved cognitive tasks [36]. This could be explained by two theories: students who have better academic performance achieve better cognitive activation during intervention, therefore gain benefits; or their limited cognitive resource, self-control, is not depleted during the intervention. On the contrary, research by Budde et al. [10] demonstrated opposite results. It was found that participants who did not perform well in the pre-test benefited most from the 12-minute session, no matter the exercise intensity (at both 50 - 65% and 70 - 85% HRmax). This contradiction, as it claims, might be the result of different working memory tests utilized, but more future studies are needed to prove whether cognition or academic performance level can affect the working memory benefits produced by exercise.

Finally, genetics is another influencing factor that is crucial but often overlooked. Research has shown that common executive function factors are 100% heritable, which means working memory is entirely dependent on genes, and the unique variance between individuals can be attributed to both genes and each child's distinct growing environment, and genetic influence appears to increase with development [38]. More interestingly, not only can maternal executive functions affect children's cognition, but negative caregiving can also have effects [39]. Mothers' executive functions can indirectly influence children through caregiving; by the time a child is 3 years old, the effects of maternal caregiving and executive functions on individual differences in children's executive functions are greater than mothers' educational level or children's verbal skills, whose impact also becomes stronger during childhood. However, the evidence is limited by the singularity of the sample, as subjects are all Caucasian and all graduated from high school; this result cannot be generalized across a wider population. Nevertheless, these two studies have demonstrated the significant role of genetic factors in working memory, emphasizing the need to control these variables in future research.

Something to be careful about here, however, is that if we emphasise individual characteristics too much, it risks overstating their moderating role and therefore might understate the overall effectiveness of exercise itself. From this perspective, it is reasonable to conclude that exercise likely has a broadly similar cognitive benefit across the whole population, even if there are some individual differences that could affect the exact magnitude of the effect. To summarise, therefore, it is essential to consider individual differences—including age, physical fitness, cognitive capabilities, and genetic factors—when designing exercise programs for children and adolescents. Equally, their role should not be exaggerated. A failure to account for the role of these factors may render sports interventions not only as less optimal than they could be, but even potentially harmful to the participants.

4. Conclusion

Overall, this dissertation finds that the motor skills involved in various sports play a key role in mediating exercise-driven cognitive enhancements, both for children and adolescents.

The targeted development of specific motor skills, regardless of the exact sport type, can bring about working memory improvements. The underlying mechanism for this improvement is that taking part in exercise activates the prefrontal cortex, a region closely associated with executive functioning. Therefore, as soon as exercise intensity and duration surpass certain exercise dosage thresholds, corresponding physical neuroplastic changes may occur, and this thereby enhances working memory function.

These findings suggest that high-intensity exercise is most optimally effective at improving working memory when engaged in for 10 to 20-minute sessions, 2–5 times per week, for at least 30 days. For moderate-intensity exercise, the ideal dosage remains unclear due to insufficient evidence and inconsistent outcomes in the research that this dissertation reviewed. Therefore, further studies are needed to determine the most effective moderate-intensity dosage.

Overall, these results align with the inverted-U-shaped relationship that has been previously established between exercise dosage and cognitive benefits, which underscores the importance of proper dosing. Furthermore, individual differences such as age, genetics, and fitness level still need to be considered—but not overstated. This is because the working memory gains that are possible are shaped by the distinct phases of an individual's neurodevelopment, inherent executive functions, and optimal thresholds for exercise benefits.

As a consequence, future research should take these factors into consideration when investigating the exercise-cognition relationship to develop more appropriate exercise recommendations for different population groups. In particular, more research that focuses on the correlations between working memory and factors such as age, fitness, level and baseline cognitive ability, and how these factors interact with different exercise intensities and durations would be highly valuable. Moreover, research that adopts more standardised outcome measures and intervention designs would be particularly useful, because not only could it improve the ability to compare between studies, but also because this will allow us to translate the results more reliably into practical, real-world dosages and exercise programmes for children and adolescents that work in all different environments.

Elsewhere, it is also important to note that mental health-related challenges, including anxiety, depression, and stress, have moderating effects on working memory and therefore are likely to influence the effectiveness of exercise-related interventions. This highlights the need for future studies to not only control for these variables, but also that more research is needed to study the potential interactions with exercise dosage more carefully. Such research will help us to better understand whether and how the benefits of exercise are consistent between different psychological conditions. For instance, a study could compare working memory outcomes, following a standardised exercise programme, for students experiencing high vs low academic stress.

Additional benefits of exercise have been found in this study, beyond simply working memory alone. These include identifying exercise as a promising and cost-effective intervention for treating treat children with (through improved working memory), and this has possible relevance for educational and clinical purposes alike. Moreover, since observed reductions in reaction time indicate that exercise may improve broader cognitive efficiency, it is a promising direction to try and use these findings to inform the design of school-based programmes which try to support learning and attention—as well as physical health.

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