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EFFECTS OF CARDIORESPIRATORY FITNESS ON COGNITIVE FUNCTION IN MIDDLE SCHOOL STUDENTS: A SYSTEMATIC REVIEW

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Abstract. *The purpose of this study is to explore the relationships between cardiorespiratory fitness and cognitive function in middle school students. Methods: An extensive literature search was performed for articles published from March 2011 to March 2021 in PubMed, Web of Science, EBSCO and CNKI (a Chinese database). Studies were included if: (1) the investigated population was aged between 6 and 18 years, (2) they reported the following outcome indicators: VO2max or VO2peak, cognitive function and/or at least one of the following three dimensions: executive function, attention network, intelligence. Studies that did not meet the aforementioned inclusion criteria or that had a study population with pathological obesity or other related diseases were excluded. Forty-nine articles were included, and the information on the relationships between cardiorespiratory fitness and cognitive function was retrieved for the systematic review. Results: As for the relationships between cardiorespiratory fitness and executive function, consistent evidence showed that adolescents with good cardiorespiratory fitness had better executive function. It should be noted that, compared to other variables corresponding to physical fitness, cardiorespiratory fitness is the most important factor of the attention network. Cardiorespiratory fitness was also found to be a mediating variable for the relationships between birth weight and intelligence. Conclusion: In previous studies, cardiorespiratory fitness was found to be related to different dimensions of middle school students' cognitive function, including executive function, attention network and intelligence. Evidence also indicated that cardiorespiratory fitness was the most important type of physical fitness related to a certain dimension of cognitive function.*

Keywords: *cardiorespiratory fitness, cognitive function, executive function, intelligence, middle school students.*

1. Definition and types of cognitive function

Cognition is a kind of human psychological activity that refers to the individual knowledge and understanding of the psychological process of things; it is the most important and active element in human psychological activities. Cognition includes one's own perception of the surrounding environment, judgment, attention, memory, learning and language. Cognitive function consists of multiple cognitive domains, including spatial orientation, attention, memory, computation, structural ability, language understanding and expression, application and executive ability, etc.

2. Cognitive function of middle school students and its influencing factors

Adolescence is an important learning stage in one's life. A large number of studies have shown that cognitive function is closely related to academic performance (Willoughby et al., 2019). At the same time, adolescents often make risky and impulsive decisions and choices that increase the risk of adverse outcomes, which is related to the relatively immature impulse control in adolescents' cognitive function during this period. Some scholars have claimed that the poor cognitive ability of adolescents is a risk factor for their mental health in the future (Gale et al., 2017). Therefore, it is very important to grasp the plasticity of cognitive ability development in adolescence to improve individuals' cognitive ability, academic performance and healthy growth.

2.1 Executive function of middle school students and its influencing factors

Executive function is a high-level cognitive function that refers to the coordinated processing of complex cognitive tasks, thus producing coordinated, orderly and purposeful behaviours. Executive function includes three categories of cognitive processes: working memory, inhibitory control and cognitive flexibility.

2.1.1 Current situation of executive function

"Cognitive control refers to the ability to control our thoughts and actions for the purpose of future goals." (Crone & Steinbeis, 2017, p. 207) Executive function has been identified as a determinant of academic performance (Best et al., 2011). More precisely, two aspects of cognitive function, namely working memory and inhibitory control, have been established by St Clair-Thompson and Gathercole (2006) to be closely related to academic performance, with math, reading and spelling skills considered as essential. These authors studied a sample of 51 British children aged 11 and 12 years and found that working memory was significantly correlated with attainment in English ($r = 0.62$, $p < 0.01$) and mathematics ($r = 0.45$, $p < 0.01$), while inhibition was associated with attainment in English ($r = 0.31$, $p < 0.05$), mathematics ($r = 0.36$, $p < 0.05$) and science ($r = 0.34$, $p < 0.05$). The results of another study (Dubuc et al., 2020) showed that neither interference control nor working memory appeared to be major predictors for any of the academic achievement measures; in fact, executive function explained at most 11.4% of the difference in academic achievement, while age explained at most 33.6% of this difference, and working memory seemed to be a better predictor of academic achievement for boys, while inhibitory control seemed to be a better predictor of academic achievement for girls. When studying academic performance or executive function, it is important to analyse boys and girls separately. Cartwright (2012) believes that "executive function plays a critical role in the development of academic skills such as reading" (p. 24), which requires the mobilisation of working memory to store and process contextual information, but inhibitory control is also needed in order to avoid interference and obtain correct information. The study conducted by Chung et al. (2018) has found that, compared to other phonetic languages such as English, reading and spelling in Chinese, a symbolic language, exert higher demands on executive functioning.

Working memory, as the most important component of executive function, is also strongly associated with the mathematical skills of children and adolescents. According to the research conducted by Bjork and Bowyer-Crane (2013), working memory plays an important role in calculating and solving arithmetic word problems. Working memory capacity is an index to evaluate working memory. Many studies have found that math learning difficulties are associated with insufficient working memory capacity. Borella and Ribaupierre (2014) and Gerst et al. (2017) have shown that working memory is closely related to reading comprehension and math calculations.

Inhibitory control is considered to be the basis of executive function. Inhibition is an active repressive process that can prevent the entry and storage of irrelevant information in working memory and its interference with working memory, thus ensuring the integrity of the cognitive process. De Weerdt et al. (2013) have found that inhibitory control is closely related to children's spelling scores and reading comprehension.

Executive function is an important factor in the development of intelligence, learning skills, social competence and physical and mental health of children and adolescents. Different executive functions develop at different rates (Theodoraki et al., 2020). According to Welsh et al. (1991), inhibitory control reaches maturation around 10-12 years of age, but Zhan et al. (2011) believe that adolescents' cognitive flexibility is still developing at the age of 17. Spencer (2020) investigated the structure and development of working memory in children aged 4-15 years and found that the basic block structure of working memory appeared at the age of 6 or even earlier, and the large-scale expansion of functional capacity was completed during primary school and youth. The study by Brockmole and Logie (2013) revealed that visual working memory improved between 8 and 20 years of age, but a steady linear decline was noticed from 21 to 75 years old.

The above indicates that the normal development of executive function is the guarantee of individual success, and effective learning in children and adolescents is inseparable from it.

2.1.2 Influence of social factors on executive function

An increasing number of studies have found that environmental factors such as cultural background, family socioeconomic status or school education can influence the development of executive function.

Family socioeconomic status includes family income, material wealth, parent education level, occupational prestige, parenting style, frequency of stressful life events and other characteristics (Farah, 2017). Lawson et al. (2018) found that socioeconomic status was related to children's executive function (with a small-to-medium correlation effect size). Children aged 4-5 years with low socioeconomic status had poorer working memory and inhibitory control accuracy (St John et al., 2019), and this correlation was likely to continue throughout childhood to adulthood. Duncan and Magnuson (2012) showed that family income was most closely related to the executive function of children and adolescents.

The influence of school education on adolescents' executive function can be divided into different educational experiences and styles. Brod et al. (2017) found that, after receiving one year of formal school education, first-grade children showed greater progress in executive function than their kindergarten peers. Older people with higher levels of education also show higher levels of executive function. In addition, it has been verified that bilingual education is beneficial to the development of children's cognitive flexibility. Bialystok (2021) found that bilingual children aged 5-6 had more advantages in tests of cognitive flexibility and working memory after controlling their vocabulary levels.

2.1.3 Influence of individual factors on executive function

Individual differences in executive function are largely due to genes or heredity. In addition, personal experience, habits, health status, intervention training but also other factors can influence the development of an individual's executive function. In developing this function, genes interact with various factors, and the positive ones should be grasped to make the individual get better development.

Among these factors, exercise is beneficial for the development of executive function and numerous researchers have reached a consensus in this regard. The study by Ai et al. (2021) addressed the effects of short-term (acute) and long-term exercise on executive function, revealing that acute high-intensity interval training (HIIT) had a positive effect on it. Davis et al. (2011) conducted a 13-week exercise programme (20 or 40 minutes per day) on sedentary overweight children aged 7-11, and the results showed improvements in both their executive function and mathematics achievements. Budde et al. (2010) randomly divided 60 high school students into two experimental groups and a control group and assessed their cognitive performance using a working memory task after a normal school lesson and after a 12-minute resting control or exercise. The study demonstrated significantly improved results for working memory “due to exercise when the groups were split into low and high performer at pre-test with a higher improvement of the low performers” (Budde et al., 2010, p. 382).

To achieve the purpose of improving executive function, in addition to exercise, music training, meditation training and other intervention methods are also recommended by a large number of researchers.

Kamijo et al. (2014) have pointed out in their study that obese children have poorer inhibitory function and working memory, namely cognitive flexibility, compared to normal-weight children, showing the extensive negative impact of obesity on executive function: the higher the degree of obesity, the higher its negative impact on executive function.

Adolescents who have experienced adverse events (physical abuse, sexual abuse, emotional neglect, family dysfunction, etc.) during their growth process have poor inhibitory control and cognitive flexibility, as well as poor individual ability to regulate their emotions. In addition, factors such as sleep and psychological disorders (e.g., depression, autism, schizophrenia) can influence the development of executive function.

2.2 Attentional function of middle school students

Attention plays a crucial role in human perception and cognition. Attention refers to the cognitive process in which consciousness prepares and processes certain aspects of the external physical environment or subjective memory storage. According to its functions, attention can be divided into selective attention, focused attention, divided attention and alternating attention. At present, the most influential model is the attention network system designed by Posner and Petersen (1990) and split into three subsystems, namely alerting network, orienting network and executive network.

2.2.1 Current situation of the attention network

Among the cognitive functions, attention is one of the major issues of concern in adolescence. As a basic cognitive ability, it involves a wide range of tasks and regulates the probability of successful behaviours in the academic, sports or social fields. The ability to concentrate on a task for a long period of time is known as focused attention, which is essential for the successful completion of various tasks. Paying attention is particularly important because “few constructs have a more direct impact on children’s academic achievement than their ability to pay attention in the classroom” (Trentacosta & Izzard, 2007, p. 78). Breslau et al. (2009) reported that an ethnically diverse cohort of 693 children was assessed at the age of 6 for behavioural problems and IQ and at the age of 17 for academic achievement in mathematics in reading. The study concluded that an increase in attention disorders between the ages of 6 and 11 predicted a decline in math and reading achievement between the ages of 11 and 17, indicating the existence of a close relationship between inattention and academic achievement among adolescents aged 11-19 years. Early attention ability has even been found to predict success in high school graduation (Blotenberg & Schmidt Atzert, 2020).

Research shows that each component of the attention network has a different developmental trajectory. The development of alertness and targeted networks mainly begins in infancy and early childhood and gradually matures towards the end of childhood (Pingault et al., 2011). By contrast, the executive control network develops slowly from the end of year 1 to puberty, and the period from the end of year 1 to the age of 7 is the key period of development. After the age of 7, the executive control network progressively becomes stable. At this time, the components of children's attention network are as independent as in adults. Compared to children, adolescents have an improved capacity for both selective attention to external information input and flexible transfer of attention between different tasks and goals, their inhibition and control function develops relatively well and they can manage conflicting interference information. The development of selective attention is regarded as an important symbol of the attention network development.

2.2.2 Influence of social factors on the attention network

A growing body of research evidence suggests that family socioeconomic status influences the development of attention. Einziger et al. (2019) found that children from low-income families were slower and less accurate than children from high-income families on the task of measuring the alertness network and performing the control network. The above authors argue that home disorder (defined as overcrowding), inconsistent daily schedules and high noise levels have a negative effect on the development of attention in children from low-income families, adding that a higher level of family chaos indicates increased impulsiveness and low attention. The suggestion for children living in chaotic households is to learn to filter out high levels of stimuli, including information that is developmentally beneficial. Higher family disorder is also associated with parents' lower verbal responses, which may be negatively correlated with children's attention ability. At the same time, the degree of family disorder and socioeconomic status are often correlated. Moreover, the school learning experience and poor attentional development at school may undermine the acquisition of basic academic skills, as attentional difficulties reduce the benefits that children derive from formal education.

2.2.3 Influence of individual factors on the attention network

Many studies have demonstrated gender differences in attention. Liu et al. (2013) tested gender differences associated with the efficiency of the three attention networks (alerting, orienting and executive control) in 73 healthy people (38 male and 35 female). All participants performed a modified version of the Attention Network Test (ANT), and females recorded higher orienting scores than males ($t = 2.172$, $p < 0.05$), meaning that women were able to orient their attention more quickly to a specific spatial location. In the above study, no gender differences were found between males and females in alertness ($t = 0.813$, $p > 0.05$) and executive control ($t = 0.945$, $p > 0.05$) in attention networks. In addition to gender, obesity is also a factor that affects attention network functioning. The study by Bauer and Manning (2016) showed that overweight/obese adolescent girls had lower scores on working memory and sustained attention tasks. The reliable detection of such decline may depend on the task difficulty and the way of measuring performance and brain activity. Furthermore, acute and chronic sleep deprivation, which is particularly common in middle school students due to academic stress, also impairs attention in children and adolescents.

2.3 Other cognitive functions of middle school students

In addition to the executive function and attention network, reasoning ability and processing speed have also been considered by a large number of studies to be closely related to the academic performance of middle school students. Reasoning or thinking ability reflects individual differences in understanding the nature of things and the connections between them. Reasoning ability mainly involves the cognitive understanding and judgment ability of individuals on word concepts, graphic changes, relationships between things and written materials. Processing speed is the ability of an individual to perform various cognitive operations quickly and slowly. It is not only an important index to measure mental ability, but also a crucial way to investigate the level of individual psychological development, which essentially reflects changes in the internal psychological mechanism of the cognitive process.

2.3.1 Current situation of other cognitive functions

The important role of reasoning ability in the acquisition of knowledge in school mainly derives from the relationship between intelligence and academic achievement (Vock et al., 2011). Classical psychometric theories often define intelligence, especially fluid intelligence, as the ability to reason based on abstract reasoning. Roth et al. (2015) have shown in their study that intelligence is the best predictor of school grades across various subjects, mainly Mathematics and Science. The correlation between academic achievement assessed by fluid intelligence tests and academic tests is about 0.5 or higher, whereas the correlation tends to be 0.5 or lower when academic achievement measures are based on teacher ratings (Soares et al., 2015). This evidence is consistent with research findings showing that improved reasoning ability is accompanied by improved subject learning in the classroom.

In the general theory of cognitive development, processing speed is conceptually defined as the core mental ability that leads to higher-order cognitive change. Researchers have linked processing speed to higher cognitive abilities. It was subsequently found that the correlation between age and intelligence disappeared when processing speed was removed. The study conducted by McAuley and White (2011) has shown that processing speed can fully explain the relationship between age and inhibitory control task performance and partly explain the relationship between age and working memory in middle childhood. When experimental manipulation was used to equalise information processing speed between adults and 6-year-olds, their average working memory length was the same. In addition, a large number of studies (Geary et al., 2012) have shown that children with lower math scores are usually slower at processing information.

2.3.2 Influence of social factors on other cognitive functions

Barrigas and Fragoso (2012) examined the association between obesity, academic achievement and reasoning ability in 394 male and 398 female students aged 6-12 from Portugal. They also assessed how this relationship was affected by chronological age, maturity and socioeconomic status, the results showing that reasoning ability was independent of socioeconomic status and level of maturity.

2.3.3 Influence of individual factors on other cognitive functions

Processing speed is a key ability related to age growth. In studies on adult cognitive development, the processing speed theory of cognitive aging claims that the slowing down of processing speed with age is the main reason for cognitive function aging. Hong-Keun (2018) investigated gender differences in the cognitive ability of Korean children and found that girls performed better than boys in the processing speed test and that there were gender differences in processing speed. The similarity in gender differences also reported in Western children proves that this cognitive function is a “culturally universal phenomenon” (Hong-Keun, 2018, p. 51).

3. Relationship between cardiorespiratory fitness and cognitive function in middle school students

Cardiorespiratory fitness refers to the ability of the body to maintain long hours of work or exercise without premature fatigue, which mainly reflects the cardiorespiratory function of the human body under a specific intensity. Cardiorespiratory fitness is an important component of physical health and the core element of each component of physical health. There are many indices for assessing cardiorespiratory fitness, but maximum oxygen uptake is generally used to perform this assessment.

Aberg et al. (2009) examined all Swedish men born in 1950 through 1976 and found that cardiorespiratory fitness changes occurring between 15 and 18 years of age predicted cognitive performance at the age of 18. In recent years, a large number of studies have also found a correlation between cardiorespiratory fitness and the higher level of cognitive function in teenagers. Reloba-Martínez et al. (2017) have pointed out that cardiorespiratory fitness is the best predictor of the correlation between positive physical health and cognitive function in adolescents.

3.1 Relationship between cardiorespiratory fitness and executive function

Among the associations between cardiorespiratory fitness and cognition, executive function has been found to be particularly associated with cardiorespiratory fitness levels in preadolescent children (Pontifex et al., 2011) and adults (Erickson et al., 2015), but less attention has been paid to executive function in adolescents. The study conducted by Westfall et al. (2018) on 523 Danish adolescents showed that cardiorespiratory fitness was highly correlated with overall inhibitory control performance, and cognitive flexibility switching tasks were associated with higher accuracy and higher cardiorespiratory fitness. Hogan et al. (2013) highlighted that participants with poor cardiorespiratory fitness had a higher error rate during rest compared to participants with better cardiorespiratory fitness. A cross-sectional study by Huang et al. (2015) (N = 525) found that, in a modified Eriksen flanker task, higher cardiorespiratory fitness was associated with shorter response times but not with response accuracy. However, Stroth et al. (2009) did not observe behavioural differences between participants with poor cardiorespiratory fitness and participants with good cardiorespiratory fitness in a combined modified Ericksen flanker and GO/NO-GO task. According to some studies, the improvement of cardiorespiratory fitness level leads to the improvement of executive function level because an improved cardiorespiratory function in adolescents is conducive to an improved brain function and structure. Studies have found that aerobic exercise facilitates the secretion of certain nerve growth factors (such as brain-derived neurotrophic factor) and increases blood supply, thus improving brain function and plasticity (Whiteman et al., 2014). Other studies have found that children with good cardiorespiratory fitness have larger brain volumes in the dorsal striatum and hippocampus (which are thought to be involved in cognitive control and memory, respectively) than children with poor cardiorespiratory fitness. Overall, the findings have been consistent, pointing to better executive function in adolescents with good cardiorespiratory fitness.

3.2 Relationship between cardiorespiratory fitness and attention network

Multiple studies have shown that physical activity during childhood and adolescence is positively associated with attention and especially improved attention. Other studies have shown that the levels of physical health in children and adolescents are associated with selective attention and attention, and cardiorespiratory fitness is one of the variables observed to better explain these associations. Pérez-Lobato et al. (2016) surveyed 49 adolescents aged 14 to 16 (M = 15.05; SD = .77) using the D-2 test to analyse their attentional processes, and the 50-meter shuttle run was used to assess their cardiorespiratory fitness. The results showed that the relationship between physical fitness and attention measures was significant, with maximum oxygen consumption being the most relevant variable. The study by Reigal et al. (2020) found that cardiorespiratory fitness was mostly associated with the grey matter volume in some cortical and subcortical brain regions, and maximum oxygen consumption was the best predictor of attention and concentration measures. This can be explained by the fact that exercise creates cognitive demands that affect the brain. In addition, physiological processes occur with increasing levels of neurotrophic or hormonal factors that promote brain plasticity (Landrigan et al., 2020).

3.3 Relationship between cardiorespiratory fitness and other cognitive functions

There are few existing studies on the relationship between cardiorespiratory fitness and reasoning ability. Among them, the study conducted by Álvarez-Bueno et al. (2019) showed that the cognitive function of children with high cardiorespiratory fitness was better than that of children with low cardiorespiratory fitness. The authors concluded that cardiorespiratory fitness was a full mediator of the relationship between birth weight, verbal factors, numerical factors and general intelligence, and only a partial mediator of the relationship between logical reasoning and the spatial factor. Hwang et al. (2018) examined young adults aged 18-29 years, measuring their cerebral vasomotor reactivity (CVMR) in response to rebreathing-induced hypercapnia, maximal oxygen uptake and simple and complex neurocognitive assessments at rest. Statistical modelling revealed that their VO2max, CVMR and fluid reasoning measures were positively correlated. Therefore, the capacity for maximal oxygen uptake of healthy young adults was associated with higher CVMR and better fluid reasoning. There have been no reports on the association between cardiorespiratory fitness and processing speed in middle school students at home and abroad. Sandroff et al. (2019) studied the relationship between cardiorespiratory fitness and processing speed in patients with multiple sclerosis and found that depression, pain and fatigue were significantly correlated with cardiorespiratory health and cognitive processing speed ($p < 0.05$). Improving cardiorespiratory fitness might improve cognitive processing speed independent of the influence of depression, pain and fatigue.

4. Summary and outlook

A review of the history of studies regarding the effects of cardiorespiratory fitness on cognitive function in middle school students has tentatively proven the positive effect of good cardiorespiratory fitness on cognitive function performance in adolescents and also proposed a variety of possible mechanisms. However, there are still many shortcomings in relevant studies and further efforts are needed in the future. In studying the relationship between cardiorespiratory fitness and cognitive function, many scholars have focused on executive function and found that it may be a mediating variable of physical health that affects adolescent academic performance. However, research on the dose-effect relationship between cardiorespiratory fitness and cognitive improvement is still very weak and needs further research. This is an important theoretical basis for a physical exercise intervention to improve the cardiorespiratory fitness and cognitive ability of adolescents in the future. A series of key scientific questions, such as the dose-effect relationship between cardiorespiratory fitness, cognitive ability and academic performance, need to be further studied.

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