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THE ASSOCIATION BETWEEN PHYSICAL ACTIVITY, EXECUTIVE FUNCTIONS AND ACADEMIC ACHIEVEMENT: A LONGITUDINAL PERSPECTIVE

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Preface

This doctoral thesis represents a comprehensive exploration of the development of cognitive abilities, in particular the development of executive functions, mainly within the realm of early childhood development. It comprises a series of interconnected studies spanning diverse methodologies and age stages (childhood and adolescence), taking into account the effects of both biological aspects and cultural context.

The intricate relationship between motor and cognitive domains has emerged as a central focus in this study, for a deeper comprehension of how cognitively-engaging physical activity might be the *via regia* to which executive functions might be fostered, and subsequently, academic achievement.

Study 1, described in Chapter 2, served as a pilot investigation, laying the groundwork for subsequent inquiries by examining the feasibility of ad hoc cognitively-engaging physical activity intervention on inhibition in kindergarteners. This initial foray provided crucial insights into methodological considerations and intervention efficacy, setting the stage for further exploration.

Building upon the findings of Study 1, Study 2 took a longitudinal approach to delve deeper into the effects of a cognitively-engaging physical activity intervention on inhibition and working memory in kindergarteners, with a focus on its consequences for academic achievement in primary school. This longitudinal study, described in Chapter 3, provided valuable insights into the sustained impact of such interventions on cognitive development and academic outcomes.

Study 3 explores the relationship between physical activity, executive functions, and academic performance in adolescents, drawing upon previously published research to elucidate this multifaceted dynamic. It was described in Chapter 4.

Furthermore, this thesis investigated both the role of biological and environmental factors in the development of executive functions. As regard biological aspects, Chapter 5 delve into the role of COMT and BDNF genes in shaping executive functions during adolescence. Additionally, Chapter 6 investigated the intricate role of environment, expanding the scope of inquiry by undertaking a cross-cultural examination of similarities and differences in executive functions and motor abilities in Italian and Japanese kindergarteners, and exploring the effects of motor abilities on executive functions between different contexts.

Throughout this thesis, each study has been guided by a commitment to rigorous inquiry, interdisciplinary collaboration, and a dedication to advancing the understanding of early childhood development.

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Abbreviations

PA	Physical Activity
EFs	Executive Functions
AA	Academic Achievement
WHO	World Health Organization
WM	Working Memory
WCST	Wisconsin Card Sorting Test
PFC	Prefrontal Cortex
DL	Dorsolateral
VM	Ventral medial
OF	Orbitofrontal
fMRI	functional Magnetic Resonance Imaging
ACC	Anterior Cingulate Cortex
CFA	Confirmatory Factor Analysis
DCCS	Dimensional Change Card Sort task
SES	Socio-Economic Status
DCCS	Dimensional Change Card Sort task
COMT	Catechol-O-methyltransferase
BDNF	Brain-Derived Neurotrophic Factor
SNP	Single-Nucleotide Polymorphism
MVPA	Moderate-to-Vigorous PA
IQ	Intelligence Quotient
RCT	Randomized Controlled Trials
Hp	Hypothesis

CG1	Control Group 1
CG2	Control Group 2
IG	Intervention Group
CG2	Control Group 2
M	Mean
SD	Standard Deviation
HSKT	Head-Shoulders-Knees-Toes
T1	Pre-test
T2	Post-test
FE-PS-2	Batteria per la valutazione delle funzioni esecutive in età prescolare – Second Edition
ESA	Enriched Sport Activities
PMA	Programma Motorio Arricchito
ICCs	Interclass Correlation Coefficients
SPSS	Statistical Package for the Social Sciences
ANOVA	ANalysis Of VAriance
η^2_p	Partial eta square
SEM	Structural Equation Model
CFI	Comparative Fit Index
TLI	Tucker Lewis Index
RMSEA	Root Mean Square Error of Approximation
SRMR	Standardized Root Mean Square Residual
CI	Confidence Interval
MANOVA	Multivariate ANalysis Of VAriance
AIP	Italian Association of Psychology
PureLink kit	PureLink Genomic DNA ThermoFisher Scientific

PCR	Polymerase Chain Reaction
dNTPs	deoxyNucleoside Triphosphate
Dream Taq	Thermo Fisher Scientific
ToL	Tower of London
BART	Balloon Analogue Risk Task
IGT	Iowa Gambling Task
BVN	Batteria di Valutazione Neuropsicologica per l'età evolutiva

Chapter 1. Association between executive functions, physical activity, and academic achievement

1.1. Introduction

A growing body of research supports a positive relationship among physical activity (PA) executive functions (EFs), and academic achievement (AA) in children and adolescents (Aadland et al., 2017a; de Greeff et al., 2018; Donnelly et al., 2016; Egger et al., 2019; McPherson et al., 2018; Oberer et al., 2018; Singh et al., 2019; Visier-Alfonso et al., 2021).

Besides the well-documented health advantages of PA in children, such as enhancing physical fitness, bone health, cardiovascular health, mental well-being, decreased body fat, and the development of psychosocial and motor skills; the World Health Organization (WHO) in 2020 recognized that it also contributes to improve cognitive outcomes, including EFs, and AA (Chaput et al., 2020).

In the following sections, a separate in-depth description of each construct is provided. The discussion starts from EFs, moving to PA, and finally talking about AA. Successively, the last paragraph describes the state of the art about the intricate relationship between PA, EFs, and AA.

1.1.1. Executive Functions

EFs refer to a wide array of higher-order cognitive processes essential for conscious control of thoughts, emotions, and behaviors to achieve a goal (Diamond, 2013). EFs encompass three core domain-general components: working memory (WM), inhibition, and cognitive flexibility; and each of them is composed of two subparts (Diamond, 2020).

WM is the ability to maintain information in mind and mentally manipulate that information (Baddeley & Hitch, 1994; Kent, 2016; Smith & Jonides, 1999). It plays a crucial role in doing mental calculations and engaging in activities that involve playing with ideas or scenarios. Diamond (2020) states "those aha moments when you suddenly see how one thing relates to another happen are made possible by your WM ability" (pp. 225). WM is not merely about holding information in mind but also involves actively processing that information and potentially manipulating it to perform various cognitive tasks. The two subparts of WM retain verbal and visuospatial WM. The former is a cognitive function that involves temporarily storing and manipulating verbal or language-based information in mind for the purpose of performing various tasks. It typically includes activities such as mentally rehearsing a phone number, solving math problems, comprehending complex sentences, or following spoken instructions. Verbal working memory is crucial for tasks that involve language, reasoning, and problem-solving. The latter pertains to the temporary storage and manipulation of visual and spatial information in mind. It involves tasks such as mentally rotating objects, remembering the spatial arrangement of objects, or navigating through a complex environment in mind. Visuospatial working memory is essential for activities that require mental imagery, spatial reasoning, and the manipulation of visual information (Logie, 2003).

Inhibition or inhibitory control refers to the capacity to manage and regulate thoughts, attention, actions, or emotions effectively, ignoring powerful internal impulses or external temptations to carry out intended actions (Diamond, 2013; Simpson et al., 2012; Watson & Bell, 2013; Wiebe et al., 2011). Therefore, it entails the capacity to counteract a potent urge to engage in a behavior and, instead, prioritize what is most essential or appropriate (Diamond, 2011). The two key sub-components: self-control (or response inhibition) and interference control. The first encompasses the ability to hinder predominant impulses to perform a more appropriate behavior. Examples of self-control are refraining from taking something without permission or payment, retaliate immediately after being hurt emotionally or refraining from speaking out the first thought that comes to mind. It represents the antithesis of impulsive behavior, since requires thoughtful consideration before speaking or acting to prevent potential regrets (Diamond, 2020). The second refers to the ability to manage attention and thoughts effectively. In terms of attention, it involves selective attention, which means being able to resist external distractions and maintain concentration (Driver, 2001). In terms of cognitive inhibition, it encompasses the ability to resist to mind wandering and internal distractions, such as unwanted or irrelevant thoughts (Keulers & Jonkman, 2019; Smallwood &

Schooler, 2015). Inhibition is crucial in preventing social mistakes and is essential for maintaining a well-ordered society where individuals adhere to established rules and social norms (Diamond & Ling, 2016). Inhibitory control is what allows us to exert conscious control over our reactions and behavior, preventing us from being solely driven by inner impulses, external stimuli, or ingrained habits of thinking and acting. It grants us the ability to make choices and modify our behaviors, rather than being purely driven by instinct (Diamond, 2013).

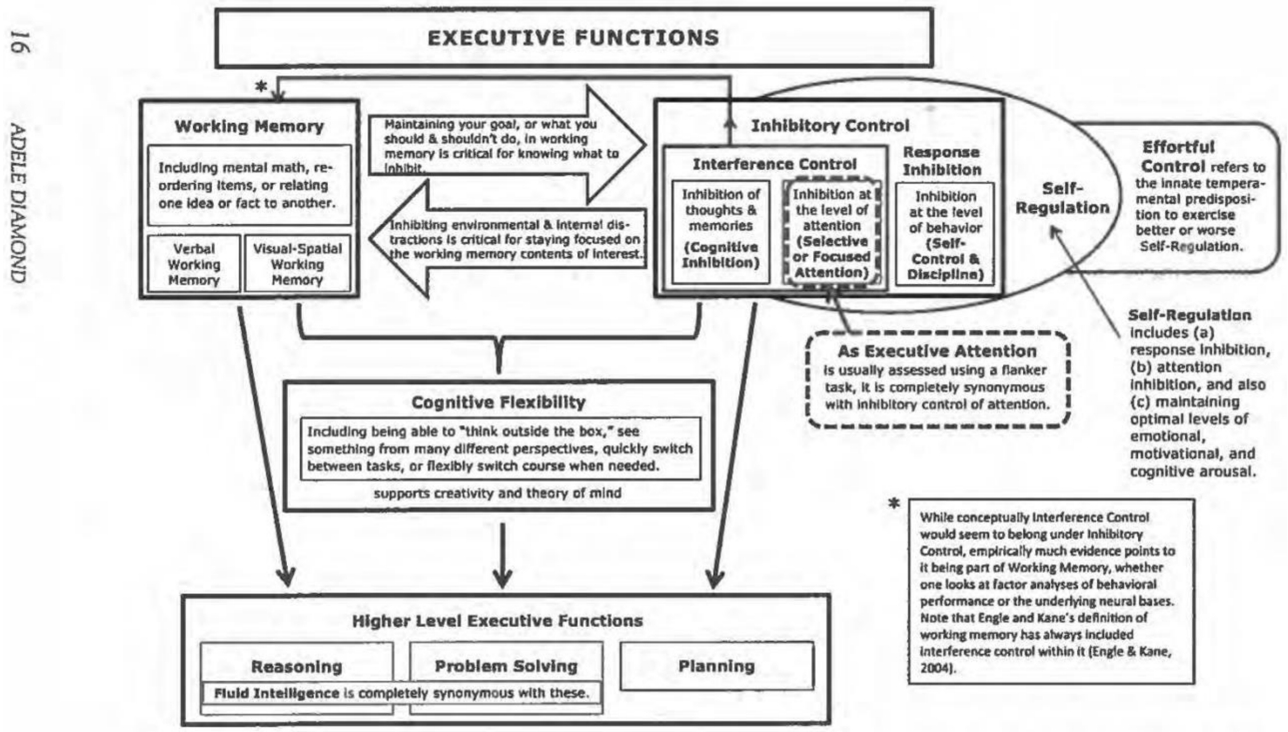
Cognitive flexibility, also known as shifting, involves two underneath subcomponents, the first one is the capacity to switch between different tasks, rules or mindsets, and the second one is the capability to swiftly and adaptively responding to change. Cognitive flexibility encompasses three features: it implies a learning process that is acquired with experience; it relies cognitive strategies; it refers to changes in behaviors and not in discrete responses (Cañas, 2006). Since it is a human adaptive ability (Payne et al., 1993), this adaptation might not always happen. For instance, in situations where a person is expected to adapt and respond flexibly to changes in the environment but struggles to do so, or a person is not able to consider alternative perspectives or adapt to changes, we speak of cognitive rigidity or cognitive inflexibility (Diamond, 2020). Cognitive flexibility depends on both attentional processes and knowledge representation. The former play a crucial role in assessing new situations, recognizing changes in the environment, and planning the necessary actions, it mostly refers to non-routine response (Cañas, 2006). Cognitive flexible individuals must be able to identify environmental conditions that may interfere with the current task, inhibit automatic responses, and plan and execute a new sequence of actions that effectively react to the new task demands. Moreover, cognitive flexibility refers to how individuals mentally represent their knowledge about the task and potential strategies they can employ (Cañas, 2006). This knowledge is acquired through learning processes from previous experiences in similar situations. To be adapted to the situation changes, this previous knowledge has to be modified. Spiro and Others (1988) introduced the Cognitive Flexibility Theory, suggesting that individuals able to view a task from various perspectives are better equipped to understand and interpret changes in the environment and exhibit greater cognitive flexibility. As a result, they are capable of swiftly restructuring their knowledge and adjusting their responses to meet shifting situational demands. It highlights the complementarity of the two explanations. To sum up, cognitive flexible person is able to address and interpret changes in situations, restructuring the existing knowledge to behave accordingly.

The three components of EFs were defined in a study carried out by Miyake and colleagues (2000), in which they investigated the structure of EFs by employing latent variable analysis, a statistical technique that utilizes several observable measures to deduce a latent variable. This latent variable is assumed to represent the core construct of EFs: WM, inhibition, and cognitive flexibility. Results revealed three main components associated with specific experimental tasks: WM on the Operation Span Task, inhibition on the Tower of Hanoi, and cognitive flexibility on the Wisconsin Card Sorting Test (WCST). In a systematic review of 106 studies spanning from 2008 to 2015, Baggetta & Alexander (2016) identified 39 different processes labeled as EFs. Findings highlighted that the most investigated component was inhibition, WM, cognitive flexibility, planning, and attention.

The construct of EFs has been explored by different disciplines, including developmental science, psychology, neuroscience, and psychiatry. The development of EFs is characterized as a gradual enhancement in domain-general component such as cognitive abilities that impact performance across various tasks and contexts (Diamond, 2013; Miyake et al., 2000).

To sum up, the core components of EFs encompass the capability to retain and manipulate information in mind (WM), to suppress automatic or predominant responses (inhibition), and to flexibly change between multiple rules, tasks or mental sets (cognitive flexibility) (Best & Miller, 2010; Miyake et al., 2000). These cognitive abilities are defined as crucial skills that emerge early in childhood enabling children to focus attention, resist internal and external temptations, and make plans (Diamond, 2016). Moreover, higher-order EFs such as planning, problem-solving, decision-making, delay of gratification, and verbal fluency are built upon the foundation of the three core EFs (Collins & Koechlin, 2012; Diamond, 2013; Lunt et al., 2012). EFs as reasoning and problem-solving encompass what is known as fluid intelligence, which is strongly correlated with WM (Chen & Li, 2007; Duncan et al., 2012; Fry & Hale, 1996; Fukuda et al., 2010; Kane & Engle, 2002). All these different but related concepts were well described by Diamond (2016), here reported in Figure 1.

Figure 1. *Overview of executive functions*



Note: Description of the three core EFs. Reprinted from "Why improving and assessing executive functions early in life is critical", by A. Diamond, In J. A. Griffin, P. McCardle, & L. S. Freund (Eds.), 2016, Executive function in preschool-age children: Integrating measurement, neurodevelopment, and translational research (pp. 11–43). Copyright 2016 by the American Psychological Association.

1.1.2. Neural networks in Executive Functions

Research on EFs derived from single-case studies with brain damage has contributed significantly to our understanding of these cognitive processes. The most well-known case study on EFs was the case of Phineas Cage, a 25 years old railroad worker who suffered from a severe injury to one of his frontal lobes after being impaled by an iron bar. This incident, documented by Harlow in 1868, resulted in notable changes in Gage's personality and behavior. Although medical reports from the same era did not definitively establish a connection between frontal lobe lesions and personality alterations (Welt, 1888), the difficulties related to inhibition, such as impulsivity and a diminished sense of social responsibility, are frequently observed in individuals with prefrontal cortex (PFC) damage. These led researchers to delve deeper into the role of the frontal lobes in cognitive processes.

Despite that, the concept of EFs has been not introduced until the 1970s, when Pribram (1973) defined the PFC as the executive of the brain. Over the subsequent years, a large amount of both theoretical and empirical research led to a greater comprehension of the core components, as well as, the neural architecture that underlie EFs, the factors that either promote or impede their development, and the connections between deficits in EFs and various clinical manifestations. The above-mentioned origins in neuropsychology and the study of frontal lobe injuries played a crucial role in combining the term EFs with the functions of the PFC (Barkley, 2012; Best & Miller, 2010; Zelazo & Müller, 2002).

Most of neuroimaging research delve into the PFC, which makes approximately two-thirds of the frontal cortex approximately. The PFC is composed of three main frontal-subcortical circuits, each associated with distinct EFs. These circuits are: Dorsolateral (DL) PFC, Ventromedial (VM) PFC, and Orbitofrontal (OF) PFC (Figure 2).

Figure 2. *Prefrontal cortex*

Note: Description of the PFC areas. Reprinted from "The role of prefrontal cortex in cognitive control and executive function", by N.P. Friedman & T.W. Robbins (2022). Neuropsychopharmacology, 47, 72-89. Copyright 2022 by the American Psychological Association

Both functional and structural neuroimaging studies have linked these three circuits to EFs processes (Alvarez & Emory, 2006). In particular, the DL-PFC predominantly projects to the dorsolateral head of the caudate nucleus, which has been implicated in the core EFs (i.e. inhibition, WM, and cognitive flexibility), and problem-solving and planning as well (Alvarez & Emory, 2006; Moriguchi & Hiraki, 2013). Additionally, studies on the functional connectivity of the DL-PFC suggested its involvement in these EFs as well (Funahashi & Andreau, 2013; Panikratova et al., 2020).

The functions of other two frontal-subcortical circuits namely, the VM-PFC and OF-PFC, have been relatively less studied. It may be due to their close association with the Hot emotional components of EFs, such as emotional control, which have been less extensively examined. The VM-PFC originates in the anterior cingulate and send projections to the amygdala, hypothalamus, hippocampus striatum, nucleus accumbens, which has been related to the social-emotional aspects of EFs, as empathy and motivation (Nejati et al., 2023; Robinson & Rogers, 2015). Whereas, the OF-PFC sends projections to the ventromedial caudate nucleus and plays a role in cognitive processes, such as attention, inhibition, and emotional processes (Bryden & Roesch, 2015; Kuusinen et al., 2018). Although these three frontal-subcortical circuits appear to be associated with distinct EFs, they are interconnected and collaborate to facilitate the diverse components of EFs (England-Mason & Dewey, 2023). However, Zelazo and Carlson (2012) suggested that measures of Hot EFs involving temptation with higher emotional significance weighted on OF-PFC, which may occur later compared to the development of DL-PFC related to Cool EFs.

Emerging empirical evidence highlighted both the unity and diversity of the components of EFs during childhood and adolescence (Fiske & Holmboe, 2019; McKenna et al., 2017), and adults (Friedman & Robbins, 2022). Studies with functional Magnetic Resonance Imaging (fMRI) displayed that laboratory tasks with the aim of assessing WM activate neural areas in the DL-PFC, Anterior Cingulate Cortex (ACC), and the parietal cortex both superior and posterior (Collette et al., 2005; Marklund et al., 2007). Cognitive flexibility tasks activate specific brain regions including the right interparietal sulcus, the left superior parietal cortex, the right supramarginal gyrus, the left middle and inferior frontal gyri, and the left precuneus (Collette et al., 2005). In addition, tasks designed to evaluate inhibition activate brain areas such as the right middle and superior frontal gyri, right orbitofrontal gyrus, and the right inferior frontal gyrus (Banich & Depue, 2015; Collette et al., 2005). Indeed, neuroimaging studies (Collette et al., 2006; Funahashi & Andreau, 2013; Goethals et al., 2004; Panikratova et al., 2020; Zhong et al., 2014) have indicated that not only the PFC but also posterior areas of the brain, such as the parietal and the temporal regions, and cerebellum as well are involved in EFs. The emerging perspective is that EFs require the engagement of large-scale brain networks. Furthermore, the core components of EFs, such as inhibition, WM, and cognitive flexibility, are linked to neural processes that are partially differentiate and partially overlapped. These results are in line with the integrative model proposed by Miyake and colleagues (2000) highlighting common neural networks involved in the core components of EFs, supporting the assumption of the unity and diversity of the three EFs components. Despite of the above-mentioned core components of EFs, also attention is another crucial component.

It encompasses networks responsible for alerting, orienting, and executive attention which share commonalities with those related to EFs. The first, known as the alerting network, pertains to how individuals attain and maintain a vigilant state. It entails input from the norepinephrine system, notably the locus coeruleus, which modulates the activity in the frontal and parietal brain structures (Rueda et al., 2023). The second, termed the orienting network, oversees selective mechanisms operating on sensory input. It involves different brain areas, such as the frontal eye fields, the inferior frontal cortex, and the superior and inferior parietal lobe as well (Vossel et al., 2016). This network is associated with two separate brain systems: one is responsible for voluntary attention using top-down mechanisms (the dorsal attention system) and another that reorients attention in response to task demands (the ventral attention system) (Corbetta et al., 2008; Corbetta & Shulman, 2002). The last, the executive network is important for thoughts, emotions, and behavior regulation. It includes the anterior cingulate and anterior insula as key components (Posner et al., 2014; Rueda et al., 2023). These attention networks start developing from infancy and continue throughout childhood. Despite having distinct anatomies, they are interconnected in influencing attention and impacting EFs (Mullane et al., 2016; Xuan et al., 2020).

Previous studies investigating developmental trajectories of EFs suggested that sex differences may not significantly affect them (Grissom & Reyes, 2019). However, recent evidence from a systematic review carried out by Gaillard and colleagues (2021) highlighted significant differences related to sex in the neural networks underneath the related performance on WM, inhibitory control, and cognitive flexibility tasks. Within-sex variability seems to be more than between-sex variability in EFs, given that environmental factors and experience significantly influence the development of EFs (Grissom & Reyes, 2019).

Further research is warranted to comprehend how sex differences contribute to the shape brain regions associated with EFs in both structural and functional way. Additionally, investigating the influence of hormones at various stages of development, such as puberty and menstrual cycle, on the neural correlates of EFs during childhood and adolescence is warranted.

In conclusion, acquiring a more comprehensive understanding of the neural basis of EFs, and the distinctions and variations between and within sexes, might offer insights into potential interventions aimed at enhancing cognitive, psychological, social, physical, and mental health in children and adolescents (England-Mason & Dewey, 2023).

1.1.3. Theoretical background

Thelen and colleagues (2001, p. 1) stated “to say that cognition is embodied means that it arises from bodily interactions with the world. From this point of view, cognition depends on the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked and that together form the matrix within which reasoning, memory, emotion, language, and all other aspects of mental life are meshed”.

The core concept of the embodied cognition approach is that cognition and motor abilities are intertwined, since cognitive processes are deeply rooted in the body’s interactions with the physical environment. Its main aim is to explain the full range of humans’ perceptual, motor, and cognitive abilities as capacities depending upon aspects of an agent’s body, and emphasizing the formative role of the environment on the development of cognition (Anderson, 2007). It suggests that these aspects of human functioning are deeply intertwined and cannot be viewed or studied in isolation from one another (Raab et al., 2021).

This assumption derives as coupling from cognitive-developmental theory proposed by Piaget (1952) and the theory of ecological psychology proposed by Gibson (1979). Glenberg and Kaschak (2002), based on the influences of the ideas of Barsalou (1999) and Gibson (1979), develop the notion that cognition is embodied. They argue for the idea is embodied and can be described as a collection of available affordances. This perspective, known as the Indexical Hypothesis of meaning, assumes that words and phrases are connected to perceptual symbols. Moreover, these perceptual symbols are considered to be sensory and motor-based, or rather, the affordances they represent are derived from perceptual experiences, and the meanings associated with these symbols that are based on the sensori-motor systems.

In contraposition to the amodal theories of cognition that consider brain as the primary regulator of mental representations and cognitive processes, embodied cognition theories propose that thinking is not separate from processes of perception and movement. According to this perspective, cognition is embodied and mental processes occur through interactions between the brain, the individual's body, including its abilities and skills, the external context (Wilson & Foglia, 2017). In essence, thought processes are not confined to internal processes within the brain but are shaped by the dynamic interplay between the individual and their environment (Rowlands, 2010). Moreover, Jonhson and Lakoff (2002) argue that the mind is inherently embodied, and this embodiment goes beyond mere neural processes. They contend that our perceptual and motor systems play a fundamental role in shaping how we define concepts and engage in rational inference. In other words, our physical experiences and interactions with the world around us are integral to the way we understand and make sense of concepts and engage in logical reasoning.

Therefore, from the perspective of embodied cognition, brain is just a component of a wider action system that integrates cognition, perception, and movement to generate solutions for various tasks. Contemporary embodied cognition approaches share a fundamental assumption that cognition, perception, and movement processes are interdependent and mutually influence each other. However, where these approaches may vary is in the specific role they assign to the body in shaping cognitive processes. Some may emphasize the body's central role in cognition, while others might view it as one of several factors contributing to cognitive functioning.

Three different perspectives have been defined: conceptualization, replacement, and constitution (Shapiro & Spaulding, 2021). *Conceptualization* perspective suggests three propositions. The first is that our perception and understanding of the world are influenced by the physical characteristics of our bodies. It posits that variations in bodily features can result in distinct worldviews or perceptions of reality. In essence, different bodies can give rise to different ways of perceiving and experiencing the world. An example related to this is color perception. The way we see and interpret colors is influenced by neurophysiological conditions that vary among individuals (Varela et al., 2017). The second is that our abilities to create and understand ideas is based on the assumption that we move using our bodies. It assumes that the creation of concepts is determined by our bodies (Jonhson & Lakoff, 2002). For example, the ideas of front and back exists only for being that have a front and a back in the body. The third one assumes a response to the symbol grounding problem, suggesting that the process through which language creates meaning is embodied (Glenberg & Kaschak, 2002; Pecher & Zwaan, 2005). In other words, language acquires meaning because, as embodied agents, we move and interact with the world, hence without interaction the acquisition of a language is meaningless (Raab et al., 2021).

Replacement perspective posits that the traditional concept of cognition could be substituted with a conceptualization in which the brain's role is significant but diminished, becoming more of an equal contributor alongside the body and the external environment in the process of cognition (Shapiro & Spaulding, 2021). Replacement highlights the notion of situated cognition, which entails that the characteristics of the world, such as factors like sunlight, influence the range of actions available to an individual based on their body. Consequently, the environmental properties are instrumental in shaping the information and opportunities accessible to the individual.

Constitution perspective postulates that cognition involves the body, along with its interactions within the environment, as opposed to idea of cognition as affected by body and environment separately. Essentially, the body with its movements, and its environment constitute cognition. As a result, the cognition should be reconceptualized to encompass not only mental processes but also the bodily movements and interactions with the environment (Shapiro & Spaulding, 2021; Wilson & Golonka, 2013).

In sum, the three approaches embodied cognition delineated by Shapiro (2011) emphasize the importance of including the bodily movements and the environment in the study of mental processes to come to accurate conclusions. This mutual influence works in both directions: when examining mental processes, bodily movements, and environmental factors should also be taken into account. Studies in the field of embodied cognition primarily focus on investigating the immediate and specific impacts of exercise on cognitive functions.

According to the strength model of self-control revised by Audiffren and André (2015), EFs and self-regulation rely on effort as a shared resource when performing demanding tasks, such as cognitively-engaging PA. When children engage in activities requiring substantial cognitive effort, their cognitive resources may be depleted for subsequent tasks. However, the training hypothesis posits a parallel to trained muscles, suggesting that while the capacity for self-control may decrease immediately after an acute intervention, but it may increase after a long-term intervention. Similar to the theory of "supercompensation" in applied training science, which describes a temporary decrease in muscle performance immediately after acute physical exercise but eventual performance improvement after cognitively-engaging PA may have a comparable effect on cognitive functions.

1.1.4. Theoretical models of Executive Functions

Empirical evidence found individual differences in EFs suggesting both diversity, in terms of separate components, and unity, concerning correlations among components indicating a shared construct (Friedman et al., 2008; Friedman & Miyake, 2017; Smolker et al., 2015). The *tricomponent model* defined the core components of EFs as the most frequently studied models, commonly utilized in research spanning various age, including kindergarteners, school-age children, adolescents, and adults. Moreover, recent research provides evidence supporting the existence of three distinct components of EFs, which become more differentiated with age (Karr et al., 2018). Nevertheless, the tricomponent model highlights both inconsistencies from a conceptual and operational point of view increasing doubts as EFs should be reduced to these three core components. Although the tricomponent perspective of EFs is widely acknowledged, existing conceptual and operational discrepancies raise doubts about whether EFs should be simplified to just these three processes. For instance, the tricomponent perspective has faced criticism because laboratory tasks designed to assess EFs showed no significant correlations with measures of self-regulation (England-Mason & Dewey, 2023). Moreover, limited evidence highlighted that findings from studies using training aimed at enhancing one or more of EFs showed improvements in non-targeted components (Doebel, 2020). Therefore, the widely accepted tricomponent perspective of EFs, which has significantly influenced the field, seems to merit reevaluation .

Besides the tricomponent model, other models have been proposed. Metcalfe and Mischel (1999) proposed the *Hot-Cool systems* framework, "Cool system" also known as the "know" system plays a crucial role in voluntary control. Whereas, effortful control relates to the "Hot system" also known as the "go" system, since operates on emotional processes and generates immediate and straightforward responses, and it is crucial for controlling external stimuli (Chae, 2022). Hot processes are not EFs but rather represent bottom-up emotional influences on behavior, since they are associated with the amygdala rather than the OF-PFC, undermining top-down processes (Mischel et al., 2003).

In the model proposed by Zelazo & Carlson (2012) EFs are differentiate into two main categories, "*Cool*" and "*Hot*". This differentiation shares some similarities with the "Hot-Cool systems" proposed by Metcalfe and Mischel (1999), although there is a fundamental difference since the concept of Hot EFs suggests that emotionally significant contexts require distinct top-down processes, contrary to the above-mentioned definition that emotional contexts solely amplify bottom-up influences or hinder top-down control. More in depth, the three core EFs components are classified as Cool and refer to top-down processes related to the cognitive components of self-regulation, used in affectively neutral, non-emotional situations. Cool task implies abstract and decontextualized issue or situations, for instance, tasks that require the ability to shift between sorting rules as the WCST fall into this category. Hot EFs refer to top-down processes involved in handling positive and negative emotional cues to reach a specific goal (Diamond, 2020; Holfelder et al., 2020; Zelazo & Carlson, 2012). Hence, they are needed when dealing with the regulation of fundamental functions regulated by the limbic system, such as emotions and motivation, as well as self-awareness and social understanding (Zelazo et al., 2005). Therefore, Hot tasks encompass stimuli, decisions, and outcomes that hold significant motivational relevance, such as delay of gratification. Cool EFs are associated with the activation in DL-PFC, and Hot EFs are associated with the VM-PFC activation (Zelazo et al., 2005). From a developmental perspective, the distinction between Hot and Cool EFs holds significance. Associations between performance on measures of Cool EFs, such as WM and cognitive flexibility, are significant in children and adolescents, and this performance improves notably with age. In contrast, correlations in Hot EFs tasks, like delay gratification and decision-making, seem to be more complex. No significant correlation has been found among measures, as well as age-related enhancements tend to be gradual and emerge later in development (O'Toole et al., 2018; Prencipe et al., 2011).

Another emerging model is the *bidirectional model* of EFs (Blair & Ursache, 2011) which aims at offering a more balanced explanation of the self-regulatory skills that play a crucial role for school readiness in childhood and are instrumental for positive outcomes across the lifespan. It delineates how the simultaneous development of brain regions responsible for EFs mutually interact with those linked to self-regulation, including executive attention, emotion regulation, and the stress response system (Blair & Ursache, 2011). The ACC plays an important role, since it transmits neural signals to the PFC to start activity in the dorsal and ventrolateral regions linked to EFs. Simultaneously, it establishes connections with limbic areas responsible for emotional processing, which, in turn, have the potential to activate a stress response and heighten neuroendocrine activity in brain areas as the hypothalamic-pituitary-adrenal axis (Blair & Ursache, 2011). In summary, EFs and self-regulation processes interact in response to environmental cues, and thus influenced by experience. In this model, EFs are seen as a crucial higher-level process in modulating aspects of self-regulation (Blair & Ursache, 2011). Research examining the development of this bidirectional relationship between EFs and self-regulation proposes that children can be categorized as "early developers" (starting with high initial self-regulation levels and making early progress), "intermediate developers" (beginning with low initial self-regulation levels but making rapid improvements), or diversity in developmental paths underscores the importance of tailored intervention strategies.

1.1.5. Executive Functions, Self-regulation, and Effortful Control

In the past decades, different terms have been used interchangeably to refer to EFs. These inconsistencies in terminology are further complicated by the overlap between EFs and other psychological constructs, such as self-regulation and effortful control.

Self-regulation includes a set of control and adjustment abilities used to maintaining an optimal arousal managing functioning across cognitive, emotional, attentional, behavioral, and social domains (Blair & Raver, 2015; McClelland & Cameron, 2012; Montroy et al., 2016; Sulik et al., 2016). It can be thought as the behavioral expression of EFs and other socioemotional abilities essential for adjusting to the environment (Duncan et al., 2017), since it involves a wide spectrum of features including cognitive and emotional aspects of behavior (Bodrova & Leong, 2012; Liew, 2012; Raver et al., 2012), which work together (Gagne et al., 2021). In one hand, cognitive self-regulation refers to children's ability to use explicit metacognitive knowledge about thinking and learning processes; as well as implementation of strategies to regulate behavior while performing a task, like planning, monitoring, cognitive control of ongoing processes, such as sustained attention (Bodrova & Leong, 2012). On the other hand, emotional self-regulation includes children's awareness about emotions, strategies to manage and adjust ways to express them behaviorally (Eisenberg et al., 2010), and their ability to meet social expectations, as well as cooperate, and resolve conflicts with peers (Bierman et al., 2008; Denham et al., 2012).

Emotional self-regulation refers to regulation of emotions and not regulation by emotions (Gross, 2014). It can be differentiated between intrinsic, that is people's ability in regulating their own emotions; and extrinsic emotion-related self-regulation, namely individuals' capacity to regulate someone else's emotions (i.e. parents' ability to regulate by soothing their son's emotions) (Gagne et al., 2021). Since the interest is on regulation of emotions in children, the focus here is on intrinsic emotion self-regulation. Emotions-related self-regulation represents the "Cool" top-down process involved in regulation of changes in physiological responses, as well as modifications in emotional experience and behaviors. Essentially, it regulates “Hot” bottom-up emotional reactions. Individuals who excessively regulate their emotions, mainly in overly controlled or rigid ways, may encounter difficulties in EFs tasks (Metcalfe & Mischel, 1999). Albeit strong emotion regulation and self-regulation skills are typically linked to positive outcomes, reaching the ultimate balance between inhibition or regulation of emotions and a good performance on cognitive tasks is crucial, especially during childhood (Gagne et al., 2021; Zelazo, 2006; Zelazo & Cunningham, 2007).

The differences between self-regulation and EFs becomes evident when considering their respective measurement approaches. Self-regulation assessments often focus on how well a child adapts to their environment and are typically conducted in naturalistic settings. Whereas, EF assessments are less influenced by context and are commonly conducted in controlled conditions. Nonetheless, in most cases, researcher use similar if not the same measures to assess EFs and emotional self-regulation (Gagne et al., 2021). In the emotion-cognition model (Zelazo & Cunningham, 2007), emotions rely on the motivational aspects of cognition during tasks involving goal-directed problem-solving. In situations where tasks demand direct regulation of emotions, emotion regulation and EFs overlap. Whereas, when the regulation of emotions is subsequent to another cognitive task, it is considered secondary to EFs (Gagne et al., 2021). Previous studies have shown that both constructs are related, and their correlations tend to be weak to moderate (Fuhs et al., 2015; Lipsey et al., 2017).

Effortful control pertains to the innate temperamental predisposition to modulate of thoughts, and behaviors in emotionally salient context, and consequently implement better or worse self-regulation (Gagne et al., 2021). Temperament refers to individual differences in reactivity and self-regulation (Rothbart & Derryberry, 1981), which are reciprocal and interactive processes that manifest in early infancy (Rothbart et al., 2011). Reactivity involves impulsivity and behavioral inhibition, and it is more related to involuntary aspects. Whereas, effortful control encompasses the more voluntary ability to inhibit a primary response and regulate attention and emotions. Effortful control is not merely related to how individuals react to their environment or governed by their inner impulses or emotions. Instead, it allows children to engage in thoughtful, deliberate, and strategic thinking and behavior. Thus, it is crucial for children's self-regulation (Gagne et al., 2021), since effortful control aligns with emotion-related self-regulation (Eisenberg et al., 2010). To sum up, EFs perspective supports cognition as a crucial aspect in emotion regulation, and inhibition is defined as a cognitive ability; besides in the effortful control view emotion-related self-regulation matter, as inhibition operates in reactivity process.

Since both EFs and effortful control include inhibition as primary dimensions for children's self-regulation, some scholars did no evidence differences between the two (Sulik et al., 2016). A Confirmatory Factor Analysis (CFA) (Lin et al., 2019) on effortful control and EFs performance-based measures mainly focused on inhibition in early childhood supports a single-factor model of self-regulation, despite the existing divergent validity among effortful control and EFs tests. Aside from their structural resemblance, EFs and emotional control also exhibit functional similarity through executive attention (Zhou et al., 2011). This affinity is often seen in an overlap in the measures for both EFs and effortful control. For example, Stroop and Go/No-go tasks are typical tools used to assess inhibition. Go/No-go tasks involve presenting participants with a series of stimuli and instructing them to respond (e.g., press a button) to certain stimuli (go trials) while inhibiting from responding to others (no-go trials) (Falkenstein et al., 1995).

Nevertheless the conceptual parallelism, scholars sought to tease apart the two constructs. EFs predominantly pertain to self-regulatory functions guided by cognitive processes that develop gradually and slowly. It refers to the "Cool system" (Mischel et al., 2003), also known as the "know" system, which plays a crucial role in voluntary control. Whereas, effortful control relates to the "Hot system" also known as the "go" system, since operates on emotional processes and generates immediate and straightforward responses, and it is crucial for controlling external stimuli (Chae, 2022).

1.1.6. Development of Executive Functions

The development of EFs starts in infancy, continues during early, middle and late childhood until adolescence (England-Mason & Dewey, 2023), following a bell-shaped normative curve (Boelema et al., 2014). The PFC is partially specialized in childhood, it reaches a complete maturation in middle adolescence, due to the synaptic pruning. Subsequently, a gradual natural decline during early adulthood occurs (Boelema et al., 2014; Poon, 2018). EFs are thought to be a unified construct in early development that evolves into a multidimensional as childhood progresses (Best & Miller, 2010; Wiebe et al., 2008). This development is evident in the differentiation between WM, inhibition, and cognitive flexibility.

1.1.6.1. Infancy

The foundation elements of EFs coming into being during the first year of life. Between the ages of six and nine months, the cognitive abilities that facilitate attentional allocation begin to develop. This capability enables infants to partake in face-to-face social interactions and engage in joint attention, where they monitor another person's focus of attention to align their own focus with the same external object (Striano et al., 2006).

Around six months of age, infants start to exhibit basic inhibition skills, such as the ability to refrain from touching an object. Related to this, at age of eight and twelve months develops the ability to sustain attention on a task even with short interruptions, as well as the detour reaching skills (reaching around physical obstacles). Detour reaching involves several cognitive processes, such as maintaining a goal in mind, strategizing a route, and suppressing the instinctual impulse to reach directly for the goal. Typically, it involves reaching in a direction away from the immediate goal object at the outset of the reaching action (Diamond, 2020).

Rudimental elements of working memory manifest at approximately at seven and nine months of age, with the development of abilities like object permanence, that is the ability to comprehend and remember that unseen objects and people continue to exist. Following this, by the age of eight and nine months, WM abilities progress to more complex calculations (Káldy & Leslie, 2003). Around nine and ten months of age, infants acquire the capability to perform two-step tasks and basic goal directed tasks (Diamond, 2020).

In the late infancy, at around age nine and eleven months, basic foundation of cognitive flexibility emerge and pertain the infants' capacity to explore alternative approaches to recover objects that are not within their immediate line of sight.

The speed at which infants process information shows a significant increase during infancy as their brains become more efficient in handling tasks (Miller & Vernon, 1997). Variations in processing speed among individuals begin to appear in early infancy, and even by the age of five-seven months, these differences can be indicative of later EFs (Diamond, 2020). Faster processing speed at five month of age is associated with better EFs at age 2, 3, and 4 (Cuevas & Bell, 2014).

The development of these foundational element of EFs are dependent on the neural circuits and systems within the PFC. The activity of neurons and elevated dopamine levels in the DL-PFC are considered particularly crucial for facilitating these cognitive advancements during the later stages of an infant's first year of life (Diamond, 2020).

1.1.6.2. Toddlerhood

Rudimental aspect of EFs continue developing and becoming more complex during toddlerhood. Evidence highlighted considerable variation among toddlers, possibly stemming from the differing and rapid advancements in language abilities and vocabulary acquisition have been related to EFs (Schonberg et al., 2018). In the second year of life, around the age 20-21 months, a significant milestone in EFs development involves an enhanced comprehension of the relationship between objects and abstract rules (Diamond, 2020).

Starting as early as two years of age, children start beginning to adapt their behaviors based on changing rules, such as putting on shoes for dry weather and boots for rainy conditions (Best & Miller, 2010; Diamond, 2020). The third year of life represents a crucial period for the symbolic representation development, involving language and symbolic play. At the same time develop social cognition related to EFs, among them the early stages of theory of mind and moral reasoning (Diamond, 2020; Panesi & Morra, 2022).

Empirical evidence suggested that the quality of early interactions is crucial for long-term EFs development (Anderson, 2007). Moreover, secure parent-child attachment and supportive caregiving represent a favourable ground for healthy EFs development (Blair, 2016). Recent studies identify factors that undermine the quality of interactions between parent and child, such as the increasing use of technology by caregivers, and screen time exposure in toddlers are associated with lower EFs during childhood (Anderson, 2007; McHarg et al., 2020). Other multiple factors may negatively affect the development of EFs, such as genetics factors, socioeconomic disadvantages (Raver & Blair, 2020).

1.1.6.3. Preschool period

Preschool age represents a crucial phase in the development of EFs. During this time, the fundamental components and processes of EFs begin to manifest prominently. At the same time, these are also the years when difficulties might appear (England-Mason & Dewey, 2023).

Working memory and inhibition are the earliest EFs components to come to light. At age 3, preschoolers' working memory evolve from the capacity to hold in mind upon two rules simultaneously and make decisions based on those rules (Zelazo, 2006). Between 4 and 5 years of age, preschool children develop the ability to hold previously acquired information in their working memory while also constructing new concepts. This cognitive development allows them to understand representational change and false beliefs more effectively (Tomasello, 2018).

The transition from ages 3 to 5 is marked by significant enhancements in inhibitory control and cognitive flexibility, particularly in the ability to shift perspectives. These cognitive advancements are evident in social cognition, including theory of mind (Wimmer & Perner, 1983) and moral development (Kohlberg, 1963). They also manifest in various cognitive tasks, such as the Dimensional Change Card Sort task (DCCS) (Zelazo, 2006), Shape School (Clark et al., 2013; Espy, 1997), ambiguous figures (Gopnik & Rosati, 2001), appearance-reality (Flavell et al., 1986), false belief (Perner et al., 1987), Luria's tapping and hand tasks (Diamond & Taylor, 1996; Hughes, 1998), the day-night Stroop task (Gerstadt et al., 1994), and the grass-snow Stroop task (Carlson & Moses, 2001). Inhibition starts emerging around 3 and 4 years of age. Initially, preschoolers manifest the ability to repress physical impulses (e.g. ability to inhibit the instinct of imitate an action), then at 4 and 5 years also verbal inhibition (Carlson et al., 2005). During preschool years inhibition refines, in terms of increased reaction time (Giordano & Alesi, 2022), as well as decreased perseveration errors (Best & Miller, 2010; Giordano & Alesi, 2022).

Notwithstanding, research findings indicate that inhibition and WM are not clearly distinguishable during the preschool period, but their differentiation increases as children progress through primary school (Hughes et al., 2009; Mungas et al., 2013; Willoughby et al., 2010). More recent empirical evidence come to the conclusion that even in preschool period, EFs are most accurately described by the two-factor model, by which WM and inhibition are distinguishable from each other (Gandolfi et al., 2014; Garon et al., 2014; Lerner & Lonigan, 2014; Miller et al., 2012; Skogan et al., 2016). From a developmental viewpoint, inhibition reaches full development during childhood (Diamond, 2013), with most of its growth occurring during the preschool years (Tomporowski et al., 2015). Additionally, Diamond (2020) inhibition matures earlier than other EFs, such as WM and cognitive flexibility. Thus, inhibition is sensitive to training during preschool years (Zelazo et al., 2016).

Starting from the latter part of the preschool period, cognitive flexibility undergoes development, enabling preschool children to adapt their behavior based on the specific context and switch back and forth between rules or different rules or sets of guidelines as required (Diamond, 2020). These substantial enhancements in the fundamental components of EFs during the preschool period also predict social cognition development; this includes theory of mind, which involves understanding own and others' mental representations, and moral development as well (Perner & Lang, 2000). Evidence supported a strong correlation between EFs at three and four years of age and theory of mind, even after controlling for sex and language skill, indicating that this link becomes more robust during the preschool phase (Müller et al., 2012). Similarly, it has been found a significant relationship between preschool children's EFs and theory of mind and their moral reasoning skills, underscoring the crucial role of EFs in mental representation (Baker et al., 2021).

1.1.6.4. Middle childhood

Middle childhood is marked by noteworthy advancements in EFs. Empirical evidence showed substantial enhancements related to age in inhibition, WM, and cognitive flexibility during middle childhood (Diamond, 2020). For instance, significant enhancements in WM are consistently observed in children between the ages of five and eleven on complex span tasks. These tasks require the manipulation of information held in memory under conditions with high interference, such as counting span and spatial span tasks. Results from cross-sectional studies highlighted similar developmental progressions on these tasks (Case, 1992). At the ages of four until eight substantial improvements become evident, followed by continuous gradual improvement. The pattern span task, which is akin to the spatial span. Performance on the pattern span task shows significant improvement between the ages of five and eleven, after which it begins to level off (Diamond, 2020). For instance, around the age of six-seven years, children begin to perform at levels comparable to adults in tasks involving the ability to disregard non relevant information. During anti-saccade tasks, they exhibit the capability to suppress their natural tendency to look toward the target and redirect their gaze in the opposite direction. This ability continues to enhance over the subsequent few years (Best & Miller, 2010). Between five to eleven years cognitive flexibility improvements are evident while measured using the WCTS (Chelune & Baer, 1986; Chelune & Thompson, 1987; Rosselli & Ardila, 1993; Welsh et al., 1991).

Planning skills develop between the age of seven and ten years (Anderson et al., 1996). In young children, the strategies they employ tend to be simple, fragmented or often inefficient. However, between the ages of seven and eleven, as they grow, their strategic behavior becomes more methodical, structured, and effective (Anderson et al., 2001; Levin et al., 1991).

In contrast to the preschool period where research focused on the development of each component and process of EFs at specific ages, in middle childhood the focus is on EFs incremental enhancements, since specific improvements associated to age are sensitive to the difficulty and demands of the task (McCormack & Atance, 2011). Throughout the first 5 or 6 years of life of children, parents and other caregivers play a crucial role as the primary partners for socialization. Starting from middle childhood, peers begin to assume a central role and exert significant influence on EFs development. As children mature, they begin to form larger social groups, cultivating lasting friendships and adjusting their conduct based on communal social norms, which may encompass collaborative efforts as well as competitive interactions (National Research Council, 1984). Middle childhood represents a crucial phase for social cognition and the Hot EFs development, which include emotional control and regulation. During this period, children's advancements in EFs are linked to their enhanced understanding of complex mental states and sophisticated theory of mind capabilities, like second-order false beliefs, for example, understanding someone else's thoughts about another person's viewpoint, emerge during this stage (Bock et al., 2015). These enhancements in social cognition are also accompanied by progress in emotional control, where children become more adept at modulating their emotional responses. During middle childhood, children develop a broader range of self-initiated strategies to regulate their emotions and rely less on caregivers for external support. They gain the capacity to pursue increasingly complex both personal and social goals, and can adjust their emotional reactions to align with the context and cultural norms (Thompson et al., 2008).

1.1.6.5. Late childhood

Older children's inhibition develops matures to the extent that they can flexibly shift their attention between a central focus and peripheral stimuli. For example, they can focus on activities like riding a bike while paying attention to road signs and pedestrians. This development typically occurs later in childhood and during adolescence (Cereatti et al., 2009).

1.1.6.6. Adolescence and early adulthood

Many improvements in EFs may not reach their peak until late adolescence or early adulthood (Diamond, 2020). Inhibition achieves its climax in adulthood allowing individuals to respond and behave in a contextually appropriate way (Best & Miller, 2010).

Also cognitive flexibility continues to develop showing enhanced accuracy in shifting focus among different stimuli and adapting to changing rules. For instance, adolescents make fewer errors on tasks like the WCST. These abilities continue to develop until they reach a complete maturity in adulthood. Ultimately, adults acquire the ability to adapt their actions and plans in response to swiftly changing circumstances (Best & Miller, 2010). Even problem solving keep developing. Planning skills continue improving during this period (Krikorian et al., 1994; Welsh et al., 1991). Improvements in EFs depends on the maturation on brain regions as PFC and alterations in the brain's reward circuitry, including the limbic system (Diamond, 2020).

Adolescence is a period characterized by various cognitive and behavioral changes. These changes include heightened autonomy and an increase in risk-taking behaviors (Nelson et al., 1999). Additionally, pubertal maturation plays a role in contributing to sex differences in brain organization and the functioning of EFs (Nguyen et al., 2017).

Studies on comparison between male and female adolescents show noteworthy enhancements in the motivational and affective aspects of EFs, known as Hot EFs (Best & Miller, 2010; Poon, 2018). In particular, adolescence is marked by improvements in decision-making, which refers to the ability to make choices in uncertain situations, and abstract reasoning, which involves thinking about and comprehending complex concepts not directly linked to concrete experiences (Best & Miller, 2010; van Duijvenvoorde et al., 2010). Longitudinal studies employing the Iowa Gambling Task, a classic Hot EFs task, found that decision-making abilities are not fully mature until the ages of 16 and 18 (Almy et al., 2018). Throughout adolescence, all the previously mentioned factors, both genetic and environmental, continue to influence the development of EFs. Moreover, child and family risk factors, such as low socioeconomic status (SES, John et al., 2019) and caregiver mental health issues, which were evident in early childhood, persist and continue to exert a significant influence on EF performance during this period (Berthelsen et al., 2017).

1.1.7. Biological and environmental factors

The development of EFs is influenced by both biological and environmental factors. Research on twins have been employed to gauge the degree to which individual differences in EFs are affected by biological factors (known as heritability), environmental factors shared by twins (maternal nutrition during pregnancy and family environment), as well as, nonshared environmental influences (educational experiences) (England-Mason & Dewey, 2023). Recent theoretical and empirical literature in developmental psychology emphasize the importance of the interaction between biological and environmental factors.

Biological features have been investigated throughout genetic studies focusing on individual differences in EFs comparing monozygotic twins (who share all their genes) with dizygotic twins (who, on average, share only half their genes) and found significant genetic contribution. Friedman and colleagues (2008) carried out a twin study with a group of young adults found that about 99% of individual differences in EFs were primarily influenced by genetics. They argued for a common genetic factor for EFs that affect the three core components. However, some genetic influences were specific to each component, such as WM of cognitive flexibility. In the same vein, Engelhardt and colleagues (2015) reported similar results in a study involving twins aged 7.89 to 15.25 years. These consistent findings across different age groups and studies provide strong support for the presence of a general heritable EF factor. Since genetic variation in behavior traits, such as EFs, involves numerous polygenic effects, a genome-wide association studies will be necessary to pinpoint genetic variants associated with EFs task performance (England-Mason & Dewey, 2023).

Empirical evidence suggested that genetic differences would lead to differences in EFs and behavioral outcomes (Harden & Koellinger, 2020). Scholars revealed that EFs are influenced by variations in genes as COMT (Catechol-O- methyltransferase) and BDNF (Brain-Derived Neurotrophic Factor) polymorphisms (Alesi et al., 2023; Jasińska et al., 2016; Kang et al., 2013; Sheldrick et al., 2008). These genetic variations can impact the development and functioning of EFs. COMT (Catechol-O- Methyltransferase) is an enzyme that plays a role in the breakdown of certain neurotransmitters, including dopamine, in the PFC of the brain. Variations in the COMT gene have been associated with differences in cognitive performance, including EFs.

One of the prominent functional polymorphisms linked to COMT is the single-nucleotide polymorphism (SNP) rs4680, also known as Val158Met. Consequently, two alleles exist for this polymorphism: the Val allele (H – with valine) and the Met allele (L- with methionine). This variation entails a substitution of guanine with adenine, leading to an alteration in the amino acid sequence from methionine to valine (Egan et al., 2003). The presence of methionine in the enzymatic activity, leads to an alteration in dopamine metabolism, resulting in a prolonged presence of the neurotransmitter in the synaptic space. This contributes to an enhancement in cognitive functions (Bowers et al., 2020). Findings yield to mixed results. In one hand, scholars support advantageous nature of the Val allele over the Met allele, others indicate a strong association between improved cognitive function and the Met allele (Moriguchi & Shinohara, 2018; Bowers et al., 2020). Interestingly, differences emerge between children and adults in attention task performance, with the Met/Met genotype associated with superior performance in adults, while the Val/Met genotype is linked to better performance in adolescents (Wahlstrom et al., 2007).

BDNF is a neurotrophin situated on chromosome 11 that supports the growth and maintenance of neurons. Several polymorphisms linked to it, but much attention has been given to rs6265, or Val66Met. This single nucleotide polymorphism entails the substitution of valine with methionine at position 66 of the protein-coding sequence. Consequently, two alleles exist: the A allele (with methionine) and the G allele (with valine). The Val66Met variant has been extensively studied for its potential implications in cognition. Genetic variants in the BDNF gene have been associated with cognitive functioning, including aspects of EFs (Nieto et al., 2013). Evidence showed that individuals with the Met allele may exhibit disadvantaged phenotypes at various levels, including cellular, structural, physiological, and behavioral (Di Carlo et al., 2019; Egan et al., 2003). This allele may hinder interactions with molecules involved in intracellular transport, such as sortilin and translin, thereby impeding the transportation of BDNF molecules to the Golgi apparatus and their subsequent secretion into the extracellular environment (Chen et al., 2006; Egan et al., 2003). Conversely, individuals homozygous for the Val allele of BDNF have been shown to moderate the relationship between cognitive reserves and EFs (Ward et al., 2015).

EFs has been defined as a developmental endophenotype, which means EFs are considered a neurobiological phenotype considered to represent a genetic predisposition or susceptibility to a clinical disorder, to various outcomes, including cognitive, behavioral, and physical health (Engelhardt et al., 2015). In a broader context, performance on EFs measures may also help identify children at risk of experiencing negative psychological, social, and health outcomes, and arrange early interventions (England-Mason & Dewey, 2023).

Although EFs have a strong genetic component and tend to remain consistent over time, they can still be influenced by environmental factors, which play a significant role as predictors of children's cognitive abilities. Early experiences play a significant role through pathways such as parenting, attachment, and the household environment (Bernier et al., 2012; Hughes & Ensor, 2009). In one hand, EFs difficulties manifest as consequences of negative effect environmental factors, such as adverse home environments, such as maltreatment, caregiver mental health symptoms like depression and anxiety, as well as low SES (Ackerman & Friedman-Krauss, 2017; Raver & Blair, 2020). On the other hand, factors that might forecast improvement in EFs include positive parenting based on supporting child's autonomy, sensitivity, responsiveness, as well as higher SES. Higher SES is given by parents' higher education (i.e. college or university) and family income as indicator of parents' job, which lead to belonging to a middle or higher social class. The WHO assumes SES as major determinant of health. Lower SES (lower parents' education and low family income) has been linked to poorer EFs in children, early as the preschool years (Miller & Vernon, 1997). These effects of SES on the development of EFs persist through middle childhood and into early adulthood, suggesting that its impact remains stable over time (Liu & Lachman, 2019).

In the last two decades attention has been paid to the effect of nutrition in children on the development of cognition. A large amount of research focused on the relationship between nutrients, quality of children's diet and cognitive outcomes (Dror & Allen, 2008; Haapala et al., 2015; Leventakou et al., 2016; Smithers et al., 2012). Particularly, specific nutrients, such as iron (Scott et al., 2018), omega-3 (Portillo-Reyes et al., 2014), zinc (Tupe & Chiplonkar, 2009) play a significant role in EFs development (Costello et al., 2021) with positive effects on WM (Petrova et al., 2019), and cognitive learning strategies (Wang et al., 2017).

Although the environment is tied to EFs, the influence of cultural context is rarely integrated into EFs models. The pathways through which diversity in families' cultural and cross-cultural identities impact EFs during childhood have not been extensively explored. Nonetheless, self-regulation that is strongly related to EFs have received significant attention in developmental cultural studies (Brown et al., 2015; Li-Grining, 2012; Matsumoto et al., 2008; Trommsdorff, 2009). Cross-cultural psychological research revealed different cognitive styles between Western and Eastern. Nisbett and colleagues (2004) defined Western' cognitive style as analytic, while that of Eastern as holistic. In other words, European children use higher analytical cognitive strategies and rule-based categorization, whereas Asian children allocate more holistic attentional resources to solve a task (Kelkar et al., 2013). The development of children's cognitive styles is influences by socialization practices, and during the preschool years, cultural environments play a crucial role in fostering culturally acceptable levels of context-sensitivity (Imada et al., 2013). Early education policies might stress the role of preschoolers' self-regulation (Tobin et al., 1989). Moreover, parenting practices and educational systems further contribute to the observed differences. Teachers from collectivist cultures give substantially more proactive task-related instructions compared with teachers from individualistic cultures (Lan et al., 2011), which in turn provides more frequent opportunities for young children to practice self-regulatory skills (Sabbagh et al., 2006). In addition, parents from Eastern culture often emphasize obedience and respect for authority, which can promote the development of inhibitory control. Whereas, western parents may prioritize open communication and autonomy, potentially influencing the development of cognitive flexibility. Likewise, Eastern educational systems often emphasize rote learning and adherence to prescribed norms, potentially enhancing specific executive functions such as attentional regulation. In contrast, Western educational systems may emphasize critical thinking and creative problem-solving, nurturing different aspects of EFs (Benito-Gomez et al., 2020).

1.2. Executive Functions and Motor Abilities

In recent decades, scholars delved into the intricate trajectories of cognitive and motor development has been documented in young children (Maurer & Roebers, 2019; Kubicek et al., 2017; van der Fels et al., 2019), adolescents (Rigoli et al., 2012), and adults (Ratey & Loehr, 2011). The interplay of cognitive and motor abilities shape children's early developmental trajectory, where every thought and movement converge to form child's interaction with their environment and pave the path for their holistic growth (Houwen et al., 2017; Maurer & Roebers, 2019). Additionally, from a developmental perspective motor and cognitive abilities share a common timetable, as both develop markedly during the preschool age (Howard et al., 2015; Rigoli et al., 2012).

The hypothesis of a relationship between the two domains stems from the above-mentioned embodied cognition perspective, a growing research framework in which cognition is understood to unfold within the context of an individuals' bodily interaction with both physical and social environment (Oudgenoeg-Paz et al., 2012; Smith & Gasser, 2005). Also Montessori (1966) highlighted the importance of movement on the cognitive development, since the action that occurs is connected with the ongoing cognitive activity. Hence, the developing child needs activity focused on tasks requiring specific hands movement guided by cognition to coordinate both motor and cognitive systems (Lilliard, 2017).

Explanations from a neurobiological point of view assume common brain areas for motor and cognitive functions, specifically motor abilities activate neural networks which also underlie cognitive abilities and vice versa (Abe & Hanakawa, 2009; Grissmer et al., 2010; Hanakawa, 2011). Neuroimaging studies have shown that brain regions, such as the cerebellum, DL- PFC, and the basal ganglia are important for motor and cognitive performance, since they co-activate during both motor and cognitive tasks (Ito, 1993).

All EFs components embrace higher order cognitive processes used to control not only cognitive processes but also motor tasks (van der Fels et al., 2019), especially if a task is new, a fast response is required, and conditions and demands of a task change (Diamond, 2020). For example, to perform a complex motor task, children need to maintain goal-directed behavior (Marcovitch et al., 2007), to control their prospective actions, inhibit task irrelevant information, and flexibly adapt their behavior to current conditions (Diamond, 2015). EFs were especially involved in difficult and demanding rather than easy and automated motor tasks. In other words, the more automated a motor task becomes, the less involved are EFs. Encouraged by findings of different lines of research and the present study, we conclude that EFs are likely to be more strongly involved in difficult (less automated) than in easy (more automated) motor tasks (van der Fels et al., 2019).

Motor abilities are composed of two main components: gross motor skills and fine motor skills. Gross motor skills are actions of the large muscle groups and enable climbing, balance, and playing catch; whereas fine motor skills are actions of the small muscle groups, which enable precise movements of the face, hands, and feet (Escolano-Perez et al., 2020). Fine motor skills support children to succeed in many daily routines. They are instrumental for the development of cognition due to their supportive function in environment interactions (Voelcker-Rehage et al., 2011). In this vein, specific dimensions of fine motor skills which support environmental interaction might be strongly related to cognitive abilities (Davis et al., 2011a).

1.3. Physical activity

PA refers to any bodily movement performed by skeletal muscles that requires energy expenditure beyond baseline levels (US Preventive Services Task Force, 1996). PA encompasses a diverse range of behaviors, each contributing to overall PA levels. Exercise, a subset of leisure-time PA, is characterized by planned, structured, and repetitive bodily movements aimed at improving or maintaining physical fitness (Hardman & Stensel, 2009). Research using PA as intervention involved a wide range of activities, including walking, running, or jumping, as well as programs such as physical education classes or participation in sports, martial arts, dance, yoga.

PA can be further classified based on frequency, duration, and intensity. Frequency refers to how often an activity is performed. Duration indicates the length of time spent on the activity. Intensity pertains to the level of effort exerted during the activity or the rate of energy expenditure required. Studies showed that intensity has inverted-U relationship with cognitive effects, meaning that both excessively low and excessively high levels of PA might result in a deficient cognitive performance (Jäger et al., 2015). In addition, Schmidt and colleagues (2016) suggested a comparable inverted-U correlation between the cognitive demands in PA intervention and the resulting cognitive outcomes. Scholars have examined either the immediate effects of a single bout of PA, known as acute PA interventions, or the impact of engaging in multiple sessions of PA over an extended period, which are referred to as chronic PA interventions.

PA, therefore, includes sports. To classify sports scholars often refer to the frameworks introduced by Poulton (1957) and Knapp (1963), which distinguish between open-skill and closed-skill movements. Accordingly, sports can be categorized as either open-skill or closed-skill sports (Singer, 2000). The former, such as basketball or tennis, involves individuals reacting and adjusting to a dynamic and constantly changing environment. Open skills sports require decision-making and problem-solving to adjust behaviors to the external stimuli (Allard & Burnett, 1985). Conversely, the latter, such as running or swimming, are typically self-paced, follow predetermined movement patterns, and occur in a predictable and stable environment (Schmidt and Lee, 2019). Scholars have demonstrated that participants engaged in open-skill sports generally outperform those practicing closed-skill sports on inhibition (Ballester et al., 2019) and problem solving (Jacobson & Matthaeus, 2014).

It is widely recognized for its positive impact on physical health starting from childhood and throughout life. Research in developmental psychology has demonstrated that regular PA is particularly beneficial both for children (Bornstein et al., 2013) and older people (Scherder et al., 2014). PA leads to improvement in physical fitness and skeletal and bone health, as well as reducing risk of diseases such as obesity and type 2 diabetes (Janssen & LeBlanc, 2010).

The WHO guidelines recommend children between the ages of 3 and 4 to participate in at least 180 minutes of PA daily, with 60 minutes falling into the MVPA (WHO, 2016). Regrettably, only a very limited number of children worldwide meet the recommended levels of PA necessary to reap these health-related advantages (Chaput et al., 2020; Guthold et al., 2020). Nonetheless, O'Brien and colleagues (2018) carried out a systematic review examining 55 studies involving 13,956 kindergarteners, and found that they engaged in low levels of PA, with less than 10 minutes per hour spent in MVPA. Additionally, these children exhibited high levels of sedentary behavior, ranging from 27 to 57 minutes per hour, although there was significant variability among different studies.

Kindergartens play a crucial role in promoting a physically active lifestyle for children, considering that children spend a significant portion of their waking hours in schools. Supporting school policies that promote PA aligns with the WHO's Global Action Plan for Physical Activity 2018–2030 and the Physical Activity Strategy for the WHO European Region 2016–2025. These initiatives urge Countries to take steps to enhance the PA levels of children and adolescents. Despite that, kindergartens' staff have identified several barriers in giving opportunities for children to be more active, including constraints related to time, training, access to natural environments, and safety concerns (Coleman & Dyment, 2013; Ellis et al., 2019). However, strategies like school-based PA programs incorporating PA lessons or active breaks within the classroom setting have shown promise in overcoming these barriers.

The inclusion of PA into the classroom can be achieved through various approaches, including active breaks (short bursts of PA, whether related to the curriculum or not), active lessons (curricular activities that involve movement, such as active math exercises), and modifications to the classroom setup (such as using adjustable height desks) (Mazzoli et al., 2021). Importantly, these strategies are low-cost (Hinckson et al., 2016) and help reduce prolonged time spent sitting (Biddle et al., 2016).

Physical education is increasingly recognized as a crucial context for nurturing students' EFs (Rudd et al., 2019). Its widespread availability in schools makes it a powerful platform to impact a broad range of students, although empirical evidence is limited (Schmidt et al., 2015). Physical education differs from interventions in other related domains, such as sports or general PA. While these interventions often prioritize PA or athletic performance, physical education is uniquely positioned to foster holistic development, aiming at enhance students' PA levels, cultivate motor skills, and provide enriching experiences that contribute to their overall growth and well-being (Ennis, 2011). Furthermore, blending PA with academic lessons has been shown to yield favorable outcomes in children's interest and enjoyment while attending primary school (Vazou & Mavilidi, 2021). Active breaks, in particular, offer a simple and teacher-friendly way to interrupt sitting and boost PA within the school setting without disrupting the curriculum. Moreover, as Diamond (2015) stated "the effect of PA needs to move beyond simple aerobic activities that require little thought (treadmill running, riding a stationary bicycle, or rapid walking) and resistance training" (p. 1014). Thus, in interventions with children, PA takes place within play contexts, characterized by brief bursts of movement and a diverse range of movement types, rather than prolonged periods of moderate-to-vigorous PA (MVPA) (Bailey et al., 1995).

Therefore, PA programs work because they not only train and challenge motor skills, but they also bring joy, pride, and self-confidence, engender a deep commitment, and provide a sense of social belonging and camaraderie (Pesce, 2012). Main factors that impact the effective implementation of PA programs like active breaks is children's enjoyment (Howie, 2014), as well as, significant aspect of intrinsic motivation (Deci & Ryan, 1985). Enjoyment has been positively linked to PA (Lubans, 2008), negatively to sedentary behavior (Darracott et al., 2019), and it is hypothesized to have a positive influence on EFs (Diamond, 2015). Although a study carried out by Bedard and colleagues (2021) found a positive association between classroom-based PA and higher enjoyment levels compared to traditional lessons, any other research investigated whether enjoyment varies between cognitively-engaging PA and simple active breaks.

School-based PA programs and physical education offer essential opportunities to reducing children's sitting time during school hours, which boost both their physical well-being but also their cognitive abilities (Bedard et al., 2021; Norris et al., 2020; Watson et al., 2017). EFs have short-term impacts on performance and academic success. For instance, lower inhibition is linked to reduced math and literacy skills. Furthermore, attention skills upon school entry rank among the top three predictors of later AA in elementary school (McClelland et al., 2013). The hypothesized mechanisms underlying PA effects on cognition primarily involve physiological factors, as an increase in cerebral blood flow that occurs as a result of engaging in PA (Lubans et al., 2016). Empirical evidence highlighted that specific types of PA may be strongly associated with EFs in children. Specifically, PA with higher cognitive tasks, known also as cognitively-engaging PA, seems to be more efficient in enhancing EFs (Best, 2010; Schmidt et al., 2015; Diamond & Ling, 2016), and in turn AA.

1.1.3.1. Cognitively-engaging physical activity

PA has garnered considerable attention as a means to enhance cognitive performance in children and adolescents (Donnelly et al., 2016; Verburgh et al., 2014), with greater profit for EFs (Barenberg et al., 2011). Currently, various theoretical perspectives have recently revealed that not all types of PA are equally beneficial to cognition (Tomporowski et al., 2015). Interventional studies showed that aside from quantitative factors (i.e. duration and intensity), qualitative factors (i.e. exercise type and modality) have been demonstrated to influence children's EFs (Aadland et al., 2017a). Up to now, one of the most frequently investigated qualitative aspects of various forms PA is cognitive engagement (Best, 2010; Pesce, 2012; Tomporowski et al., 2015). Cognitive engagement refers to the level of attentional resources and cognitive effort needed to manage challenging skills (Tomporowski et al., 2015), and it seems to be crucial since it arise from heightened cognitive demands (Best, 2012; Budde et al., 2008; Pesce, 2012; Tomporowski et al., 2015). Tomporowski and colleagues (2015) suggested to adhere to three principles of mental engagement when designing cognitively-engaging PA. Specifically, they suggested to highlighting contextual interference, emphasizing mental control, and promoting discovery. The first, contextual interference involves changing the context and conditions of PA, necessitating children to engage in unpredictable sequences of actions. To create contextual interference, activities should immerse children in non-repetitive, random conditions, where required actions are not automated but change randomly. Such conditions facilitate better learning as they are compelled to deeply consider the evolving aspects of the activity.

Moreover, to respond to the changing conditions of PA, mental effort is required to memorize the diverse movement required and to strategize multiple mental operations and actions. Given the frequent and sometimes unpredictable changes in game conditions, individuals must actively hold and manipulate information about various aspects of PA, such as appropriate movement patterns or applied rules in different conditions, and change their actions or respond to various signals, even when contradictory. It refers to the second aspect, mental control. The last characteristics is promoting discovery. Cognitively-engaging PA includes problem-solving conditions that necessitate students to generate multiple solutions to open-ended movement problems. Additionally, discovery is encouraged through the utilization of open-ended activities, where certain aspects are defined, such as objectives, starting points, rules, and children are required to select the most suitable actions or strategies to succeed (Kolovelonis et al., 2022).

It has been theorized that engaging in PA tasks that involve cognitive challenges might yield more significant improvements in children's EFs compared to those engaged solely in PA or only cognitively-engaging activities (Best, 2010; Diamond, 2015). Thus, empirical studies found that larger cognitive benefits might be produced by PA enriched with increasing complexity of cognitive and motor demands (Álvarez-Bueno et al., 2017; de Greeff et al., 2018; Vazou et al., 2019).

A theoretical explanation is provided by the cognitive stimulation hypothesis according to which PA with higher cognitive demanding task activates the same brain networks associated with higher-order cognitive processes (Best, 2010; Diamond & Lee, 2011). Specifically, PA results in physiological changes in the brain areas such as releases of BDNF (Chaddock et al., 2011) or changes in grey matter volume (Lubans et al., 2016). Engaging in cognitively-engaging PA, which necessitate the utilization of EFs, may enhance these skills for future use (Best, 2012; Pesce et al., 2009). This phenomenon, referred to as priming, suggests that participating in exercises requiring cognitive effort activates brain regions involved in EF-related tasks. This activation, in turn, leads to cognitive benefits, particularly in the areas of executive functioning (Pesce, 2012; Pesce & Ben-Soussan, 2016). These benefits may manifest in tasks within a similar domain (near-transfer) or in other EF domains (far-transfer). For this reason, cognitively-engaging PA is likely to yield more favorable outcomes for children's cognitive development compared to participating in simple PA (Best, 2010; Schmidt et al., 2015; Diamond & Ling, 2016). More in depth, Best (2010) proposed three pathways by which PA can affect EFs: (a) by causing physiological changes in the brain; (b) by eliciting cognitive demands inherent in novel PA, which can enhance self-regulation abilities and goal-oriented behavior transferable to EFs tasks; and (c) by necessitating cognitive demands for executing complex motor movements.

PA and EFs are intricately interrelated, affecting on and co-activating each other (Doherty & Forés Miravalles, 2019). Specifically, EFs have been linked to the activity in the DL-PFC (Funahashi & Andreau, 2013), which is the same brain area activated during PA with cognitive demand (Serrien et al., 2007). As can be seen, specific neural network activation might increase their efficiency, as well as, foster cognitive processes linked to them such as EFs (Pesce & Ben-Soussan, 2016). Scholars found increases in alpha activity within the precuneus region and reductions in beta activity within the left temporal areas (Schneider et al., 2009), in cerebral blood flow in the PFC (Endo et al., 2013), and release of BDNF (Piepmeier & Etnier, 2015), as well as in gray matter volume in the frontal and hippocampus regions (Mandolesi et al., 2018).

Thus, the improved cognitive performance following a single session of acute PA is attributed to the specific activation of cognitive processes underneath the cognitive tasks (Budde et al., 2008). Concerning the effects of chronic PA, it is theorized that the repeated engagement of EFs throughout structured PA results in long-term changes in those EFs that are specifically targeted by the training (Herold et al., 2018). Evidence suggested improvements in EFs among children that were closely related to the tasks they engaged in (near-transfer effect), but not those that were more distantly related (far-transfer effects) (Kassai et al., 2019). Cognitively-engaging PA represent a promising avenue within physical education for fostering cognitive abilities (Pesce et al., 2013). These activities immerse children in dynamic and unpredictable scenarios, stimulating the ability to adapt to changing conditions, problem-solving, and creative thinking. By introducing challenges and mental complexities or increasing the coordination demands of movement patterns, these activities stimulate EFs (Tomporowski et al., 2011). Additionally, they offer students opportunities to engage in novel and varied tasks, avoiding excessive repetition and promoting cognitive flexibility (Pesce et al., 2016).

The effects of cognitively-engaging PA on EFs can be evaluated determining the level of cognitive load in the activity required to being performed (Pontifex et al., 2019). Cognitive load theory offers a comprehensive framework for understanding how individual differences and task features interact. Differences among individuals refers to level of expertise and age; whereas tasks characteristics encompasses factors like instructional pace, complexity, and time required (Paas et al., 2003). Moreover, cognitive load theory encompasses three key constructs: mental load, mental effort, and task performance. Additionally, cognitive load includes three constructs: mental load, mental effort, and task performance. The first construct refers to the task characteristics (Paas & Van Merriënboer, 1994). For instance, basketball requires abilities as running, dribbling, catching, and shooting a ball. All of these movements are more complex than simple treadmill running, since they require the coordination of various body parts and the ability to adjust to changing circumstances, and as consequence more mental load. The second construct embeds both task characteristics with individual differences, including age, expertise, and prior experience to understand the level of cognitive resources that an individual invests in completing a task (Paas & Van Merriënboer, 1994). Mental effort can be measured through self-report measures or physiological indicators like heart rate variability, and fMRI (de Jong, 2010). The third construct, task performance, is influenced by both mental load and mental effort, as individuals may compensate for increased task complexity by exerting greater mental effort to maintain performance levels.

Cognitively-engaging PA required a higher level of complex cognitive involvement, including cooperation with peers, predicting the behavior of companions and opponents, adjusting movements based on changing task demands, and engaging in more cognitive and social interactions. All of these aspects require the mobilization of neural circuits associated with EFs to effectively participate in such activities (Mazzoli et al., 2019). Moreover, incorporates an added dimension of cognitive involvement, it can encompass activities that integrate with academic subjects (Vazou & Smiley-Oyen, 2014), sport (i.e. tennis lessons) (Ishihara et al., 2017), or team participation (Gallotta et al., 2020; Meijer et al., 2021), or exercise video gaming, namely exergaming (Benzing et al., 2016; Best, 2012). EFs are best developed when students engage in cognitively complex PA (Schmidt et al., 2015) characterized by novelty, challenge, and diversity, without being overly repetitive or automatized (Pesce et al., 2016). These conditions are inherent in cognitively-engaging PA. Thus, this specific type of PA represents a promising approach for fostering both physical and cognitive development.

1.4. Academic achievement

Generally, AA has been attributed to the performance outcomes that signify the degree to which an individual has attained particular objectives that were the focal point of educational activities within instructional settings, notably in schools, colleges, and universities. Educational systems often delineate cognitive objectives that are either applicable across various subject areas, such as critical thinking, or encompass the acquisition of knowledge and comprehension within a specific intellectual domain, such as numeracy or literacy (Steinmayr et al., 2014).

The definition of AA relies on the indicators employed for its measurement. They range from general metrics such as the procedural and declarative knowledge acquired within an educational framework, to more specific criteria like grades or performance on standardized educational tests. Additionally, cumulative indicators such as educational degrees and certificates are also considered. Regardless of the specific criteria used, they all reflect intellectual pursuits to varying degrees, thereby serving as a reflection of an individual's intellectual capacity (Steinmayr et al., 2014).

Steinmayr and colleagues (2012) offered a concise yet comprehensive overview of AA, highlighting its significance from various perspectives, including individual, societal, and within the realms of psychological and educational research. Indeed, the concept of AA is multifaceted involving a wide range of outcomes influenced by cognitive, social, and environmental factors (Bean & Sidora-Arcoleo, 2012). Indeed, it extends beyond traditional measures like grades and test scores.

Hence, in addition to quantitative measures, qualitative aspects of education, such as social and interpersonal outcomes, are essential for overall health and wellbeing.

Individuals learn the information they encounter, and then encode, detail and organize them by employing the cognitive processes (Onan, 2013). Considering psychological processes as influenced by existing conditions, as well as processes that empower people to create outcomes, AA in conceptualized as the product of self-regulated learning. Two specific psychological aspects are taken into account. The former pertains to a psychology centered on the way things are. This refers to psychological phenomena that are essentially universal among learners and across various subjects, and are typically beyond learners' control. Thus, cognition has a finite capacity to manage tasks or chunks of information concurrently. Moreover, learners exhibiting biases that can be influenced by environmental information, known as the framing effect. Additionally, information that is studied and immediately reviewed tends to be recalled less comprehensively and accurately compared to when the review is delayed. The latter pertains to a psychology focused on how learners construct knowledge. Here, learners are viewed as active agents who make decisions regarding their learning processes. These decisions include selecting tasks and choosing psychological strategies to tackle them. For instance, learners might decide whether to study for an exam using massed or spaced review techniques. Another example is the decision of whether and for how long to attempt recalling information when it seems just out of reach but a sense of familiarity persists. Armed with knowledge of various mnemonic techniques, learners can select the most suitable one for their needs. If an initial strategy fails but strengthens their sense of familiarity, learners can monitor their decision-making process to inform their next choice of mnemonic technique. They also have the ability to interpret outcomes, attributing success or failure to either effort or ability. Through these decisions and actions, learners actively shape their learning environments and contribute to the creation of new knowledge.

Metacognition refers to cognitive processes that involve understanding and managing one's own thoughts and mental actions. It involves the ability to reflect on and regulate one's own thinking, including monitoring, evaluating, and controlling cognitive processes (Flavell, 1979). It encompasses higher-order cognitive processes involved in learning, such as scheduling study sessions, employing appropriate problem-solving techniques, estimating performance accuracy, and regulating the depth of learning (Dunlosky & Thiede, 1998). Schraw and Moshman (1995) identified two primary components of metacognition: metacognitive knowledge and metacognitive regulation. Metacognitive knowledge pertains to understanding of cognitive processes, including awareness of effective skills and strategies for learning, as well as knowing when and how to utilize these strategies to enhance learning outcomes. Metacognitive regulation involves actively monitoring comprehension, evaluating progress, and making adjustments as needed during the learning process (Artzt & Armour-Thomas, 1992; Schraw & Dennison, 1994). Therefore, metacognition is recognized as a crucial factor in academic success, serving as a strong predictor of AA (Dunning et al., 2003; Kruger & Dunning, 1999).

AA is influenced by different factors that take into account individual features (i.e. motivation, quality of life, wellbeing), family support (i.e. family size, SES, home environment), school characteristics (i.e. teaching, material resources, extracurricular activities), and community (outdoor activities, PA, club involvement) (WHO, 2021). AA is one of the extensively examined factors linked to cognitive abilities, such as EFs, and psychological skills, including goal setting, stress management, and self-regulation. It is widely considered as a crucial element in facing the various child's lifetime challenges (Clark et al., 2013).

EFs affect performance and achievement in school (Blair and Diamond, 2008). Blair and Razza (2007) found that poor EFs are often associated with lower proficiency in mathematics and literacy during kindergarten. Additionally, Duncan and colleagues (2017) showed that attentional levels at the beginning of the school can be considered as a stronger predictor of future AA during elementary school. Thus, EFs play a crucial role for success both in school and in life, affecting individual's physical and mental wellbeing, as well as social harmony (Miller et al., 2011; Moffitt et al., 2011). Individual differences in EFs predict gains in AA even after controlling for intelligence quotient (IQ) (Duckworth and Seligman, 2005; Dumontheil & Klingberg, 2012) or SES (Duckworth and Seligman, 2005). Indeed, Hendry and colleagues (2016) call EFs "the cognitive toolkit of success." Cool EFs seem to be more predictive of AA (Brock et al., 2009) whereas hot EFs are particularly indicative of behavior in emotionally charged contexts (Kim et al., 2013).

Although recent systematic reviews and meta-analyses have indicated that interventions based on PA are linked to improved AA, there is still no unanimous agreement in the literature on this matter (de Greeff et al., 2018; Ferreira et al., 2021; Sember et al., 2020; Singh et al., 2019).

Unfortunately, children have often limited opportunities to being involved in PA during the school day, since many educators think that PA may interfere with AA(Howie & Pate, 2012). Despite these concerns, there is little evidence to support the idea that PA negatively impacts academic performance (Singh et al., 2019). In fact, some studies suggest that PA may even have positive effects on academic performance (de Greeff et al., 2018).

1.5. The relationship between cognitively-engaging Physical Activity, Executive Functions, Academic Achievement

A substantial body of empirical evidence suggests that PA is a promising and cost-effective method for enhancing children's cognitive functions, particularly EFs, and AA (Vazou et al., 2019). The association between PA and AA has been suggested to be underlain by some mediators, among which cognitive functions such as EFs, physical fitness, adiposity, behavior, and mental well-being (Visier-Alfonso et al., 2021). Particularly, the positive effects of cognitively-engaging PA on AA might be partially mediated through the EFs (Donnelly et al., 2016), since this specific type of PA increase physiological arousal, stimulate neural growth and modify synaptic transmission, trigger the release of neurotransmitters leading to changes in cognitive processes particularly related to the PFC (Kopp, 2012). These mechanisms suggest that PA can be beneficial for both physical health and cognitive performance, making it a valuable component of the school environment (Alvarez-Bueno et al., 2016). Moreover, evidence suggested that if training can enhance EFs, it should lead to transfer effects on diverse tasks that require the untrained executive processes, thus benefiting everyday functioning aspects reliant on EFs. Interventions effects are typically categorized as near-transfer and far-transfer effects. The former pertain to the impact of cognitive interventions on tasks involving the same trained cognitive mechanisms; the latter refer to the effects of intervention on various aspects of behavior and learning that are functionally related but distinct from EFs (Melby-Lervåg and Hulme, 2013; Sala & Gobet, 2016, 2017). However, some authors also consider far-transfer effects in relation to tasks involving other executive processes not directly trained by the intervention activities (Kassai et al., 2019). This consideration arises from the question of whether training one EF in children can influence other untrained executive skills.

Nonetheless, a wide number of studies have investigated the association between cognitively-engaging PA and EFs and AA, focused on either EFs (Bedard et al., 2021; Benzing et al., 2016; Bulten et al., 2022; de Greeff et al., 2016; Egger et al., 2018; Giordano & Alesi, 2022; Ishihara et al., 2017; Mavilidi et al., 2022; Schmidt et al., 2015; Preston, 2020) or AA, as separate outcomes (de Bruijn et al., 2020; Watson et al., 2017).

As regard EFs, research found benefits of cognitively-engaging PA interventions on WM, inhibition (Biino et al., 2021; Ishihara et al., 2017) and cognitive flexibility (Benzing et al., 2016; Schmidt et al., 2015; Song et al., 2022). Results from a recent systematic review from Song and colleagues (2022) highlighted improvement on WM and shifting after cognitively-engaging PA intervention in 4-to-12-years-old children. Other found no effects (Bedard et al., 2021; Schmidt et al., 2017) or even negative effects (Egger et al., 2018). Although the majority of studies have demonstrated a positive effect of PA on at least one aspect of EFs in children aged 6 to 12 years (Ishihara et al., 2017), it remains unclear whether a similar effect exists in preschoolers aged 3 to 6 years. However, research about the effects of different forms of PA on cognitive outcomes is still in the early stages of development.

Studies in kindergarteners found significant effects of cognitively-engaging PA on EFs, WM (Biino et al., 2021; Preston, 2020), inhibition (Giordano & Alesi, 2022), and cognitive flexibility (Gao et al., 2013) among 4-to-5 years-old (Preston, 2020; Vazou & Mavilidi, 2021), 5-to-6-years-old (Giordano & Alesi, 2022), and 3 to 6 years old (Biino et al., 2021) children. Biino and colleagues

(2021) recruited 36 children aged 3 to 6 years old involved in 45-minute sessions twice a week for 12 weeks intervention and found a better WM performance at post-test compared to a control group. Preston (2020) recruited one hundred-eleven 4 years old children divided into three groups, one control group and the other two involved in two different single session interventions lasting around 15 minutes. The first one was PA combined with higher cognitive engagement, while the second one entailed activities low in PA but high in cognitive engagement. The findings indicated that children with initially low shifting ability demonstrated improved performance after participating in the first intervention, whereas children with higher initial shifting ability derived benefits from both cognitively-engaging PA interventions. Giordano and Alesi (2022) found a significant improvement in inhibition in children engaged in the 20-minute sessions three times a week for six weeks intervention compared the those in control one (described in Chapter 2). Nonetheless, some studies found no significant effects (Mavilidi et al., 2023; Vazou & Mavilidi, 2021).

In summary, despite numerous studies focused on the impact of cognitively-engaging PA on EFs across various populations, they yield to mixed results. Discrepancies might be related to number of sessions, duration, intensity of PA or physical demands, as well as variability in study design, and different methodology used to measure the differences in children's performance on tasks during the intervention (Egger et al., 2019; Schmidt et al., 2015; Song et al., 2022), because of this make comparisons across existing research is problematic. Moreover, quantitative analysis establishing a clear relationship between cognitive engagement in PA and EFs is lacking. There is a gap in understanding the "dose effect" of PA on EFs with varying cognitive engagement modalities, intensity, and duration. In addition, certain variables might interact as moderators, such as age, sex, SES, BMI, although this role is yet to be fully determined.

Davis and colleagues (2007) implemented a RCT study, which involved a tightly controlled exercise intervention and standardized achievement tests, suggesting that various types of PA interventions have specific effects on children's cognitive functions. Findings indicated that EFs are more difficult to influence through long-term classroom-based PA interventions compared to AA. A meta-analysis conducted by Watson and colleagues (2017) supported this assumption demonstrating enhancements in academic performance but no impact on cognitive functions like EFs through classroom-based PA.

Recent research has shown a positive association between PA and academic performance. The term academic performance refers not only to AA, in terms of exam results and grade, but also academic skills (behavior, attendance, and time spent on tasks) that are closely tied to the development of EFs (Vazou et al., 2021). A positive association between PA and AA has been found (de Bruijn et al., 2020; Donnelly et al., 2016; Lees and Hopkins, 2013; Marques et al., 2017; Mura et al., 2015; Singh et al., 2012). Small significant relationship between PA and AA in mathematics, reading and language (Fedewa & Ahn, 2011; Hapala, 2012; Pucher, Boot & de Vries, 2013; Sibley and Etnier, 2003; Spruit et al., 2016; Watson et al., 2017). Other studies yield to mixed results (Donnelly et al., 2016; Poitras et al., 2016; Resaland et al., 2016; Ruiz-Ariza et al., 2017), or no significant effects (Ahamed et al., 2007; de Greeff et al., 2018; Esteban-Cornejo et al., 2015; Lees and Hopkins, 2013; Martin & Murtagh, 2015).

As EFs are closely related to AA (Diamond, 2012), it is plausible to investigate the effects of PA on AA as a result of improved EFs (Donnelly et al., 2016). Scholars suggested that if training can enhance EFs, it should lead to transfer effects on diverse tasks that require the untrained executive processes, thus benefiting everyday functioning aspects reliant on EFs. Interventions effects are typically categorized as near-transfer and far-transfer effects. The former pertain to the impact of cognitive interventions on tasks involving the same trained cognitive mechanisms (Melby-Lervåg and Hulme, 2013; Sala & Gobet, 2016, 2017; Kassai et al., 2019). The latter refer to the effects of intervention on various aspects of behavior and learning that are functionally related but distinct from EFs (Melby-Lervåg and Hulme, 2013; Sala & Gobet, 2016, 2017). However, some authors also consider far-transfer effects in relation to tasks involving other processes not directly trained by the intervention activities (Kassai et al., 2019). This consideration arises from the question of whether training one EF in children can influence other untrained ones (Scionti et al., 2020). Moreover, training specific EFs important for academic success might lead to precisely tailored interventions for children (Wilson et al., 2021).

Considering the importance of EFs in human development, it is valuable to support and bolster the development of these skills in typically developing preschoolers. Research has demonstrated that cognitive training can enhance EFs that are directly trained (near-transfer), especially WM, across childhood (Wass et al., 2012). However, meta-analytic studies focusing on the effectiveness of such intervention in the critical age range of 3 to 6 years old are still lacking, which corresponds to a pivotal period for EFs development (Diamond & Lee, 2011). In their research on cognitive interventions, Diamond and Lee (2011) discovered that training inhibitory control significantly enhanced these skills. However, they observed that the effects did not extend to improvements in delay of gratification performance among school-age children. Regarding working memory treatments, a meta-analysis conducted by Melby-Lervåg and Hulme (2013) conducted a meta-analysis involving studies based on EFs trainings and concluded that while these interventions reliably improved WM skills, the enhancements did not far-transfer to other skills such as reasoning, inhibitory processes, word decoding, and arithmetic skills. However, Sala & Gobet (2017) reported only a minor far-transfer effect of an intervention of WM on mathematics and literacy in typically developing school-aged children. Indeed, processes such as controlling, regulating, and actively maintaining relevant numerical information are crucial for mental and written calculations, as well as problem-solving (Scionti et al., 2020). However, far-transfer effects might occur when children learn and automatize a new cognitive routine through training activities, which is not yet established in their cognitive architecture (Gathercole et al., 2019).

Nonetheless, only few studies examined the effect of EFs in the relationship between cognitively-engaging PA and AA (Aadland, et al., 2017b; Egger et al., 2019) leading to mixed results. Aadland and colleagues (2017b) found no significant effect of PA on EFs or on AA. Egger and colleagues (2019) examined the effects of 20-week PA program implemented in classroom. Participants were 142 7-to- 9-years-old children divided into three groups, which differed for levels of cognitive engagement and physical exertion of activities proposed. The first group (cognition group) with high cognitive engagement and low physical exertion; the second (aerobic group) with low cognitive engagement and high physical exertion; and the last (combo group) with high cognitive engagement and high physical exertion. They tested the three core EFs and AA, in terms of mathematics, spelling, and reading. Authors found a significant improvement in cognitive flexibility and mathematics in the combo group, enhancement in mathematics as well in the cognitive group, while no significant benefits for the aerobic group.

Becker and colleagues (2014) investigated the association between PA, EFs and AA in kindergarteners. PA was considered as active play during recess, and it was assessed with a single 30 minutes session. They found a significant direct effect of PA on EFs, and a significant indirect relationship between active play and early math and literacy achievement through EFs. Moreover, another previous study from Kraybill & Bell (2013) highlighted that EFs evaluated in children at the age of 4 can anticipate their readiness for school, including both social and academic skills post-kindergarten (Kraybill & Bell, 2013).

Therefore, early interventions aiming at enhancing kindergarteners' EFs might promote both academic and social development (Stein et al., 2017), since preschool period is a sensitive period for the development of EFs (Diamond, 2015; Stein et al., 2017). In particular, early based-PA interventions might have a crucial effect on the development of essential skills in children, influencing their cognitive, psychological, and social development (Heckman et al., 2010). Indeed, given that new cognitive routines are likely more easily established in preschoolers compared to older children, it is reasonable to expect that far-transfer effects to learning and behaviors are more probable in preschoolers. Several studies have demonstrated that interventions targeting younger individuals have shown more widespread transfer of training effects, with young children generally exhibiting significantly larger benefits from training compared to older children (Wass et al., 2012; Melby-Lervåg and Hulme, 2013). Moreover, these interventions can yield long-lasting benefits extending into adulthood (Astuto & Ruck, 2017).

1.6. Overview

The rationale behind this thesis aimed at investigating the association between PA, EFs, and AA in kindergarteners is multifaceted. First of all, the focus is on cognitive development, especially the development of EFs in early childhood. Preschool period represents a sensitive period for EFs development. Secondly, PA has been demonstrated to benefit both physical and cognitive health in children. The interconnectedness of physical and cognitive domains lay the foundation to an intervention in one domain that might affect outcomes in another. Greater benefits have been found for PA with cognitive engagement. Therefore, this specific type of PA was used in ad hoc intervention as mean to train EFs. Thirdly, EFs play a critical role in academic success by enabling children to focus attention, regulate behaviors, plan, and organize tasks. Investigating how EFs relate to AA might help in identifying potential areas for intervention to support children's development and learning. Moreover, by examining the interplay of PA, EFs, and AA, this thesis adopted and holistic approach to understand child cognitive development and learning.

The design of the current thesis included five studies. The first study was a pilot study with a longitudinal design implemented to test the feasibility of the ad-hoc intervention to enhance EFs by involving a small number of kindergarteners. The second study aimed at unveiling the intricate association between PA, EFs, and AA by implementing a longitudinal study involving a larger number of kindergarteners aged 5-to-6-years old. Specifically, the effects of PA on EFs were tested during kindergartner years, and the effects of the intervention on AA while attending primary school. Since different types of PA might influence EFs in different ways, a comparison between PA with and without cognitive demands were taken into account in both studies.

Moreover, to better understand how EFs develop during childhood and adolescence, the association between PA, EFs, and AA was also tested in a sample of children and adolescents aged 12-15 years old by adopting a cross-sectional study design. As PA, even sports have been found to benefit EFs. Here, two different types of sport, open-skill and closed-skill were compared.

Finally, the development of EFs might be influenced by both biological and environmental factors. Two studied presented in this thesis investigate respectively one aspect related to biological factors, namely the effect of two genetic polymorphisms; and one aspect linked to environmental factors, the impact of culture. Data collection of the second one was carried out during the research period abroad in Japan. The aim of this cross-cultural study was to delve into similarity and differences between Italian and Japanese kindergarteners in EFs and motor abilities.

Chapter 2. Investigating the effects of cognitively-engaging physical activity on inhibition in kindergarteners: a pilot study

A version of this chapter has been published in *Perceptual and motor skills* (Annex A)

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2.1. Introduction

Empirical evidence suggested children's EFs might be influenced by quantitative factors of PA, such as duration and intensity; but also by qualitative factors, as type of exercise proposed, modality, and cognitive engagement. Cognitive engagement is one of the most frequently studied qualitative characteristics of PA (Best, 2010; Pesce, 2012; Tomporowski et al., 2015) in influencing EFs. Thus, interventional studies found that cognitively-engaging PA led to higher EFs benefits (Aadland, et al., 2017b; Álvarez-Bueno et al., 2017; de Greeff et al., 2018; Vazou et al., 2019). The cognitive stimulation hypothesis provides a theoretical explanation since PA with higher cognitive loading tasks activates the same brain areas (DL-PFC) associated with EFs (Best, 2010; Diamond & Lee, 2011).

Based on the early research regarding the effect of cognitively-engaging PA on early EFs development widely described in Chapter 1, the main purpose of the current study was to test the effects of 18 sessions cognitively-engaging PA ad hoc intervention on kindergarteners' inhibition. Two qualitative different types of PA were compared: Free Play and cognitively-engaging PA. The former referred to PA without cognitive demands, and the latter concerned PA with cognitive load. A pilot study was implemented with the aim of assessing the feasibility of the intervention proposed.

Two hypotheses were proposed:

(i) *Hp₁*: Children engaged in both PA modalities would show more consistent improvement on inhibition than a control group (CG2);

(ii) *Hp₂*: Children involved in cognitively engaging PA (IG) would perform better on inhibition tasks than children in engaged in Free Play (CG1).

2.2. Method

Participants

Seventy-five kindergarteners were involved in the pilot study. Participants mean age of 68.1 months (SD = 3.86; age range: 61–75 months, 48 % girls). Inclusion criteria were age range between 5–6 years old and attending the last year at kindergarten. The exclusion criterion was the presence of any neurodevelopmental disease or physical disability. Intact classes were used to assigned children to one of the three groups, the intervention group or one of the two control groups:

- CG1: control group involved in Free Play (n = 25; M_{age} = 67.3 months; SD_{age} = 3.95; age range: 61–74 months, 48 % girls);
- CG2: control group with not involved in any PA (n = 25; M_{age} = 68.2 months; SD_{age} = 3.68; age range: 61–74 months, 48 % girls);
- IG: intervention group involved in cognitively-engaging PA (n = 25; M_{age} = 68.7 months; SD_{age} = 3.95 ; age range: 62–75 months, 48 % girls).

Medium SES was prevalent 52.4% defined by middle and high school for parents' education, and shop assistant or employer for parents' job.

Procedure

A longitudinal quasi-experimental study design with three time points (T1, intervention, and T2) was adopted. Children we recruited from three kindergartens for a total of fourteen classes. Schools were located in rural small town in Sicily. School headmasters were met to illustrate the purpose of the study and invited them to participate. After obtaining approval from the schools, the parents or legal representatives of the children were approached to introduce them to the study's aims and address any inquiries they might have. Prior to the commencement of the research, parents of each participant completed and signed a written informed consent.

The child was administered EFs measures individually in a quiet room in the school. EFs assessment was carried out at the pre and post-test phases (T1 and T2). Both Cool and Hot EFs were tested by using cognitive (Day-Night Stroop test, Gift Wrap, and Snack Delay), and motor inhibition tests (Head-Shoulders-Knees-Toes, HSKT). Between the pre-test (T1) and post-test (T2) phases, the IG performed 18 sessions of cognitively-engaging PA, and the CG1 performed 18 Free Play sessions. Due to COVID-19 social restriction, each child in both groups performed individually sessions of 20 minutes, three sessions per week for six consecutive weeks. The CG2 did not perform any PA.

Measures

Demographic questionnaire

A parent-reported demographics questionnaire included information regarding parental information about age, sex, education, and occupation. SES was defined considering a number of children per family, parents' education, and parents' job. The medium SES status was described by middle and high school parental education and job status as a shop assistant or similar employment position.

Executive functions assessment

The Day-Night Stroop test (Gerstadt et al., 1994) from the FE-PS 2-6 (Batteria per la valutazione delle Funzioni Esecutive in età Prescolare, Usai et al., 2017) assesses Cool cognitive inhibition in children aged between 3 and 7 years old. It is composed of a total of 16 cards: 8 with a white background and a yellow sun, and 8 with a black background and a white moon. Before starting the task, the child was instructed to not give impulsive responses and answer by saying "night" when shown the white card with the sun, and "day" when shown the black card with the moon. The deck of cards was kept in a face-down position on the table, ensuring that the child remained unaware of the stimulus until the card was flipped over. The child was presented with cards one by one in a fluid and smooth manner. Scores for accuracy and reaction time were assigned. A score of "1" was attributed for each correct answer representing score for accuracy. Seconds was indicated as reaction time score. The number of correct responses was totaled and converted to a percentage of the total number of responses. The Day-Night Stroop test has demonstrated strong internal validity (von Stauffenberg & Campbell, 2007), and test-rest reliability (Thorell & Wahlstedt, 2006).

The Head-Shoulders-Knees-Toes test (Ponitz et al., 2009) was administered using the Italian version "Testa-Spalle-Gambe-Piedi". It is a measure of motor inhibition. Before starting the task, at first the child was asked to touch these parts of the body, and at a later time, the child was instructed to inhibit prepotent responses and follow the rules of this game. The test has two tasks, in the first one the parts of the body were paired two by two (head-toes *or* shoulder-knees). The child was asked to touch "head" and the expected response is the child touching "toes" and vice versa; or the child was asked to touch "shoulder" and inhibiting the dominant response the child touched "knees" and vice versa. In the second task, four paired orders were used (head-toes *and* shoulder-knees). Three possible scores can be assigned: "0" for incorrect answers, "1" for self-corrected incorrect answers, and "2" for correct answers. The HSKT test has shown good construct of reliability and constitutive validity (McClelland et al., 2014).

The Gift Wrap (Kochanska et al., 2000) adapted from the FE-PS 2-6 (Batteria per la valutazione delle Funzioni Esecutive in età Prescolare, Usai et al., 2017) is a "Hot" EF measure of delay of gratification or inhibitory control. The child was told that a present was bought but it was not wrapped yet. The child sat down with their back to the table and was instructed to not look while the researcher wrapped the gift making noisy sounds. After 60 seconds, the child was told to turn and given the present, which was a small box with candies inside. Scores for accuracy and reaction time were assigned. A score of "1" was attributed for any violations of instructions not to peek or speak during the wrapping, representing score for accuracy. Lower z scores indicated higher levels of control and inhibition. Latency from the instruction to the first possible violation to the first peek in seconds was indicated as reaction time score (ICCs = 0.86–0.96). Scores were converted to z scores. Higher z scores indicated higher levels of control and inhibition.

Snack Delay (Ebbesen, 1970) adapted from the FE-PS 2-6 (Batteria per la valutazione delle Funzioni Esecutive in età Prescolare, Usai et al., 2017) is a “Hot” EF task used to test the child’s ability to inhibit automatic responses. The child was asked to wait before opening the wrapped gift from the previous test, the Gift Wrap, for a maximum waiting time of 240 seconds. Latency in seconds until the child opened the gift was recorded and then converted to z scores. Higher z scores indicated higher levels of control and inhibition. For both tests, the Gift Wrap and the Snack Delay, the construct of validity as well as reliability have been confirmed (Smith-Donald, et al., 2007).

Intervention

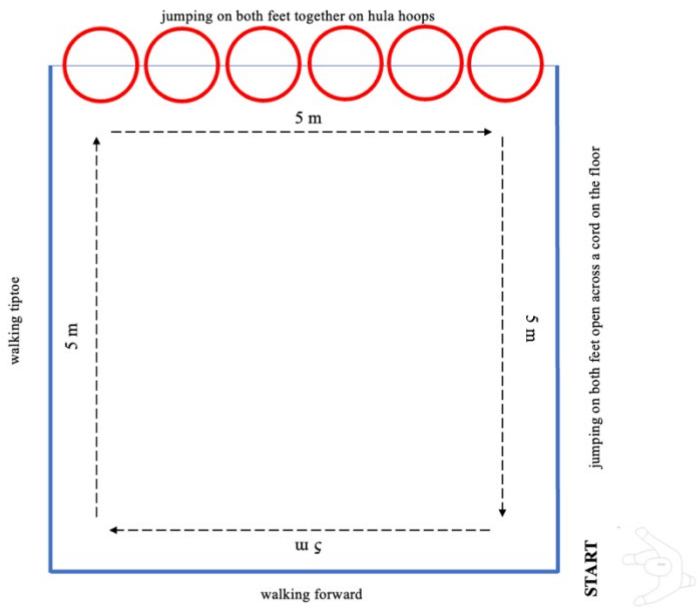
To test the effect of cognitively-engaging PA on EFs, ad hoc intervention has been created, taking the cue from already tested activities proposed in the Enriched Sport Activities (ESA) Program - Erasmus + Sport Programme (2017–2019), and the PMA (Programma Motorio Arricchito – Enriched Motor Program, Alesi et al., 2016). ESA Program provides an enriched protocol of physical exercises integrating cognitive and motor task with the purpose of stimulating cognitive domain, in particular the three core EFs. PMA is a program of motor activities (i.e. catching, kicking, pulling, pushing, picking up objects, using tools like pencils, button up clothes, threading beads) coupled with EFs tasks (i.e. Stroop task with fruit, body span tasks, and fluency tasks) aimed at enhancing EFs (i.e. WM, inhibition, cognitive flexibility, and planning), and motor abilities (i.e. fine motor skills).

The IG performed individually 18 sessions of cognitively-engaging PA, three sessions per week for six consecutive weeks. Cognitive demands involved movement inhibition with three increasing levels of difficulty: beginner, intermediate, and advanced. Each level lasted two weeks, three 20-minute sessions per week, and each session was divided into two phases: baseline and experimental (10 minutes per each). Movement inhibition stimuli changed from one level to another. The auditory stimulus was used at the beginner level, visual stimuli at the intermediate, and a Stroop task at the advanced one.

For the beginner and intermediate levels, a quadrangular circuit was made in the kindergarten gym using blue adhesive tape. Gym equipment (i.e. hula hoops) was used on the third side to define a specific movement. For the advanced level, gym equipment such as hula hoops and gym cones were used to create a course. In order to increase the level of difficulty: stimuli changed from one level to the next one; circuit repetition increased by one per session (once in the first session, twice in the second, and three times in the third session), and circuit sides enlarged by one meter (5 meters per side in the first week and 6 meters per side in the second week of each level).

In the baseline phase of the beginner level, oral instructions were given to define movements required to complete clockwise 5 meters per side circuit. A specific movement per each side of the circuit was defined as follow: walking forward; walking tiptoe; jumping on both feet together on hula hoops; jumping on both feet open across the blue tape on the floor (Figure 3).

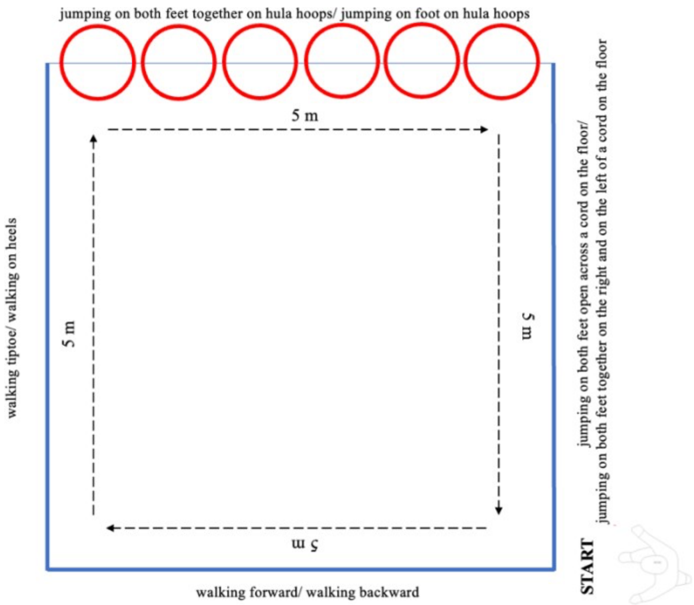
Figure 3. The b*aseline phase of the beginner level*



Before the start of the experimental phase, the child was taught to change baseline movement to the associated one when a key stimulus was presented (e.g. auditory or visual stimuli). Baseline movements are associated with another movement as follows: walking forward/ walking backward;

walking tiptoe/ walking on heels; jumping on both feet together on hula hoops/ jumping on foot on hula hoops; jumping on feet open across a cord on the floor/ jumping on both feet together on the right and on the left of a cord on the floor (Figure 4).

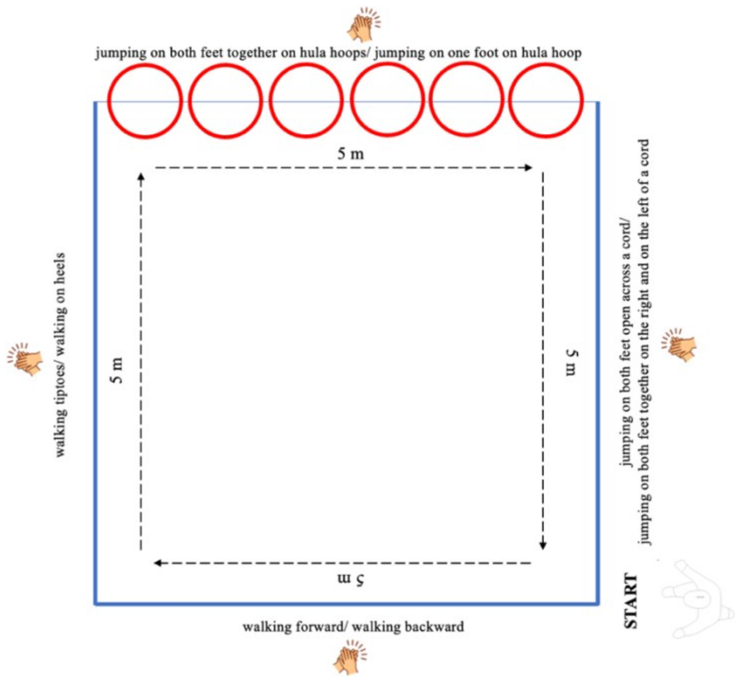
Figure 4. *Baseline movements and the respective associated ones of the beginner level*



In the experimental phase, the auditory stimulus (clap) was presented once per circuit side per session. The child performed once the circuit with 5 meters per side in the first session, twice in the second session, and three times in the third session. During the second week, the auditory stimulus (clap) was presented twice per circuit side per session. The circuit was modified by adding 1 meter per side between the first and the second week. Circuit competition lasted 20 minutes, 10 minutes for the baseline phase and 10 minutes for the experimental phase.

An example of an activity for the beginner level was based on a clockwise performance of a quadrangular circuit (Figure 5). In the baseline phase, the child performed walking forward on the first side of the circuit, walking tiptoe on the second, jumping with two feet in the hula hoops on the third, and jumping on both feet open across a cord on the floor on the fourth and last side. In the experimental phase, the auditory stimulus (clap) was presented once in a random order per each circuit side while the child was performing the baseline movement. The instruction was "Complete the circuit by performing the movements you already know. Remember to change the movement every time you hear a clap". The child started performing walking forward, the experimenter clapped and the child changed the movement by performing the associated one: walking backward; once finished on the first side of the circuit, the child performed walking tiptoe on the second side, the experimenter clapped and the child changed performing walking on heels; the child arrived to the third side and started jumping with two feet in the hula hoops, the researcher clapped and child changed performing jumping with one foot inside the hula hoops, once arrived to the last side child performed jumping on both feet open across a cord on the floor, the researcher clapped and child changed performing jumping on both feet together on the right and the left of a cord on the floor.

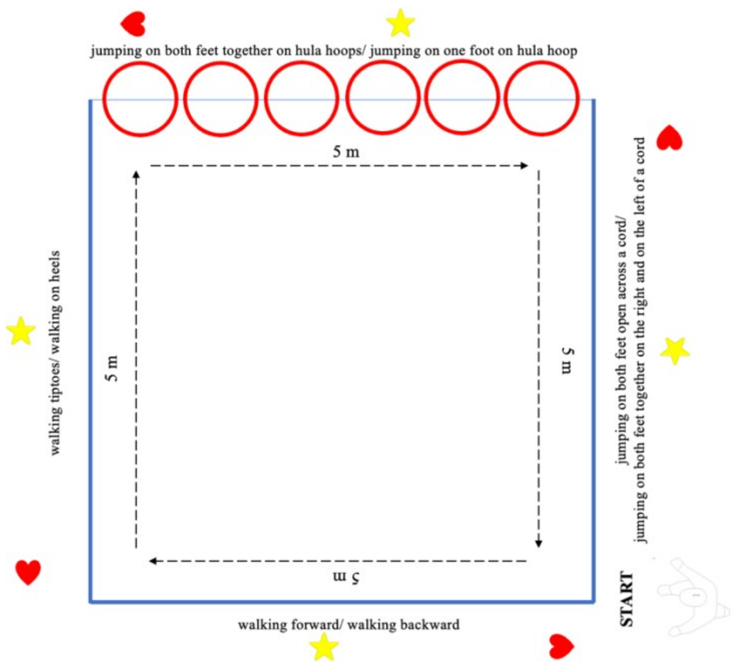
Figure 5. The e*xperimental phase of the beginner level*



At the intermediate level, visual stimuli induced movement inhibition. Visual stimuli differed in shapes and colors. They were images of a red heart and a yellow star on each circuit side (Figure 6). In the baseline phase, the child was instructed to associate the red heart with each side baseline movement, and the yellow star with the respective associated ones. The. yellow star represented the stimulus associated with movement inhibition. Each time a yellow star was presented, the child had to stop performing the baseline movement and change by doing the associated one.

In the baseline phase, both visual stimuli (the red heart and the yellow star) were presented once per each side of the circuit while the child was performing the baseline movement. A red heart and a yellow star were displayed on the external side of the circuit, namely on the left side of the blue adhesive tape. Before starting, the child was shown and pointed out that something had changed in the circuit, the experimenter explained that he/she would no longer hear a clap, but from now on it was drawings that gave him/her suggestions as to which movements to perform. The child was instructed to associate the red heart with the baseline movement and the yellow star with the inhibition stimulus. Each circuit side started with a red heart, in this way the child had to start with the baseline movement, and in a random part of each side a yellow star was displayed and the child had to stop performing the baseline movement and change with the associated one.

Figure 6. The e*xperimental phase of the intermediate level*

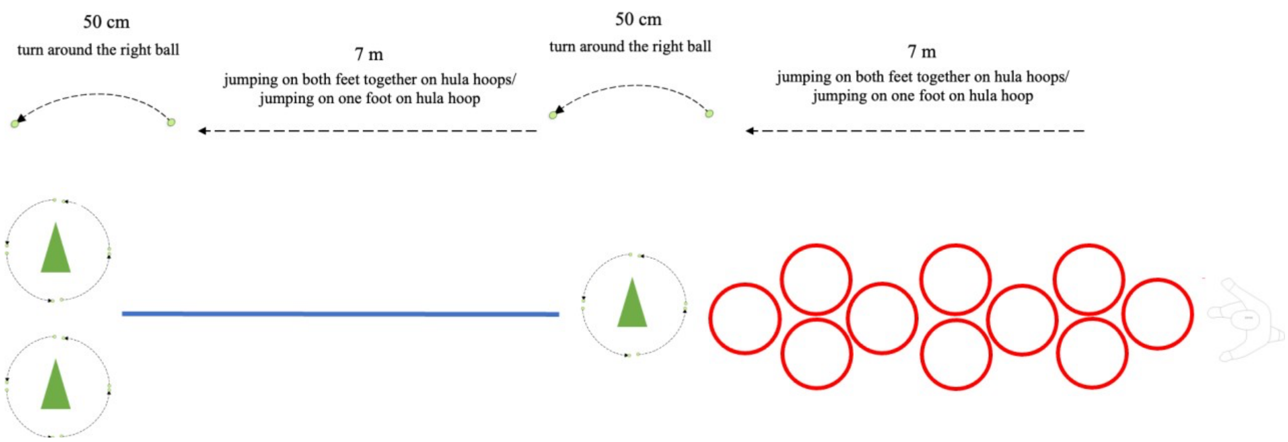


In the experimental phase in the second week, to increase the level of difficulty other two visual stimuli were added (blue hearts and green stars). The idea was the same, hearts were linked to the baseline movement performance, while stars represented the target stimuli to movement inhibition, and performed the associated one. The circuit was modified adding 1 meter for each side. The child performed once 6 meters per side circuit in the first session, twice in the second session, and three times in the third session.

An example of baseline activity for the intermediate level was based on a clockwise performance of the same quadrangular circuit of the beginner level. The instructions were "Complete the circuit by performing the movements you already know. Remember from now on you will not hear a clap, but you will change the movement every time you see the yellow star". A red heart was placed at the beginning of each circuit side starting with the baseline movements. The child and started walking forward, once he/she saw a yellow star change and started performing the associate movement: walking backward. Once finished the first side of the circuit, the child saw a red heart at the beginning of the second side, associated with the performance of walking tiptoe, when he/she saw a yellow star child changed performing walking on heels; the child arrived to the third side and a red hearth was showed and the child started jumping with two feet in the hula hoops, when he/she saw a yellow star the child changed performing jumping with one foot inside the hula hoops, once arrived to the last side the child saw a red heart drawing and started performing jumping on both feet open across a cord on the floor, until the child saw a yellow star that was associated with the performance of jumping on both feet together on the right and on the left of a blue adhesive tape on the floor.

The advanced level was represented by a task with the Stroop effect. In the kindergarten gym was created a 15 meters course using the same gym equipment as the previous levels (i.e. hula hoops, gym cones, and blue adhesive tape). The course was composed of four parts that required four specific movements to complete it. The first part was 7 meters in length, and seven hula hoops (each 92 cm in diameter) were arranged in the following order: one, two, one, two, one, two, one. The second part was 50 cm in length and a gym cone was used. The following part was 7 meters in length and made using a blue adhesive tape. The last part was 50 cm long and made using two gym cones placed 1 meter apart (Figure 7).

Figure 7. *The baseline phase of the advanced level*



The Stroop effect was made using prints of four sports balls that differed in color and shape: football, rugby, basketball, and tennis. The ball used in football has a spherical shape, stitched from 32 panels, 12 regular black pentagons, and 20 regular white hexagons. The rugby ball is oval-shaped, made of four panels, typically brown with two white circle strips close to the extremities. The ball used in basketball is a spherical-shaped, orangish surface with black ribs that are recessed below the surface. The tennis ball is spherical, smaller than the other ones, in fluorescent yellow with two white ribs on the surface. Two matches were proposed: football/rugby balls and basketball/tennis balls. Matches fall into two categories: congruent and incongruent stimuli. The former two were defined according to the correspondence between color and shape, sports balls that were printed out in the same ink color and shape as the original ones (i.e., football ball with black and white panels), whereas the latter were defined by the non-correspondence, and sports balls were printed out in colors that did not match the shape (i.e., football ball with rugby ball colors).

In the baseline phase, oral commands were given to define movements to complete the course. The child was instructed to jump with both feet when there was a single hula hoop in the course; jump with feet apart when there were two hula hoops; turn around when a gym cone was in the course; and walking tiptoe on a line when a blue adhesive tape was arranged on the floor. Then, the child was shown the four sports balls to ensure he/she was able to recognize and name them.

An example of baseline activity for the intermediate level was based on the performance of 15-meter course. The instruction was "Complete the course and turn around the gym cone with a rugby ball". The child started jumping alternatively with both feet on a single hula hoop, and with feet apart on two hula hoops, then turned around a cone, walking tiptoe on a line made of blue adhesive tape, once finished the child turned around the gym cone with the sport ball chosen. If the child made the right decision he/she turned around the gym cone with a rugby ball.

In the experimental phase, the child was introduced to the Stroop task, which coincided with the last part of the course. On each of the two gym cones placed at the end of the course, there were stuck on a white paper sheet with a sports ball printed out (Figure 6). Then, the child was instructed to choose the sports ball following a given stimulus (i.e. color), inhibiting stimuli linked to conventional features (i.e. shape or dimension), by turning around the gym cone with the ball chosen printed out on the white sheet stuck on it.

An example of baseline activity for the intermediate level was based on the performance of a 15-meter course in 10 minutes. The instructions were "Complete the course and turn around the gym cone with a rugby ball. Remember that something "strange" happened to the sports ball, which changed a little bit". The child started jumping alternatively with both feet on a single hula hoop, and with feet apart on two hula hoops, then turned around a cone, walking tiptoe on a line made of blue adhesive tape, once finished the child turned around the gym cone with the sport ball chosen. If the child made the right decision he/she turned around the gym cone with a sports ball football-shaped but colored as the rugby one.

Data Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, Version 26, NY, USA), and statistical significance was set at $p < .05$. Then, a G-Power software was used to test post-hoc power analysis and it showed that a sample size of 66 yielded to 95% of statical power. Preliminary analyses of variance (ANOVAs) were run to test group differences in demographic characteristics such as age and sex at T1, and on each EF tests as dependent variables. Repeated measure ANOVAs were then computed on the dependent variables to test differences within groups at T1 and T2, and to investigate differences between groups. Partial eta square (η^2_p) was reported as an indicator of effect size. Once ANOVAs showed significant differences, Bonferroni correction for post hoc comparisons was computed to determine group differences between the three groups.

2.3. Results

Means and standard deviations for EF tasks at pre and post-test are presented split by group in Table 1. Preliminary ANOVAs showed no group differences for age [F (2,73) = .851, p = .43], and sex [F (2,73) =.153, p = .85]. As regards differences in the dependent variables at T1, ANOVA displayed no group differences on Cool EFs measured Day-Night Stroop accuracy [F (2,73) = .4174, p = .66], on Hot EF measured by Gift Wrap reaction time [F (2,73) =.0543, p = .95], and Snack Delay reaction time [F (2,73) = 2.96, p = .06]. Significant statistical differences were found for "Cool" EF measured by Day-Night Stroop reaction time [F (2,73) =13.31, p < .001], and HSKT [F (2,73) = 5.16, p = .008].

Table 1. *Descriptive analysis of Day-Night Stroop, HSKT, Gift Wrap and Snack Delay at pre and post-test for the three groups.*

Groups	Phases		Day-Night Stroop		HSKT	Gift Wrap	Snack Delay
			Accuracy	Reaction time	Accuracy	Reaction time	Reaction time
			N	sec	N	sec	sec
CG1	T1	M	-.64	-2.06	5.08	.54	5.52
		SD	1.83	1.56	5.47	.75	5.57
	T2	M	-.66	.04	9.67	.89	5.54
		SD	.64	.95	6.18	.51	5.33
	Δ	M	-.04	-2.02	-4.91	-.38	-.21
		SD	.37	.35	1.18	.20	1.13
CG2	T1	M	-.27	.09	10.4	.59	9.78
		SD	1.34	1.13	6.12	.87	6.85
	T2	M	-.53	.32	10.6	.29	8.67
		SD	1.36	.69	6.68	1.04	6.31
	Δ	M	.25	-.23	-.24	.30	1.10
		SD	.36	.34	1.16	.19	1.11
IG	T1	M	-.58	-1.56	9.20	.61	8.86
		SD	1.32	1.86	6.77	.90	6.96
	T2	M	.07	.75	17.0	.75	9.39

	SD	.44	.49	4.32	.87	5.68
Δ	M	-.66	-2.32	-7.76	-.14	-.53
	SD	.36	.34	1.16	.19	1.11

Note. CG1: free play group; CG2: no additional physical activity group; IG: cognitively engaging physical activity; M: mean; SD: standard deviation; T1: pre-test; T2: post-test; Δ: comparison; HSKT: Head-Shoulder-Knees-Toes; N: total; sec: seconds.

Repeated measures ANOVAs revealed significant interaction effects Time x Group. In particular, significant differences on Cool inhibition measured by Day-Night Stroop reaction time [*F* (1,74) = 11.0, $p < .001$, $\eta^2_p = 2.36$] and HSKT [*F* (1,74) = 10.7, $p < .001$, $\eta^2_p = .232$], as well as significant differences in Hot inhibition measured by Gift Wrap reaction time [*F* (1,74) = 3.16, $p = .04$, $\eta^2_p = .082$]. No significant differences were found for Day-Night Stroop test accuracy [*p* (1,74) = 1.62, $p = .20$, $\eta^2_p = .044$], and Snack Delay reaction time [*F* (1,74) = .60, $p = .54$, $\eta^2_p = .017$]. Results are shown in Table 2.

Table 2. *Repeated measures ANOVAs for Cool and Hot executive functions tasks.*

Inhibition		**F**	***p***	***d***
Day-Night Stroop	Accuracy	.491	.034*	.47
	Reaction Time	46.0	<.001***	1.17
HSKT	Total	32.1	<.001***	1.25
Gift Wrap	Accuracy	1.35	.24	.29
	Reaction Time	.379	.54	.08
Snack Delay	Time	.0387	.84	.00

* $p < .05$; *** $p < .001$

2.4. Discussion

The main aim of this pilot study was to test the efficacy of a cognitively-engaging PA intervention on both cognitive and motor inhibition in kindergarteners. Specifically, two qualitatively different PA conditions with different levels of cognitive load were compared, namely PA without cognitive tasks (Free Play) and cognitively-engaging PA. 18 sessions of cognitively-engaging PA intervention was created ad hoc with increasing levels of difficulty given by challenging cognitive stimuli aimed at enhance inhibition.

In this study, cognitive inhibition was tested including both Cool (i.e., non-emotional or motivational) and Hot (i.e., emotional or motivational) aspects. Motor inhibition was tested as well.

Findings from this pilot study partially confirmed the first hypothesis since children involved in a cognitively-engaging PA (IG), but not those engaged in Free Play (CG1) showed significant improvements in inhibition compared to the control group with no PA (CG2). Moreover, IG increased their Cool inhibition both cognitive and motor, and in one Hot inhibition task (delay of gratification), corroborating the second hypothesis. A possible explanation refers to the cognitive stimulation hypothesis according to which PA with cognitive tasks seems to activate the same neural areas as EFs (Best, 2010). No significant differences between groups were found for Day-Night Stroop test accuracy and Snack Delay. This might be due to the ceiling effect since pre-test initial scores were higher for all participants, which made it complicated to measure significant improvements related to the effect of the intervention.

Chapter 3. Longitudinal study: the mediating role of Cool and Hot executive functions in the association between cognitively-engaging physical activity on academic achievement

3.1. Introduction

The relationship between PA and AA is thought to be mediated by several factors, including EFs, physical fitness, adiposity, behavior, and mental well-being (Visier-Alfonso et al., 2021). Specifically, the positive impact of cognitively-engaging PA on AA may be partly mediated through EFs (Donnelly et al., 2016). This type of PA can enhance physiological arousal, stimulate neural growth, modify synaptic transmission, and trigger the release of neurotransmitters, thereby influencing cognitive processes associated with the PFC (Kopp, 2012). These mechanisms suggest that PA can benefit both physical health and cognitive performance, making it a valuable component of the school environment (Alvarez-Bueno et al., 2016).

Hence, interventions targeting the improvements of children's EFs during early preschool years could potentially foster both academic and social growth. Given that the preschool period is recognized as a critical stage for EFs development (Diamond, 2015; Stein et al., 2017), early PA-based interventions might play a pivotal role in shaping children's cognitive, psychological, and social skills (Heckman et al., 2010).

Once the study method and procedure of the intervention had been tested in the pilot study, a longitudinal study was carried out during the last year of kindergarten, in which the intervention on EFs through PA was implemented. Then, once children were in the first year of primary school, the effect of PA intervention on AA was tested, taking into account the mediating role of EFs.

The general aim of this longitudinal study was to investigate the effect of PA on AA by the mediating role of Cool and Hot EFs. The first specific goal was to examine the effects of 24 sessions of two types of PA on kindergartener's EFs (i.e. inhibition and WM). As in the pilot study, cognitively-engaging PA refers to PA with cognitive demands, and Free Play refers to PA without cognitive demands.

Two hypotheses have been proposed:

(i) *Hp1*: Children involved in both PA modalities (IG and CG1) would show more consistent improvement on Cool and Hot EFs at the end of kindergarten than a control group;

(ii) *Hp2*: Children engaged in cognitively-engaging PA (IG) would perform better on Cool and Hot EFs than children engaged in Free Play.

A second specific goal was to test the effect of the PA intervention on AA once the same children attended the first year of primary school. Consequently, two hypotheses have been proposed:

(iii) *Hp3*: Children involved in both PA modalities (IG and CG1) during the last year of kindergarten would show more consistent improvement on AA during the first year of primary school than a control group (CG2);

(iv) *Hp4*: Children engaged in cognitively-engaging PA intervention (IG) during the last year of kindergarten would perform better on AA tasks than children in engaged in Free Play (CG1).

Lastly, a third goal was to test the mediating effect of EFs in the association between PA and AA in children attending the first year of primary school. A specific hypothesis has been proposed:

(v) *Hp5:* EFs would mediate the relationship between PA and AA.

3.2. Method

Participants

A total of 132 kindergarteners were involved in this study. The participants' mean age was 63.9 months (SD = 3.58; age range: 56–71 months, 50 % girls). Participant inclusion criteria were to be 5–6 years old and attending the last year at kindergarten school, and the sole exclusion criterion was the presence of any neurodevelopmental disease or physical disability. Intact classes were used to assigned children to one of the three groups:

- CG1: active control group involved in Free Play (n = 45; M_{age} = 63.6 months; SD_{age} = 3.59; age range: 56–71 months, 50 % girls)
- *CG2:* non-active control group not involved in any PA (n = 43; M_{age} = 63.6 months; SD_{age} = 3.54; age range: 57–69 months, 50 % girls)
- IG: intervention group involved in cognitively-engaging PA (n = 44; M_{age} = 63.4 months; SD_{age} = 3.57; age range: 58–71 months, 50 % girls)

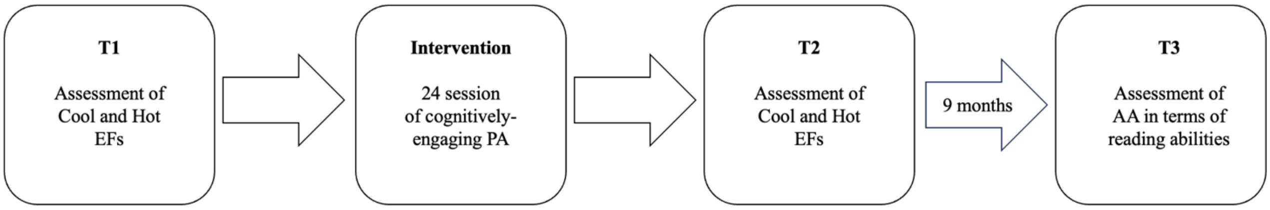
Medium SES was prevalent at 67.3%. It was defined by parents' education ranging between middle and high school, and parents' job as a shop assistant or employer.

Procedure

A longitudinal quasi-experimental research design with four time points (T1, intervention, T2, and T3) was employed to compare three groups over time (Figure 8). Participants were recruited from two kindergartens for a total of seventeen classes. Schools were located in rural small towns in Sicily. School headmasters were met to explain the aim of the study and invited them to participate. Following schools' approval, children's parents or legal representatives were met to introduce them to the study's objectives and answer their questions. Before the start of the research, each participant's parents completed and signed the written informed consent. The experimental protocol (n. 62/2021) was approved by the Bioethics Committee of the University of Palermo.

In the pre and post-test phases (T1 and T2) a set of cognitive tests were administered to assess participants' Cool inhibition skills (Day-Night Stroop test), WM (Batteria di memeoria di lavoro), Hot EFs, in terms of delay of gratification (Gift Wrap and Snack Delay). The EFs assessment was carried out individually in a separate quiet room in their preschools. Pre and post-test sessions (T1 and T2) lasted about 40-50 minutes for each child. Between the pre-test and post-test phases, the IG and the CG1 individually performed 24 sessions (20 minutes per session, three sessions per week) of cognitively-engaging PA and Free Play respectively. The CG2 did not perform any PA beyond regular school activities. Nine months after the T2, once children attended the first year of primary school, AA in terms of reading abilities (MT Battery) was tested (T3).

Figure 8. Study design with activities implemented (T1, intervention, T2, and T3)



Measures

Socio-demographic questionnaire

A parent-reported demographics questionnaire included information regarding parental information about age, sex, education, and occupation. SES classes were defined taking into account parents' education, job, and number of children. The medium SES status was described by middle or high school education and job as a shop assistant or employer.

Executive functions assessment

The same tests as the pilot study described in Chapter 2 were used to measure both Cool and Hot EFs: Day-Night Stroop test (Gerstadt et al., 1994), Gift Wrap (Kochanska et al., 2000), Snack Delay (Ebbesen, 1970) from the adapted version FE-PS 2–6 (Batteria per la valutazione delle Funzioni Esecutive in età Prescolare - Usai et al., 2017). Moreover, a test for WM has been administered.

The Batteria per la memoria di lavoro (Lanfranchi, Cornoldi, 2004), as Cool EF test, was used to assess WM. It is a battery composed of 12 WM tasks, three for each stimulus presentation modality (verbal, visual, spatial-sequential, and spatial-simultaneous) with an increasing level of active control over the information. For each presentation modality, the material was the same, but three different tasks were administered. The first involved attentional resources to a lesser extent, only requiring the recall of the material as presented. The second involved a moderate degree of manipulation, requiring selective recall of only some of the information presented. The third task demanded a high level of cognitive control, requiring specific item recall and the performance of a concurrent task. The instructions and practice trials were carefully designed to make the child feel confident about the task. In this study, only verbal, spatial-sequential, and spatial-simultaneous high cognitive control tasks were administered since they are more related to WM assessment.

In the verbal high cognitive control task participants were presented orally with a list of two to five disyllabic words. Children were asked to remember the first word on the list and to tap on the table when they heard the target word (ball). The word "ball" was present in each trial. In this task, tapping is presented as a secondary task. A score of "1" was awarded for every trial completed correctly (i.e., when the child remembered the first word of the list and tapped the table). In all other cases, they scored 0.

In the spatial-simultaneous high cognitive task children were given 8 seconds to look at the positions of red squares in a matrix, sometimes it also contained a blue square (in half of the trials). Then the matrix was removed, and children were asked to point to the locations of the red squares on an empty matrix and tap on the table with their hand if they saw a blue square (concurrent task). The task presents four levels of difficulty depending on the size of the matrix and the number of squares to retrieve (2×2 on the first level; 3×3 on the second and third levels, with two and three red squares; and 4×4 on the fourth level with three red squares). A score of 1 was awarded for every trial completed correctly (i.e. when the child recalled the right position of all the red squares and tapped the table when saw the blue one). In every other case, a score of 0 was given.

In the spatial-sequential high cognitive control children were shown the path taken by a small frog on a 3×3 or 4×4 matrix and immediately afterward were asked to repeat the frog's steps from cell to cell, and to tap on the table whenever the frog jumped onto the red square. The frog jumped onto the red square once in each trial. The position from where it jumped onto the red square varied across trials. There were four levels of difficulty depending on the dimensions of the matrix and the number of steps along the frog's path (3×3 for the first level of difficulty, with the frog taking two steps; 4×4 for the other levels, with the frog taking two, three, and then four steps). The frog's steps were presented at a rate of a step every 2 seconds. A score of 1 was awarded for every trial completed correctly (i.e., when the child remembered the path's starting point and tapped the table at the right moment). In all other cases, they scored 0.

Academic Achievement

The MT Battery (Cornoldi et al., 2017) a standardized Italian reading, evaluates reading accuracy, speed (or fluency), and comprehension. The materials used in the assessment corresponded to those typically read by children in school. For each scholastic grade, reading can be assessed at three different moments of the year: initial, intermediate, and final evaluation. Specifically, two versions for the intermediate and final evaluation of first grade; and three versions for the initial, intermediate, and final evaluation of the other grades of primary school. The accuracy and speed test consisted of a written paragraph on a card, the child was asked to read the paragraph aloud as quickly as possible while avoiding errors. There were no time limits for this task, but the duration taken by the child to complete it was recorded. The accuracy score was given by the sum of errors made during the reading, including letter omissions, substitutions, and pauses exceeding 5 seconds. Speed scores are calculated by dividing the number of seconds spent reading by the number of syllables in the text. Lower scores indicate better performance for both accuracy and speed tests. The text administered was "Babbo Natale" ("Santa Claus"), the intermediate evaluation in the first year of primary school. It was 16 lines long, composed of a total of 126 syllables.

The comprehension test evaluates the understanding of a written text by answering fifteen multiple-choice questions created by using different words from those in the text that children read. Scores are given by the number of correct answers. Higher scores indicate better performance. The child was given a small booklet containing a story along with some questions, a pencil, and a rubber. Then, the child was required to select only one correct answer from the four options provided. It was allowed to reread the text as many times as the child needed. The reliability of the tests is measured by Cronbach's alpha coefficient, ranging from 0.75 to 0.89 for the accuracy test, from 0.94 to 0.96 for the speed test, and from 0.70 to 0.77 for the comprehension test.

Intervention

Based on the first version implemented in the pilot study, the intervention in the current study has been modified adding more challenging tasks to foster inhibition and WM in kindergarteners.

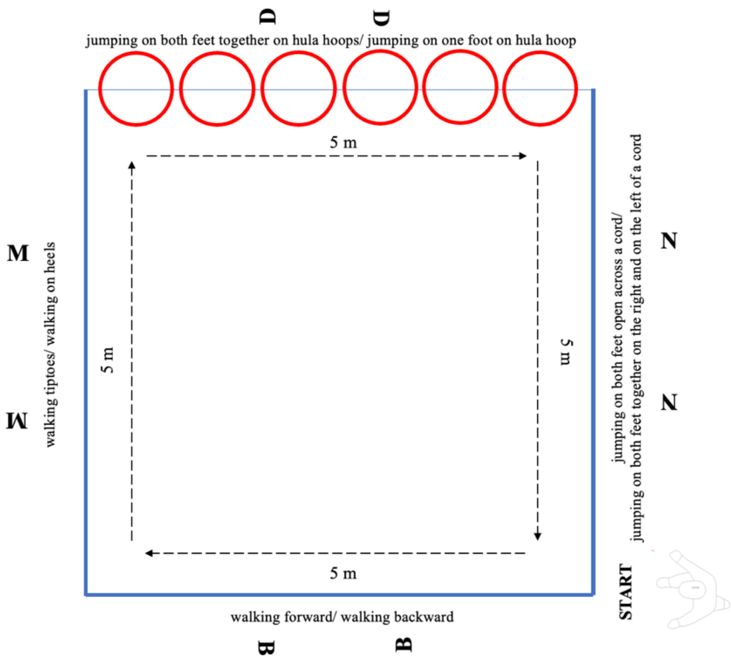
The IG performed individually 24 sessions of cognitively-engaging PA, three sessions per week for eight consecutive weeks. As the intervention in the pilot study, cognitive demands involved movement inhibition with three increasing levels of difficulty: beginner, intermediate, and advanced. As in the pilot study, the beginner level lasted two weeks; while the intermediate and the advanced levels lasted three weeks each. Each session lasted 20 minutes and was divided into two phases: baseline and experimental (10 minutes per each). The same quadrangular circuit as in the pilot study was made in the kindergarten gym using blue adhesive tape. Moreover, the activities required to complete the circuit were the same as in the pilot study. Levels have been improved by adding new stimuli and increasing the duration, in terms of weeks. The underlying mechanism was the same, it was based on movement inhibition. Stimuli used changed from one level to another: auditory stimulus in the beginner, visual stimuli in the intermediate, and the Stroop task in the advanced level. To increase the level of difficulty: stimuli changed from one level to the next one; circuit repetition increased by one per session (once in the first session, twice in the second, and three times in the third session), and circuit sides enlarged by one meter (5 meters per side in the first week, and 6 meters per side in the second week in the beginner level, and the second and third in the intermediate one).

The beginner level was identical to the pilot study (Figure 3, Figure 4, and Figure 5).

The intermediate level was improved and three different visual stimuli were proposed: drawings of hearts and stars, alphabetic letters, and numbers. Stimuli were printed on A4 white sheet paper for the pilot study intervention. At the intermediate level, visual stimuli induced movement inhibition. In the first two weeks, visual stimuli were the same as in the pilot study (Figure 6). This level was modified by adding new visual stimuli (alphabetic letters and numbers) and increasing the duration (two weeks were added, one at the intermediate level and one in the advanced level). Visual stimuli differed in shapes and colors: red and blue hearts, yellow and green stars, and black alphabetic letters and numbers. Different from the pilot study intervention, this level was implemented in three weeks. The baseline phase and the second week coincided with the experimental one, in which hearts and stars were used as stimuli.

In the baseline phase, new visual stimuli were introduced. Four alphabetic letters were chosen: B, M, D, and N. Letters were printed out on A4 white sheet paper in black ink. Each letter was printed also in a specular manner and used as a distractor. Stimuli were presented once per each side of the circuit while the child was performing the baseline movement. Letters were displayed on the external side of the circuit, namely on the left side of the blue adhesive tape. Before starting, the child was pointed out that something had changed in the circuit, the experimenter explained that he/she would no longer see a red heart or a yellow star, but from now on alphabetic letters will give him/her suggestions about the movement inhibition stimulus. The child was shown the four letters to ensure he/she was able to recognize and name them. Then, he/she was instructed to start each circuit side with the baseline movement, and to associate the letters B, M, D, and N with the movement inhibition stimulus. Letters were displayed in a random part of each side of the circuit, and the child had to stop performing the baseline movement and change with the associated one. Distractors were displayed at 1 m distance from the target letters (Figure 9).

Figure 9. *Baseline phase of the intermediate level (third week)*



In the experimental phase was implemented in the second and third sessions of the third week. In the second session, to increase the level of difficulty, letters from the baseline level were changed and for each letter, two distractors were added. Two distractors were chosen based on similarity: higher (stimulus differed for a small detail) and lower (stimulus was completely different). Four target letters were chosen: B, M, P, and G. Higher similarity distractors were D, N, R, and C respectively. Letters B and D, M, and N are similar in terms of sounds, while P and R, G, and C are similar in terms of shapes. Lower similarity distractors were: L, Q, S, and F respectively, which differed both in sound and shape. See Table 3. Letters were printed out on an A4 white sheet of paper in black ink. The child was instructed to change movement every time saw the target letters (B, M, P, and G). The underlying mechanism was the same as the baseline phase, the target letters were linked to movement inhibition. The circuit was modified adding 1 meter for each side. The child performed once 5 meters per side circuit in the first session, twice in the second session, and three times in the third session.

Table 3. *Visual stimuli (alphabetic letters) for the second session of the intermediate level*

Target letters	Distractors	
	Higher similarity	Lower similarity
B	D	L
M	N	Q
P	R	S
G	C	F

In the third session new visual stimuli were introduced. Letters were replaced with numbers. Four numbers were chosen: 1, 4, 7, and 6. Numbers were printed out in a A4 white sheet paper in black ink. Stimuli were presented once per each side of the circuit while child was performing the baseline movement. Per each side a distractor number was added: 8, 9, 2, and 3. Numbers were displayed on the external side of the circuit, namely on the left side of the blue adhesive tape. Before starting, the child was pointed out that something had changed in the circuit, the experimenter explained that he/she will no longer see alphabetic letters, but from now on numbers will give him/her suggestions about the movement inhibition. The child was shown the four target numbers to ensure he/she was able to recognize and name them. Then, he/she was instructed to start each circuit side with the baseline movements, and to associated the numbers 1, 4, 7, and 6 with the movement inhibition. The child was shown distractors (8, 9, 2, and 3) and he/she was told to ignore them. Numbers were displayed in a random part of each side of the circuit, and child had to stop performing the baseline movement and change with the associated one. Distractors were displayed at 1 m distance from the target letters.

An example of baseline activity for the intermediate level was based on a clockwise performance of the same quadrangular circuit of the beginner level. The instruction was "Complete the circuit by performing the movements you already know. Remember from now on you will not see a red heart and a yellow star. You will change the movement every time you see the letters B, M, D, and N. Be careful that some letters you will see are written in the wrong way, upside down, like this (showing the distractor on the first side). Change only when you see the letter written correctly". The child started walking forward, once he/she saw the letter B changed and started performing the associate movement: walking backward. Once finished the first side of the circuit, the child started the second side walking tiptoe, when he/she saw the letter M changed performing walking on heels. Once the child started the third side jumping with two feet in the hula hoops, and when he/she saw the letter D changed performing jumping with one foot inside the hula hoops. On the last side, the child started performing jumping on both feet open across a cord on the floor until the child saw the letter N that was associated with the performance of the associate movement jumping on both feet together on the right and on the left of a blue adhesive tape on the floor.

The advanced level, as in the pilot study, was represented by a task with the Stroop effect. In the kindergarten gym was created a 15-meter course and three movements were required to complete it: jumping with both feet on one the hula hoop or jumping with feet apart on two parallel hula hoops; go around the cone; jumping with both feet on the right and on the left of a blue adhesive tape on the floor. The Stroop effect was made using different stimuli from those used in the pilot study (i.e. sport balls, as football, rugby, basketball, and tennis). New stimuli were cartoon version images of eight animals: penguin, giraffe, mouse, elephant, zebra, and horse. Three matches were proposed: penguin/giraffe, mouse/elephant, and zebra/horse. Matches were implemented with increasing levels of difficulty. The first match was of low difficulty since the two animals (penguin and giraffe) were completely different in terms of colors and shape. The second one was of medium difficulty since the animals (mouse and elephant) were of the same colors but different shapes. The third one was of high difficulty since animals (horse and zebra) had the same shapes but different colors. Matches fall into two categories: congruent and incongruent stimuli. The former two were defined according to the correspondence between head and body, an animal as it is in real life (i.e., a penguin, a giraffe), whereas the latter were defined by the non-correspondence, animals matched was created combining the head of the first and the body of the second, so that did not match with the real one (i.e., penguin head and giraffe body and vice versa).

As regards the baseline phase, oral commands were given to define movements to complete the course and choose the right image (i.e. go around the mouse). The child was instructed to jump with both feet when there was a single hula hoop in the course; jump with feet apart when there were two hula hoops; turn around when a gym cone was in the course; and walking tiptoe on a line when a blue adhesive tape was arranged on the floor. Then, the child was shown the eight animals to ensure he/she was able to recognize and name them.

An example of activity for the baseline phase of the advanced level was based on a circuit lasting around 15 minutes. An example of baseline activity for the intermediate level was based on the performance of 15-meter course. The instruction was "Complete the course and turn around the gym cone with a giraffe". The child started jumping alternatively with both feet on a single hula hoop, and with feet apart on two hula hoops, then turned around a cone, walking tiptoe on a line made of blue adhesive tape, once finished the child turned around the gym cone with the sport ball chosen. If the child made the right decision he/she turned around the gym cone with a giraffe.

Data Analysis

All analyses were run with R software (R Core Team, 2021). Descriptive statistics were performed and "psych" package (Revelle, 2021). For multivariate normality check the "mvn" package was used (Korkmaz et al., 2014). SEM was performed using the "lavaan" package (Rosseel, 2012).

As a preliminary step, descriptive statistics (means, standard deviations, skewness, and kurtosis) were performed for the study variables, as EFs (Stroop accuracy, Stroop time, WM accuracy, Gift Wrap accuracy, Gift Wrap time, Snack Delay time) and AA (Reading accuracy, Reading speed, Reading comprehension accuracy) for all the kindergarteners and split by group. Values of skewness lower than 3 and of kurtosis lower than 10 were considered sufficient to verify normal univariate distribution (Kline, 2008). Then, Pearson correlation coefficients were computed for all the variables. To test the hypothesis of the current study, a priori power analysis was calculated by using the R function "sem.power.apriori" to determine the optimal sample size. As the first step, the standard error effect for the latent variables (beta) was assumed of .20, the statistical power of .80, and α of .05. Results showed N = 116. Then, by assuming a smaller standard error effect of .10, the optimal sample size was N = 143. Therefore, the sample was collected ranging between these two limits (116-143).

To test the main hypotheses, a CFA to test factor structures was performed for EFs measures and Structural Equation Modeling (SEM) to estimate the structural paths among latent factors. To check multivariate normality of items of each factor structures considered in the SEM, and the assumption of normality for EFs and AA measures was violated. Based on these results, "bestNormalize" function was used to normalize scores and the Weighted Least Squares Mean and Variance adjusted (WLSMR) method was adopted to estimate the parameters of the SEM. This method has been demonstrated to provide a consistent parameter estimation even with numeric variables and when multivariate normality assumptions are violated.

As first step, a CFA was performed, corroborating the two factors structure of EFs: EFs at T1 and EFs at T2. Robust Maximum Likelihood estimation method with robust standard error and robust fit statistics was considered for conducting the CFA. Specifically, fit statistics ($\chi 2$, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA)). Fit indices indicate good fit when RMSEA and Standardized Root Mean Square Residual (SRMR) values $\leq .08$ (preferably $\leq .05$), and CFI values $\geq .95$. The latent variable EFs at T1 was defined by six observed variables measured at pre-test: Stroop accuracy, Stroop time, WM accuracy, Gift Wrap accuracy, Gift Wrap time, Snack Delay time. The latent variable EFs at T2 was defined by the same six variables measured at post-test. Since the loadings for Stroop time, WM accuracy, and Snack Delay time, for both EFs at T1 and T2 were too low ($\lambda < .20$), these variables were removed from the final model.

To test the main aim of the current study and evaluate the effect of the PA intervention on EFs and AA in the three groups, a SEM was conducted using "lavaan" package. PA had three categories represented by groups: intervention, Free Play, and control. Before starting the analysis, two dummy variables were created using CG2 as term of comparison for the other two, since the general rule is to use one fewer dummy variables than categories. Therefore, PA was represented by two dummy variables: control vs. free play; control vs. cognitively-engaging PA. The SEM model was defined by specifying the observed variables (x) to each latent variable (y).

$$y_1 = \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n$$

In the model tested in the current study, three latent variables were specified: EFs at T1, EFs at T2, and AA. The latent variables EFs at T1 and EFs at T2 were defined as the factor loadings Gift Wrap accuracy and Gift Wrap time. The latent variable AA was defined by three observed variables related to reading abilities: Reading accuracy, Reading time, and Reading Comprehension. The model was adjusted for the confounding effects of age and sex.

The path diagram represented in Figure 8 shows the relationships between variables in the SEM model. In the SEM here presented, the relationship between PA and reading is direct, as well as the relationship between PA and EFs, or between EFs and reading. Whereas, the indirect effect is the relationship between PA and AA, where PA influences AA indirectly with the variable EFs as the mediator. Two regressions were defined: delay of gratification by PA, and T1, and AA by PA, delay of gratification at T2, controlling for T1, age, and sex. Parameter estimates are the values of the coefficients for the predictor variable (PA) in the model, these parameter estimates explain how PA affects the mediator (delay of gratification) and the outcome (reading). Standard errors are the measure of uncertainty in the estimation of coefficients, thus the lower the standard error of the coefficient of the variable the more certain the estimation of the variable is.

The model was tested using the robust WLSMR estimation method. In measuring the goodness of fit, fit indices are used (Kline 2015): CFI, a value ≥ .90 indicates a good fit, while a value ≥ .95 an excellent fit. RMSEA a value ≤ .05 is considered a good fit while a value between .05 and .08 indicates a reasonable fit. Values ≥ 1 are considered a poor fit. TLI, a value ≥ .90 above indicates a good fit, while a value ≥ .95 indicates an excellent fit. SRMR a value ≤ .08 or less is considered a good fit, while a value between .08 and .10 indicates a reasonable fit. Values ≥ .10 are considered a poor fit.

3.3. Results

Means and standard deviations for EF tasks and AA at pre and post-test are presented split by group in Table 4 and Table 5.

Preliminary ANOVAs highlighted no significant differences between groups on demographic characteristics at pre-tests, such as age [F (2, 130) = .003, p = .997; Wilk's λ = .847, η^2 = .000], sex [F (2, 130) = .486, p = .616; Wilk's λ = .847, η^2 = .008], and SES [F (3, 130) = .003, p = .517; Wilk's λ = .697, η^2 = .003].

Table 4. *Descriptive statistics for Day-Night Stroop, WM, Gift Wrap, and Snack Delay at pre and post-test for the three groups.*

Groups	Phases		Day-Night Stroop		WM	Gift Wrap	Gift Wrap	Snack Delay
			Accuracy	Reaction time	Accuracy	Accuracy	Reaction time	Reaction time
			errors	sec	Correct answer	Violations	sec	sec
CG1	T1	M	-.226	.303	11.9	.545	.197	13.9
		SD	1.07	.750	5.33	.371	.937	10.0
		skewness	-1.06	-1.16	-.211	-.930	-.402	.589
		kurtosis	2.65	1.34	-1.33	-.095	-1.41	.982
	T2	M	-.392	.385	13.3	.723	.713	10.1
		SD	.943	.849	5.41	.391	.819	6.15
		skewness	-.487	-1.38	-.446	-2.41	-1.21	.150
		kurtosis	-.208	2.66	-.668	7.24	.634	-.789
CG2	T1	M	-.206	.266	11.9	.621	.649	12.1
		SD	1.31	.586	5.19	.459	.773	8.11
		skewness	-1.71	-.447	.289	-2.41	-1.69	.071
		kurtosis	5.42	-.120	-.652	6.39	1.94	-1.22
	T2	M	-.431	.380	13.3	.770	.765	8.76
		SD	1.44	.699	5.59	.309	.770	7.78
		skewness	-3.07	-.764	-.467	-1.65	-1.85	.772
		kurtosis	13.9	-.059	-.488	1.55	2.05	-.051
IG	T1	M	.158	.234	9.72	.517	.545	11.2
		SD	1.07	.617	5.61	.622	.807	8.34
		skewness	-1.29	-.357	.252	-3.55	-1.35	.212
		kurtosis	5.34	.255	-.257	16.9	.490	-1.12
	T2	M	.390	.735	14.1	.826	.957	12.7
		SD	.928	.849	6.01	.265	.459	6.02
		skewness	4.04	-1.76	-.740	-3.54	-2.46	-.726
		kurtosis	22.5	4.01	-.027	15.1	5.11	.231

Table 5. *Descriptive statistics for Reading and Comprehension for the three groups.*

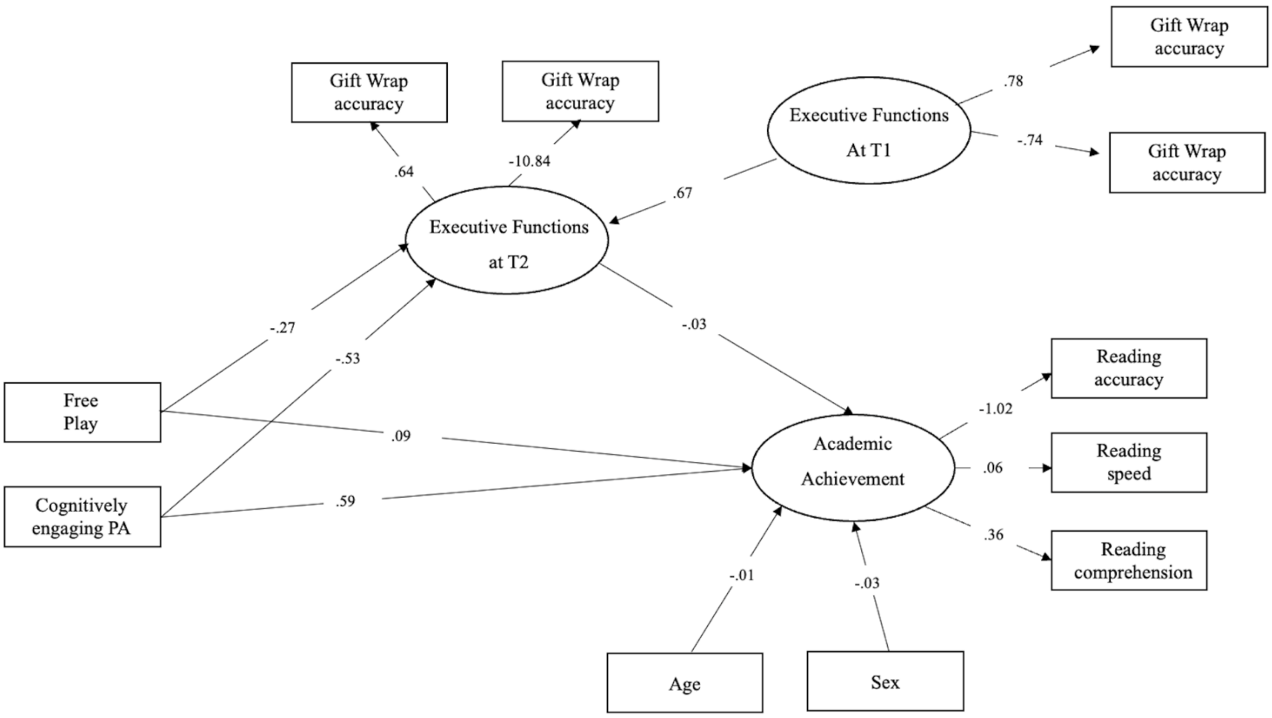
Groups		Reading		Comprehension
		Accuracy	**Speed**	**Accuracy**
		errors	sec	Correct answer
CG1	M	6.70	.940	12.1
	SD	6.12	.630	1.83
	skewness	1.17	.982	-.416
	kurtosis	.395	.525	-.636
CG2	M	6.73	.907	12.2
	SD	5.08	.575	1.44
	skewness	.909	2.31	-.495
	kurtosis	-.301	7.46	.072
IG	M	4.06	1.15	11.7
	SD	5.37	.653	1.79
	skewness	3.09	1.19	-1.46
	kurtosis	11.5	2.13	3.38

Robust fit statistics for the two-factor model are indicative of satisfactory were robust CFI = .98; robust TLI = 0.97; and RMSEA = .019 (90% confidence interval (CI): .000; .058). Latent correlations were positive and high for one of the "Hot" EF measuring delay of gratification (Gift Wrap, both for accuracy and time), showing a high degree of overlap for these constructs, both at T1 and T2.

Thus, these two latent variables were used in the SEM model. Results showed really satisfactory fit indices for the hypothesized model (χ^2 (49) = 416.345, *p* < .000; CFI = .993; TLI = .990; RMSEA = .017, RMSEA 90% C.I. [.000; .068]; SRMR = .045). Considering the structural paths (Figure 10) cognitively-engaging PA has a significant and negative direct effect on the delay of gratification (β = -.53, se = .254, *p* = .037, bootstrap 95% C.I. [-1.029, -.031]). No significant effect was found for Free Play (β = -.27, se = .297, *p* = .365, bootstrap 95% C.I. [-.852, .314]). Turning to the prediction of the AA significant positive and direct effect of the intervention was found (β = .59; se = .228, *p* = .010, bootstrap 95% C.I. [.138, 1.032]). No significant effect of Free Play was found (β= .09, se = .297, *p* = .637, bootstrap 95% C.I. [-.288, .471]). EFs showed no significant direct effect on AA (β = -.03, se = .081, *p* = .712, bootstrap 95% C.I. [-.188, .128]). Even confounding variables showed no significant effects, sex (β = -.03, se = .172, p = .844, bootstrap 95% C.I. [-.371, .303]), and age (β = -.01, se = .026, p = .854, bootstrap 95% C.I. [.047, -.005]).

No significant effect of the mediator EFs has been found in the association between Free Play and AA (β = -.008, se = .022, p = .722, bootstrap 95% C.I. [-.036, .052]). Neither in the relationship between cognitively-engaging PA and AA (β = .016, se = .042, p = .707, bootstrap 95% C.I. [-.066, .098]).

Figure 10. *Structural Relationships among Physical Activity, Executive Functions, and Academic Achievement*



3.4. Discussion

The purpose of the current study was to test the efficacy of a PA intervention program aimed at enhancing Cool and Hot EFs in kindergarteners, and in turn on AA once in primary school. In particular, the effects of two qualitatively different PA (i.e. different cognitive load levels) on kindergarteners' EFs were tested. And successively, the effect of the intervention on AA, in terms of reading, once the same children were in the first year of primary school.

The majority of studies delving into the association between PA and cognition have demonstrated a positive effect of PA on at least one aspect of EFs in children aged 6 to 12 years, it remains unclear whether a similar effect exists in kindergarteners aged 3 to 6 years. Thus, this study aimed at add empirical evidence to the fill existing gap in the literature on the research on the effects of PA on EFs during kindergartener years. The preschool period is still less investigated.

Therefore, it was firstly hypothesized a positive effect of PA on Cool and Hot EFs in kindergarteners. Two different types of PA were proposed, the first was named Free Play, referring to PA without cognitive demands; whereas the second one, PA with cognitive demands. Results were in line with previous studies showing a better performance in the intervention group compared to the control one (Giordano & Alesi, 2022; Lundy & Trawick-Smith, 2021; Xiong et al., 2018). In most of the studies with kindergarteners, PA interventions used motor games. Specifically, motor games for motor skill development (Xiong et al., 2018), coordination games of moderate intensity with little or no movement (Stein et al., 2017), and outdoor motor play sessions (Lundy & Trawick- Smith, 2021).

Recent evidence has focused on cognitive engagement, as a qualitative aspect of PA, since cognitively-engaging PA seems to be more effective in enhancing children's Cool and Hot EFs than simple PA (Best, 2010; Diamond & Ling, 2016; Pesce, 2012; Tomporowski et al., 2015). It was hypothesized that cognitively-engaging PA intervention would have a greater positive effect on EFs in kindergarteners compared to those involved in PA without cognitive demands. Higher improvements were found only for Hot EF, delay of gratification, in children involved in cognitively-engaging PA, corroborating the second hypothesis. Children involved in IG showed lower errors in Gift Wrap accuracy and were faster in Gift Wrap time. Findings were in line with previous studies displaying better EFs in the cognitively-engaging PA intervention group (Biino et al., 2021; Giordano & Alesi, 2022; Song et al., 2022). Moreover, Preston (2020) proposed two interventions, the first involved PA in combination with higher cognitive engagement, and the second one implied activities low in PA but high in cognitive engagement. Results showed that children initially exhibiting low shifting ability showed better performance after being involved in the first intervention. Interestingly, children with higher initial shifting ability benefited from both cognitively-engaging interventions.

A possible explanation was provided by neuroimaging studies showing a simultaneous activation of brain regions associated with cognition and movement that might produce synergistic effects when combining cognitive tasks with PA. In situations where the task is new, challenging, demands focus and requires quick and unpredictable responses, the co-activation of neurons is maximized. Neural network activation enhancement results in heightened neuronal functioning, which potentially leads to improvements in cognitive task performance (Bedard et al., 2021; Diamond & Lee, 2011; Diamond & Ling, 2016). It is likely that only the correct dosage of cognitive engagement, PA type, duration, and intensity improves children's cognitive abilities efficiently. To date, cognitively-engaging PA interventions have been implemented in several different ways, integrating school subjects (McPherson et al., 2018), sports (i.e. tennis lessons) (Ishihara et al., 2017), or team participation (Gallotta et al., 2020; Meijer et al., 2021), or exercise video gaming (Benzing et al., 2016; Gao et al., 2013).

To confirm the third hypothesis, findings from this longitudinal study found direct effect of PA on reading, which is consistent with previous studies showing potential benefits of PA on reading abilities in primary school children (De Bruijn et al., 2020; de Greeff et al., 2018; Ericsson & Karlsson, 2014; Oberer et al., 2018). Moreover, De Brujin and colleagues (2020) found that the impact of the intervention based on cognitively-engaging PA varied depending on the initial level of AA, with greater enhancements observed in lower achievers. Specifically, those who had lower achievement levels in reading at the pre-test exhibited notable improvements following the intervention.

Finally, it was hypothesized a mediating effect of EFs in the relationship between PA on AA. The link between Hot EF and AA is still unclear, due to the limited number of studies and their mixed findings. Since EFs are closely related to AA (Diamond, 2012), scholars investigated the effects of PA on AA as a result of improved EFs (Donnelly et al., 2016). On the one hand, some studies found no significant relationship between Hot EF and AA (Brock et al., 2009; Kim et al., 2013). Consistently with these research, results from the current study showed that delay of gratification did not mediate the association between PA and reading in primary school children. On the other hand, some earlier longitudinal studies suggested an association between delay of gratification and AA in kindergarteners (Mischel et al., 1989). Moreover, a more recent research found a predictive role of delay of gratification with more advanced reading and mathematical skills (Chen & Yeung, 2024). However, most of previous studies have predominantly centered on Cool EF, with relatively few exploring the association between Hot EF and AA (Best et al., 2009; Zelazo et al., 2005). Future studies should consider exploring a wide range of EFs, including EFs, to better understand the development of emotional aspects of EFs in preschoolers and its association with AA.

Chapter 4. The association between sport, executive functions and academic achievement in children and adolescents. A comparison between team sports, martial arts, and inactive

A version of this chapter has been published in *International Journal of Environmental Research and Public Health* (Annex B)

Giordano, G., Gómez-López, M., & Alesi, M. (2021). Sports, executive functions and academic performance: A comparison between martial arts, team sports, and sedentary children. *International Journal of Environmental Research and Public Health, 18(22),* 11745. https://doi.org/10.3390/ijerph182211745

4.1. Introduction

Sports provide beneficial effects on EFs and better AA (Becker et al., 2018; Errisuriz et al., 2018; Gu et al., 2019; Pancar, 2020). Scholars suggested that EFs' improvements via sport depend on the movement characteristics involved in the activities (Chang et al., 2017; Su-Youn et al., 2017). Based on the environmental influences on motor skills, sports can be classified as open or closed skills. Open skills sports take place in dynamic and unpredictable environments (Gu et al., 2019) (i.e. basketball, tennis, karate, soccer, and volleyball squash), and involve complex cognitive processes (i.e. perception, attention, planning, cognitive flexibility, and decision-making). Closed skills involve are performed in a predictable environment, and are self-paced (i.e. running, cycling, and swimming), and fewer cognitive demands are required (Wang et al., 2013). Scholars indicates that participation in open-skill sports can enhance cognitive functions, including perception, attention, and short-term memory, and EFs as well (Dai et al., 2013; Di Russo et al., 2010; Gu et al., 2019). Being involved in open-skill sports imply adapting to a constantly changing environment, showing better EFs compared to performing closed-skill sports (Lo et al., 2019; Wang et al., 2013; Yu et al., 2017). More than the other open-skill sports, engaging in martial arts stimulates goal-directed behaviors to effectively navigate dynamic situations and movements, requiring high cognitive engagement activating EFs components (i.e. updating and monitoring information in memory, inhibiting automatic behaviors, and switching attention resources from one task to another). Several different pathways whereby martial arts might improve cognition have been proposed: they stimulate changes in brain structure by defining an "enriched environment"; providing opportunities for social interaction; and improving self-awareness, as well as self-confidence (Zaggelidis, 2016). Children practicing karate performed better on EFs (Alesi et al., 2014). Although scholars found significant results, little is known about the influence of specific sports categories leading to mixed results. On the one hand, research emphasized team sports (Dyer et al., 2017); on the other hand, many studies supported improvements due to martial arts (Mavilidi et al., 2020; Milligan et al., 2017; Pinto-Escalona et al., 2024). To sum up, sports require different demands linked to different cognitive load (Mann et al., 2007).

The positive effects of PA on the cognitive domain are widely supported in the literature. Whereas, studied on the influence of PA on school achievement led to mixed results (Mullender-Wijnsma et al., 2015; Reed et al., 2010; Resaland et al., 2018), although no study has demonstrated detrimental effects of PA, some research suggests that PA may not always yield significant effects on certain outcomes (Puder et al., 2011). Being involved in open-skill sports was associated with better mathematic marks (Becker et al., 2018). This relationship might be due to an enhancement in spatial skills, crucial in open-skill sports, which, in turn, might be associated with mathematics task performance.

The purpose of this study was to compare Cool and Hot EF tasks performance and AA, in terms of school achievement in children (7-11 years old) and adolescents (12-15 years old) involved in martial arts, team sports, and sedentary children. Differences between groups were hypothesized.

(i) Hp_1: participants involved in sports groups would show better performance on EF tasks compared with sedentary peers;

(ii) Hp_2: participants involved in martial arts would show better performance on EFs compared with peers practicing team sports;

(iii) *Hp₃*: a better performance on EFs tasks would reflect better school marks on mathematical and linguistic school subjects;

(iv) *Hp₄*: 12-to-15-years-old group would outperform on EF tasks and AA compared to the younger group (7-to-11-years-old)

4.2. Method

Participants

A total of 102 Italian children and adolescents (56.9 % boys, M_{age} = 11.84 years, SD_{age} = 2.41) were involved in this study. Participants were split in two age groups: 43.1 % in 7-to-11-years-old group, and 56.9 % in 12-to-15-years-old group. Three sport group were defined: martial arts (40.2 %), team sports (41.2 %), both groups practicing sport three times per week at least in the 2 years prior to the research; and a control group of sedentary children (18.6 %, did not participate in any sport at least in the 2 years prior to the research). Table 6 shows number of participants for each age and sport group. Inclusion criteria were the absence of intellectual disability, visual or neurological impairment, and/or neurodevelopmental disorders; and to be able to understand and speak Italian language. The medium SES was predominant (51.7%), based on parents' education and employment parameters.

Table 6. *Number of participants for age group and sport category.*

	Martial Arts	Sedentary	Team Sports	Total
Age				
7–11	13	6	25	44
12–15	28	13	17	58
N	41	19	42	102

Procedure

A cross-sectional study design was adopted. Participants recruitment took place in public schools or gyms, based on voluntary participation in the research project. After the headmaster of each school or gym gave the approval, parents were contacted and meet to introduce the aim of the research project, guaranteeing the anonymity for participants. Parents provided written consent since participants were underage. This study was implemented following the recommendations of the Declaration of Helsinki (2013) and the Ethical Code of the Italian Association of Psychology (AIP).

Measures

Socio-demographic questionnaire

A socio-Demographic Schedule was administered to collect participants' age, education, school marks, and SES. The criteria for SES evaluation were the family size, parents' education, and job. The medium-high status was given by the parental qualification of high school or graduation and job requiring a diploma or high qualification. The medium status was defined by parental qualification or middle school and highly qualified job as a teacher, employee, shop assistant, or similar. The medium-low status was given from the parental qualification of primary school and qualified to require as housekeeper or student.

Executive functions assessment

A battery of multiple standardized tasks was used, consisting of the following tests: The Stroop test and The Distributed Attention test derived by the CD-ROM from Attenzione e Concentrazione (Di Nuovo, 2001). The Tower of London (Shallice et al., 1997); The IGT (Bechara et al., 1994) derived from the Millisecond Inquisit Software (already described in the previous study – Chapter 5), The Digit Span (described in Chapter 5) and The Verbal fluency were measured using the BVN 5–11 (Bisiacchi et al., 2005) and BVN 12–18 (Gugliotta et al., 2009).

The Stroop test assessed the ability to inhibit cognitive interference of word meaning on the ability to name the color of the words appearing on the screen (blue, black, red, and green). There were two categories of stimuli fallen into two categories: congruent trials including words in which the color word and the color print matched (i.e., the word "red" painted in red color); incongruent trials including words in which the color word and color print were different (i.e., RED printed in blue color). Scores resulted in reaction time and accuracy for congruent and incongruent trials.

The Attenzione e Concentrazione test (Di Nuovo, 2001) was used to test distributed attention through a dual-task test. Participants were instructed to push a button whenever a target appeared, simultaneously a list of words, and the child was asked to push another button when he heard the word target. Thus, attention was distributed on two parallel tasks, the visual one and the auditory one.

Two main scores were used: correct answers and errors.

The Verbal Fluency Test is a measure of the speed of access to the lexicon. It consisted of two tasks: category and phonemic fluency. Participants were asked to say as many words as possible within a specific category (i.e., animal, fruits) or starting with a given letter (i.e., S) respectively, in a minute. Scores were computed for each category and given letter, and a total score was given by summing the two scores.

School achievement

School achievement was scored using school marks in linguistic and mathematical at the end of the first term of the school year. School marks ranged from 1 to 10, where 1 is the lowest and 10 is the highest mark, indicating better school achievement.

Procedure

Tasks were administered to each participant by a researcher in a quiet room of the school/gym and required one session of 30 about minutes. Tasks were presented in a balanced order to avoid the effect of sequence.

Data Analysis

All statistical analysis were performed using SPSS software (SPSS, Version 26, NY, USA). To compare Cool and Hot EFs in children involved in martial arts, team sports, and sedentary children a Multivariate ANOVA was computed. Sport and age were used as independent variables, and Cool and Hot EFs tasks as dependent variables. The significance level was set at $p < 0.05$.

4.3. Results

Data analysis showed significant differences between the three groups for the following cognitive abilities. As concerns the age main effect, 12-to-15-year-old participants had higher scores in working memory [F (1102) = 13.137, p = 0.000, η^2_p = 0.123], inhibition [F (1102) = 6.230, p = 0.014, η^2_p = 0.062], verbal fluency [F (1102) = 19.106, p = 0.000, η^2_p = 0.169], and in auditory distributed attention [F (1102) = 3.771, p = 0.05, η^2_p = 0.039]. Moreover, significant differences were found on the IOWA test in the criterion of differences between good and bad play [$F(1102) = 10.074$, $p = 0.002$, $\eta^2_p = 0.097$]. Results are showed in Table 7.

Table 7. *Means, standard deviations, and ANOVA results for EFs tasks stratified by age.*

Executive Functions Tasks	Age 7–11 M	SD	Age 12–15 M	SD	F	*p*	η^2p
Working memory	3.81	(1.31)	5.03	(1.21)	13.137	0.000 ***	0.123
Inhibition	28.24	(8.74)	35.00	(12.28)	6.320	0.014 **	0.062
Verbal Fluency	41.81	(9.25)	51.55	(9.18)	19.106	0.000 ***	0.169
Auditory distributed attention	4.76	(1.41)	5.34	(1.61)	3.771	0.05 *	0.039
IOWA difference between good and bad play	−2.41	(6.95)	1.90	(6.56)	10.074	0.002 **	0.097

*= $p < .05$; **= $p < .01$

As concerns the sports category main effect, children who practiced martial arts performed better in working memory [$F(2102) = 3.680$, $p = 0.029$, $\eta^2_p = 0.073$], inhibition [$F(2102) = 10.891$, p = 0.000, η2p = 0.188], distributed attention [$F(2102) = 6.410$, $p = 0.002$, $\eta^2_p = 0.120$], visual distributed attention [$F(2102) = 6.921$, $p = 0.002$, $\eta^2_p = 0.128$], and auditory distributed attention [$F(2102) = 5.120$, $p = 0.008$, $\eta^2_p = 0.098$]. Regarding Hot EFs, a significant difference on IOWA test in good play [$F(2102) = 3.232$, $p = 0.04$, $\eta^2_p = 0.064$] was found. Results are showed in Table 8.

Table 8. *Means, standard deviations, and ANOVA results for EFs tasks stratified by groups*

Executive Functions Tasks	Sport category: Martial Arts M	SD	Team Sports M	SD	Sedentary M	SD	F	*p*	η^2p
Working memory	5.13	(1.41)	4.00	(1.21)	4.42	(1.26)	3.680	0.029 *	0.073
Inhibition	39.00	(14.45)	28.50	(5.00)	26.21	(6.73)	10.891	0.000 ***	0.188
Verbal Fluency	49.13	(11.73)	45.55	(8.85)	48.26	(10.30)	0.068	0.935	0.001
Distributed attention	11.08	(4.42)	8.81	(1.29)	8.32	(1.45)	6.410	0.002 **	0.120
Auditory distributed attention	5.69	(2.14)	4.83	(.58)	4.47	(1.21)	5.120	0.008 **	0.098
IOWA good play	71.89	(16.03)	79.27	(13.48)	78.83	(15.76)	3.232	0.044 *	0.064

*= $p < .05$; **= $p < .01$

No interaction effects of factors were found. School marks in linguistic and mathematics were higher in children involved in martial arts than their peers involved in team sport and sedentary children. The martial arts group outperformed in linguistic, both at the ages of 7-to-11-years-old (M = 8.56) and 12-to-15-years-old (M = 7.59). In mathematics, only 7-to-11-years-old children practicing martial arts reported higher scores (M = 8.56) compared to other groups. The means and standard deviations are summarized in Table 9, separately for martial arts, team sports, and sedentary.

Table 9. *School marks in linguistic and mathematics for the three-sport categories: martial arts, team sport, and sedentary*

		Sport Category		
School Marks	Age	Martial Arts	Team Sports	Sedentary
Linguistic	7–11	8.56 (0.73)	8.04 (1.10)	7.50 (1.38)
	12–15	7.59 (1.55)	7.12 (0.78)	7.38 (1.26)
Mathematics	7–11	8.56 (0.88)	8.04 (1.219	6.83 (1.17)
	12–15	7.48 (1.28)	7.65 (0.93)	7.15 (1.28)

*= p< .05; **= p< .01

4.4. Discussion

The purpose of this study was to compare EFs and AA performance of children and adolescents practicing sports, such as team sports and martial arts, to sedentary peers. Groups were also divided into two age subgroups: children (7-to-11-years-old) and adolescents (12-to-15-years-old). Both age groups involved in sports showed a better performance on EFs tasks compared to the group of sedentary peers, corroborating the first hypothesis. The results are coherent with the previous studies (Dai et al., 2013; Di Russo et al., 2010; Gu et al., 2019).

Specifically, participants who practiced martial arts displayed a better performance on all EFs tasks, confirming the second hypothesis. Results showed higher performance in inhibition, WM distributed attention, verbal and auditory, verbal fluency tasks, and decision-making. A possible explanation might be related to the principle of discipline and control distinctive of martial arts, which are strongly tied to self-regulatory skills, in particular to inhibition (Nanay, 2010). Moreover, martial arts might affect cognition by stimulating changes in the brain networks. It offers an enriched environment characterized by social interaction, giving the opportunity to enhance self-confidence and self-awareness (Zaggelidis, 2016). Open-skills sports, and in particular martial arts, occur in dynamic and unpredictable environments, requiring changing movement to adapt to the new situations (Gu et al., 2019), stimulating those cognitive goal-directed skills.

Moreover, children involved in extra-school sports, in particular those practicing martial arts displayed significantly higher AA, measured considering school marks in linguistic and mathematic areas, supporting the third hypothesis. Results are consistent with previous research supporting the positive effects of PA on EFs and, in turn, on AA (Egger et al., 2019; Mavilidi et al., 2020; Pinto-Escalona et al., 2024; Singh et al., 2019). Findings from this study displayed that the group of adolescents performed better in both Cool and Hot EF tests. They showed higher scores in WM, inhibition, verbal fluency, distributed attention, and decision-making tasks, corroborating the fourth hypothesis. This is coherent with developmental trajectories showing a gradual linear maturation of EFs (Best, 2010). The development of EFs is tied to the structural and functional growth of the DL-PFC, which becomes more specialized during adolescence due to the synaptic pruning, resulting in the optimal connection between brain areas (England-Mason & Dewey, 2023).

Chapter 5. Investigating the effects of epigenetic regulatory polymorphisms BDNF and COMT on Executive Functions in adolescence

A version of this chapter has been published in *Life Span and Disability* (Annex C)

Alesi, M., Giordano, G., Sacco, A., & Proia, P. (2023). Effects of BDNF and COMT epigenetic regulatory polymorphisms on Executive Functions in adolescents. *Life Span and Disability, 26(1)*, 7-27. doi: 10.57643/lsadj.2023.26.1_01

5.1. Introduction

EFs begin to emerge during infancy, undergo significant changes during the preschool years, and continue to develop throughout adolescence in correspondence with the maturation of the PFC (Zelazo et al., 2008). In adolescence, brain maturation involves the structural development of neural regions like the PFC and dopaminergic circuits, associated with Cool and Hot EFs (Prencipe et al., 2011). Therefore, the focus was on genes implicated in regulating dopaminergic function and neuronal growth factors, such as BDNF, along with genes involved in neurotransmitter metabolism critical for cognitive function, like COMT (Khanthiyong et al., 2019). Regarding the BDNF genotype, it was found that individuals characterized as Val (G) homozygotes exhibited a moderation effect on the relationship between cognitive reserves and EFs (Ward et al., 2015), whilst BDNF Met (A) alleles were found to be linked to decreased memory abilities (Egan et al., 2003). Regarding COMT, the results are still mixed. On the one hand, scholars highlighted higher cognitive performance in the Val (H) allele rather than in individuals with the Met (L) allele. On the other hand, studies showed a strong correlation between the Met allele and improvement in cognition (Moriguchi & Shinohara, 2018; Bowers et al., 2020). Moreover, empirical evidence showed differences between children and adults. Scholars found higher performances in adolescents with the Val/Met genotype, and adults with the Met/Met genotype (Wahlstrom et al., 2007). BDNF affects the dopaminergic system and this has drawn attention to a potential association with COMT. The presence of the Val variant of COMT and the Met variant of BDNF appears to be associated with a decline in EFs (Chen et al., 2016).

The purpose of this study was to compare Cool and Hot EFs among adolescents with different combinations of BDNF and COMT genes. To date, the Val/Val for COMT and the Met/Met for BDNF determine a reduction of EFs, therefore COMT (Met) and BDNF (Val) might determine an increase in EFs performance.

(i) Hp_1: Participants with the Val/Val (G/G) homozygous for BDNF and the Met/Met (H/H) homozygous for COMT would show a better performance on Cool EFs tasks compared to peers with the Met/Met (A/A) for BDNF and the Val/Val (L/L) for COMT;

(ii) Hp_2. Participants with the Val/Val (G/G) allele for BDNF and the Met/Met (H/H) allele for COMT would perform better on tasks measuring Hot EFs compared to peers with the Met/Met (A/A) for BDNF and the Val/Val (L/L) for COMT.

5.1. Methods

Participants

A total of 128 Italian preadolescents and adolescents (69 boys, 59 girls; M_{age} = 12.9 years, SD_{age} = 2.92) were involved in the study. 48 completed all research phases, including the salivary sampling. Thus, the final sample was composed of 48 participants (70.8% boys, M_{age} = 12.5 years, SD_{age} = 2.07) and split into three subgroups for BDNF (8 = Val/Val, 35 = Val/Met, 5 = Met/Met) and in three subgroups for COMT (16 = Val/Val, 23 = Val/Met, 9 = Met/Met). Inclusion criteria were the absence of intellectual disability, visual or neurological impairment, absence of neurodevelopmental disorder, and being Caucasian. A medium SES was predominant.

Procedure

A cross-sectional design was employed. Participants were recruited in their schools or gyms. Parents' participants were contacted through flyers announcing the aim of the research project. Since participants were underage, parents were asked to provide written consent, and confidentiality and anonymity were guaranteed. This study was implemented following the recommendations of the

Declaration of Helsinki and the Ethical Code of the Italian Association of Psychology (AIP). EFs tasks were administered individually in a quiet room of the school/gym in a single session of about 30/40 minutes. Tasks were presented in a balanced order to avoid the effect of sequence. Moreover, for each participant, a saliva sample was taken by passive drool. The samples were collected in a sterile 15-mL centrifuge tube and stored at −80 °C until assay. Genomic DNA was isolated from 1 ml of the whole saliva using a PureLink kit (PureLink Genomic DNA ThermoFisher Scientific) according to the manufacturer's protocol. The genotyping was carried out by polymerase chain reaction (PCR) in a total reaction volume of 50 µl containing 50 ng of template, 1 µl of 10 mM deoxynucleoside triphosphate (dNTPs), 1 µl of 30 pmol each primer, and 5 µl of 10X reaction buffer with MgCl2. The target sequence was amplified using a 5U/µl Dream Taq (Thermo Fisher Scientific) and the primers were the following: P1 (forward) 5' CCTACAGTTCCACCAGGTGAGAAGAGTG-3'; P2 (reverse) 5' TCATGGACATGTTTGCAGCATCTAGGTA 3'; P3 (G allele specific-reverse) 5' CTGGTCCTCATCCAACAGCTCTTCTATaAC 3'; P4 (A allele specific-forward) 5' ATCATTGGCTGACACTTTCGAACcCA 3' used to determine the BDNF genotype and 5' GGAGCTGGGGGCCTACTGTG 3' (forward) and 5' 59- GGCCCTTTTTCCAGGTCTGACA 3' (reverse) used to determine the COMT genotype. PCR amplification was performed with the following protocol: denaturation at 94°C for 5 minutes, followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 62,5°C for 60 seconds for BDNF and at 60°C for 60 seconds for COMT, extension at 72°C for 60 seconds and final extension at 72°C for 7 minutes. The fragments were separated on 8% vertical polyacrylamide gel at 100 V for one hour and visualized with .5 mg/ml of ethidium bromide.

Measures

A Socio-Demographic Schedule was administered to collect information about age, education, school grades, and SES. The criteria for SES were parents' number of children, parents' education, and employment. A medium-high SES was attributed to the presence of parental qualification at high school or graduation and a job requiring a diploma or a higher qualification.

Medium SES status was given if parental qualification was middle school and a high-qualified job, such as a shop assistant or similar. Medium-low status was attributed if the parental qualification was primary school, and the job was qualified as a housekeeper or student.

Executive Functions assessment

Executive Functions were measured by administering standardized tasks. Four neuropsychological tests were selected from the Inquisit Millisecond Software2: The Digit Span Test (Gugliotta et al., 2009), The Tower of London (Shallice, 1982), The Balloon Analogue Risk Task – BART (Lejuez et al., 2002) and the Iowa Gambling Task – IGT (Bechara et al., 1994).

The Digit Span Test is a test of memory and WM. It is composed of two subtests: Forward and Backward Digit Span. In the former, participants were instructed to repeat a sequence of digits in the same order. It consists of 27 sequences ranging from two to nine digits. In the latter, participants were instructed to repeat the digits in reverse order. The Backward Digit Span consists of 24 sequences ranging from two to eight digits. The experimenter verbally presented each sequence at the rate of a digit per second, after which participants were asked to repeat the digits immediately. Two trials were administered for each sequence length. A correct answer on one of the two trials led the task to proceed to the next sequence with the number of digits increasing by one. The test ended when participants failed on two consecutive trials of the same length. Scores were computed by summing the total number of digits successfully remembered in both tasks. Forward Digit Span and Backward Digit Span were analyzed as separate variables (Lezak, 1995) since the first is a task more related to memory, and the second one is linked to WM.

The Tower of London (ToL) (Shallice et al., 1997) is a measure of visuospatial problem-solving requiring planning strategy. Participants were shown on the laptop screen a wooden set with three pegs and three balls (blue, red, and green). Participants were asked to move the balls to reach the right configuration (with two or one ball, respectively) in each peg, by using a predetermined set of moves and following specific rules, such as only one ball can be moved at a time, it is not allowed to place balls outside the set. ToL is composed of 12 trials with an increasing level of difficulty. Three indices were given. A total score is given by summing each trial score (maximum score = 48); planning time in seconds by summing the time spent between the instruction and the first move for each trial; and execution time in seconds resulting from the difference between the sum of the total time spent on each item and the planning time.

The BART (Lejuez et al., 2002) is a measure of risk decision-making. Participants were shown a small balloon with a balloon pump on the laptop screen, they were offered the opportunity to earn money for each balloon pump up by pressing a button. As the size of the balloon grew, also the monetary reward increased, as well as the associated risk of explosion. For each pump on the balloon, 5 cents were collected on a counter. A "pop" sound effect was emitted from the computer when the balloon exploded. As a consequence, the money gained was lost, and the new uninflated balloon appeared on the laptop screen. At any time during the test, the participant was allowed to stop pumping the balloon and collect money. BART was composed of a total of 90 trials. Two scores were derived: total balloons exploded and total balloons not exploded.

The IGT (Bechara et al., 1994) is a computerized card game used to assess decision-making, by simulating real-life situations with rewards and punishments. It is composed of four card decks: A, B, C, and D. The A and B decks are "disadvantageous", short-term, and risky card desks. Each participant was asked to choose a card and s/he immediately gained money, but the choice was followed by a high penalty. The C and D are "advantageous", long-term, and safe card decks. The participant's choice, in this case, was followed by a smaller gain and a lower penalty. The task consisted of 100 trials (1 trial = 1 card drawn, 20 trials = 1 block), which were blind to each participant. Long-term decision-making is reflected in the IGT score which is calculated as the number of cards selected from the advantageous, safe decks minus those selected from the disadvantageous, risky decks. The net score of the first 40 trials reflects decision-making in the uncertainty phase because the choice outcomes are relatively unknown in the initial trials; the net score of the last 40 trials reflects decision-making in the risk phase because the choice outcomes are known in the later trials (Brand et al., 2007). A high net score is given by selecting fewer cards from the disadvantageous but immediate reward decks (A and B) and drawing more cards from the advantageous reward decks (C and D). Two singles scores were obtained: “good play”, given by the choice from advantageous, good, decks outweighing those from disadvantageous, bad decks; “bad play” given by the choice from risky, bad decks exceeding those from safe, good decks. Influence of genotypes on both Cool and Hot Executive Functions.

Data analysis

Statistical analyses were performed by using The SPSS software (SPSS, Version 26, NY, USA). As preliminary step, normality was tested and since the assumption was not satisfied, Kruskal-Wallis ANOVA and Spearman rho were used. To examine the possible differences in mean rankings between the rankings obtained in the three groups (Val/Val, Val/Met, Met/Met) for BDNF and the three groups (Val/Val, Val/Met, Met/Met) for COMT, a non-parametric ANOVA was used to compare the outcome of EFs in the three groups. The independent variables were the polymorphisms (BDNF and COMT), while the dependent variables were the scores on Hot and Cool EF tasks. Significance level was set at $p < .05$.

5.2. Results

A significant correlation was found between Cool and Hot EFs. More specifically, between the planning measured by the ToL execution, and the IGT good play (r = -.286). Table 10 shown correlation matrix.

Table 10. *Correlation between Cool and Hot EFs tests for BDNF and COMT*

Variables	M (SD)	1	2	3	4	5	6	7	8	9	10
Forward WM	4.71 (1.74)	-									
Backward WM	4.25 (1.74)	.606**	-								
WM tot	9.27 (3.23)	.761**	.897**	-							
ToL	8.73 (2.87)	.049	.112	.090	-						
ToL plan	33.7 (38.4)	.093	.013	.036	.053	-					
ToL exec	120 (75.5)	.247	.249*	.353*	.180	.746**	-				

BART exploded	6.90 (3.57)	.042	.216	.119	.101	-.169	-.105	-			
BART not exploded	23.1 (5.73)	-.042	-.216	-.119	-.101	.169	.105	NA	-		
IOWA good play	73.8 (17.0)	-.101	-.166	-.103	-.070	-.286*	-.213	.135	-.135	-	
IOWA bad play	74.9 (14.2)	-.184	-.227	-.190	.010	-.005	-.092	.171	-.171	.838**	-

Significant mean rank differences were found for the three BDNF groups for both Cool and Hot EFs. Significant differences in Forward Digit Span ($p = .01$), as measure of Cool EF. Moreover, significant differences were found for Hot EFs. Both exploded and not exploded balloon scores of the BART task were significant ($p = .001$). Results are shown in Table 11.

Table 11. *Mean ranks of the three subsamples of BDNF and COMT for the Digit Span Test, the Tower of London, the Balloon Analogue Risk Task and the Iowa Gambling Task*

	BDNF					COMT				
	Met/Val (n=35)	Val/Val (n=8)	Met/Met (n=5)	*p*	Post hoc	Met/Val (n=23)	Val/Val (n=16)	Met/Met (n=9)	*p*	Post hoc
Forward WM	21.16	37.00	27.90	.003**	1,2	23.61	24.34	27.06	.81	
Backward WM	25.97	16.13	27.60	.15		21.61	27.34	26.83	.36	
WM tot	23.93	25.50	26.90	.88		21.46	27.84	26.33	.33	
ToL	24.90	23.63	23.10	.94		27.17	20.72	24.39	.36	
ToL plan	23.14	28.38	27.80	.54		23.57	27.25	22.00	.60	
ToL exec	24.14	24.56	26.90	.92		22.11	27.66	25.00	.47	
BART exploded	29.00	10.81	14.90	.03*	1,2	19.63	28.13	30.50	.06	
BART not exploded	20.00	38.19	34.10	.004**	1,2	29.37	20.88	18.50	.06	
IOWA good play	25.07	24.81	20.00	.75		19.24	30.22	27.78	.04*	1,3
IOWA bad play	25.51	25.06	16.50	.40		20.46	29.19	26.50	.14	
IOWA pn	22.09	27.00	32.20	.24		22.09	25.73	26.00	.64	

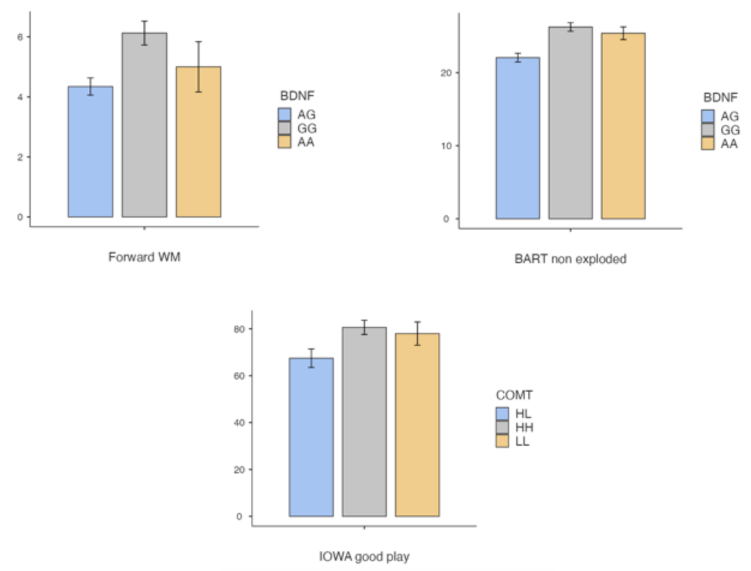
Note. WM = working memory; WM tot = sum of Forward and Backward working memory; ToL= Tower of London test; ToL plan = time spent planning on the Tower of London (seconds) ; ToL exec = time spent in execution on Tower of London (seconds); BART exploded = number of exploded balloon on Balloon Analogue Risk Task; BART not exploded = number of not exploded balloon on Balloon Analogue Risk Task; IOWA good play = score given by the sum of the choices from advantageous decks; IOWA bad play = score given by the sum of the choices from disadvantageous decks. *p<.05. **p < .01. ***p < .001.

The Bonferroni post-hoc test showed significant differences between the Met/Val and Val/Val groups of BDNF on the Forward Memory Task ($p = .003$) and on the BART test, both the exploded balloon ($p = .03$) and not exploded balloon scores ($p = .004$). The Val/Val groups showed better memory performance, and higher performance on the BART test (i.e. lower number of exploded balloons, and higher number of not exploded balloons).

The COMT group displayed significant differences only on Hot EFs. More specifically, significant between-subject differences were found for the IGT "good play" measure (p = .04).

The post hoc showed significant differences between the Val/Met and Val/Val groups on the IGT "good play" (p = .02), the Val/Val group showed a better performance. Bonferroni adjustment to the p-value was used. Differences between BDNF and COMT are shown in Figure 11.

Figure 11. *Significant differences among the subsamples for BDNF and COMT*



5.3. Discussion

This aim of the current study was to delve into the effects of COMT and BDNF polymorphisms on Hot and Cool EFs in adolescents. As regard BDNF, findings highlighted that the Val/Val (G/G) homozygosity showed a better performance on memory abilities measured by Forward Digit Span than peers with the Met/Val (A/G) and the Met/Met (A/A), confirming the first hypothesis. Consistently with previous studies highlighting the association between the Met-BDNF allele and the decreased hippocampal function, arising with a worse performance on episodic memory (Egan et al., 2003; Galloway et al., 2008; Hariri et al., 2003). Although the Backward Digit Span task is considered as a better EF index since it measures WM, the Forward Digit Span task represent a reliable measure of short-term memory and it was used as a warm-up task of memory abilities. However, other studies did not support WM impairments in Met BDNF allele (Egan et al., 2003; Hansell et al., 2007).

Regarding Hot EFs, significant differences were observed in risk decision-making tasks, specifically the BART. Participants with the Val/Val (G/G) genotype exhibited better risk decision-making abilities. This suggests that they displayed more cautious behavior, potentially indicating greater inhibitory control. This positive correlation between the Val allele and cognitive abilities is consistent with prior research (Sheldrick et al., 2008; Kang et al., 2013; Jasińska et al., 2016).

Regarding COMT, a noteworthy finding emerged from the IGT, where participants homozygous for the Val/Val (L/L) genotype exhibited better performance in the measure of "good play". This result deviated from the first hypothesis. A plausible explanation for this outcome relates to the nature of the IGT. This test evaluates the ability to learn to forgo immediate rewards in favor of long-term gains (Brand et al., 2007). However, some studies have demonstrated that the Met polymorphism was associated with a lack of improvement in IGT scores. The reason might be that improvement in this task necessitates gradual learning from accumulated experience regarding the outcomes of choices (Wahlstrom et al., 2007). Moreover, age differences among participants may contribute to disparities between our findings and those of previous studies. Most existing research on COMT and decision-making has focused on adult samples. Performance on the IGT has been shown to vary significantly with age, with adults demonstrating a greater propensity to avoid risky play and favor long-term gains compared to preadolescents and adolescents. Therefore, age-related developmental differences may influence performance on decision-making tasks like the IGT. Scholars have shown that the inclination to steer clear of risky choices, such as drawing cards from the most disadvantageous decks, increases steadily with age in a linear fashion. Adults typically exhibit a greater tendency to avoid disadvantageous options and prioritize long-term gains, showing a propensity to delay immediate gratification more than preadolescents and adolescents (Cauffman et al., 2010). The lack of consistency between the results obtained on the BART and IGT tests could potentially be attributed to differences in their nature, as they assess different aspects of decision-making ability (Balagueró et al., 2016). The IGT is considered more challenging as it necessitates complex verbal comprehension and intact functioning of various executive functions, including memory and attention, to understand the reward and punishment structure. On the other hand, the BART test is a simpler computerized task that involves making decisions to maximize earnings without adhering to a predetermined strategy.

Chapter 6. The association between executive functions and motor abilities in Italian and Japanese kindergarteners: a cross-cultural investigation

6.1. Introduction

Theoretical and empirical literature in developmental psychology emphasizes the importance of the interaction between biological and environmental factors on cognition. Cultural neuroscience represents an empirical approach to demonstrating bidirectional interactions between biological and environmental factors, with particular attention paid to culture. Culture is a set of values and conduct of behaviors, including traditions, customs, institutions, living styles, and educational practices to which children are exposed to, and getting involved in these cultural practices stimulates changes in neural activities (Han et al., 2013; Kitayama & Uskul, 2011; Kitayama & Salvador, 2017). Culture is generally divided into two main categories: collectivistic culture (Eastern or Asian) versus individualistic culture (Western, European, or American) (Fatima & Sharif, 2019). In Eastern culture, people are expected to adjust behaviors in social situations and engage in an indirect communication style to maintain group harmony (Gudykunst & Matsumoto, 1996; Markus & Kitayama, 1991; Triandis, 1994). In contrast, Western culture is characterized by a direct and explicit communication style (Gudykunst & Matsumoto, 1996). Culture starts influencing children's cognition from the day they are born (Tomasello et al., 2005). Therefore, cultural differences might begin to emerge at early stage of childhood (Kuwabara et al., 2011). Nevertheless, scholars have predominantly focused on examining cultural differences during early and late adulthood (Kitayama & Park, 2010).

In recent decades, a noticeable upsurge in attention dedicated to unraveling the intricate trajectories of cognitive and motor development has been documented in young children (Maurer & Roebers, 2019; Kubicek et al., 2017; van der Fels et al., 2019), adolescents (Rigoli et al., 2012), and adults (Ratey & Loehr, 2011). The interplay between cognitive and motor abilities shapes children's early developmental trajectory, where every thought and movement converge to form the child's interactions with the environment and pave the path for their holistic growth (Houwen et al., 2017;

Maurer & Roebers, 2019). According to the embodied cognition perspective, cognition occurs in the context of the individual's bodily interaction with both physical and social environment (Oudgenoeg-Paz et al., 2012; Smith & Gasser, 2005).

Behavioral and psychological processes across Western and Eastern cultures have been investigated. However, research on cultural differences in motor and cognitive abilities is in its initial stage (Fatima & Sharif, 2019). To date, studies investigated culture as an indicator of a causal role of fine motor skills with the EFs (Chow et al., 2001; Huntsinger et al., 2011). Empirical cross-cultural evidence suggested that children who have experienced superior motor skills during early childhood showed higher cognitive abilities. It has been found that Asian children showed higher fine motor skills due to socio-cultural influences compared to European one. In particular, the early use of chopsticks in addition to parent behaviors, such as incorporating motor activities into their children's daily routines (i.e. buttoning up, tying shoelaces, using utensils during meals, building blocks, puzzles, arts and crafts, threading beads, using scissors, playing with small manipulative toys) seem to benefit fine motor skills (Chow et al., 2001; Huntsinger et al., 2011). Fine motor skills support children to succeed in many daily routines, therefore they appear to be strongly related to cognitive abilities (Davis et al., 2011b). Indeed, cross-cultural studies underlined that preschoolers from East Asian countries outperform their Western counterparts on measures of EFs, especially tests of inhibitory control (Sabbagh et al., 2006; Oh & Lewis, 2008; Lan et al., 2011).

The main aim of this study was to investigate the association of motor skills with cognitive abilities in Italian and Japanese kindergarteners. Specifically, the study aimed at testing the association of gross and fine motor abilities with Cool and Hot EFs. Two specific hypotheses are proposed:

(i) Hp_1: group differences in EFs and motor abilities;

(ii) Hp_2: fine motor abilities would have more positive association with Cool and Hot EFs than gross motor abilities.

6.2. Method

Participants

A total of 98 participants were children attending the last year of kindergarten during the time of data collection. Children aged 5 to 6 years old were included in the study. Preschoolers with neuropsychological disorders and multilinguals were excluded from the study. Forty-nine Italian children participated in the study (25 boys, and 24 girls; M_{age} = 68.4 months; SD_{age} = 3.08 months; age range = 61-74 months) recruited from nine classes of two kindergartens. Schools were located in rural small town in Sicily. Forty-nine Japanese preschoolers took part in the study (18 boys, 31 girls; M_{age} = 68.5 months; SD_{age} = 3.26 months; age range = 61-74 months) from three classes in a single kindergarten. This school was located in the suburbs of a city in Japan.

Procedure

A cross-sectional study design was implemented to compare Italian and Japanese kindergarteners. Preschool principals from Italy and Japan were contacted to recruit participants for the present study. After preschool directors provided consent, an information sheet, and consent paper were sent to parents of preschoolers to request for their children's participation in the present study. When parents returned the signed consent paper to preschools, a battery of tests to assess EFs, and motor abilities were administered to the children by trained research assistants. Tests were administered individually in a separate quiet room in their respective preschools. The test sessions lasted about 40-50 minutes for each child. The present research was approved by the Bukkyo University Human Research Ethics Review Committee (No. 2022-4-B) and by the Bioethics Committee of the University of Palermo (No. 62/2021).

Measures

Executive Functions assessment

The same tests as the longitudinal study (Chapter 3) were used to measure both Cool and Hot EFs: Day-Night Stroop test (Gerstadt et al., 1994), Gift Wrap (Kochanska et al., 2000), Snack Delay (Ebbesen, 1970) from the adapted version FE-PS 2–6 (Batteria per la valutazione delle Funzioni

Esecutive in età Prescolare - Usai et al., 2017).

Only the test Battery of WM (Batteria per la memoria di lavoro (Lanfranchi, Cornoldi, 2004) was adapted for the Japanese sample by choosing words that meet test requirements. In the verbal high cognitive control task participants were presented orally with a list of two to five disyllabic words. The original version was modified and adapted for the Japanese sample by choosing words that meet test requirements. Firstly, words from the English version were translated to Japanese (i.e. cat/neko, mum/mama, flower/hana), and only a few words were substituted since in Japanese were not disyllabic. For example, the Japanese translation of the word "fish" was "sakana", since it was a trisyllabic word it was changed to the word "bird" which in Japanese is "tori"). Children were asked to remember the first word on the list and to tap on the table when they heard the target word (ball/bohl). The word "ball/bohl" was present in each trial. In this task, tapping served as a secondary task. A score of 1 was awarded for every trial completed correctly (i.e. when the child remembered the first word of the list and tapped the table). In all other cases, they scored 0. The spatial-simultaneous high cognitive task children and the spatial-sequential high cognitive control children were the same as in the longitudinal study. For every trial completed correctly, a score of 1. In every other case, a score of 0 was given.

Motor abilities assessment

The Movement ABC-2 (Henderson et al., 2010) was used to assess both fine and gross motor skills. It consists of three main sections: Manual Dexterity, Aiming and Catching, and Balance. The first assesses fine motor abilities, whereas the other two assess gross motor abilities.

The manual dexterity section is composed of three tasks: Posting Coin, Cubes, and Drawing Trail. In the Posting Coins task, the child was asked to pick up 12 plastic coins and insert them into a box, one at a time, as fast as possible. This task was done twice with the dominant hand, and twice with the other hand. The total time of the two trials was recorded. The faster of the two trials for both hands was used as the dependent variable. In the Cubes task, the child was asked to thread 12 cubes on a lace as fast as possible. This task was performed twice. The total time of the two trials was recorded, and the faster one was used in the analysis. In the Drawing Trail task, the child was asked to draw a single continuous line in a path between two lines, without crossing the boundaries. This task was performed twice with the dominant hand. The number of errors, in terms of times in which the child's drawing crossed the lines' boundaries, was used in the statistical analysis.

The Aiming and Catching section encompasses two tasks. Six mats were arranged on the floor one next to the other to create a path made with blue and yellow mats. In the first task, the child was standing on the last mat while the researcher was standing in the first mat with a red circle inside, the child was asked to catch a small bag with beans inside five times as training and ten for the test. The second task was almost the same without the researcher, the child was asked to aim and throw the same bag on the mat with a red circle inside trying to reach the center. For both tasks, numbers of correct catching and aiming were recorded and used as dependent variables.

The balance section is composed of three tasks. The first task was One-Leg-Stand, in which the child was asked to balance on one foot without touching the floor for a maximum of 30 seconds. This task was performed alternatively twice with the dominant leg, and twice with the other leg. The total time of the two performances was recorded. The longest of the two for both legs was used in the analysis. The second task was Jump, the child was asked to jump with both feet in five thin mats laid down on the floor, with a maximum of 5 jumps. The third task was Walk, the child was asked to walk at the same length as the previous task with a maximum of 15 steps. For both tasks, the total number of jumps and steps was used in the analysis.

Since the Japanese version of Movement ABC was not available, the English one was used, and due to the standardization on a different population raw scores were used for each subtest of the three main sections (Manual Dexterity, Aiming and Catching, and Balance): Posting Coin, Cubes, Drawing Trail, Aim, Catching, One-Leg-Stand, Jump, and Walk. For each subtest a performance score was recorded in terms of the correct number of movements, and time to complete the task. Higher scores indicate better motor performance. Henderson and colleagues (2010) provide significant psychometric properties for the Movement ABC-2. They found a .80 reliability coefficient for the total test score, and for the individual component scores coefficients ranging from .73 to .84.

Data analysis

Descriptive statistics (means, standard deviations or percentages, skewness, and kurtosis) were calculated for all studied variables for Italian and Japanese kindergarteners. Preliminary independent sample t-tests were run to test group differences for age and sex. Then, a Multivariate analysis of variance (MANOVA) was applied to analyze differences in EFs and motor abilities in both groups. All the dependent measures were not standardized since the Japanese version of the tasks used was not available, hence raw scores were used for all the measures for both Italian and Japanese participants. To investigate the effects of motor abilities (gross and fine) on Cool (i.e. inhibition and WM) and Hot (i.e. impulse control and delay of gratification) in Italian and Japanese kindergarteners a series of linear regressions were run.

The Statistical Package for the Social Sciences (SPSS, Version 26, NY, USA) was used to perform the statistical analyses. Statistical significance was set at $p < .05$.

6.3. Results

Demographic information for sex and age split for Italian and Japanese are presented split by group in Table 12.

Table 12. *Demographic information for sex and age split by group*

		ITALY	JAPAN
SEX	M	25	18
	F	24	31
AGE	MONTHS	68.4 (3.08)	68.5 (3.26)
	RANGE	61-74 months	61-74 months

Independent sample t-tests depicted no significant differences between the two samples on kindergarteners' age measured in months [(M_{Italy}= 68.4, SD_{Italy}= 3.10; M_{Japan}= 68.5, SD_{Japan}= 3.26); t (2, 96) = -.159, p= .87], and sex [t (2, 96) = -1.22, p = .23]. MANOVA displayed significant groups differences on EFs [F (6, 91) = 2.74, p = .017; Wilk's λ = .847, η^2 = .256], and motor abilities [F (9, 88) = 6.278, p < .000; Wilk's λ = .609, η^2 = .391]. Differences are shown in Table 13.

Table 13. *Means, standard deviations and ANOVAs of executive functions and motor abilities for Italian and Japanese kindergarteners*

	Italy	Japan		
	M (SD)	*M (SD)*	*F*	*p*
Executive Functions Tests				
Stroop accuracy	1.35 (2.63)	2.27 (3.81)	1.924	.17
Stroop time	37.7 (19.0)	31.50 (7.13)	4.688	.03
Working memory	13.9 (5.25)	13.9 (5.45)	.001	.97
Gift wrap accuracy	.53 (1.06)	.51 (1.45)	.006	.93
Gift wrap time	51.6 (15.8)	51.3 (17.2)	.012	.91
Snack Delay time	180 (81.7)	224 (51.4)	10.118	.002
Motor abilities Tests				
Coin	23.0 (3.87)	18.7 (2.74)	41.11	<.001
Cubes	60.8 (20.2)	44.1 (9.23)	27.73	<.001
Trail	.26 (.78)	.59 (1.06)	3.01	.08
Catch	7.57 (2.49)	6.84 (2.51)	2.11	.14
Balance dx	18.6 (9.54)	23.0 (19.0)	1.14	.28
Balance sx	18.6 (9.54)	23.0 (19.0)	1.14	.28
Walk	15.0 (.00)	15.0 (.00)		
Jump	5.00 (.00)	4.90 (.71)		

Preliminary analysis revealed no variance for Walk and Jump subtests due to the ceiling effect. Thus, these two variables were omitted in the regression analysis. Results from the linear regressions displayed that Coin was significant in determining Hot inhibition in Italian children (β = 1.107, *p* =.046), but not in Japanese peers. Cubes significantly predicted inhibition in the Italian group (β=.318, *p* = .036), and WM in the Japanese one (β=-.417). Trail predicted positively inhibition (β=.398, *p* = .006) and negatively WM (β = -.305, *p* = .033) in Japanese kindergarteners but not in the Italian group. Catch and Balance right leg positively affect WM (β = .401, *p* = .004) and (β = .378, *p* = .036) respectively in Japanese children. Balance left leg negatively predict inhibition measured by Stroop time (β=-.490, *p* < .001).

6.4. Discussion

The purpose of this study was delved into the effects of gross and fine motor abilities on Cool and Hot EFs in Italian and Japanese kindergarteners. Since cultural differences might begin to emerge at early stage of childhood (Kuwabara et al., 2011), groups differences have been hypothesized. Findings revealed significant difference both in cognitive and motor skills between the two groups.

As regards EFs, Japanese kindergarteners outperformed their Italian counterpart in both Cool and Hot inhibition. In line with a recent systematic review (Schirmbeck et al., 2020) investigating cross-cultural similarities and differences in EFs, Japanese children displayed higher performance on inhibition measures. No significant differences were found for WM, this results is in a previous study comparing Japanese and American children (Imada et al., 2013). Moreover, Italian and Japanese kindergarteners' performance did not differ in the Gift Delay task, due to the ceiling effect since both groups showed the highest scores in both accuracy and time scores. Several reasons might explain why Eastern children tend to exhibit higher EFs than Western peers. Cross-cultural psychological research has highlighted a difference in cognitive styles between Western and Eastern cultures. Nisbett and colleagues (2004) characterized Western cognitive style as analytic, while Eastern cognitive style was described as holistic. Essentially, this means that European children tend to employ more analytical cognitive strategies and rule-based categorization, whereas Asian children typically allocate more holistic attentional resources to solve tasks (Kelkar et al., 2013). Differences in inhibition might be addressed to the role of educational systems that might focus on the importance of self-regulation in children (Tobin et al., 1989). On the one hand, teachers from collectivist cultures tend to provide significantly more proactive task-related instructions compared to teachers from individualistic cultures (Lan et al., 2011). Indeed, this difference in teaching style offers more frequent opportunities for young Eastern children to practice self-regulatory skills (Sabbagh et al., 2006). On the other hand, parenting practices contribute to the observed differences between Eastern and Western children. In Eastern cultures, parents often prioritize obedience and respect for authority, which can foster the development of inhibitory control. Conversely, Western parents may prioritize open communication and autonomy, potentially influencing the development of cognitive flexibility (Sabbagh et al., 2006).

Regarding motor abilities, Japanese kindergarteners outperform their Italian counterparts in fine motor abilities. Tasks such as inserting coins into a box or cubes into a lace demand precise hand movements, requiring accurate visual perception and attention. Indeed, the use of chopsticks is common from a young age, thus Japanese tend to demonstrate earlier development of fine motor skills (Adolph et al., 2007).

In addition, results showed an association between motor abilities and EFs, corroborating the second hypothesis. Specifically, results showed that fine and gross motor skills might positively affect inhibition and WM in Japanese children. Whereas, in the Italian group fine motor abilities might have effects on inhibition only. Findings are coherent with previous studies documenting a significant association between motor abilities and EFs (Davis et al., 2011a; Maurer & Roebers, 2019). Research indicates that the amount of time spent by kindergarteners in fine motor activities can impact cognitive abilities (Kretch et al., 2014). Coordination and integration of visual and motor information might explain the association between EFs and motor abilities (Cameron et al., 2016). Kindergarteners face challenges with fine motor abilities, particularly in tasks requiring precise visual-motor coordination and fine motor precision. Activities like inserting coins into a box or threading cubes onto a lace demand accurate visual perception and attention for precise hand movements. Similarly, drawing trails necessitates finely coordinated visual and motor skills. Scholars suggested that the time spent on fine motor activities in kindergarten correlates with cognitive development (Kretch et al., 2014). Cultural contexts might unveil a nuanced picture of differences in motor abilities. Eastern kindergarteners, raised in environments that often prioritize cooperation and communal engagement, displayed remarkable finesse in fine motor coordination, potentially influenced by their participation in culturally rich activities that emphasize precision.

Chapter 7. General Discussion

The main aim of this research project was to investigate the effects of cognitively-engaging PA on Cool and Hot EFs in kindergarteners and, in turn, on AA once in primary school.

It's important to highlight that cognitively-engaging in PA involves the use of executive processing skills (Best, 2010) thought two mechanisms synergistically enhance children's Es: physiological changes in the brain induced by the PA, and the cognitive engagement demands of the activity, which activate higher-order cognitive processes, thereby preparing EFs for subsequent use (Best, 2012; Pesce et al., 2009). Also crucial to the findings of this study is the concept of cognitive engagement, which involves tasks that heighten cognitive load (Paas et al., 2016). Cognitive load was increased by introducing more complexity to the tasks, thereby necessitating children to allocate more mental resources to achieve successful performance. In the ad hoc intervention, tasks were designed to challenge children's EFs by requiring them to remember multiple changing rules, inhibit movement by stopping when a stimulus appeared. Moreover, to make it more difficult, stimuli were changed in the different levels. Research indicates that tasks with higher cognitive demands, including those related to attention, WM (Biino et al., 2021), cognitive flexibility (Gao et al., 2013; Schmidt et al., 2015), and inhibition (Giordano & Alesi, 2022; Schmidt et al., 2023) tend to yield more significant enhancement in EFs.

Assessing EFs by using measures encompassing both Cool and Hot aspects of emotion-related self-regulation would offer a more holistic view. This approach enables the exploration of reactivity and regulation considering inhibitory control in both cognitive and emotional contexts. It also allows a more nuanced analysis of how children regulate their positive emotions, as well as the negative one (i.e. frustration).

It was hypothesized that PA in combination with cognitive engagement would have the most impact on improving children's inhibition and WM compared to Free Play or any PA.

In the pilot study, the focus was on inhibition, namely the ability to repress predominant thoughts and behaviors (Diamond, 2013). The main strength of the study was the implementation and evaluation of the feasibility of an innovative long-term cognitively-engaging PA intervention. Results showed that the IG, children involved in cognitively-engaging PA, improved both Cool and Hot inhibition, supporting the hypothesis that PA with cognitive demands led to a higher improvement on EFs than PA without cognitive stimuli. However, many participants scored at the ceiling on some pre-test tasks, as for the delay of gratification, making it difficult to measure intervention-induced inhibition enhancements at the post-test.

Based on the limitations of the pilot study, a larger sample was recruited in the longitudinal study, controlling for the effects of confounding variables such as age and sex. Moreover, aside from Cool and Hot inhibition even WM has been tested. Consequently, new activities and sessions have been added to the intervention aimed at improving both EFs. Besides the effect of a cognitively-engaging PA intervention on EFs, also the impact of the intervention on AA thought the mediating role of EFs have been hypothesized. Specifically, the ad hoc intervention was implemented during the last year of kindergarten. Thus, the effect of the intervention on EFs has been tested in kindergarteners. Successively, AA was tested while the same children were attending the first year of primary school. Therefore, it was possible to delve into the mediating role of EFs in the association between PA and AA. Results highlighted two main effects. The first showed that only Hot inhibition (i.e. delay of gratification) was affected by the cognitively-engaging PA intervention. No significant effects on WM might be due to a non-complete differentiation from inhibition differentiated during the preschool period, which becomes more differentiated during primary school (Hughes et al., 2009; Shing et al., 2010; Willoughby et al., 2010; Wiebe et al., 2011; Mungas et al., 2013). The second finding displayed a direct effect of PA on AA, in terms of reading abilities. This result is coherent with previous studies (de Bruijn et al., 2020; Watson et al., 2017). However, effects on reading seem to be untied to changes in delay of gratification. Coherently with previous studies, no significant relationship between EFs and AA has been found (Brock et al., 2009; Kim et al., 2013). A possible explanation for null findings for the mediator might be due to the short duration of a period of 9 months might have been an insufficient duration to cause a change in EFs and AA. To observe significant changes in AA a longer time might be necessary.

Moreover, the relationship between PA, EFs, and AA has been investigated even in a sample of children and adolescents. In particular, two age groups (7-11 and 12-15 years old) were compared. Results displayed that the group of adolescents (12-to-15-years-old) performed better in both Cool and Hot EFs tasks. This observation aligns with developmental trajectories indicating a gradual linear maturation of EFs (Best, 2010). The development of EFs is intricately linked to the structural and functional growth of the DL-PFC, which undergoes specialization during adolescence through synaptic pruning, thereby optimizing connectivity between brain regions (England-Mason & Dewey, 2023). PA in this study was considered as sport, differentiating for open and closed-skills sports. Participants involved in martial arts and in team sports were compared to sedentary peers. Results highlighted higher performance in EFs, in particular inhibition, WM, decision-making, and distributed attention. Self-regulation abilities lay the foundation of martial arts, and the stronger connected aspects of self-control and discipline (Nanay, 2010). The ability to acquire self-control could be reframed as the capability to restrain, suppress, and manage automatic reactions while generating responses through attention and rational thinking. Furthermore, martial arts and similar open-skill sports involve dynamic movements and scenarios, prompting goal-oriented behaviors. Martial arts, more than other sports, contribute to improving EFs and school abilities, as a measure of AA. Practiting PA led to improvement in EFs and, in turn, in AA (Egger et al., 2019; Mavilidi et al., 2020; Pinto-Escalona et al., 2024; Singh et al., 2019).

To date, it is largely unknown how biological and environmental aspects interact and shape cognitive development at the neural level in young children. The understanding of EFs has been enriched by genetic studies, which have demonstrated that variations in phenotype among individuals arise from interactions between genes, as well as interactions between genes and the environment (McClearn, 2006). To better understand the effects of environment, such as parenting, educational and school environment, economic conditions, culture, explain whether and how genetic differences would influence differences in EFs and behavioral outcomes (Harden & Koellinger, 2020), two studies investigating biological and environmental aspects respectively have been carried out.

Considering that the development of EFs strongly depends on the maturation of the PFC and the dopaminergic circuits, attention has been paid to the role of genes related to the regulation of dopaminergic function (COMT) and neuronal growth factors (BDNF) in adolescents. Adolescence is a developmental phase crucial in the long process of maturation of the neural system involving EFs. The relationship between polymorphisms and cognitive functions took into account the presence of specific alleles which might cause alteration in EFs. In particular, the Val/Val (H/H) for COMT and the Met/Met (A/A) for BDNF determine a reduction of EFs. Findings indicated that adolescents who were homozygous for the Val (G) allele for BDNF exhibited better performance on memory tasks and decision-making compared to the Val/Met (A/G) and the Met/Met (A/A) peers. Similarly, participants homozygous for the Met (L) allele for COMT performed better on decision-making tasks. These results suggested that the Val allele for BDNF and the Met allele for COMT were linked to higher performance on EFs.

Genetic predispositions lay the foundation for EFs development, whereas environmental factors, including cultural influences, significantly shape children's cognitive abilities. Since cultural differences might begin to emerge at early stage of childhood (Kuwabara et al., 2011), scholars have delved into the cultural context as an indicator of the causal role in shaping motor skills in EFs. Socio-cultural influences, such as the use of chopsticks in Asian cultures or engagement in arts and crafts activities, have been identified as pivotal factors in shaping motor abilities in children (Chow et al., 2001; Huntsinger et al., 2011). Remarkably, children who have experienced superior motor skills during early childhood often exhibit higher cognitive abilities. This phenomenon underscores the importance of engaging in activities demanding complex motor coordination, which have been shown to enhance EFs across different contexts (Best, 2010). The observed correlation between motor skills and cognitive abilities finds support in neuroscientific research, which highlights the close developmental alignment and interaction between the neural substrates responsible for motor coordination (the cerebellum) and EFs (PFC). Previous studies (Diamond, 2000; Rigoli et al., 2012) have elucidated the intricate neural connections underlying this relationship, suggesting a synergistic interplay between motor abilities and cognitive functions. Moreover, the embodied cognition perspective offers a compelling framework for understanding the direct link between movement and thought processes. This perspective posits that EFs are an extension of the motor control system, emphasizing the integral role of physical movement in shaping cognitive abilities. In the exploration of the effects of motor skills on cognitive abilities, a comparative analysis of Italian and Japanese kindergarteners has been conducted. As expected, this cross-cultural investigation highlighted effects of gross and fine motor abilities on EFs in Japanese children. As expected, Japanese kindergarteners outperform their Italian counterparts in EFs and motor abilities tasks, in particular they showed remarkable finesse in fine motor coordination, which might be potentially influenced by their participation in culturally rich activities that emphasize precision, such as origami.

7.1. Conclusion

The main strength of this research project concerns the investigation of cognitive abilities with a specific focus on the preschool years, which represents a crucial period for cognitive development, nevertheless, it remains under-investigated. Identifying specific components of EFs crucial for academic success might pave the way for more precisely tailored interventions for children (Wilson et al., 2021). Nowadays, in the field of EFs research emphasis is laid on applying the knowledge held on protective factors especially during the early years and in preschool programs. The aim is to develop interventions to support children's long-term neurocognitive health, emotional well-being, as well as academic success (Raver & Blair, 2020). PA with higher cognitive tasks, known also as cognitively-engaging PA, seems to be more efficient in enhancing EFs. Fostering EFs throughout PA programs works because they not only train and challenge cognitive and motor skills, but they also bring joy, and pride, and provide a sense of social belonging (Howie, 2014, Pesce, 2012). Another strength of this research project was the adoption of a longitudinal study design to delve into the effects of cognitively-engaging PA intervention on both EFs in kindergarteners, and on AA. The effect of the intervention on EFs was tested during the preschool period, and its impact on AA was investigated once the same children were attending the first year of primary school. It is commonly assumed that EFs and self-regulation are universally beneficial, and context plays a crucial role. Thus, to better understand cultural similarities and differences, it was investigated in two Countries (Italy and Japan) belonging to different cultures. To sum up, enhancements in EFs during childhood are widely recognize in influencing diverse developmental domains, leading to significant benefits in adulthood. These benefits result in long-term improvements in quality of life, which are reflected in a greater ability to obtain and maintain employment and a greater likelihood of experiencing harmony in married life (Singh et al., 2019).

It should be noted that some studies presented in this thesis had limitations. Both pilot and longitudinal studies have been carried out during the COVID-19 pandemic in Italy (2021- 2022). Participant recruitment was difficult whereby kindergarteners' attendance was not compulsory, made even more difficult due to periodical closure caused by virus infections. Moreover, headmasters restricted access to those people who did not work in those schools. These circumstances implied a small sample size and the employment of a quasi-experimental study design. Participants were recruited from rural geographic areas because of COVID-19 restrictions on mobility. This made it difficult to compare different contexts, such as urban areas. However, this might help in reducing SES inequities among children. In addition, due to social restrictions children were unable to perform PA during school hours, and likely might not be able to practice sports or outdoor exercises during their free time. This allowed to control for intervenient variables related to PA since any other exercise or motor activity might be overlapped with the effect of the intervention proposed. Unfortunately data were not collected by using neurological or physiological measurements or accelerometer movement data, since the University did not have those tools to be used.

Another limitation was related to the cross-sectional study design employed in the other three studies. Hence, the interpretation of the results was limited to between-subject differences without taking into account within-subject patterns of development, allowing a limited understanding of the investigated topics.

7.2. Future directions for research and educational implications

Building upon the foundation laid by this thesis, future lines of research could explore several promising approaches to expand understanding of the relationship between PA, EFs, and AA in children. Taking into consideration individual differences (i.e. age, sex, baseline EFs) in response to PA interventions, makes it possible to plan and implement interventions to individual needs and characteristics optimizing their effectiveness in improving EFs and AA.

Implementing interventions aiming at improving children's EFs during early preschool years could significantly enhance both academic and social success later in time (Stein et al., 2017). This period is considered extremely sensitive for the development of EFs (Diamond, 2015; Stein et al., 2017). Specifically, PA interventions might play a critical role in fostering fundamental skills in children, influencing their cognitive, psychological, and social growth (Heckman et al., 2010). Longitudinal studies involving larger samples would be encouraged, as well as experimental research design, coupled with follow-ups to better understand the long-term effects of PA interventions on EFs and AA. A cluster-RCT would help improve knowledge of the causal-effect relationship between PA, cognition, and academic performance. Moreover, such interventions might lead to enduring benefits that extend well into adolescence and adulthood (Astuto & Ruck, 2017).

To date, due to the still existing gap in understanding the "dose effect" of PA on EFs, future research should investigate PA by varying the intensity, duration, and frequency of interventions, to reach the optimal dosage required to elicit significant improvements in EFs and AA during preschool years. In doing this, exploring neural mechanisms underlying EFs and cognitively-engaging PA using advanced neuroimaging techniques, to understand how PA influences brain structure and function providing valuable insights into cognitive benefits. In addition, researchers and practitioners need to discern which PA, sports, and exercise interventions are most conducive to cognitive development, ensuring an optimal alignment between specific motor tasks and EFs.

Interesting implications on the educational fields are supported. Firstly, coherently, it is imperative to encourage participation in PA at a young age. The intervention fine-tuned and tested in this thesis was based on 20 minutes sessions of cognitively-engaging PA, which might be combined to physical education aiming to enhance kindergarteners' daily involvement in PA during school hours. The ad hoc intervention has a protocol of well-defined activities that might be easily used by teachers to implement physical education lessons.

Moreover, specific educational programs for parents and teachers would be necessary to share good practices deriving from the awareness of PA and its contribution to a child's cognitive development in enhancing EFs by enjoying activities. To involve parents in supporting and promoting PA intervention as a crucial aspect for the development of EFs and, in turn, AA. Assess the feasibility and effectiveness of implementing such programs on a larger scale within educational settings, whereby PA becomes accessible to every student.

Since this is the era of technological advancement, it is worth exploring the potential of integrating innovative technology-based interventions (i.e. exergaming) in engaging children and promoting cognitive development, as well as AA.

Chapter 8. Overview of the doctoral activities

8.1. Research period abroad

Two study periods abroad were carried out for six months, three months in a European Country (the UK) and the other three months in an Asian Country (Japan).

The first period abroad, from May to August 2022, was at the Department of Education of the Bukkyo University (Kyoto, Japan) under the supervision of Professor Kyoko Imai-Matsumura. Together with the supervisor, the project was defined in the months before the departure from Italy. It was based on a cross-cultural investigation of EFs and motor abilities in kindergartners. Data on the Italian sample was collected between February and April. Once in Japan, cognitive and motor tests were translated from Italian to English, and then from English to Japanese. A small group of 4 students was trained on how to administer tests to children. A sample of 48 children was recruited from the kindergarten belonging to the University. Together with the supervisor and group of students, data were collected on Japanese kindergarteners. Successively tests were scored and once returned to Italy analyses were performed to investigate differences between Italian and Japanese on EFs and motor abilities, and the effects of motor abilities on EFs. This period was instrumental in enhancing my understanding of cultural differences between Eastern and Western. The period spent in Japan let me experience and live Eastern culture in a 360-degree view. This let me explore a completely new Country and see the world with new eyes and from a different perspective. In general, my experience there has been extraordinary and enriching, both personally and professionally.

The second period abroad, from April to July 2023, was at the School of Psychology of the University of Birmingham (England, the UK) under the supervision of Professor Rory Devine. The project aimed at investigating the associations between EFs and body weight, while controlling for potential confounding variables including general intelligence. Then, it was investigated whether links between EFs and body weight were moderated by SES. Longitudinal data from a representative sample (around 15.000) of children aged between 11 and 14 years from the UK Millennium Cohort Study were analyzed using cross-lagged longitudinal models. This period was crucial to improving my understanding of effects of environmental aspect as SES, as well as biological as body fat, in affecting the development of EFs. Moreover, these months were instrumental in enhancing my statistical knowledge and skills on analysis for longitudinal data, such as cross-lagged models by using tools like Mplus and R. During this period I had the chance to attend several seminars meeting professors and PhD students studying interesting psychological topic by using different tools, such as EEG. These neuropsychological techniques intrigued me and I attended several sessions of experiments as a participant, since being involved in is one of the best ways to learn.

8.2. Skills and tools

Throughout the three years of doctoral studies, my research interests have been characterized by a continual quest for knowledge and skill enhancement, particularly within the domain of cognitive functions, with a specific emphasis on EFs. I have broadened my proficiency in test administration, acquiring expertise in administering a variety of psychological measures of cognitive abilities in children and adolescents.

In the first year of my doctoral studies, my focus was on laying a solid groundwork in statistical analysis. I dedicated myself to mastering statistical techniques, attending online courses and summer schools, with particular attention to regression models with mediation and moderation analysis. Moreover, I attended online courses and statistical classes to acquire proficiency in basic coding for statistical analysis by using R Studio. Concurrently, I recognized the importance of effective communication in disseminating research findings and thus dedicated a lot of time to enhancing my proficiency in scientific English, by attending English classes tailored for PhD students at the University of Palermo to provide key skills crucial to articulating and disseminating research findings in papers and National and International conferences.

The second year of my doctoral studies was marked by a significant expansion of my knowledge of EFs by exploring similarities and differences related to culture. The research period abroad allowed me to learn more about how environmental aspects might affect the development of cognition, in particular of EFs. I had the opportunity to go to the kindergarten to collect data and see how is the Japanese educational system and how self-regulation is important to them. Children were diligent, self-regulated, and respectful of school rules. It was a completely different experience from those I had during data collection in Italy.

As I progressed into the third year, I continued studying statistical analysis, focusing on advanced statistical techniques including cross-lagged models and structural equation modeling, which I diligently pursued to effectively analyze longitudinal data sets. The research period abroad at the University of Birmingham was crucial to making it possible since I had the chance to apply longitudinal analysis on second data from a Cohort study of about 15.000 individuals.

This progressive skill development throughout my doctoral studies has prepared me with a comprehensive understanding of both the theoretical and practical aspects of research in developmental psychology, focusing on EFs and some of the variables that might positively affect their development, as well as those that might negatively impact them (i.e. PA, BMI, SES, biological, and environmental factors).

utilize a multifaceted approach in my studies and contribute significantly to the field. This period of exploration broadened my understanding of data collection methodologies, providing me with new insights into the intricacies of physiological measurements

8.3.Titles of published papers as first or co-author during the three years

Alesi, M., Giordano, G., Ingoglia, S. & Inguglia, C. (2024). The association among executive functions, academic motivation, anxiety and depression: a comparison between students with specific learning disabilities and undiagnosed peers. *European Journal of Special Needs Education,* 1-15. https://doi.org/10.1080/08856257.2023.2300172

Alesi, M., Giordano, G., Gentile, A., & Caci, B. (2023). The Switch to Online Learning during the COVID-19 Pandemic: The Interplay between Personality and Mental Health on University Students. *International Journal of Environmental Research and Public Health, 20(7),* 5255. https://doi.org/10.3390/ijerph20075255

Alesi, M., Giordano, G., Gentile, A., Roccella, M., Carola, C., & Caci, B. (2023). The Mediating Role of Academic Motivation in the Relationship between Self-Efficacy and Learning Strategies during the COVID-19 Pandemic. *Frontiers in Education, (8),* 1339211. https://doi.org/10.3389/feduc.2023.1339211

Giordano, G., Alesi, M., & Gentile, A. (2023). Effectiveness of cognitive and mathematical programs on dyscalculia and mathematical difficulties. *International Review of Research in Developmental Disabilities, 65,* 217-264. https://doi.org/10.1016/bs.irrdd.2023.08.004

Alesi, M., Giordano, G., Sacco, A., & Proia, P. (2023). Effects of BDNF and COMT epigenetic regulatory polymorphisms on Executive Functions in adolescents. *Life Span and Disability, 26(1)*, 7-27. doi: 10.57643/lsadj.2023.26.1_01

Gentile, A., Polizzi, C., Giordano, G., Burgio, S., & Alesi, M. (2023). Parental Resources in Parents of Children with Special Needs (SNs) at the Time of COVID-19. *Journal of Clinical Medicine, 12(2),* 475. https://doi.org/10.3390/jcm12020475

Polizzi, C., Giordano, G., Burgio, S., Lavanco, G., & Alesi, M. (2022). Maternal Competence, Maternal Burnout and Personality Traits in Italian Mothers after the First COVID-19 Lockdown. *International Journal of Environmental Research and Public Health, 19(16),* 9791. https://doi.org/10.3390/ijerph19169791

Giordano, G., & Alesi, M. (2022). Does Physical Activity Improve Inhibition in Kindergarteners? A Pilot Study. *Perceptual and Motor Skills*, 129(4), 1001-1013. https://doi.org/10.1177/00315125221109216

Giordano, G., Gómez-López, M., & Alesi, M. (2021). Sports, executive functions and academic performance: A comparison between martial arts, team sports, and sedentary children.

International Journal of Environmental Research and Public Health, 18(22), 11745. https://doi.org/10.3390/ijerph182211745

Conferences Proceeding

Caci, B., Giordano, G., & Alesi, M. (2022). The Psychological Impact of Online Learning During the COVID-19 Pandemic. A Survey on a Sample of Italian Undergraduates. In International Workshop on Higher Education Learning Methodologies and Technologies Online. *Springer Nature Switzerland.*

8.3.1. Publications arising from this thesis

Giordano, G., & Alesi, M. (2022). Does Physical Activity Improve Inhibition in Kindergarteners? A Pilot Study. Perceptual and Motor Skills, 129(4), 1001-1013. DOI: 10.1177/00315125221109216 (Chapter 2)

Alesi, M., Giordano, G., Sacco, A., & Proia, P. (2023). Effects of BDNF and COMT epigenetic regulatory polymorphisms on Executive Functions in adolescents. Life Span and Disability, 26(1), 7-27. doi: 10.57643/lsadj.2023.26.1_01 (Chapter 5)

Giordano, G., Gómez-López, M., & Alesi, M. (2021). Sports, executive functions and academic performance: A comparison between martial arts, team sports, and sedentary children. International Journal of Environmental Research and Public Health, 18(22), 11745. https://doi.org/10.3390/ijerph182211745 (Chapter 6)

8.4. Conferences attended

• *22-23 September 2023 - XXXI National Conference of Italian Association of Learning Disabilities (AIRIPA) online*

Oral presentation: Giordano, G., Ingoglia, S. & Inguglia, C. "Cognitive, emotional and motivational skills during the COVID-19 pandemic: a comparison between students with Learning Disabilities and typically developing students".

• *28 August -2 September 2023 – European Conference on Developmental Psychology (ECDP) in Turku (Finland)*

Oral presentation: Giordano, G., Alesi, M. & Matsumura, K. "Italian and Japanese at kindergarten: a cross-cultural investigation of executive functions".

• *27-30 September 2022 - XXX National Conferences of Italian Association of Psychology (AIP) in Padua (Italy)*

Oral presentation: Caci, B., Giordano, G., & Alesi, M. "Academic Motivation and Self-Efficacy in Learning Strategies outcomes in university students during COVID-19 pandemic".

• *22-24 September 2022 – XXX National Conference of Italian Association of Learning Disabilities (AIRIPA) in Padua (Italy)*

Oral presentation: Giordano, G. & Alesi, A. "Physical activity and Executive Functions in kindergarteners: a pilot study".

• *31 August – 2 September 2022 – VIII International Congress on Emotional Intelligence (ICEI) in Palermo (Italy)*

Oral presentation: Giordano, G., Alesi, M. "Hot Executive Functions in Sporty and Sedentary adolescents".

• *20-23 September 2021- XXXIII National Conferences of Italian Association of Psychology (AIP) in Bari (Italy)*

Oral presentation: Giordano, G., Alesi, M. "Hot and Cool executive functions in children and adolescents: a comparison between sportif and inactive".

• *24-25 September 2021 – XXXIII National Conference of Italian Association of Learning Disabilities (AIRIPA) in Bari (Italy)*

Oral presentation: Giordano, G., Alesi, M. "Learning and emotional-motivational profiles in learning disabilities students during Covid 19".

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Annex A

Original Manuscript

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Does Physical Activity Improve Inhibition in Kindergarteners? A Pilot Study

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Abstract

Substantial empirical evidence supports the positive effects of physical activity (PA) on executive functions, but not all forms of physical activity benefit equally. Among kindergarteners, cognitively-engaging exercise seems to more strongly effect EF than simple exercise. We aimed to investigate several qualitatively different exercise formats on kindergarteners' inhibition. Participants were 75 children (M age = 68.1 months), recruited from 14 classrooms of three kindergarten schools. They were randomly assigned to three groups: control group, free play group (non-cognitively-engaging PA), and an intervention group (cognitively-engaging PA). The intervention group performed 18 sessions of a cognitively engaging PA (tasks requiring movements and inhibitory behavior skills). We assessed "hot" and "cool" aspects of inhibition using the Day-Night Stroop test, Head-Shoulders-Knees-Toes, Gift Wrap, and Snack Delay. We found that the intervention group obtained a more consistent performance improvement on post-test measures of hot and cool inhibition than did the free play group.

Keywords

children, executive functions, inhibition, kindergarten, physical activity

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Introduction

Physical activity (PA) and executive functions (EFs) are intrinsically and reciprocally interrelated (Doherty & Miravalles, 2019) with simultaneous neural network activation between the cerebellum, basal ganglia, and prefrontal cortex (PFC) (Diamond, 2000). EFs have been defined as a set of higher-order, self-regulatory cognitive processes required for goal-directed behaviors (Best, 2010). EFs have been differentiated neurologically and behaviorally, with three distinguishable but interrelated components of working memory, inhibition, and cognitive flexibility (Miyake et al., 2000; Miyake & Friedman, 2012). *Working memory* is the ability to monitor and modify information held or retained in mind; *inhibition* is the ability to repress automated and impulsive mental and behavioral reactions; *cognitive flexibility* is the capability to adapt to continuously changing demands, by shifting operations and mental sets (Diamond, 2015). Zelazo and Carlson (2012) proposed a framework of two distinct "hot" and "cool" aspects of EFs. While either hot or cool processes may be predominant in a task performance, they are coordinated. Hot EFs involve top-down processes needed for goal-directed behavior in significant emotional or motivational contexts, such as for delay of gratification and decision-making. In contrast, cool EFs refer to top-down processes needed in situations that are affectively or motivationally neutral, such as for inhibition and cognitive flexibility (Kouklari et al., 2017). The occurrence of hot and cool EFs depend upon maturation of the brain's PFC. EF development proceeds across the childhood population according to a bell-shaped normative curve (Boelema et al., 2014). During childhood, the structural growth of the PFC is partially specialized, achieving its peak during middle adolescence, as caused by synaptic pruning, and reach complete maturation and then initiate a slow natural decline during early adulthood (Boelema et al., 2014; Poon, 2018; Giordano et al., 2021). EFs assessed in children at 4-years-of-age can predict school readiness for post-kindergarten social and scholastic skills (Kraybill & Bell, 2013). Hence, early preschool interventions to improve children's executive functions might promote social and academic development (Stein et al., 2017), as preschool years represent a sensitive period for EF development (Diamond, 2015; Stein et al., 2017).

Best (2010) proposed three pathways for affecting EF: (a) through physiological changes in the PFC and grey matter volume (Lubans et al., 2016); (b) through cognitive demands that are linked to engaging new neuronal paths that let children improve self-regulation abilities and goal-oriented behavior that may generalize to other EF tasks; and (c) through cognitive demands required to perform a complex motor movement. Diamond (2015) affirmed this with this comment, "the effect of physical activity needs to move beyond simple aerobic activities that require little thought (treadmill running, riding a stationary bicycle, or rapid walking) and resistance training" (p. 1014). Specific types of PA may be strongly associated with EFs in children in that cognitively engaging PA seems to have more substantial effects on EF enhancement than non-engaging PA (Best, 2010; Diamond, 2015; Diamond & Ling, 2016). The *cognitive stimulation hypothesis* can explain how PA with higher cognitively demanding tasks activates the same brain networks used for EF (Best, 2010). Cognitively engaging, long-term PA interventions are likely to have more beneficial outcomes for children's cognitive development than do cognitively simple PA (Schimdt et al., 2015). From a developmental perspective, inhibition is fully developed in childhood (Diamond, 2013), with its growth having mainly occurred during preschool years (Tomporowski et al., 2008). Diamond (2015) also highlighted that inhibition matures first among EFs, with working memory and mental set shifting developing last. Thus, inhibition is sensitive to training during preschool years (Zelazo et al., 2016).

There has been minimal PA-related EF research with kindergarteners, and most published studies have been correlational (Becker et al., 2014; Oberer et al., 2018; Stein et al., 2017; Willoughby et al., 2018). To our awareness, only three recent studies described PA interventions. Chang and colleagues (2013) studied an 8-week soccer program for kindergarteners and found improvement in inhibition. Mulvey et al. (2018) demonstrated improvement in EFs among 3-to-6-year-old kindergarteners who participated in a 6-weeks motor skill program. Similarly, Preston (2020) showed that cognitively engaging PA led to consistent EF improvements among 4 - 5 years-old children.

Based on our understanding of the nature and neuroanatomical basis of EF and on this early research regarding the importance of cognitively engaging PA on early EF development, our general objective in this pilot study was to examine the effects on kindergarterner's development of inhibition skills of 18 sessions of varied types of PA administered during school hours. Here, *cognitively engaging PA* refers to PA with cognitive demands, and *free play* refers to PA without reinforced cognitive demands. Consequently, a specific objective was to compare the effects on inhibition during the last year of kindergarten (ages 5–6). We proposed two hypotheses: (i) Hp1: Children involved in both PA modalities would show more consistent improvement on inhibition at the end of kindergarten than a control group; and (ii) Hp2: Children engaged in cognitively engaging PA would perform better on inhibition tasks than children in engaged in free play. Based on these issues, we conducted a pilot study to improve our experience with the study method and procedure and to assess the feasibility of the intervention. As results were significant even with this small sample size, this pilot study is reported here.

Method

Participants and Study Design

Our experimental protocol (n. 40/2021) was approved by the Bioethics Committee of University of Palermo. The principal investigator contacted and met with the headmasters of three kindergartens and class presidents to explain the study's aim and invite them to participate. Following their approval, the investigator met with parents and legal representatives of all children to answer their questions and introduce them to the study's objectives. Before participation, each participant's parents completed and signed the written informed consent.

Our participant sample of 75 children were recruited from the three Italian kindergartens that were approached. The participants' mean age was 68.1 months (*SD* = 3.86; age range: 61–75 months, male = 39 and female = 36). Participant inclusion criteria were to be 5–6 years old and attending the last year at kindergarten school; and the sole exclusion criterion was the presence of any neuro-developmental disease or physical disability. Participants were from 14 different kindergarten classes. These classes were used as a random variable in a cluster-randomized controlled trial in which the children were also randomly assigned to one of three groups of 25 participants each: *cognitively engaging physical activity* (IG) or one of two control groups - *free play* (CG1) or no additional physical activity (CG2). Regarding socio-economic status (SES), medium SES was prevalent (52.4%). The criteria for SES evaluation were number of children per family, parents' education, and parents' job. The medium SES status was described by middle and high school parental education and job status as a shop assistant or similar employment position.

We employed a longitudinal data collection method with a pre-test evaluation (T1 in April), an intervention (April, May and June), and a post-test evaluation (T2 in June). We assessed all three groups' inhibition skills directly with cognitive and motor tests (Day-Night Stroop test, Gift Wrap, Snack Delay, and Head-Shoulders-Knees-Toes) within pre and post-testing phases that lasted about 2 weeks each. Between pre-test and post-test phases, the IG individually performed 18 sessions of cognitively engaging PA (15 minutes per session, three sessions per week), the CG1 performed 18 free play sessions (15 minutes per session, three sessions per week), and the CG2 performed no PA beyond their regular school activities.

Procedures and Measures

The EF tasks were administered individually to each child in a quiet room of his/her school. Each child completed the same EF assessment twice, before (pre-test) and after (post-test) the intervention, each completed in a session lasted about 20 minutes. All tests were scored by the same researcher, carefully following the assessments guidelines. We tested hot and cool aspects of EF (motor inhibition and cognitive inhibition).

Executive Functions Assessment. The Day-Night Stroop test (Gerstadt et al., 1994) – a "cool" EF test - has been used to evaluate cognitive inhibition in children aged 3–7 years old. It is composed of 16 cards with images of a sun (8) or a moon (8). We presented these cards to each child one at a time in a smooth, fluid manner. The deck of the stimulus cards was held face down in the experimenter's hand, ensuring that the child did not see the stimulus until the experimenter turned the card over. Before the start of the task, the experimenter instructed each child not to give automatic, implusive responses but to inhibit those responses by saying "night" when shown the white, sun card and "day" when shown the black, moon card. Then the experimenter showed the child the black, moon card and child was instructed to say "day" when shown that card. Two scores were given: accuracy and reaction time. For accuracy, a score of "1" was attributed for each correct answer; reaction time execution was measured in seconds. The number of correct responses was totaled and converted to a percentage of the total number of responses. The Day-Night Stroop test has demonstrated strong internal validity (von Stauffenberg & Campbell, 2007; Rhoades et al., 2009), and test-rest reliability (Thorell & Wahlstedt, 2006).

The Head-Shoulders-Knees-Toes test (Cameron Ponitz et al., 2009) – a "cool" EF test - was given in its Italian version to test motor inhibition. The child had to first touch his/her head, shoulder, knees or toes when directed to do so, and, in a second direction had to touch the body part they were *not* directed to touch. This test was subdivided into two parts. In the first part, there were two paired orders (head-toes or shoulder-knees). When asked to touch "head," the child had to touch "toes" and vice versa, or, when asked to touch "shoulder," the child had to touch "knees" and vice versa. The second part involved four paired orders (head-toes and shoulder-knees). There were three possible scores: 0 for incorrect answers, 1 for self-corrected incorrect answers, and 2 for correct answers. The HSKT test has shown good construct of reliability and constitutive validity (McClelland et al., 2014).

The Gift Wrap (Kochanska et al., 2000) – a "hot" EF task adapted from the FE- PS 2–6 (Batteria per la valutazione delle Funzioni Esecutive in età Prescolare) (Usai et al., 2017) - is a measure of delay of gratification or inhibitory control. In this task, the researcher explained to the child that she had brought a present but had forgotten to wrap it. The child sat down with their back to the table and was instructed not to 'look' while the researcher wrapped the gift for one minute. At the end of 60 seconds, the child was given the present, which contained candies. During the task, the researcher recorded on the score sheet both any violations of instructions not to peek or speak during the wrapping and the reaction time in seconds from the instruction to the first possible violation. Latency to the first peek in seconds was used in the analyses (ICCs = 0.86–0.96). Scores were converted to z scores. Higher z scores indicated higher levels of control and inhibition.

Snack Delay (Mischel & Ebbesen, 1970) – a "hot" EF task adapted from the FE-PS-2 (Usai et al., 2017) - was used to measure the child's ability to inhibit pre-potent or automatic responses. In this task, the child was asked to wait before opening the wrapped gift of the Gift Wrap test. The maximum waiting time was 240 seconds. Latency until the child opened the gift was used in the analyses (ICCs = 0.92–0.99). The latency time was recorded (in seconds) on the score sheet and then converted to z scores. Higher scores indicated higher levels of control and inhibition. Both for the Gift Wrap and Snack Delay the construct of validity as well as reliability have been confirmed (Smith-Donald, et al., 2007).

Intervention

During the intervention phase of the experiment, the IG participants individually performed about 20 minute sessions of motor activity involving three cognitive tasks, three sessions per week for six consecutive weeks. Cognitive tasks involved inhibition process with three increasing levels of difficulty (beginner, intermediate, advanced). PA at each cognitive difficulty level lasted 2 weeks and was divided in two phases in each session: baseline and experimental (each lasting about 10 minutes).

For the beginner and intermediate difficulty, a quadrangular circuit was made in the kindergarten gym using gym equipment (hula hoops, gym cones, cord). In the baseline phase, oral instructions were given to define movements that children performed to complete the circuit. A specific motor activity for each side of the circuit was defined: walking forward; walking tiptoe; jumping on both feet together on hula hoops; and jumping on both feet open across a cord on the floor. Before the start of the experimental phase, the child was instructed to change each previously learned movement with another new movement as directed by the researcher, as follows: walking forward/walking backward; walking tiptoe/walking on heels; jumping on both feet together on hula hoops/jumping on foot on hula hoops; jumping with open feet across a cord on the floor/jumping with both feet together on the right side and the left side of a cord on the floor. The child changed the baseline movement and performed the directed movement when they heard or saw a key stimulus (i.e., claps for the beginner level and visual stimuli for the intermediate level. In order to increase the level of difficulty, new stimuli were added from one level to the next one, and there were an increasing number of repetitions, and meters for each side of the circuit.

An example of beginner-level activity was based on a circuit lasting 15 minutes. In the baseline phase, lasting about seven minutes, the required movements to complete the circuit were illustrated to the child. In the experimental phase, lasting about seven minutes, the movements were the same as the baseline phase, but a clap, as auditory stimulus, was added and the child was instructed to inhibit the previous movement and perform the new associated movement. For example, the child started walking forward, the experimenter clapped, and the child performed walking backward; the child then arrived to the corner and turned to their right walking tiptoe, the experimenter clapped and the child changed to walking on heels; the child arrived to the corner and turned to the right and started to jump with two feet in the hula hoops, the researcher clapped, and the child began jumping with one foot inside the hula hoops; the child arrived to the corner turned to the right and began jumping on both feet open across a cord on the floor.

The advanced level included a task with Stroop effect. A 15 m course was created in the kindergarten gym requiring three movements to complete it: (a) jumping with both feet in the hula hoop or jumping with feet apart in two parallel hula hoops; (b) going around the cone; and (c) jumping with both feet on the right and on the left sides of a cord. At the end of the course, the child found two balls pictures (between football, rugby, basketball, and tennis) at a 1-m distance from each other. In the baseline phase, verbal commands were given to the child to perform movements to complete the course and go around the cone with the picture named by the experimenter (i.e., go around the cone with the football ball). Before starting the experimental phase, the balls pictures were modified using unconventional colour and conventional dimension or vice-versa (i.e. rugby ball with the color of a football ball). The child was instructed to go around the ball picture with a target stimulus feature (i.e., color or dimension), by recognizing the picture by the color while inhibiting the impulse to use the conventional stimulus feature (i.e., shape or dimension). An example of an activity for the advanced level was based on a circuit lasting a total of around 15 minutes. In the 7-minute baseline phase, the required movements to complete the course were fully explained to the child, while in the 7-minute experimental phase, the child was asked to complete the course and then go around the rugby ball between two options (a rugby ball shape with football ball color or a football ball shape with rugby ball color). The child had to choose and go around the ball picture with the *color* of a rugby ball.

Statistical Analysis

In preliminary analyses, different analyses of variance (ANOVAs) were run to check for any group differences on dependent measures (cool and hot inhibition) at T1 based on participant characteristics (age and gender). ANOVAs were conducted on accuracy and mean reaction times of the four EF tasks as dependent variables. Repeated measure ANOVAs were then computed on dependent variables to test for group differences from T1 to T2. Partial eta square (η_p^2) was reported to estimate effect size. For the significant differences detected by the ANOVAs, Bonferroni correction post hoc comparisons were computed to determine specific group differences between the three groups. All computations were completed using the Statistical Package for the Social Sciences (SPSS, Version 26, NY, USA), and statistical significance was set at $p < .05$. We then used G-Power software for a post-hoc power analysis and found that a sample size of 66 yielded 95% statical power.

Results

The participant's means and standard deviations for the accuracy and reaction times of the four EF tasks at pre- and post-testing by group membership are presented in Table 1. Preliminary ANOVAs were used to test for pre-test group differences on dependent variables that might be associated with participant age and gender. There were no T1 differences between the three groups for age [F (2,73) = .851, $p = .43$] or gender [F (2,73) =.153, $p = .85$].

Regarding pre-intervention differences in ability on the dependent variables, there were no group differences on cool EF as measured by accuracy on the Day-Night Stroop [F (2,73) = .4174, $p = .66$], on hot EF as measured by reaction time on Gift Wrap [F (2,73) =.0543, $p = .95$] or on hot EF as measured by reaction time on Snack Delay [F (2,73) = 2.96, $p = .06$]. Significant differences were found for cool EF as measured by

Table 1. Descriptive analysis of Day-Night Stroop, HSKT, Gift Wrap and Snack Delay at Pre and Post-Test for the Three Groups.

Groups	Phases		Day-night stroop Accuracy N	Day-night stroop Reaction time Sec	HSKT Accuracy N	Gift wrap Reaction time Sec	Snack delay Reaction time Sec
CG1	T1	M	−.64	−2.06	5.08	.54	5.52
		SD	1.83	1.56	5.47	.75	5.57
	T2	M	−.66	.04	9.67	.89	5.54
		SD	.64	.95	6.18	.51	5.33
	Δ	M	−.04	−2.02	−4.91	−.38	−.21
		SD	.37	.35	1.18	.20	1.13
CG2	T1	M	−.27	.09	10.4	.59	9.78
		SD	1.34	1.13	6.12	.87	6.85
	T2	M	−.53	.32	10.6	.29	8.67
		SD	1.36	.69	6.68	1.04	6.31
	Δ	M	.25	−.23	−.24	.30	1.10
		SD	.36	.34	1.16	.19	1.11
IG	T1	M	−.58	−1.56	9.20	.61	8.86
		SD	1.32	1.86	6.77	.90	6.96
	T2	M	.07	.75	17.0	.75	9.39
		SD	.44	.49	4.32	.87	5.68
	Δ	M	−.66	−2.32	−7.76	−.14	−.53
		SD	.36	.34	1.16	.19	1.11

Note. CG1: free play group; CG2: no additional physical activity group; IG: cognitively engaging physical activity; M: mean; SD: standard deviation; T1: pre-test; T2: post-test; Δ: comparison; HSKT: Head-Shoulder-Knees-Toes; N: total; sec: seconds.

reaction time on the Day-Night Stroop test [F (2,73) =13.31, $p < .001$] and the HSKT [F (2,73) = 5.16, $p = .008$].

On analyses of possible intervention differences between groups, repeated measures ANOVAs revealed significant cool EF inhibition differences as measured by Day-Night Stroop reaction time [F (1,74) = 11.0, $p < .001$, $\eta_{p2} = .236$] and HSKT accuracy [F (1,74) = 10.7, $p < .001$, $\eta_{p2} = .232$] and significant hot EF inhibition as measured by Gift Wrap reaction time [F (1,74) = 3.16, $p = .04$, $\eta_{p2} = .082$]. No statistically significant differences were found on cool EF inhibition as measured by Day-Night Stroop test accuracy [F (1,74) = 1.62, $p = .20$, $\eta_{p2} = .044$] or for hot EF inhibition as measured by Snack Delay reaction time [F (1,74) = .60, $p = .54$, $\eta_{p2} = .017$]. See Table 2 for details.

Discussion

Our purpose in this study was to test the efficacy of a PA intervention program aimed at enhancing EF inhibition in kindergarteners. In particular, we investigated the effects of

Table 2. Repeated Measures ANOVAs for Executive Functions Tasks.

Inhibition		F	*p*	*d*
Cognitive inhibition	Accuracy	.491	.034*	.47
	Reaction time	46.0	<.001***	1.17
Motor inhibition	Total	32.1	<.001***	1.25
Delay of gratification	Accuracy	1.35	.24	.29
	Reaction time	.379	.54	.08
Waiting time for gratification	Time	.0387	.84	.00

*$p < .05$; ***$p < .001$.

two qualitatively different PA conditions, with different levels of cognitive load, on kindergarteners' cognitive and motor inhibition as measured by a series of different tasks. We hypothesized that a cognitively engaging PA intervention would have a greater positive affect on inhibition in kindergarteners than free play involving PA without cognitive demands. These hypotheses were based on the *cognitive stimulation hypothesis* (Best, 2010) by which PA with higher cognitively demanding tasks activate the same brain networks as are used to perform EF tasks. In this study, we tested both cool (i.e., non-emotional or motivation) and hot (i.e., emotional or motivational) aspects of inhibition. Cool inhibition tasks were day-night response judgments paired with day-night pictures and head, shoulder, knee toe touching paired with experimental directions. Hot inhibition tasks involved delay of gratification. Data from this pilot study partially confirmed our first hypothesis. Relative to our control group who engaged in no PA beyond normal school activities (CG2), children involved in a cognitively engaging PA program (IG), but not those engaged in free play (CG1), showed significant inhibition improvements. Regarding our second hypothesis, children engaged in cognitively engaging PA (IG) increased their cool EF inhibition (cognitive and motor) and one hot EF inhibition task (delay of gratification). Cognitive load during PA was increased by adding new stimuli with increasing difficulty levels, increasing circuit repetitions and distances for each side of the circuit, making it more complex and challenging for kindergarteners to inhibit completing responses. Our finding of no group differences in the children's performance on two inhibition tasks (Day-Night Stroop test accuracy and Snack Delay waiting time) might be explained by a ceiling effect at pre-test since all participants achieved high initial scores on those tasks.

Limitation and Directions for Further Research

Among limitations of this study, we were limited to a small sample size of 25 participants in each condition. Due to the Covid-19 pandemic, few children attended school in Italy where kindergarteners' attendance is not compulsory. Secondly, as is usual for studies in a school-based setting, we conducted randomization using class as a cluster randomized variable in a controlled trial. Finally, many participants scored at the ceiling on some pre-test tasks, making it difficult to measure intervention-induced inhibition enhancements at post-test. Future studies should continue to explore how PA interventions for kindergarteners might enhance EF development, perhaps particularly for children with known EF difficulties, such as those with attention-deficit hyperactivity disorder and related neurodevelopmental disorders. Future investigators should expand on these findings using other cognitively engaging PA interventions and EF tasks and employing sufficiently large participant samples to examine any differential age and sex effects as modifying variables.

Conclusion

This study highlighted benefits to cognitively engaging PA for the development of EFs in young school children. In this study, the focus was on inhibition, the ability to repress predominant behaviors and thoughts. A main strength of the study was the development and evaluation of a feasible and innovative long-term cognitively engaging PA intervention for kindergarteners. Our results showed that only cognitively engaging PA led to an enhancement of cool and hot inhibition. We discussed limitations to this study and directions for further investigations.

Authors' Contributions

Conceptualization, G.G. and M.A..; methodology, M.A. and G.G; software, G.G.; formal analysis, G.G.; data curation, G.G.; writing—original draft preparation, G.G.; writing—review and editing, M.A. and G.G.; supervision, M.A.; project administration, G.G. All authors have read and agreed to the published version of the manuscript. All Authors approved the final paper.

Declaration of Conflicting Interests

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Ethical Approval

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Bioethics Committee of the University of Palermo (n. 40/2021).

Informed Consent

Consent to participate: the participants' parent completed and signed the written informed consent. Consent for publication (consent statement regarding publishing an individual's data or image): the participants gave their consent to the publication of the data

Data Availability

Availability of data and material (data transparency): the data is available via email to the corresponding author.

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Annex B

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Article

Sports, Executive Functions and Academic Performance: A Comparison between Martial Arts, Team Sports, and Sedentary Children

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Abstract: It is well known that curricular physical activity benefits children's executive functions and academic performance. Therefore, this study aimed to determine whether there is an influence of extracurricular sports on executive functions and academic performance. However, it is less known which specific types of the sport better enhance executive functions in children; to investigate this issue, this study compared the performance on executive functions tasks and academic performance in one hundred and two boys and girls with an average age of 11.84 years recruited from Italian schools and gyms (N = 102), who participated in martial arts or team sports or were sedentary children. Executive functions were measured with the tests: Attenzione e Concentrazione, Digit Span test, Tower of London, IOWA Gambling task BVN 5-11, and BVN 12-18. Results demonstrated that children practicing martial arts showed better executive functioning and higher school marks than those involved in team sports or not involved in any sports. Furthermore, participants aged 12 to 15 years old outperformed in cool and hot executive functions tasks and had a better academic performance. Thus, the present findings supported the view that regular practice of extracurricular sports enhances executive functions development and consequently influences academic performance.

Keywords: sport; physical activity and sport in youth; executive functions; academic performance

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1. Introduction

The World Health Organization (WHO) has identified the school as a key setting for the promotion of physical activity (PA) in children [1]. The school setting is an ideal environment where develop PA interventions in childhood [2]. PA in schools has not only advantages from a child's physical and emotional development, but at the same time, it has also potentially wide school benefits [1,3–5]. Moreover, recent studies focus on the positive effect of extracurricular sport on AP [6,7]. It has been proven that sport has beneficial effects upon concentration, enhanced cognitive performance, and better academic performance (AP) [7–10].

Haapala [11] carried out a systematic literature review and analyzed studies from 1966 to 2011 on the PA, AP, and Cognition in Children and Adolescents. In summary, the author demonstrated how 14- to 36-week physical exercise training programs enhanced children's performances in mathematical, reading, and language. Within the study's statistical analysis, it was found that there was no direct relationship between physical activity and academic performance in the population group studied. This Relationship is supposed to be indirect and mediated by the action of the executive functions (EF) [12,13], which are considered a crucial and robust indicator of school success from preschool age [14–18].

EFs are a collective term under which a broad spectrum of cognitive abilities is summarized. These abilities are needed for goal-directed, purposeful thoughts and behaviors [19–21]. Working memory, inhibition, and cognitive flexibility are considered three core EFs and are classified as "Cool" [22] because they refer to the cognitive components of self-regulation. In addition to these, effortful control defines the "Hot" EFs of self-regulation that are involved in processing positive or negative emotional cues to achieve a goal [23,24]. EFs depend on the prefrontal cortex (PFC) area. This region's structural growth develops slowly across development; from childhood, when it results less specialized, through adolescence with synaptic pruning processes up to early adulthood, characterized by complete maturation [25,26]. Hot and Cool EFs follow a bell-shaped curve, with an ascendant line from early adolescence and a peak in middle childhood, between 14 and 15 years old [27].

Evidence suggests that different types of sport may influence EFs in various ways: movement, motivational and emotional enhancement, social interaction, and cooperation [28–30]. Currently, several researchers have proposed that EFs' improvements via sport depend on the movement characteristics involved in the activities [31,32]. Since the environment influences motor skills, sports can be classified as open or closed skills [9]. Open skills sports involve complex cognitive processes, such as perception, attention, planning, strategy development, set changes, ongoing adaptability, and active decision making [33]. They are performed in dynamic and unpredictable environments [9,34]. Basketball, tennis, karate, soccer, and volleyball squash are examples of typical open-skill exercises. Conversely, closed skills involve fewer cognitive demands [33], are performed in a predictable environment [9], and are self-paced [33]. Typical exercises are running, cycling, and swimming [9]. Recent studies suggest that open-skill sports improve cognitive functions, such as attention, perception, short-term memory, as well as EFs, as cognitive flexibility, and inhibition [9,35,36]. People involved in open-skill exercises, who are required to adapt in a constantly changing environment, are hypothesized to have better EFs than those who participate in closed-skill ones [33,37,38].

Despite the increasing occurrence of studies that demonstrate the positive effects of PA on the cognitive domain, results concerning the influence of PA on school achievement are variegated [39–41], although no study showed PA having detrimental effects, but at least no effects [42].

Becker and colleagues [7] found a positive association between sports, EFs, and AP, particularly in math. According to their results, participating in various open-skill sports (i.e., basketball, martial arts, or football) was linked to higher mathematic marks. The authors explained this relationship as increased spatial skills that could be connected to performance on math-related tasks and involvement in open-skill sports. They did not find a significant outcome for literacy since phoneme and letter identification of reading are processes that may less benefit from EFs. In their study, Alesi and colleagues (2014) [43] showed that participants who were involved in karate performed better on working memory, attention, and executive functions tasks.

Moreover, tennis play was associated with better working memory, cognitive flexibility, and inhibition [6]. Dyer and colleagues (2017) [44] found a positive relationship between sport and AP. Their results showed that sports participation predicted English and math performance.

Despite these results from the studies mentioned earlier, little is known about AP as influenced by specific sport categories. For example, research has supported team sports [44]; on the other hand, many studies have emphasized the benefits of martial arts [45–47].

In conclusion, specific sports require different demands related to varying cognitive loading [48].

The purpose of this study is to compare the performance of Cool EF and Hot EF tasks and school achievement, among participants involved in martial arts, team sports, and sedentary children with ages ranging from 7 to 15 years.

Difference among the two sports groups was hypothesized; in particular, that participants involved in martial arts would show better performance on tasks measuring EFs when compared with peers practicing team sports. Moreover, all sports groups would show better performance on EF tasks compared with sedentary peers. Lastly, it was hypothesized that better performance on EFs tasks reflects better school marks on mathematical and linguistic school subjects. As concerning age, the 12-to-15-years-old group was hypothesized to outperform on EF tasks.

2. Materials & Methods

2.1. Participants

A total of 102 Italian school children (58 boys, 44 girls) with an average chronological age of 11.84 (2.41) years were involved in this study.

Participants were classified into two age groups 7–11 (43.1%), 12–15 (56.9%). In addition, 40.2% did martial arts, 18.6% were sedentary, and 41.2% practiced team sports. As concerning gender, 56.9% were male and 43.1% were female. Inclusion criteria were the absence of intellectual disability, visual or neurological impairment, and/or neurodevelopmental disorders; and to correctly understand and speak the Italian language.

Participants practiced martial arts or team sports in their leisure time three times per week at least in the 2 years prior to the research. Sedentary children did not participate in any sport at least in the 2 years prior to the research.

The medium socio-economic level was predominant (51.7%), based on parents' education and employment parameters. Participants were recruited in public schools or gyms, all located in an urban area, based on voluntary participation in the research project. After the headmaster of each school or gym approval, parents were contacted through flyers announcing the research project with aims, procedures, and a guarantee of anonymity and confidentiality for participants. Then parents were invited to allow their children to participate in the study and provide their written consent. This study was carried out following the recommendations of the Declaration of Helsinki (2013) and the Ethical Code of the Italian Association of Psychology (AIP).

Table 1 displays the number of participants for each age group and sport category.

Table 1. Number of participants for age group and sport category.

	Martial Arts	Sedentary	Team Sports	Total
Age				
7–11	13	6	25	44
12–15	28	13	17	58
N	41	19	42	102

2.2. Design

Firstly, a Socio-Demographic Schedule was administered to collect participants' age, education, school marks, and SES. The criteria for SES evaluation were the family size, parents' education, and job. The medium-high status was given by the parental qualification of high school or graduation and job requiring a diploma or high qualification. The medium status was given by parental qualification or middle school and high qualified job as a teacher, employee, shop assistant, or similar. The medium-low status was given from the parental qualification of primary school and qualified to require as housekeeper or student.

A battery of multiple standardized tasks was used to measure executive functioning and multiple standardized tasks were used. This consisted of the following tests: The Stroop test and The Distributed Attention test derived by the CD-ROM from Attenzione e Concentrazione [49]; The Tower of London [50]; The IOWA Gambling Task [51] derived from the Millisecond Inquisit Software; and The Digit Span and The Verbal fluency were measured using the BVN 5–11 [52] and BVN 12–18 [53].

The Digit Span Test was composed of two tasks: the Forward Digit Span, which required participants to repeat a sequence of digits in the same order of the instructions, and the Backward Digit Span, which required participants to repeat the digits in the reverse order of the instructions. Forward Digit Span consisted of 27 sequences ranging from two to nine digits, while Backward Digit Span contained 24 sequences ranging from two to eight digits. The experimenter verbally presented each sequence at the rate of one digit per second. Two trials were administered for each sequence length; if participants were correct on either trial, then they advanced to the following sequence with the number of digits increasing by one. The test was ended when participants failed on two trials of the same length. Scores were computed by counting the total number of digits successfully remembered Forward Digit Span and Backward Digit Span were analyzed as separate dependent variables, and two scores were obtained [54].

The Stroop test assessed the ability to inhibit cognitive interference of word meaning on the ability to name the color of the words appearing on the screen (blue, black, red, and green). There were two categories of stimuli fallen into two categories: congruent trials including words in which color word and the color print matched (i.e., RED painted in red color); incongruent trials including words in which color word and color print were different (i.e., RED printed in blue color). Scores resulted in reaction time and accuracy for congruent and incongruent trials.

The Tower of London (ToL) measured planning strategies. Participants were showed on the laptop screen a wooden set with three pegs and three balls (red, blue, and green), and participants were asked to move balls to reach the configuration, following specific rules (i.e., to move only one ball at a time, do not place ball outside the set, to use a predetermined set of moves). The ToL was composed of 12 trials with an increasing level of difficulty. Scores were computed by counting the correct configuration from 0 to 12 points.

The Iowa Gambling Task (IGT) is a computerized card game to assess decision-making abilities by simulating real-life situations with rewards and punishments. It is composed of four card decks: A, B, C, and D. The A and B decks are "disadvantageous," short-term, and risky card desks. Each participant chooses a card, and s/he immediately gains money, but a high penalty follows the choice. The C and D are "advantageous", long-term, and safe card decks. A smaller gain and lower penalty followed participant's choice. The task is unknown to the participant, consisting of 100 trials (1 trial = 1 card drawn, 20 trials = 1 block). Long-term decision-making is reflected in the IGT score calculated as the number of cards selected from the advantageous, safe decks minus those selected from the disadvantageous, risky decks. The net score of the first 40 trials reflected uncertainty decision-making; the net score of the last 40 trials reflected risk decision-making. A high net score was given by selecting fewer cards from the disadvantageous but immediate reward decks (A and B) and drawing more cards from the advantageous reward decks (C and D). Two singles scores were obtained: 1. "good play," given by the choice from advantageous, good, decks outweigh those from disadvantageous, bad one; 2. "bad play" given by choices from risky, bad decks exceed those from safe, good ones.

The Attenzione e Concentrazione test was used to test distributed attention through a dual-task test. Participants were instructed to push a button whenever a target appeared, simultaneously a list of words, and the child was asked to push another button when he heard the word target. Thus, attention was distributed on two parallel tasks, the visual one and the auditory one. Two scores were entered: correct answers and errors.

The Verbal Fluency Test derived consisted of category fluency and phonemic fluency to test the speed of access to the lexicon. Participants were given a minute to produce as many words as possible within a specific category (i.e., animal, fruits) or starting with a given letter (i.e., S). Scores were computed for each category (or given letter) and a total as a summary by adding all the scores together.

Tasks were administered to each participant by a researcher in a quiet room of the school/gym and required one session of 30 to 40 min. Tasks were presented in a balanced order to avoid the effect of sequence. For example, the initial order was: 1. The Digit Span; 2. The Distributed Attention, 3. The ToL; 4. The Stroop test; 5. The IOWA Gambling Task; 6. The Verbal fluency. Then, the order was 1. The Distributed Attention; 2. The ToL; 3. The Stroop test; 4. The IOWA Gambling Task; 5. The Verbal fluency; 6. The Digit Span, and so on.

School achievement was measured through the final school marks in linguistic and mathematical subjects reported by each participant at the end of the first four months of the school year. School marks ranged from 1 to 10, with higher scores indicating better school achievement. The researcher verified the matching between the self-reported school marks and school report cards.

2.3. Statistical Analysis

SPSS software (Released 26, SPSS Inc. NY, USA) was used to run statistical analyses. Multivariate ANOVA was computed to compare cognitive outcomes in children involved in martial arts, team sports, and sedentary children. The independent variables were sport and age, and the dependent variables were the scores on Hot EFs and Cool EFs tasks, such as working memory, inhibition, planning, attention, and decision making. The significance level was set at $p \leq 0.05$.

3. Results

Data analysis showed significant differences between the three groups for the following cognitive abilities. As concerns the age main effect, 12-to-15-year-old participants had higher scores in working memory [F (1102) = 13.137, p = 0.000, η^2p = 0.123], inhibition [F(1102) = 6.230, p = 0.014, η^2p = 0.062], verbal fluency [F(1102) = 19.106, p = 0.000, η^2p = 0.169], and in auditory distributed attention [F(1102) = 3.771, p = 0.05, η^2p = 0.039]. Moreover, significant differences were found on the IOWA test in the criterion of differences between good and bad play [F(1102) = 10.074, p = 0.002, η^2p = 0.097]. Results are showed in Table 2. As concerns the sport category main effect, children who practiced martial arts performed better in working memory [F(2102) = 3.680, p = 0.029, η^2p = 0.073], inhibition [F(2102) = 10.891, p = 0.000, η^2p = 0.188], distributed attention [F(2102) = 6.410, p = 0.002, η^2p = 0.120], visual distributed attention [F(2102) = 6.921, p = 0.002, η^2p = 0.128], and auditory distributed attention [F(2102) = 5.120, p = 0.008, η^2p = 0.098]. Regarding Hot EFs, a significant difference on IOWA test in good play [F(2102) = 3.232, p = 0.04, η^2p = 0.064] was found. Results are showed in Table 3.

Table 2. Means, standard deviations, and ANOVA results for EFs tasks stratified by age.

	Age						
Executive Functions Tasks	7–11		12–15				
	M	SD	M	SD	F	p	η^2p
Working memory	3.81	(1.31)	5.03	(1.21)	13.137	0.000 ***	0.123
Inhibition	28.24	(8.74)	35.00	(12.28)	6.320	0.014 **	0.062
Verbal Fluency	41.81	(9.25)	51.55	(9.18)	19.106	0.000 ***	0.169
Auditory distributed attention	4.76	(1.41)	5.34	(1.61)	3.771	0.05 *	0.039
IOWA difference between good and bad play	−2.41	(6.95)	1.90	(6.56)	10.074	0.002 **	0.097

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

Table 3. Means, standard deviations, and ANOVA results for EFs tasks stratified by groups.

	Sport Category								
Executive Functions Tasks	Martial Arts		Team Sports		Sedentary				
	M	SD	M	SD	M	SD	F	*p*	η^2p
Working memory	5.13	(1.41)	4.00	(1.21)	4.42	(1.26)	3.680	0.029 *	0.073
Inhibition	39.00	(14.45)	28.50	(5.00)	26.21	(6.73)	10.891	0.000 ***	0.188
Verbal Fluency	49.13	(11.73)	45.55	(8.85)	48.26	(10.30)	0.068	0.935	0.001
Distributed attention	11.08	(4.42)	8.81	(1.29)	8.32	(1.45)	6.410	0.002 **	0.120
Auditory distributed attention	5.69	(2.14)	4.83	(.58)	4.47	(1.21)	5.120	0.008 **	0.098
IOWA good play	71.89	(16.03)	79.27	(13.48)	78.83	(15.76)	3.232	0.044 *	0.064

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

No interaction effects of factors were found.

School marks in linguistic and mathematics were higher in children involved in martial arts than their peers involved in team sport and sedentary children. The martial arts group outperformed in linguistic, both at the ages of 7-to-11-years-old (M = 8.56) and 12-to-15-years-old (M = 7.59). In mathematics, only 7-to-11-years-old children practicing martial arts reported higher scores (M = 8.56) compared to other groups. The means and standard deviations are summarized in Table 4, separately for martial arts, team sports, and sedentary.

Table 4. School marks in linguistic and mathematics for the three-sport categories: martial arts, team sport, and sedentary.

		Sport Category		
School Marks	Age	Martial Arts	Team Sports	Sedentary
Linguistic	7–11 12–15	8.56 (0.73) 7.59 (1.55)	8.04 (1.10) 7.12 (0.78)	7.50 (1.38) 7.38 (1.26)
Mathematics	7–11 12–15	8.56 (0.88) 7.48 (1.28)	8.04 (1.219) 7.65 (0.93)	6.83 (1.17) 7.15 (1.28)

4. Discussion

This study aimed to compare performance on EFs and AP of children practicing martial arts, team sports, and sedentary children with an average age of 11.84 years. Our findings show that the 12-to-15-years-old group would perform better in EF tasks, both Cool and Hot. Higher performances were found in working memory, inhibition, verbal fluency, distributed attention, and decision-making tasks. This is coherent with developmental trajectories showing how a gradual linear maturation defines EFs from preschool throughout adolescence [55].

The gradual growth of EF is widely due to the involvement of the prefrontal cortex (PFC), particularly in the dorsolateral region. Structurally, this region develops slowly across age; from the age of six years, an activation of PFC, although less specialized, is evident when children perform EFs tasks, but this development carries on with the age until reaching the complete maturation in early adulthood age [25,26]

Moreover, participants practicing martial arts displayed a better performance on EF tasks and AP than those who attended team sports or were sedentary. In addition, they performed better in inhibition, working memory, distributed attention, verbal and auditory, verbal fluency tasks, and decision making.

Historically, martial arts have highlighted the importance of self-regulation abilities, and for this reason, the terms self-control and discipline are strongly connected to them [56]. The ability to learn self-control might be recast as the ability to inhibit, repress, control automatic responses, and create responses by using attention and reasoning. In martial arts, attention is focused on the main object, such as the rival, but at the same time distributed across its various features [56]. Moreover, martial arts and other open-skills sport are defined by changing movements and situations, stimulating goal-directed behaviors. As stated in a previous study, children practicing karate regularly show better cognitive functioning in visual selective attention, verbal working memory, reaction time; all these cognitive abilities improve karate performance and differentiate athletes and novices [57]. Specifically, successful karate performance needs high cognitive engagement and EFs components, such as updating and monitoring information in memory, switching attention resources from one task to another, and inhibiting automatic thoughts and behaviors. Moreover, karate triggers goal-directed behaviors to face changing situations and movements.

In the study, a significant benefit was observed for AP, and it consisted in higher marks on linguistic and mathematic areas for children regularly practicing extra-school sports; these results are in line with previous researches and reinforce the beneficial effects of PA on EFs and as a consequence on AP [46,47,57,58]. Moreover, children practicing martial arts had the highest school performance. Based on research, we conjecture that martial arts may improve cognitive development by different pathways: stimulating changes in the brain structure; offering an "enriched environment"; generating social interaction opportunities; enhancing self-confidence and self-awareness [59]. In addition, sports produce benefits on health and EFs and promote the enjoyment, higher self-esteem levels, and social inclusion [60,61].

To sum up, based on our results, PA as martial arts would be helpful to improve school abilities, not only as AP but also as school readiness. As proof of this, Pinto-Escalona et colleagues [47] implemented a one-year karate intervention in five different European countries. In the school gyms, an enriched environment was designed to provide sensomotor stimuli for the motor skills growth and cognitive performance, and the intervention group was trained for 2 h/week on a standard education curriculum through karate exercises. Their significant results included cognitive functioning and physical fitness and AC with a more significant increase in school marks.

Limitations and Future Lines of Research

Interesting implications on the educational fields are supported. Firstly, coherently, it is imperative to encourage sport participation at a young age. Specific parent or teacher education programs would be necessary to share good practices deriving from the awareness of sports benefits. Too often, these benefits are linked only to physical health, as the limitation of overweight and obesity for an increasingly inactive lifestyle on childhood. Teachers and families need to understand how sports activities can contribute to child cognitive development by enhancing planning, sustained and divided attention, working memory, inhibition abilities by enjoying activities. In a complementary way, researchers and practitioners need to understand what sports and exercise interventions are suitable for cognitive development to create the perfect matching between one sports task and one executive function. In particular, as concern the martial arts, it would be remarkable to study the cognitive profiles of children practicing different components such as kumitè and kata characterized by different levels of open or closed skill activities, different goals, and different exercises training programs.

5. Conclusions

To sum up, the findings of this study suggest how sport participation and the practice of martial arts, in particular, contribute to improving school abilities. This study's strength is highlighting the influence of participation in after-school sports activities on the development of EFs and on academic performance. With the recognized benefits of physical fitness for health since childhood, most studies have focused on the benefits of school physical activities.

Furthermore, future research is needed to remedy the shortcomings of this study. A significant limitation lies in methodological concerns as the measurement of children's AP through school grades at the end of the term. Even if the grades were reliable, direct measurements of academic skills such as reading, writing, and arithmetic should be made. This is because EFs directly influence the acquisition of the school-skills as mentioned above, which, together with other contextual and social factors, ultimately result in school grades.

More future research is needed to fully understand the link between sport, EFs, and AP. Results from this study further our understanding of martial arts, which can enhance cognitive development, in particular EFs. Martial arts represent an exercise program supporting life-long physical and psychological positive effects, with significant consequences on EFs and AP.

From the psycho-educational point of view, it is essential promoting participation in sports. It has been shown to significantly increase opportunities for children to be physically active, both in curriculum physical activity and extracurricular sports [62,63].

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Informed Consent Statement: Informed consent was obtained from all subjects' parents involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

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Abbreviations

WHO (World Health Organization), PA (Physical Activity), EF (Executive Functions), AP (Academic Performance).

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Annex C

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Effects of BDNF and COMT epigenetic regulatory polymorphisms on Executive Functions in adolescents

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Abstract

Executive Functions (EFs) are higher-order cognitive processes required for goal-directed behaviors. Literature on the genetic basis of executive functions suggests that these functions are mediated by the modulation of dopaminergic neurotransmission. The aim of the present study was to investigate how the Brain-derived neurotrophic factor (BDNF) Val66Met and the catechol-O-methyltransferase (COMT) Val158Met polymorphisms affect Cool and Hot executive functions. A total of 48 healthy Italian preadolescents, between 8 and 14 years of age, were included in the study. Participants completed the Digit Span Test, the Tower of London, The Balloon Analogue Risk Task, and The Iowa Gambling Task (IGT). The participants who were homozygous for the Val allele for BDNF performed better on the memory task and the decision-making task than Val/Met and Met/Met subjects, while those who were homozygous for the Met allele for COMT performed better on the decision-making task. Results suggest that the Val allele for BDNF and the Met allele for COMT are associated with higher performances on

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some tasks of EFs.
The results reinforce the hypothesis that Val and Met alleles show functional changes related to high order cognitive processes both for BDNF and COMT polymorphisms.

Keywords: BDNF; COMT; Polymorphisms; Executive Functions; Adolescence.

1. Introduction

Executive Functions (EFs) represent a set of higher-order, self-regulatory cognitive processes required for goal-directed thought and behavior (Best, Miller, & Naglieri, 2011; Carlson, Zelazo, & Faja, 2013). EFs include three main cognitive components, such as working memory, inhibition, and cognitive flexibility (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000), as well as emotional control. Working memory concerns the ability to manipulate items and mental representations that are held in mind; inhibition refers to the ability to control and suppress a prevailing response in favor of another response or no response, while cognitive flexibility refers to the ability to switch from one perspective or mindset to another (van der Ven, Kroesbergen, Boom, & Leseman, 2012). Moreover, these cognitive processes are closely related to other higher processes, such as reasoning, problem-solving, planning, and emotional control. Working memory, inhibition and cognitive flexibility are classified as "Cool" EFs (Poon, 2017) and designate cognitive components of self-regulation, while "Hot" EFs are characterized by emotional and motivational components. The latter require a person to process positive or negative emotional cues to achieve a goal and assess risk in everyday tasks that are ecologically conditioned by motivational and emotional influences (Prencipe, Kesek, Cohen, Lamm, Lewis, & Zelazo, 2011). Procrastination or decision-making tasks are typical examples of Hot EFs. The development of EFs suggests that they emerge during infancy, they change during the preschool years, and they continue to develop throughout adolescence in line with the maturation of the prefrontal cortex (Zelazo, Carlson, & Kesek, 2008). During adolescence, brain maturation follows an ongoing structural development of neural regions associated with both Hot and Cool EFs (Prencipe *et al.*, 2011). Further knowledge on the characteristics of EFs has come from genetic studies showing that interindividual differences in phenotype result from gene-gene interactions and gene-environment interactions (McClearn, 2006). Considering the involvement of the pre-frontal cortex and dopaminergic circuits in cognition, this study focused on genes that are involved in the regulation of the dopaminergic function and on the neuronal growth factor, like the Brain-derived neurotrophic factor (BDNF), as well as in the metabolism of the neurotransmitter involved in cognitive function, like catechol-O-methyltransferase (COMT) (Khanthiyong, Thanoi, Reynold, & Nudmamud-Thanoi, 2019). In the metabolism of catecholamines, including dopamine, the COMT gene plays an important role in the proper functioning of the prefrontal cortex, encoding the enzyme which is involved in the metabolism of dopamine (Bowers, Buzzell, Salo, Troller-Renfree, Hodgkinson, Goldman *et al.*, 2020). More specifically, COMT is responsible for the inactivation of dopamine at the pre-frontal cortex. Consequently, alterations in the activity of this enzyme have a high impact on neurological activity. Several functional polymorphisms, associated with this gene, regulate the modification of enzymatic activity; among these, the most studied is a single-nucleotide polymorphism (SNPs) rs4680, also called Val158Met. This polymorphism involves the replacement of guanine with adenine, which determines a replacement in amino acids from methionine to valine (Egan, Goldberg, Kolachana, Callicott, Mazzanti, Straub *et al.*, 2001). In terms of enzymatic activity, methionine determines an alteration of the metabolism of dopamine that induces a longer presence stay in the synaptic space of the neurotransmitter, determining an improvement in cognitive functions (Bowers *et al.*, 2020). Several studies have been carried out to explain the relationship between COMT polymorphisms and cognitive functions, but the results are conflicting. Most of them emphasized the presence of the Val allele being more advantageous compared with the Met allele while other studies showed a strong correlation between an improvement in cognitive function and the Met allele (Moriguchi & Shinohara, 2018; Bowers *et al.*, 2020). Of note is a difference between children and adults in the performance on attention tasks in which the Met/Met genotype was associated with better adult performance, whereas a Val/Met genotype was associated with better adolescent performance (Wahlstrom, Hooper, Vrshek-Schallhorn, Oetting, Brott, & Luciana, 2007). BDNF is the main neurotrophin responsible of the correct functioning of the brain because of its role in the growth and differentiation of neurons and in synaptic plasticity involving dopaminergic neurons (Huang & Reichardt, 2001; De Assis, Gasanov, De Sousa, Kozacz, & Murawska-Cialowicz, 2018). A growing number of studies from the last two decades has shown that BDNF influences synaptic plasticity by causing changes in cognitive functions, learning, and memory (Nieto, Kukuljan, & Silva, 2013). The BDNF gene is located on chromosome 11 and several polymorphisms associated with this gene are known but, since 2008, most studies have focused on rs6265, also known as Val66Met. This single nucleotide polymorphism is the result of the replacement of the amino acid valine with the amino acid methionine at position 66 of the sequence that codes for the protein. This determines the existence of two alleles: the A allele (containing methionine) and the G allele (containing valine). The Val66Met polymorphism has a deep impact on the cell biology of BDNF resulting in trafficking and subcellular behavior of BDNF alteration in both humans and mice. Historically, empirical evidence has indicated that the Met allele confers disadvantaged phenotypes at the cellular, structural, physiological, and behavioral level (Di Carlo, Punzi, & Ursini, 2019) and possibly prevents the interaction with molecules responsible for intracellular transport, such as sortilin and translin (Chen, 2006), which determines the inability of BDNF molecules to be vehiculated in the Golgi apparatus and subsequently secreted into the external environment (Egan, Kojima, Callicott, Goldberg, Kolachana, Bertolino *et al.*, 2003). Consistently, the BDNF genotype that characterizes Val homozygotes was demonstrated to moderate the relationship between cognitive reserves and EFs (Ward, Summers, Saunders, Ritchie, Summers, & Vickers, 2015), whilst BDNF Met alleles were found to be associated with decreased memory abilities (Egan *et al.*, 2003). Moreover, BDNF affects the dopaminergic system and this has focused the attention on the possible link between the polymorphism Val66Met and the Val158Met of the COMT gene. The possible relationship between BDNF and COMT starts from the interaction influencing both working memory and executive functions: the coexistence of the H (Val) variant of COMT and the A (Met) variant of BDNF seems to determine a decrease in EFs (Chen, Chen, Xia, Wu, Chen, He *et al.*, 2016).

2. Aim and hypotheses

The aim of this study was to compare the performance on Cool and Hot EF tasks among adolescents with different polymorphisms of BDNF and COMT with the attempt to fill the knowledge gap in this age group.

Since the literature published to date found that Val/Val for COMT and Met/Met for BDNF determine a reduction of EFs, we hypothesized that the other alleles for COMT (Met) and BDNF (Val) could determine an increase in EFs performance. More specifically, we tested the following hypotheses:

Hypothesis 1. Participants that are Val/Val homozygous for BDNF and Met/Met homozygous for COMT might show a better performance on tasks measuring Cool EFs (working memory, fluency, and inhibitory control) compared to peers with Met/Met for BDNF and Val/Val for COMT.

Hypothesis 2. Participants with the Val/Val allele for BDNF and the Met/Met allele for COMT might show a better performance on tasks measuring Hot EFs (decision-making) compared to peers with Met/Met for BDNF and Val/Val for COMT.

3. Methods

3.1. Sample

Participants were 128 Italian preadolescents and adolescents (69 boys, 59 girls) with an average age of 12.9 years old (*SD* = 2.92). Of these, 48 attended all research phases, included the salivary sampling. Thus, the final sample of this study was composed of 48 participants with an average age of 12.5 years old (± 2.07) and a higher percentage of boys (70.8%) over girls (29.2%). The 48 participants were divided, in turn, in three subsamples for BDNF (8 = Val/Val, 35 = Val/Met, 5 = Met/Met) and in three groups for COMT (16 = Val/Val, 23 = Val/Met, 9 = Met/Met). Inclusion criteria were the following: 1. the absence of intellectual disability, visual or neurological impairment; 2. the absence of neurodevelopmental disorder; 3. to be Caucasian. A medium socio-economic level was predominant, based on the parameters of parents' education and employment. Participants were recruited in their schools or gyms. Parents were contacted through flyers announcing the research project with the aims and procedures clearly described, and anonymity and confidentiality were guaranteed for all the participants. Parents were invited to allow their children to participate in the study and asked to provide written consent. This study was carried out following the recommendations of the Declaration of Helsinki (World Medical Association, 2013) and the Ethical Code of the Italian Association of Psychology (AIP, 1997). Participants were provided with all the information for the correct compilation of the consent form and confidentiality and anonymity were guaranteed making it clear that participants to the study could decide to withhold from participation at all phases of the research. Firstly, a Socio-Demographic Schedule was administered to collect participants' information concerning their age, education, school grades, and SES. The criteria for SES evaluation were parents' number of children, parents' education, and employment. A medium-high status was attributed in the presence of parental qualification at high school or graduation and a job requiring a diploma or a higher qualification. Medium SES status was given if parental qualification was middle school and a high-qualified job, such as a shop assistant or similar. Medium-low status was attributed if the parental qualification was primary school, and the job was qualified as a housekeeper or student.

3.2. Instruments: Executive Functions assessment

Executive Functions were measured by multiple standardized tasks. Four neuropsychological tests derived by the Inquisit Millisecond Software[2] were administered with keyboard inputs: The Digit Span Test (Gugliotta, Bisiacchi, Cendron, Tressoldi, & Vio, 2019), The Tower of London (Shallice, 1982), The Balloon Analogue Risk Task - BART (Lejuez, Read, Kahler, Richards, Ramsey, Stuart *et al.*, 2002), and the Iowa Gambling Task – IGT (Bechara, Damasio, Damasio, & Anderson, 1994).

The Digit Span Test is composed of two types of assessment: Forward Digit Span, which requires participants to repeat a sequence of digits in the same order, and Backward Digit Span, which requires participants to repeat the digits in reverse order. Forward Digit Span consists of 27 sequences ranging from two to nine digits, while Backward Digit Span consists of 24 sequences ranging from two to eight digits. The experimenter verbally presented each sequence at the rate of one digit per second, after which participants were asked to repeat the digits immediately. Two trials were administered for each sequence length; if participants were correct on either trial, then they advanced to the next sequence with the number of digits increasing by one. The test ended when participants failed on two consecutive trials of the same length. Scores were computed by counting the total number of digits successfully remembered in each condition. Forward Digit Span and Backward Digit Span were analyzed as separate variables (Lezak, 1995).

The Tower of London (ToL) is generally considered a measure of visuospatial problem solving because it requires planning strategy. Participants were shown a wooden set with three pegs and three balls (red, blue, and green) on the laptop screen. In the task, participants were asked to move the balls to reach the right configuration (with two or one ball, respectively) in each peg, by using a predetermined set of moves and following specific rules (i.e. only one ball could be moved at a time, no ball could be placed outside the set). ToL is composed of 12 trials with an increasing level of difficulty. The following indexes were calculated: the total score, which corresponds to the sum of the scoring on each trial (maximum score = 48); the planning time in seconds, which results from the sum of the time spent on each item between the instruction and the first move; and execution time in seconds, which results from the difference between the sum of the total time spent on each item and the planning time.

[2] Inquisit Millisecond is a platform to deliver tests to measure cognitive and neuropsychological variables.

The Balloon Analogue Risk Task (BART) is a computerized measure of risk decision-making. In the task, the participants were shown a virtual small balloon with a balloon pump and were offered the opportunity to earn money by pumping up the balloon by pressing a button. As the size of the balloon increased, the associated risk of explosion, as well as the monetary reward, also increased. Each pump allowed the balloon to inflate and 5 cents were collected in a counter until its explosion point was reached, then a "pop" sound effect was emitted from the computer. As soon as the balloon exploded, the money was lost and the new uninflated balloon appeared on the screen. The participant could stop pumping the balloon and collect the money at any time of the test. The exposure to a specific balloon ended following each balloon explosion or money collection and a new balloon appeared up to a total of 90 balloons. Two scores were derived: total balloons exploded and total balloons not exploded.

Finally, the Iowa Gambling Task (IGT) is a computerized card game used to assess decision-making, by simulating real-life situations with rewards and punishments. It is composed of four card decks: A, B, C, and D. The A and B decks are "disadvantageous", short-term and risky card desks. Each participant was asked to choose a card and s/he immediately gained money, but the choice was followed by a high penalty. The C and D are "advantageous", long-term, and safe card decks. Participant's choice, in this case, was followed by a smaller gain and a lower penalty. The task consisted of 100 trials (1 trial = 1 card drawn, 20 trials = 1 block), which were blind to each participant. Long-term decision-making is reflected in the IGT score that is calculated as the number of cards selected from the advantageous, safe decks minus those selected from the disadvantageous, risky decks. The net score of the first 40 trials reflects decision-making in the uncertainty phase because the choice outcomes are relatively unknown in the initial trials; the net score of the last 40 trials reflects decision-making in the risk phase because the choice outcomes are known in the later trials (Brand, Recknor, Grabenhorst, & Bechara, 2007). A high net score is given by selecting fewer cards from the disadvantageous but immediate reward decks (A and B) and drawing more cards from the advantageous reward decks (C and D). Two singles scores were obtained: 1. "good play", given by the choice from advantageous, good, decks outweighing those from disadvantageous, bad decks; 2. "bad play" given by the choice from risky, bad decks exceeding those from safe, good decks.

3.3. Procedure

The above tasks were administered individually to participants in a quiet room of his/her school/gym and required 1 session of 30 to 40 minutes. Tasks were presented in a balanced order to avoid the effect of sequence.

Moreover, for each participant, a saliva sample was taken by passive drool. The samples were collected in a sterile 15-mL centrifuge tube and stored at −80 °C until assay. Genomic DNA was isolated from 1 ml of the whole saliva using a PureLink kit (PureLink Genomic DNA ThermoFisher Scientific) according to the manufacturer's protocol. The genotyping was carried out by polymerase chain reaction (PCR) in a total reaction volume of 50 µl containing 50 ng of template, 1 µl of 10 mM deoxynucleoside triphosphate (dNTPs), 1 µl of 30 pmol each primer, and 5 µl of 10X reaction buffer with $MgCl_2$. The target sequence was amplified using a 5U/µl Dream Taq (Thermo Fisher Scientific) and the primers were the following: P1 (forward) 5' CCTACAGTTCCACCAGGTGAGAAGAGTG-3'; P2 (reverse) 5' TCATGGACATGTTTGCAGCATCTAGGTA 3'; P3 (G allele specific-reverse) 5' CTGGTCCTCATCCAACAGCTCTTCTATaAC 3'; P4 (A allele specific-forward) 5' ATCATTGGCTGACACTTTCGAAC cCA 3' used to determine the BDNF genotype and 5' GGAGCTGGGGGC CTACTGTG 3' (forward) and 5' 59- GGCCCTTTTTCCAGGTCTGACA 3' (reverse) used to determine the COMT genotype. PCR amplification was performed with the following protocol: denaturation at 94°C for 5 minutes, followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 62,5°C for 60 seconds for BDNF and at 60°C for 60 seconds for COMT, extension at 72°C for 60 seconds and final extension at 72°C for 7 minutes. The fragments were separated on 8% vertical polyacrylamide gel at 100 V for one hour and visualized with .5 mg/ml of ethidium bromide.

4. Data analysis

The SPSS software (Released 16, SPSS Inc. NY, USA) was used to run statistical analysis. A preliminary analysis showed that data was not normally distributed. Since assumption was not satisfied, the Spearman rho was used to measure the correlations between the variables studied. A Kruskal-Wallis ANOVA was further performed to examine the possible differences in mean rankings between the rankings obtained in the three groups (Val/Val, Val/Met, Met/Met) for BDNF and the three groups (Val/Val, Val/Met, Met/Met) for COMT.

Non-parametric ANOVA was used to compare the outcome of EFs in the two groups, setting the significance level at $p \leq .05$. The independent variables were the polymorphisms (BDNF and COMT), while the dependent variables were the scores on Hot and Cool EF tasks.

5. Results

A significant correlation was found between Cool and Hot EFs. More specifically, between the planning measured by the ToL execution and the IGT good play ($r = -.286$). Correlations are shown in Table 1.

Table 1 – *Correlation between Cool and Hot EFs tests for BDNF and COMT*

Variables	M (SD)	1	2	3	4	5	6	7	8	9	10
Forward WM	4.71 (1.74)	-									
Backward WM	4.25 (1.74)	.606**	-								
WM tot	9.27 (3.23)	.761**	.897**	-							
ToL	8.73 (2.87)	.049	.112	.090	-						
ToL plan	33.7 (38.4)	.093	.013	.036	.053	-					
ToL exec	120 (75.5)	.247	.249*	.353*	.180	.746**	-				
BART exploded	6.90 (3.57)	.042	.216	.119	.101	-.169	-.105	-			
BART not exploded	23.1 (5.73)	-.042	-.216	-.119	-.101	.169	.105	NA	-		
IOWA good play	73.8 (17.0)	-.101	-.166	-.103	-.070	-.286*	-.213	.135	-.135	-	
IOWA bad play	74.9 (14.2)	-.184	-.227	-.190	.010	-.005	-.092	.171	-.171	.838**	-

Legend: WM = working memory; WM tot = sum of Forward and Backward working memory; ToL = Tower of London test; ToL plan = time spent planning on the Tower of London (seconds); ToL exec = time spent in execution on the Tower of London (seconds); BART exploded = number of exploded balloons on the Balloon Analogue Risk Task; BART not exploded = number of not exploded balloons on the Balloon Analogue Risk Task; IOWA good play = score given by the sum of the choices from advantageous decks; IOWA bad play = score given by the sum of the choices from disadvantageous decks.
*$p < .05$. **$p < .01$.

Significant mean rank differences among the three groups with different BDNF polymorphisms (Val/Val, Val/Met, Met/Met) were found for both Cool (memory tasks) and Hot (decision-making tasks) EFs. As regards Cool EF tasks, significant differences were found for the Forward Memory Task ($p = .010$; see Tab. 2 for more details).

Table 2 – *Mean ranks of the three subsamples of BDNF and COMT for the Digit Span Test, the Tower of London, the Balloon Analogue Risk Task and the Iowa Gambling Task*

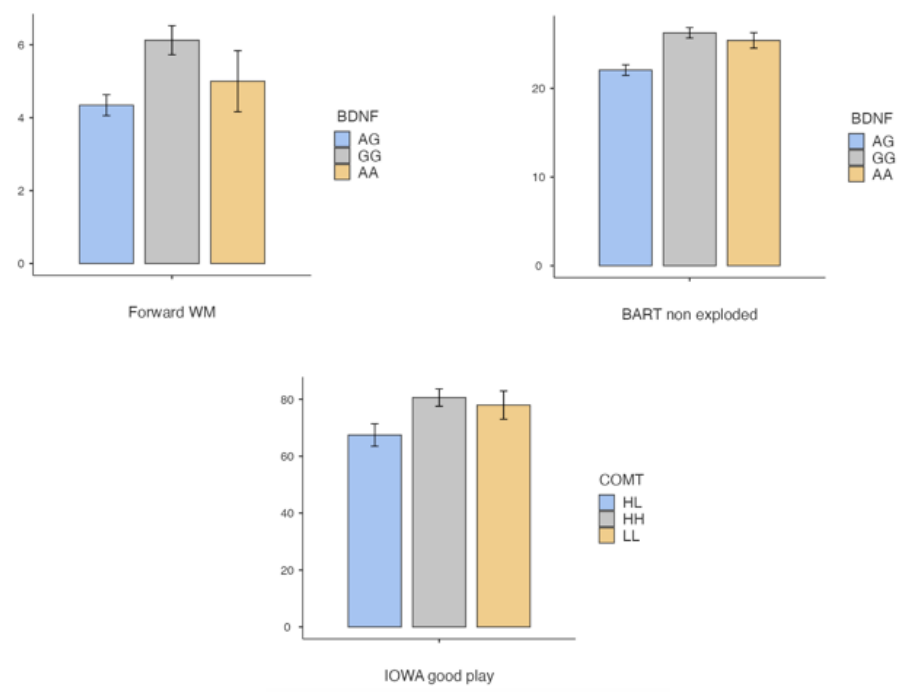
	BDNF					COMT				
	Met/Val (n = 35)	Val/Val (n = 8)	Met/Met (n = 5)	*p*	Post hoc	Met/Val (n = 23)	Val/Val (n = 16)	Met/Met (n = 9)	*p*	Post hoc
Forward WM	21.16	37.00	27.90	.01**	1,2	23.61	24.34	27.06	.81	
Backward WM	25.97	16.13	27.60	.15		21.61	27.34	26.83	.36	
WM tot	23.93	25.50	26.90	.88		21.46	27.84	26.33	.33	
ToL	24.90	23.63	23.10	.94		27.17	20.72	24.39	.36	
ToL plan	23.14	28.38	27.80	.54		23.57	27.25	22.00	.60	
ToL exec	24.14	24.56	26.90	.92		22.11	27.66	25.00	.47	
BART exploded	29.00	10.81	14.90	.001***	1,2	19.63	28.13	30.50	.06	
BART not exploded	20.00	38.19	34.10	.001**	1,2	29.37	20.88	18.50	.06	
IOWA good play	25.07	24.81	20.00	.75		19.24	30.22	27.78	.04*	1,3
IOWA bad play	25.51	25.06	16.50	.40		20.46	29.19	26.50	.14	

Legend: WM = working memory; WM tot = sum of Forward and Backward working memory; ToL = Tower of London test; ToL plan = time spent planning on the Tower of London (seconds); ToL exec = time spent in execution on the Tower of London (seconds); BART exploded = number of exploded balloons on the Balloon Analogue Risk Task; BART not exploded = number of not exploded balloons on the Balloon Analogue Risk Task; IOWA good play = score given by the sum of the choices from advantageous decks; IOWA bad play = score given by the sum of the choices from disadvantageous decks.
1 Met/Val
2 Val/Val
2 Met/Met
**p* < .05. ***p* < .01. ****p* < .001.

As regards Hot EF tasks, significant differences were found for tasks connected to decision-making. In fact, both exploded and not exploded balloon measures of the BART task were highly significant (p = .001). The post hoc Bonferroni test showed significant differences between the Met/Val and Val/Val groups on the Forward Memory Task (p = .003) and on both the exploded balloon (p = .03) and not exploded balloon (p = .004) of the BART test. The Val/Val groups showed the best memory performance. Moreover, Val/Val showed the best performance with the lowest number of exploded balloons and highest number of not exploded balloons.

Regarding the COMT polymorphism, significant differences were found only for Hot EFs but not for Cool EFs. More specifically, significant between-subject differences were found for the Iowa "good play" measure (p = .04; refer to Tab. 2 for more details). The post hoc Bonferroni test showed significant differences between the Val/Met and Val/Val groups on the IGT "good play" (p = .02) with the Val/Val group scoring the highest performance. Figure 1 depicts the significant differences among the subsamples for BDNF and COMT.

Figure 1 – *Significant differences among the subsamples for BDNF and COMT*



6. Discussion

This study was aimed to examine COMT and BDNF polymorphisms on Hot and Cool EFs in adolescents.

We hypothesized that participants with Val/Val for BDNF and Met/Met for COMT would show a better performance both on tasks measuring Cool EFs (working memory and planning tasks) and Hot EFs (decision-making).

Indeed, as assumed, COMT and BDNF had some effect on EFs. For BDNF, in the case of Cool EFs, our findings showed that Val/Val homozygosity resulted in significant differences for tasks that involved Forward Memory abilities. Although the Backward Digit Span task is considered a better index of EF since it requires both the maintenance and manipulation of information in working memory, the Forward Digit Span task is still a reliable measure of short-term memory and was used in this study as a warm-up task of memory abilities. Participants with Val/Val for BDNF were better on memory performance than peers with Met/Val and Met/Met. This result is coherent with previous research that highlighted the association between the Met-BDNF allele and the decreased hippocampal function in humans, such as, the decreased performance on episodic memory tasks (Egan *et al.*, 2003; Hariri, Goldberg, Mattay, Kolachana, Callicott, Egan *et al.*, 2003; Galloway, Woo, & Lu, 2008) as well as the reduction in PFC gray matter volume (Pezawas, Verchinski, Mattay, Callicott, Kolachana, & Straub, 2004). However, other studies did not support these significant impairments in working memory (Egan *et al.*, 2003; Hansell, James, Duffy, Birley, Luciano, Geffen *et al.*, 2007).

Hot EFs displayed significant differences in the risk decision-making task for the BART test. Participants who were Val/Val homozygous for BDNF showed better risk decision-making abilities, scoring the highest number of not exploded balloons and the lowest number of exploded balloons. Thus, they appeared more cautious by using more inhibitory control. This positive correlation of the BDNF Val allele with cognitive abilities is consistent with previous research (Sheldrick, Krug, Markov, Leube, Michel, Zerres *et al.*, 2008; Kang, Namkoong, Ha, Jhung, Kim, & Kim, 2010; Jasinska, Molfese, Kornilov, Mencl, Frost, Lee *et al.*, 2016). In a previous study, Kang and colleagues (Kang *et al.*, 2010) demonstrated that the Met allele of BDNF was associated with a poorer performance in decision-making tasks in adults, measured by the IGT.

Regarding COMT, only one significant difference was found on the IGT test. Participants who were homozygous for Val/Val performed better on the measure of "good play". This result was not in line with our hypotheses. A plausible explanation for this result lies in the nature of the IGT. This test was used to measure the ability to learn to sacrifice immediate rewards in favor of long-term gains. Participants' performance tends to change from the initial, potentially adverse, phase of exploration, in which a participant has no explicit knowledge of rewards/punishments, to the next phase, in which subjects can learn about the choices made with long-term rewards (Brand *et al.*, 2007). Subjects become increasingly more able to understand the logic of the game and to differentiate between advantageous and disadvantageous decks. However, some findings demonstrated that the Met polymorphism of COMT was significantly associated with a lack of improvement on the IOWA score. Improvement requires the gradual learning by the experience accumulated concerned with the choice-outcomes of rewards and punishments (Wahlstrom *et al.*, 2007). Other studies demonstrated a disadvantageous choice on the decision-making task by adults with the Met allele for COMT (van der Bos, Homberg, Gijsbers, den Heijer, & Cuppen, 2009; Malloy-Diniz, Lage, Campos, de Paula, de Souza Costa, Romano-Silva *et al.*, 2013). Malloy-Diniz and colleagues found that the Met allele in adult individuals was linked with a poor performance in a decision-making task, using IGT (Malloy-Diniz *et al.*, 2013). Moreover, we assume that the participants' age may account for discrepancies between our findings and those of other studies. To date, most studies were carried out on adult samples and performances on IGT have been shown to be very sensitive to developmental differences. Previous research demonstrated that the propensity to avoid play by drawing cards from the riskiest decks enhances with age in a linear way and adults tend to avoid disadvantageous decks and delay immediate gratification more than preadolescents and adolescents (Cauffman, Shulman, Steinberg, Claus, Banich, Graham *et al.*, 2010).

A potential reason for the lack of consistency between the results obtained on the BART and IGT tests lies in their nature because they measure different aspects of the decision-making ability (Balagueró, Jodar Vicente, Garcia Molina, Tormos, & Roig Rovira, 2016). IGT is more difficult to perform because it requires abilities of complex verbal comprehension and intact functioning of most executive functions, i.e. mnesic and attentional abilities, to realize the reward and punishment. Instead, the BART test is a simpler computerized task that requires a simpler decision to obtain as much money as possible without any predetermined logic.

Despite the limitations, a strength of this study was the extensive testing of Cool and Hot EFs performed, while previous studies addressed one or the other component of the EFs. Moreover, another strength was the age of the participants. To the best of our knowledge, the study of BDNF and COMT polymorphisms on Hot EFs was carried out only in adult samples or clinical samples (Colliva, Ferrari, Benatti, Guerra, Tascedda, & Blom, 2019). Our study addresses adolescence, which as a developmental phase is crucial in the long process of maturation of the EF system. Thus, we argue that the impact of the findings of the present study has targeted the area of social science genetic research aimed at better understanding environmental effects (family parenting, educational and school environment, policy interventions, economic conditions etc.) and at explaining whether and how genetic differences would influence differences in behavioral outcomes and contribute to educational attainment (Harden & Koellinger, 2020).

However, a shortcoming of this study lies in the limited sample size due to recruitment difficulties. Only a minority of parents in the initial sample gave consent to allow their children to participate in the saliva sampling and genotyping. This caused the higher prevalence of males in our final sample, which prevented us from comparing performances on EF tasks between boys and girls. But at the same time this indicates skepticism of the genetic procedures on the part of the parents, even if the saliva sampling was not invasive, as they were told.

Future research on the involvement of BDNF and COMT in EFs during preadolescence and adolescence is needed to better understand the delicate processes underlying their role in EFs.

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