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IMPORTANCE OF MOTOR SKILLS IN EARLY CHILDHOOD

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List of publications that the Dissertation is based upon

Study	Publication	Status	Impact Factor
1	**Gandotra, A.,** Csaba, S., Sattar, Y., Cserényi, V., Bizonics, R., Cserjesi, R., & Kotyuk, E. (2021). A Meta-analysis of the Relationship between Motor Skills and Executive Functions in Typically-developing Children. *Journal of Cognition and Development*, 1-28	Accepted, published online	1.82
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3	**Gandotra, A**., Cserjesi, R., Bizonics, R., & Kotyuk, E. (2021). Age differences in executive functions among Hungarian preschoolers. *European Journal of Developmental Psychology*, *18*(5), 695-710.	Accepted, published online	2.08
4	**Gandotra, A.,** Kotyuk, E., Szekely, A., Kasos, K., Csirmaz, L., & Cserjesi, R. (2020). Fundamental movement skills in children with autism spectrum disorder: A systematic review. *Research in Autism Spectrum Disorders*, *78*, 101632.	Accepted, published online	2.08

List of publications that are not in the topic of Dissertation

Study	Publication	Status	Impact Factor
1	**Gandotra, A.,** Mehrotra, S., & Bharath, S. (2017). Psychological recovery and its correlates in adults seeking outpatient psychiatric services: An exploratory study from an Indian tertiary care setting. *Asian journal of psychiatry*, *29*, 77-82.	Accepted, published online	3.54
2	Mehrotra, S., **Gandotra, A.,** Sudhir, P. M., Thirthalli, J., & Rao, G. N. (2017). Why urban Indians are interested in an internet-based self-care app for depression? a brief pilot survey. *International Journal of Community Medicine and Public Health*, *4*(6), 2197-2201.	Accepted, published online	1.23
3	Mehrotra, S., Sudhir, P. M., Thirthalli, J., Rao, G. N., Srikanth, T. K., & **Gandotra, A. (**2017). Profile of seekers of an internet-based self-help program for depression in India: observations and implications. *International Journal of Community Medicine and Public Health*, *4*(9), 3202-3211.	Accepted, published online	1.23
4	Mehrotra, S., Kumar, S., Sudhir, P., Rao, G. N., Thirthalli, J., & **Gandotra, A**. (2017). Unguided mental health self-help apps: Reflections on challenges through a clinician's lens. *Indian Journal of Psychological Medicine*, *39*(5), 707.	Accepted, published online	1.072

1. SUMMARY OF THE DISSERTATION

Movement is an essential factor in the optimal and healthy development of children. Movement forms an important foundation for the child's physical development and is considered to be a strong predictor for an active lifestyle. Besides being important for physical development, movement also contributes to children's cognitive functioning, social skills and adaptive behaviour. Despite its significance, movement is often an overlooked aspect of development in the discipline of child psychology. In light of this, the purpose of the present dissertation was to demonstrate the importance of motor skills by investigating its relationship with other developmental domains during early childhood. To address this objective, a total of four studies were carried out. Out of which, one was a meta-analytic study, two were cross-sectional studies and the final study consisted of a systematic review.

The purpose of the meta-analytic study was to provide evidence for the relationship between motor skills and executive functions (EFs) in typically developing children. The results demonstrated significant positive associations between the different components of motor skills and EFs, confirming the theoretical notion about the fundamental interdependence between the two developmental domains.

With respect to the cross-sectional studies, the aim of the first study was to examine the link between motor skills and indicators of cognitive and socio-emotional development in a sample of Hungarian preschoolers. The vast majority of the existing studies on the relationship between motor skills and EFs are done in school going children and the extent to which the results can be generalized to preschoolers is still not clear. Alongside cognition, motor skills are also considered to play an important role in a child's social and emotional functioning. An important component of socio-emotional development in childhood that has been less studied in conjunction with motor skills is prosocial behaviour, a key element in the social adjustment of the children. The results showed significant positive association of motor skills with executive functions and prosocial behaviour. It was also found that fine motor skills compared to gross motor skills were a stronger predictor for response inhibition whereas gross motor skills dominated over fine motor skills in predicting prosocial behaviour in preschool-aged children.

In our next cross-sectional study, we decided to investigate the developmental trajectories of executive functions amongst Hungarian preschoolers. Executive functions like motor skills are particularly crucial during early childhood as they are associated with myriad of positive outcomes including school readiness, academic success, socioemotional competence and mental health. These benefits along with the rapid brain maturational processes that take place during this developmental period makes it an ideal time to investigate the nature and factors influencing the development of EFs. In addition, the preschool education system in Hungary has several distinctive characteristics compared to the USA and most Western European countries which makes it essential for a thorough examination of the development of EFs among Hungarian preschoolers. The results of our study showed that all the three components of EF improved as a function of age. However, unlike previous studies, our study found that most of the 3-years old participants demonstrated superior performance on cognitive flexibility task, thereby drawing our attention to the potential influence of early childhood education, via child-rearing beliefs and practices on the promotion of EF skills.

In the final study of the dissertation, a systematic review was carried out to determine whether impairments in fundamental movement skills (FMS) have the potential to be an early motor marker in the diagnosis of autism spectrum disorder (ASD). This need was necessitated in the context of the increasing prevalence and significant costs associated with the management of ASD. The results indicated that impairments in FMS were highly widespread in children with ASD and have the potential to be early motor marker in children with ASD

The findings of the dissertation clearly highlight that motor skills are an important pillar of child development. It is therefore highly recommended that the development and promotion of motor skills should be considered as an integral part of early childhood development programs.

2. GENERAL INTRODUCTION

Movement is an essential part of children's lives from the very moment they are born and is a window into typical development. Movement creates new experiences that facilitates child's learning and growth. Early childhood is considered to be a sensitive period in terms of children's overall growth and development. During this period, motor skills develop markedly, laying the foundations for success in a number of other developmental areas, including language, cognition, physical and social development (Bar-Haim & Bart, 2006; Campos et al., 2000; Diamond, 2007; Iverson, 2010; Rosenbaum et al., 2001). Despite its significance, movement is an overlooked aspect of development in the discipline of child psychology. In view of this, the present dissertation was undertaken to extend the knowledge about the significance of motor skills, by studying its association with cognitive skills and socio-emotional skills in early childhood. During early childhood (defined as ages 3 to 7 years in this dissertation), movement is based on the children's ability to perform motor skills.

2.1 Definition of Terms and Constructs

2.1.1. Motor Skills

Motor skills (also known as movement skills in this dissertation) are defined as observable, "goal-directed movement patterns" (Burton & Miller, 1998, p.44). Motor skills during early childhood can be broadly classified into two different groups i.e., gross motor skills and fine motor skills (Magill & Anderson, 2010). *Gross motor skills* refer to the ability to effectively move through space using the large, force-producing muscles of the body (Haywood & Getchell, 2009). A specific set of gross motor skills are *Fundamental movement skills* (FMS). These are large movements that involve different body parts such as the feet, legs, trunk, hands, arms and head

(Hulteen et al., 2018). FMS can be broadly classified into three groups (Fig. 1): locomotor skills, stability skills (or balance), and manipulative (or object control) skills. *Locomotor skills* are those that engage the body in movement in different directions. *Balance skills* are those that enhance body balance when in situ or in motion. *Manipulative skills* involve handling and controlling objects with the hand or foot (Haywood & Getchell, 2009).

Figure 1.

Classification of Fundamental Movement Skills

LOCOMOTOR SKILLS	STABILITY SKILLS	MANIPULATIVE SKILLS
Walking	Balancing	Throwing
Running	Landing	Catching
Hopping	Turning	Striking
Skipping	Twisting	Kicking
Bounding	Bending	Dribbling
Leaping	Stretching	Bouncing
Jumping	Extending	Pushing
Rolling	Flexing	Pulling
Galloping	Hanging	Carrying
Sliding	Bracing	Trapping

The other group of the classification is *Fine motor skills*, refer to the precise movements of small muscle groups in the fingers, hands, and wrists to efficiently manipulate objects such as tying shoelaces, flipping pages of books, cutting with scissors, and making shapes from folding paper (Clark & Whitall, 1989). These types of abilities require eye-hand coordination and high accuracy of movements (James & Engelhardt, 2012; Santrock, 2007).

Models of Motor Development

There are a number of models that explains the motor development during early childhood. The basic tenets of these models i.e., hierarchical model (Seefeldt, 1980); triangulated hourglass model (Gallahue & Colleagues, 2012); and the mountain of motor development model (Clark and Metcalfe, 2002) are as follows:

1. Development of motor skills during early childhood takes place in broadly four different phases namely, reflexive phase; rudimentary movement phase; fundamental movement skills phase and specialized movement phase.

a) During the reflexive phase (birth to approximately 1 year), infants demonstrate involuntary movements that are necessary for their survival. This phase is quite important as it forms the basis for the infant's capacity to make future movements (Seefeldt, 1980).

b) The reflexive phase is followed by the rudimentary movement phase (1-2 years). This phase is characterized by the growing ability of the infant to make voluntarily movements such as reaching, grasping and crawling, sitting and walking.

c) The next phase is the fundamental movement skills phase (2-7 years). During this phase, children acquire and gain proficiency over balance, locomotor and object-control skills.

d) In the specialized movement phase (8-13 years) children engage in a wide range of sports and dance specific skills.

2. The progress from one phase to another takes place over a period of time as a result of dynamic interplay between biological and environmental factors.

3. All of the models of motor development emphasize the importance of gaining competence in FMS during early childhood as it is a significant factor underlying children's engagement in current and future physical activity.

Significance of Motor Skills

Motor skills are critical for a child's healthy development as they form an important foundation for their physical, cognitive and socio-emotional development. Good motor skills have been found to provide a basis for active lifestyle (Lubans et al., 2012; Williams et al., 2008), high levels of participation in sports (Clark, 1994), optimum body weight (Logan and Getchell 2010) and cardiorespiratory fitness (Okely et al., 2001). Similarly, several studies have indicated that motor skills initiates tremendous consequences in other developmental domains such cognitive development (Diamond & Lee, 2011), language development (Walle & Campos, 2014) and socio-emotional development (Bar-Haim & Bart, 2006; Campos et al., 2000; Karasik et al., 2014). Lastly, there is also growing evidence suggesting that impairments in motor skills may have the potential to be an earlier behavioural maker for many neurodevelopmental disorders (NDD) (see review Micai et al., 2020).

In the following section, we will elucidate on the other constructs of our dissertation i.e., cognitive skills and socio-emotional skills and will look into the role of motor skills in relation with them.

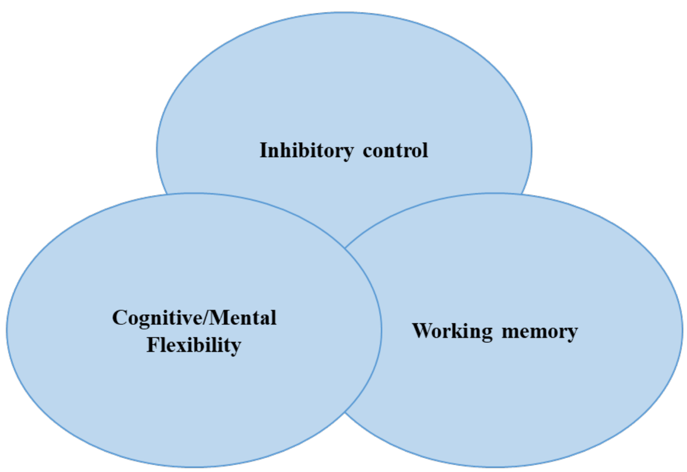
2.1.2. Cognitive Skills

"Cognitive skills refer to the processes or faculties by which knowledge is acquired and manipulated" (Bjorklund, 2005a, p. 2). In simple words, cognition are mental processes that enables children to receive, process, integrate and respond to information. These cognitive processes include learning, attention, memory, perception, thinking and problem-solving. It is important to note that these processes cannot be directly measured but have to be inferred from the behaviour that can be observed (Bjorklund, 2005a). Cognitive skills can be classified into basic mental processes (such as encoding and classifying a stimulus) and higher order processes (such as solving a problem, evaluating a situation and modify a behaviour). The higher order cognitive processes are also known as executive functions (EFs). Executive functions are one of the main focuses of the dissertation.

Executive Functions. Is an umbrella term that refers to a set of higher order cognitive processes which enables individuals to interact with their environment in an adaptive manner (Diamond, 2013). Currently, several authors have established that executive functions in preschool children comprises of three interrelated (Fig. 2) yet distinct components – namely, response inhibition (RI), working memory (WM), and cognitive flexibility (CF) (or set shifting) (Diamond, 2013; Miyake et al., 2000).

Figure 2.

Three- category Model of Executive Functions



Response inhibition or inhibitory control refers to the ability to override an automatic response in favour of a more appropriate subordinate response. Response inhibition is considered to be the foundation of EFs since it is the first component to develop (Miyake et al., 2000). *Working memory* is defined as the ability to temporarily hold information in mind and mentally work on it to achieve a goal (Garon et al., 2008). *Cognitive flexibility* (also known as set shifting) is the last

EF component to develop as it builds on inhibitory control and working memory, is defined as the ability to rapidly switch between mental sets (Miyake et al., 2000).

Executive functions develop rapidly during preschool years and are associated with host of positive outcomes such as school readiness (Welsch et al., 2010), academic success (Blair & Razza, 2007), socio-emotional competence (Kraybill & Bell, 2013), and mental health (Schoemaker et al., 2012). The significance of executive functions in development is further implicated in evidence showing deficits in EFs as central to the aetiology of a wide range of neurodevelopmental disorders such as attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder (ASD) (Roselli et al., 2008; Willcutt et al., 2005).

During early childhood, EFs undergo dramatic changes as a result of the rapid brain maturation processes (Casey et al., 2005; Kagan et al., 2005; Thompson & Nelson, 2001), such as increased myelination, synaptic pruning, and the formation of neural networks in the prefrontal cortex (an area of the brain thought to underlie EF) (Blair & Ursache, 2011; Zelazo et al., 2016). Besides biological influences, the development of EFs is also related to broader environmental factors including early childhood education and care (also known as preschool education). A growing body of research suggests that early learning opportunities through preschool education are positively associated with a child's cognitive and intellectual performance (Anderson 2002; Burger, 2010; Currie, 2001; Karoly et al., 2005). For instance, the enriched learning environment provided through preschool curriculum has been linked to an improvement in children's working memory, inhibitory control and set-shifting abilities (Bierman et al., 2008).

2.1.3. Relationship between Motor Skills and Executive Functions

Traditionally, motor skills and cognitive skills have been viewed as separate entities, developing independently and involving different brain structures (Schmuckler,1993). However, in recent years there has been a growing recognition that children's ability to move may have important implications for their cognitive development. One explanation stem from neurobiological studies, which have demonstrated the parallel activation of the prefrontal cortex (responsible for EFs), the cerebellum (responsible for coordinating voluntary movements), and the basal ganglia (responsible for the planning and execution of movements) during the performance of complex motor and EFs tasks (Diamond, 2000; Pangelinan et al., 2011; Pulvermüller et al., 2005).

A second explanation of the relationship between motor skills and EFs comes from behavioural studies involving children with developmental disorders, who are characterized by high levels of comorbidity between cognitive and motor symptoms such as attention-deficit/hyperactivity disorder (ADHD) (Klimkeit et al., 2004; Pitcher et al., 2003), developmental coordination disorder (DCD) (Dewey et al., 2002; Mandich et al., 2003), and developmental apraxia of speech (DAS) (Viholainen et al., 2002). Children with these disorders have been found to consistently demonstrate lower scores on tests for motor coordination (Kaplan et al., 1998; Piek et al., 1999), response inhibition (Michel et al., 2019), and working memory (Pennington & Ozonoff, 1996; Piek et al., 2007). Children with motor coordination difficulties such as DCD, for example, have been found to exhibit particular difficulties in the performance of EFs (Leonard et al., 2015; Molitor et al., 2015; Rahimi-Golkhandan et al., 2014). Conversely, motor impairments have been identified in children diagnosed with cognitive disorders (Houwen et al., 2016).

A third explanation is that complex motor and cognitive tasks, share several common underlying processes, such as information processing, monitoring and organization of behaviour, attention to or inhibition of irrelevant stimuli and sequencing of actions (Livesey, Keen, Rouse, & White, 2006; Roebers & Kauer, 2009; Wassenberg et al., 2005).

Finally, intervention studies have provided indirect evidence for the link between motor skills and EFs by demonstrating an improvement in children's executive functioning following exposure to cognitively enriching physical activities (Budde et al., 2008; Ellemberg & St-Louis-Deschênes, 2010; Schmidt et al., 2015).

Despite the growing body of evidence suggesting an association between motor skills and higher-order cognitive processes (e.g., response inhibition, working memory, and cognitive flexibility) (Miyake et al., 2000), there is no clear picture of the precise nature of the relationship between these two domains in typically developing children.

2.1.4. Socio-Emotional Skills

In the present dissertation, prosocial behaviour is used as an indicator of socio-emotional development because it has been less studied in conjunction with motor skills during early childhood. Prosocial behaviour is a key element in the social adjustment of the child (Eisenberg & Fabes, 1990) and is defined as an intentional or voluntary act in which an individual engages in order to benefit another person (Eisenberg et al., 2006). Prosocial behaviour develops rapidly during early childhood and is typically demonstrated by preschoolers in the form of cooperation, sharing, helping, and comforting acts (Svetlova et al., 2010; Warneken & Tomasello, 2007). Much of the existing work on the developmental origins of prosocial behaviour has focused on the child's early socialization processes (Hay, 1994; Eivers et al., 2012), cognitive maturity (Aguilar-Pardo et al., 2013), and emotional regulation (Laible et al., 2014; Miller et al., 1996). However, it is important to consider that the appearance of early forms of prosociality precedes the emergence of these forms of complex social cognition, leaving the sources that contribute to prosocial behaviour during early childhood as less understood. Findings from studies on infants have shown that basic developmental attainment, namely gross motor and fine motor skills give rise to early prosocial behaviour (Köster et al., 2019). Motor abilities may provide infants with a novel awareness for their own competence to help (i.e., action-perception coupling; Anderson et al., 2013), an important prerequisite for helping behaviour (Rheingold, 1982. p. 114). This emerging realization of their competence in motor skills may facilitate infant's early prosocial actions by providing them with a number of opportunities for social interactions (Caputi et al., 2012; Layous et al., 2012; Pellegrini & Smith, 1998).

2.2. Theoretical Perspectives

There are several theoretical perspectives which states that motor skills are functionally intertwined with other developmental domains. Some of these theories are described below:

Piaget's theory of cognitive development (1936): One of the earliest theorists who proposed that children's ability to move has important implications for the emergence of their cognitive abilities was Piaget (1953). Piaget hypothesized that children's sensorimotor experiences are necessary for the attainment of higher cognitive skills (Piaget & Inhelder, 1996).

Influenced by the work of Piaget, Campos & colleagues (2000) provided contemporary account on the relationship between motor skills and cognition. Campos & colleagues posited that independent mobility in the form of locomotor activities initiates a cascade of consequences affecting children's cognitive development and social interactions. According to them, walking offers numerous advantages for children's interactions with the world. For instance, walking affords a more flexible viewpoint while locomoting (Clearfield, 2011), and frees the hands to manipulate and direct attention to objects of interest (Clearfield et al., 2008). However, the authors emphasizes that it is not the emergence of locomotor abilities per se that is responsible for creating a phenomenon, but rather the functional consequences of its acquisition on development, such as, increased ability to shift attention, increased intentionality and goal-directed behaviour, better concept formation, changes in parental expectations, and widespread social interactions (Bertenthal etal., 1984; Campos, Kermoian, Witherington, & Chen, 1997).

Embodied cognition perspective: The idea that there is a relationship between motor skills and other developmental domains also in part stem from embodied cognition perspective (Wilson, 2002). The main principle of embodied cognition is that cognitive processes occur in the context of individual's bodily interaction with the world. The basic views of embodied cognition theory are as follows: 1). Cognition is situated: meaning that cognitive development takes place in the context of a real-world environment. 2). Cognition is time pressured: suggesting that cognition must be understood in terms of how it evolves within environmental time-limits. 3). We off-load cognitive work onto the environment: The individual offloads information to the environment due to its limited information-processing capacity. For instance, it has been shown that there are numerous cases where the person needs to offload cognitive work to the sensorimotor control, such as when opting to use a pen and paper to perform calculations rather than performing mental arithmetic (Anderson et al., 2003). 4). The environment is part of the cognitive system: Because of the continuous flow of information between mind and the physical world, cognition needs to be understood in relation with the environment. 5) Cognition is for action: cognitive mechanism must be understood in terms of their involvement in serving appropriate behaviour according to the situational demands. 6) Offline cognition is body based: the activity of the mind is grounded in mechanisms evolved for environmental interaction; such as sensorimotor control.

The above six principles of embodied cognition provide useful insights on the relationship between motor and cognitive skills and suggests that children come to understand the world through the use of motor skills (Thelen, 1995)

Theories of Reciprocity and Automaticity: In keeping with the above ideas, more recent theoretical accounts based on the concepts of reciprocity and automaticity have offered explanations of the relationship between the development of motor skills and EFs (Kim et al., 2018).

The notion of *reciprocity* suggest that motor skills and cognition develop and improve alongside each other (McClelland & Cameron, 2019). For instance, in early childhood, the increasing ability of the child to learn to control, coordinate, and integrate multiple body movements into a coherent organized system supports their cognitive functioning, which in turn allows for the acquisition of more diverse and complex movement skills (Adolph, 2008). *Automaticity,* on the other hand refers to the competition for attentional resources between motor and cognitive tasks. When a new motor task is performed, there is a greater need for cognitive attentional resources. However, practicing motor tasks leads to automaticity, meaning that fewer cognitive attentional resources are required for their successful performance (Floyer-Lea & Matthews, 2004). Once a skill becomes automatic, attentional resources can rather be devoted to cognitive processes (Cameron et al., 2012). At the same time, if EFs are no longer involved in the performance of an automated motor task, it becomes easier to simultaneously perform a second task that does require EFs (Floyer-Lea & Matthews, 2004).

Collectively, the above theoretical models suggest that motor skills are interlinked with other developmental domains and that they cannot be viewed as independent entities.

2.3. Motor Skills as an early behavioural marker for Neurodevelopmental Disorders

Neurodevelopmental disorders (NDDs) are multifaceted conditions characterized by difficulties in language and speech, cognition, behaviour, motor skills or other neurological functions. These conditions arise from atypical brain development and include intellectual developmental disorders, autism spectrum disorder (ASD), attention deficit/hyperactivity disorder (ADHD) specific learning disorder, and motor disorders (DSM-5; American Psychiatric Association, 2013). Autism spectrum disorder (ASD) is one of the most commonly diagnosed and investigated NDDs' in childhood (Maenner, 2020). The increased prevalence and significant costs related to the care of children with ASD (Lavelle et al., 2014) have fuelled a renewed interest in identifying the biomarkers and symptoms of ASD for early detection and the development of effective interventions. A number of studies have demonstrated that motor disturbances may precede and even exacerbate the cardinal characteristics i.e., social-communicative symptoms in ASD (Harris, 2017; Leary & Hill, 1996; MacDonald, Lord, & Ulrich, 2014). For instance, a prospective study on infants at high risk of ASD demonstrated that parental concerns regarding children's motor development at six months of age were a significant predictor of ASD diagnosis, whereas parental concerns regarding social communication and repetitive motor behaviours were not predictive of ASD until after 12 months of age (Sacrey et al., 2015). Similarly, a recent longitudinal study using standardized developmental tests on high-risk infants demonstrated that fine and gross motor skills at six months of age were a significant predictor of ASD diagnosis at 24–26 months of age (LeBarton & Landa, 2019). Despite the large presence of studies showing a range of motor deficits associated with ASD such as motor incoordination, postural instability and altered gait patterns (for review see Fournier et al., 2010**;** Kindregan, Gallagher, & Gormley, 2015), they have not shed sufficient light on the degree to which impairments FMS account for motor deficiencies in children with ASD. Furthermore, the existing literature on impairments in FMS have sampled individuals across broad age groups (Biscaldi et al., 2015**;** Hannant, Cassidy, Tavassoli, & Mann, 2016; Jansiewicz et al., 2006**;** Stins, Emck, de Vries, Doop, & Beek, 2015), thus obscuring the extent and developmental trajectory of FMS impairments in children with ASD. Systematically reviewing the existing studies may represent a fruitful starting point in identifying early movement-related markers that are specific to ASD.

3. AIM OF THE DISSERTATION

The general aim of the dissertation was to investigate the importance of motor skills in early childhood by investigating its relationship with other developmental domains namely, cognitive and socio-emotional development. A total of four studies were carried out to answer this overreaching research question.

3.1.Summary of the four presented studies

3.1.1. A meta-analysis of the relationship between motor skills and executive functions in typically developing children.

Motor skills and executive functions are important factors in child development and are assumed to be interlinked. However, there is no conclusive evidence for the association between these two developmental domains in typically developing children. To address this, we carried out a meta-analytic study to investigate the relationship between the global domains of motor skills and EFs; and to explore specific associations between different components of motor skills (balance, manual dexterity, locomotor skills, and object control skills) and EFs (response inhibition, working memory, and cognitive flexibility) in typically developing children. The results showed a significant positive association between motor skills and EF's. Specifically, manual dexterity skills and balance were found to have the strongest independent associations with all EF components. This information contributes to our currently limited knowledge of which motor skills and EFs are strongly associated with one another, and it might also be of benefit to childcare practitioners when designing comprehensive training and intervention programs aimed at improving motor and cognitive functioning in children.

3.1.2. Relationship between motor skills and indicators of cognitive and socio-emotional development in preschoolers.

Motor skills develop rapidly during early childhood and is considered to play a significant role in a number of other developmental areas. Previous studies investigating the relationship of motor skills (i.e., gross motor and fine motor skills) with executive functions have yielded inconsistent findings regarding the strength and nature of the association, and while many of the studies were carried out in schoolchildren, the extent to which the results can be generalized to preschoolers is still unclear (Cameron et al., 2012; Houwen et al., 2017; Oberer et al., 2017). Alongside cognition, an important component of socioemotional competence in childhood that has been relatively less studied in conjunction with motor skills is prosocial behaviour, a key element in the healthy adjustment of the child (Eisenberg & Fabes, 1990). More research is needed to enhance our understanding of the associations between these skills as it can have direct implications for teachers and policy makers to consider motor activities as an essential part of the preschool curriculum. Keeping this in mind, we aimed: (a) to examine the relationship between specific motor skills (i.e., gross motor and fine motor skills) with the different components of EFs (i.e., RI, WM, and CF); and (b) to examine the relationship between motor skills and prosocial behaviour in typically developing preschoolers. The results found that motor skills were significantly associated with both executive functions and prosocial behaviour. Specifically, fine motor skills were twice as strong as a predictor for response inhibition compared to gross motor skills whereas gross motor skills dominated over fine motor skills in predicting prosocial behaviour in preschool-aged children.

3.1.3. Developmental pathways of executive function components among Hungarian preschoolers

Executive functions are vital as it significantly contributes to children's school readiness, academic success, socioemotional competence, and menta health (J. A. Welsh et al., 2010; Kraybill & Bell, 2013; Schoemaker et al., 2012). This makes it imperative to examine the nature and factors that influences the development of EFs during early childhood. An important factor that has been less studied but may have the potential to impact the development of EFs is the preschool education system. Preschool education system in Eastern European countries, especially Hungary, has several distinctive characteristics compared to the USA and most Western European countries. For instance, children in Hungary start preschool education at 3 years of age and spend at least 4 hours per day in kindergarten (Hungarian Government, 2011). As opposed to rote learning and subject knowledge, the educational curriculum of kindergartens in Hungary (Ministry of Culture and Education, 1997) places a strong emphasis on fostering children's imagination and ability to think flexibly by introducing them to a variety of activities such as music, art, movement, and handicrafts. This kind of creative curriculum, which gives children equal exposure to the arts and the sciences, in a preschool environment that is characterized by social connectedness as an important child rearing practise (Brayfield & Korintus, 2011) has been found to have a positive outcome on children's literacy skills, such as reading and writing (Podlozny, 2000). However, its impact on children's executive functions is not yet known. In light of this, the present study used a sample of Hungarian preschoolers to investigate age-related difference in EFs, including response inhibition, working memory, and cognitive flexibility. The results revealed significant age effect on performance in all EF tests with a trend towards better performance with age. It was also found that younger participants (3-years-old) unlike those in previous studies showed superior performance on cognitive flexibility tasks, thereby drawing our attention to the potential influence of early childhood education, via child-rearing beliefs and practices on the promotion of EF skills.

3.1.4. Identification of movement related markers that are specific to autism spectrum disorder (ASD).

Identification of earliest signs and symptoms of ASD in children can lead to early diagnosis and intervention of the disorder, which in turn can have a significant positive impact on the developmental outcomes of children with ASD (Dawson et al., 2010; Kasari et al., 2010). There is a growing consensus that motor disturbances precede and even exacerbate, the defining characteristics i.e. the social-communicative symptoms in ASD (Harris, 2017**;** Leary & Hill, 1996**;** MacDonald, Lord, & Ulrich, 2014). However, it is not clear the degree to which impairments in basic or fundamental movement skills account for deficiencies in children with ASD. To address this, we systematically reviewed the literature to determine the prevalence and developmental trajectory of FMS impairments in children with ASD by comparing their performance on standardized movement assessment batteries with that of typically developing children and children with other developmental disorders, in an attempt to identify movement-related markers that are specific to ASD. The results demonstrated that impairments in FMS especially object control and locomotor skills were highly prevalent across the ASD spectrum and thus have the potential to be an early motor marker in children with ASD.

4. STUDIES THAT ARE BASED UPON THE DISSERTATION

The following section describes in length the four studies that were undertaken as a part of this dissertation. It is important to note that for the cross-sectional studies, ethical approval was granted by the university committee under the registration number 2018/218-2. Also, the permission of the head of the kindergartens as well as the written consent of the caretakers of the children were duly taken before carrying out the studies.

4.1. STUDY I

A Meta-Analysis of the Relationship between Motor Skills and Executive Functions in Typically Developing Children

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Abstract

The relationship between motor skills and executive functions (EFs) is gaining prominence in the field of developmental psychology. However, evidence of the motor skills–EFs link in children with typical development is somewhat inconsistent and there has been no adequate attempt to evaluate it systematically across studies. In view of this, the present meta-analysis was carried out to investigate the relationship between the global domains of motor skills and EFs; and to explore specific associations between different components of motor skills (balance, manual dexterity, locomotor skills, and object control skills) and EFs (response inhibition, working memory, and cognitive flexibility) in typically developing children. The analysis involved data on 4,866 children between the ages of 3 and 12 years, taken from 32 studies. The results revealed a significant positive association between motor skills and EFs at the global level, as well as at the specific level of analysis. At the specific level of analysis, balance and manual dexterity were found to have the strongest independent associations with all EF components. Moderator analysis revealed an age effect between balance and response inhibition only. In summary, the present meta-analysis provides evidence for the theoretical assumption of a link between motor skills and EFs and emphasizes the importance of including cognitively engaging motor tasks in intervention programs designed to promote motor skills and higher-order cognitive skills in children.

Introduction

The relationship between motor skills and executive functions (EFs) is receiving increased attention in the discipline of psychology following reports showing an equally protracted developmental trajectories of these two domains in childhood (Ahnert et al., 2009; Rosenbaum, 2001). The idea that motor skills and cognitive processes are interrelated goes back to the work of Piaget (1936), who proposed that children's ability to move has important implications for the emergence of their cognitive abilities. Similarly, Campos et al. (2000) suggested that the early onset of locomotor experiences provides children with increased opportunities to explore and interact with their environment, which in turn enhances their cognitive skills. This argument was further supported by the embodied cognition perspective, in which cognitive development is considered to take place in the context of the individual's sensory–motor interactions with their physical as well as their social environment (Barsalou, 1999; Gibbs, 2005; Smith & Gasser, 2005). In keeping with these ideas, more recent theoretical accounts based on the concepts of reciprocity and automaticity have offered explanations of the relationship between the development of motor skills and EFs (Kim et al., 2018). *Reciprocity* occurs when motor skills and EFs develop and improve alongside each other (McClelland & Cameron, 2019), while *automaticity* refers to the competition for attentional resources between motor and cognitive tasks. When a new motor task is performed, there is a greater need for cognitive attentional resources. However, practicing motor tasks leads to automaticity, meaning that fewer cognitive attentional resources are required for their successful performance (Floyer-Lea & Matthews, 2004). Once a skill becomes automatic, attentional resources can rather be devoted to cognitive processes (Cameron et al., 2012). At the same time, if EFs are no longer involved in the performance of an automated motor task, it becomes easier to simultaneously perform a second task that does require EFs (Floyer-Lea &

Matthews, 2004). Collectively, these theoretical perspectives suggest that motor skills and EFs are functionally intertwined and cannot be viewed as separate entities.

There is a large body of research that further supports these theoretical ideas by providing evidence for the link between motor skills and EFs. Some of this evidence stems from neurobiological studies, which have demonstrated the parallel activation of the prefrontal cortex (responsible for EFs), the cerebellum (responsible for coordinating voluntary movements), and the basal ganglia (responsible for the planning and execution of movements) during the performance of complex motor and EFs tasks (Diamond, 2000; Pangelinan et al., 2011; Pulvermüller et al., 2005). Further confirmation of the relationship between motor skills and EFs has come from behavioural studies involving children with developmental disorders, who were characterized by high levels of comorbidity between cognitive and motor symptoms such as attention-deficit/hyperactivity disorder (ADHD) (Klimkeit et al., 2004; Pitcher et al., 2003), developmental coordination disorder (DCD) (Dewey et al., 2002; Mandich et al., 2003), and developmental apraxia of speech (DAS) (Viholainen et al., 2002). Children with these disorders have been found to consistently demonstrate lower scores on tests for motor coordination (Kaplan et al., 1998; Piek et al., 1999), response inhibition (Michel et al., 2011), and working memory (Pennington & Ozonoff, 1996; Piek et al., 2007). Children with motor coordination difficulties such as DCD, for example, have been found to exhibit particular difficulties in the performance of EFs (Leonard et al., 2015; Molitor et al., 2015; Rahimi-Golkhandan et al., 2014). Conversely, motor impairments have been identified in children diagnosed with cognitive disorders (Houwen et al., 2016). There is also compelling evidence from normative studies suggesting that motor skills and EFs share several underlying cognitive processes such as attention, information processing, monitoring, and sequencing of actions (Livesey et al., 2006; Luz et al., 2015; Piek et al., 2004; Roebers & Kaurer, 2009; Wassenberg et al., 2005). Lastly, intervention studies have provided indirect evidence for the link between motor skills and EFs by demonstrating an improvement in children's executive functioning following exposure to cognitively enriching physical activities (Budde et al., 2008; Ellemberg & St-Louis-Deschênes, 2010; Schmidt et al., 2015).

Despite the growing body of evidence suggesting an association between motor skills and higher-order cognitive processes (e.g., response inhibition, working memory, and cognitive flexibility) (Miyake et al., 2000), there is no clear picture of the precise nature of the relationship between these two domains in typically developing children. This is because the existing studies have either focused selectively on only one or two motor skills and/or EFs (Cook et al., 2019; Chang & Gu, 2018; Gashaj et al., 2019; Livesey et al., 2006; Ludyga et al., 2019; Martins et al., 2020; Roebers & Kaurer, 2009; Stein et al., 2017), or have investigated the relationship between motor skills and EFs at global domain level (Aadland et al., 2017; Hudson et al., 2020; MacDonald et al., 2016; Michel et al., 2016; Piek et al., 2008; van der Fels et al., 2019), thereby obscuring our understanding of the multilevel nature of this relationship in children. Obtaining an in-depth understanding of the nature of the relationship between motor skills and EFs can be valuable from both a theoretical and a practical point of view. It can contribute to our currently limited knowledge of which motor skills and EFs are strongly associated with one another, and this information might also be of benefit to childcare practitioners when designing comprehensive training and intervention programs aimed at improving motor and cognitive functioning in children. With this in mind, the present meta-analytic study was undertaken to examine the relationship between the global domains of motor skills and EFs; and to investigate the specific associations between different components of motor skills (balance, manual dexterity, locomotor skills, and object control skills) and EFs (response inhibition, working memory, and cognitive flexibility) in typically developing children. The study also examined whether age moderates the relationship between motor skills and EFs. Based on the assumption that motor skills performance and executive functioning change over the course of development (Ackerman, 1988; Ahnert et al., 2009; Best et al., 2009; De Luca et al., 2003; Huzinga et al., 2006), we expected the strength of the interrelationships between these skills to vary as a function of age.

Method

Operational Definitions

For the purposes of the present study, the terms used throughout are defined as follows. *Motor skills* refer to learned sequences of movements that are combined to produce a smooth, efficient action in order to master a particular task (Davis et al., 2011). Motor skills are divided into the following categories: (1) *balance skills*, which enhance balance when the body is in situ or in motion; (2) *manual dexterity* (also referred to as *fine motor skills* in the present study), which involves the coordination of small muscle movements in the fingers, hands, and wrists (Clark & Whitall, 1989); (3) *locomotor skills*, which engage the body in movement in different directions, such as running, hopping, galloping, leaping, jumping, sliding, and skipping (Haywood & Getchell, 2009); (4) *object control skills* (also referred to as *ball skills* in the present study), which involve handling and controlling objects with the hand or foot, for example catching and throwing; and (5) *global motor skills*, which comprise the total score for the combination of the motor skills in the other four categories.

Executive functions are the higher-order cognitive processes that enable individuals to interact with their environment in an adaptive manner (Diamond, 2013). In the present study, EFs consisted of the following components: (1) *response inhibition*, which is defined as the ability to suppress a prepotent response in favor of a more appropriate subordinate response (Miyake et al., 2000); (2) *working memory*, which refers to the capacity to hold information in the mind and to mentally work on it over a period of time (Garon et al., 2008); and (3) *cognitive flexibility*, which refers to the ability to rapidly switch attention between different concepts (Miyake et al., 2000). The EF composite is defined as the total score for the sum of all three EF components.

Retrieval of Studies

The literature search was carried out by the author and coauthors in the electronic databases of PubMed, Web of Science, PsychInfo, ERIC, and Scopus. The search terms were discussed among the research team and included the following combination of keywords (1 AND 2):

1. Motor skills (OR motor performance OR fine motor skills OR object control skills OR object manipulation skills OR balance OR stability skills OR locomotor skills OR throwing skills OR aiming and catching skills OR ball skills OR manual dexterity skills OR motor coordination skills).
2. Executive functions (OR response inhibition [OR cognitive control] OR working memory OR cognitive flexibility [OR set shifting]).

It is important to note that the search was limited to published or unpublished articles in the English language, and that no restrictions were made regarding date/year during the retrieval of the articles. In addition, efforts were made to search through unpublished documents, such as conference proceedings, presentations, and dissertations/theses, in order to ensure that all the necessary evidence was taken into account.

Eligibility Criteria

In order to be included in the meta-analysis, the studies had to meet the following criteria: (a) they involved typically developing children between 3 and 12 years of age; (b) they concurrently measured at least one category of motor skills (balance, manual dexterity, locomotor skills, object control skills, or global motor skills performance) and EFs (response inhibition, working memory, cognitive flexibility, or the EF composite); (c) they used standardized tasks in the assessment of motor skills and EFs; and (d) they reported findings in English. In the case of studies with a longitudinal design and interventional studies, only the first assessment was chosen so as to enable meaningful comparison with other studies without coloring the effects of maturation or intervention on the relationship between motor skills and EFs.

Studies were excluded if: (a) they examined special populations only (e.g., children with developmental disorders, brain injuries, and motor impairments, or children born preterm); (b) they used non-standardized tests to assess motor skills and EFs; (c) they did not measure motor skills and EFs simultaneously; (d) they did not provide sufficient data for the computation of effect sizes; (e) they involved participants below the age of 3 years or over the age of 12 years; and (f) they were published in a language other than English. The list of excluded studies is available from the corresponding author.

Study Selection and Data Extraction Process

The electronic database search was conducted independently by the author and two of the reviewers to ensure its reliability. A total of 890 articles were identified at this stage. After removing duplicates, the remaining articles were screened by assessing the title and abstract for eligibility, followed by a thorough assessment of the full text of the articles to determine whether they met the eligibility criteria. A total of 137 articles were identified at this stage, 105 of which did not meet the inclusion criteria. A total of 32 studies were selected for the final review (Fig. 3). After the final selection, information pertinent to the present meta-analysis was extracted by one of the co-authors. This included (see Table 1): (a) descriptive information (e.g., title, author[s], year of publication, and the country where the data were collected); (b) study design (i.e., cross-sectional, longitudinal, or interventional); (c) sample characteristics (i.e., sample size, gender, and age range of participants); (d) motor skills components (e.g., balance, manual dexterity, locomotor skills, object control skills, and global motor skills); (e) EF components (e.g., response inhibition, working memory, and cognitive flexibility, or EF composite); and (f) the tests used to measure motor skills and EFs. In order to ensure the accuracy of the information derived from these studies, 15 studies were randomly selected and independently coded by a third reviewer. Interrater reliability ranged from 90% to 95% and the disagreement was resolved via consensus until 100% accuracy was achieved.

Figure 3.

PRISMA Flowchart of Study Selection Process

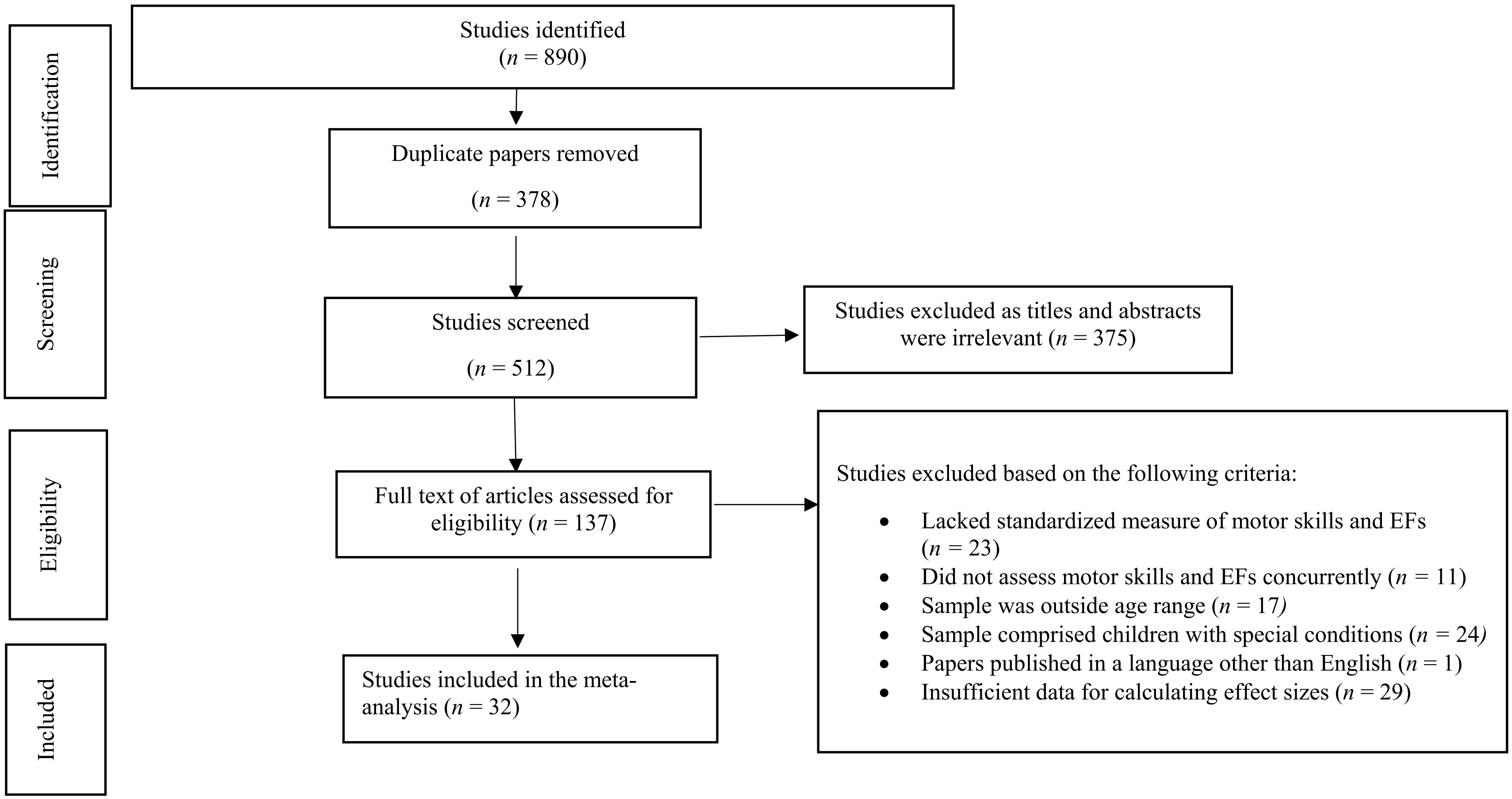


Table 1

Studies Included in the Meta-Analysis

Author (year)	Study design	Sample characteristics	Type of motor skills	Motor skills task	Type of executive functions	Executive functions task
Aadland et al. (2017)	Cross-sectional	*N* = 697 (357 girls & 340 boys); age 10 years	Global motor skills	MABC-2	Response inhibition, working memory, & cognitive flexibility	Stroop color and word test, digit span test, verbal fluency, & TMT
Augustijn et al. (2018)	Cross-sectional	*N* = 64 (13 girls, 19 boys); age 7–11 years	Balance, manual dexterity, and object control skills	MABC-2	Response inhibition & cognitive flexibility	CANTAB
Becker et al. (2014)	Cross-sectional	*N* = 127; age 4–6 years	Manual dexterity	Beery VMI-6	Response inhibition & working memory	DNS & Woodcock-Johnson working memory subtest
Cameron et al. (2012)	Cross-sectional	*N* = 213; age 3–4 years	Manual dexterity	ESI-R	EF composite	HTKS
Chang & Gu (2018)	Cross-sectional	*N* = 145 (74 boys & 71 girls); age 5 years	Locomotor and object control skills	PE Metrics™	Response inhibition, working memory, & cognitive flexibility	BRIEF-P (teacher-rated EF)

Cook et al. (2019)	Cross-sectional	*N* = 129*;* age 3–6 years	Locomotor and object control skills	TGMD-2	Response inhibition, working memory, & cognitive flexibility	Go/no-go task, Mr. Ant, & card sorting test
Fang et al. (2017)	Cross-sectional	*N* = 151 (70 girls and 81 boys); age 4–6 years	Manual dexterity	Beery VMI-6	Response inhibition, working memory, & cognitive flexibility	DNS, self-ordered pointing task, & DCCS
Gashaj et al. (2019)	Longitudinal	*N* = 136 (66 boys & 70 girls)*;* age 6.45 years	Manual dexterity	MABC-2	Response inhibition, working memory, & cognitive flexibility	Flanker task, backward color recall task, & mixed flanker task
Geertsen et al. (2016)	Cross-sectional	*N* = 423 (214 boys & 209 girls)*;* age 8–10 years	Manual dexterity	VAT	Working memory	CANTAB
Houwen et al. (2017)	Cross-sectional	*N* = 153 (75 boys & 78 girls); age 3–4 years	Manual dexterity, object control skills, & balance	MABC-2	Response inhibition, working memory, & cognitive flexibility	BRIEF-P (parent-rated EF)
Hudson et al. (2020)	Interventional	*N* = 53 (31 girls & 22 boys); age 3–5 years	Global motor Skills	BOT-2	EF composite	EF Touch

Lehmann et al. (2014)	Cross-sectional	*N* = 65 (32 boys & 33 girls); age 3–6 years	Manual dexterity, balance, & object control skills	MABC-2	Working memory	CBT
Livesey et al. (2006)	Cross-sectional	*N* = 36 (15 boys & 21 girls); age 5–6 years	Manual dexterity, object control skills, & balance	MABC	Response inhibition	DNS
Ludyga et al. (2019)	Cross-sectional	*N* = 89 (45 boys & 44 girls); age 10–12 years	Object control skills & locomotor skills	MOBAK-5	Response inhibition & working memory	Flanker task & N-back task
MacDonald et al. (2016)	Cross-sectional	*N* = 92; age 3–5 years	Global motor skills	PDMS-2	EF composite	HTKS
Martins et al. (2020)	Cross-sectional	*N* = 42 (24 boys & 18 girls); age 3–5 years	Locomotor and object control skills	TGMD-2	Response inhibition	Go/no-go task
Maurer & Roebers (2019)	Cross-sectional	*N* = 124 (57 boys & 67 girls); age 5–6 years	Locomotor skills, balance, & manual dexterity	MABC-2 & KTK	Response inhibition, working memory, & cognitive flexibility	Flanker task, pictorial updating task & advanced DCCS
Michel et al. (2016)	Longitudinal	*N* = 96 (64 boys & 32 girls); age 4–6 years	Global motor skills	MABC-2	Response inhibition, working memory, & cognitive flexibility	Go/no-go task, backward color recall task, & mixed flanker task

Michel et al. (2019)	Cross-sectional	*N* = 173 (98 boys & 75 girls); age 4–7 years	Balance, object control skills, & manual dexterity	MABC-2	Response inhibition, working memory, & cognitive flexibility	Go/no-go task, backward color recall task, & mixed flanker task
Obeid & Brooks (2018)	Cross-sectional	*N* = 63 (30 boys & 33 girls); age 6–11 years	Manual dexterity	Grooved pegboard test	Working memory	One-shape array memory task
Oberer et al. (2017)	Cross-sectional	*N* = 156 (79 girls & 77 boys); age 6.5 years	Manual dexterity, locomotor skills, & balance	MABC-2 & KTK	Response inhibition, working memory, & cognitive flexibility	Flanker task, backward color recall task, & mixed flanker task
Piek et al. (2008)	Cross-sectional	*N* = 33 (17 boys & 16 girls); age 6–11 years	Global motor skills	McCarron assessment of neuromuscular development (MAND)	Working memory	Digit span test
Policastro et al. (2018)	Cross-sectional	*N* = 75 (53 boys & 22 girls); age 7–11 years	Global motor skills	MABC-2	Response inhibition, working memory, & cognitive flexibility	NEPSY II & CBT

Rigoli et al. (2013)	Cross-sectional	*N* = 41 (14 boys & 27 girls); age 5–11 years	Balance & manual dexterity	MAND	Working memory	One-back task–Cogstate brief battery
Roebers & Kauer (2009)	Cross-sectional	*N* = 112 (57 girls & 55 boys); age 7 years	Manual dexterity & locomotor skills	MABC-2	Response inhibition, working memory, & cognitive flexibility	Flanker task, backward color recall task, & cognitive flexibility task
Roebers et al. (2014)	Longitudinal	*N* = 169 (93 boys & 76 girls); age 5–6 years	Manual dexterity	MABC-2	Response inhibition, working memory, & cognitive flexibility	Fruit Stroop task, backward color recall task, & cognitive flexibility task
Stein et al. (2017)	Cross-sectional	*N* = 102; age 5–6 years	Manual dexterity, object control skills, & balance	MABC-2	Response inhibition & cognitive flexibility	Simon says task & hearts and flowers task
Stöckel & Hughes (2016)	Cross-sectional	*N* = 40 (25 girls & 15 boys); age 5–6 years	Manual dexterity	MABC-2	Response inhibition & working memory	AS & CBT
Stuhr et al. (2020)	Cross-sectional	*N* = 41 (18 boys & 23 girls); age 5–6 years	Manual dexterity & balance	SEBT & Purdue pegboard test	Response inhibition, working memory, & cognitive flexibility	Hearts and flowers test, list sorting working memory test, & WCST
van der Fels et al. (2019)	Cross-sectional	*N* = 732 (369 boys & 363 girls); age 8–10 years	Global motor skills	KTK & BOT-2	Response inhibition & working memory	SST & digit span test

van der Veer et al. (2020)	Cross-sectional	N = 193 (102 boys & 91 girls); age 3–5 years	Locomotor skills, manual dexterity, & object control skills	MABC-2	Response inhibition, working memory, & cognitive flexibility	DNS, forward CBT, & conflict task
Wu et al. (2017)	Longitudinal	N = 96 (55 girls & 41 boys); age 3 years	Manual dexterity	BSID-3	Response inhibition & working memory	DNS & working memory span task

Note. MABC-2 – movement assessment battery for children, 2nd edition (Brown & Lalor, 2009); BRIEF-P – brief rating inventory of executive function – preschool version (Sherman & Brooks, 2010); KTK – Körperkoordinationstest für Kinder (Kiphard, 1974); flanker task (Eriksen & Eriksen, 1974); mixed flanker task (Diamond et al., 2007); backward color recall task (Zoelch et al., 2005); CBT – Corsi block-tapping test (Kessels et al., 2000); AS – animal Stroop task (Wright et al., 2003); Simon says task (Carlson & Wang, 2007); working memory span task (Willoughby et al., 2010); hearts and flowers task (Davidson et al., 2006); ESI-R – early screening inventory – revised edition (Meisels et al., 1997); self-ordered pointing task (Petrides & Milner, 1982); HTKS – head-toes-knees-shoulders (Ponitz et al., 2009); DNS – day/night Stroop task (Berlin & Bohlin, 2002); Beery VMI-6 – Beery visual-motor integration, 6th edition (Beery et al., 2010); DCCS – dimensional change card sorting task (Zelazo, 2006); TGMD-2 – test of gross motor development, 2nd edition (Ulrich, 2000); PDMS-2 – Peabody developmental motor scales, 2nd edition (Folio & Fewell, 2000); BSID-3 – Bayley scales of infant and toddler development, 3rd edition (Bayley, 2006); go/no-go task (Hasselhorn et al., 2012); cognitive flexibility task (Zimmermann et al., 2002); MABC – movement assessment battery for children (Henderson & Sugden, 1992); PE Metrics™ (NASPE, 2010); VAT – visuomotor accuracy-tracking task (Thomas et al., 2016); BOT-2 – Bruininks-Oseretsky test of motor proficiency, 2nd edition (Bruininks & Bruininks, 2005); BOT-2 short form – Bruininks-Oseretsky test of motor proficiency short form, 2nd edition (Bruininks & Bruininks, 2005); MOBAK-5 – basic motor competencies in fifth grade (Herrmann & Seelig, 2017); MAND – McCarron assessment of neuromuscular development (McCarron, 1997); grooved pegboard test (Ruff & Parker, 1993); Purdue pegboard test (Tiffin & Asher, 1948); SEBT – star excursion balance test (Gray, 1995); pictorial updating task (Lee et al., 2011); one-shape array memory task (Cowan et al., 2011); list sorting working memory test (Tulsky et al., 2014); WCST – Wisconsin card sorting test (Heaton et al., 1993); Woodcock-Johnson working memory subtest (Woodcock et al., 2001); digit span test (Wechsler, 1991; Wechsler, 2003); CANTAB – Cambridge neuropsychological test automated battery (Luciana & Nelson, 2002); Stroop color and word test (Golden, 1978); verbal fluency test (Spreen & Strauss, 1998); TMT – trail-making test (Spreen & Strauss, 1998); Mr. Ant task (Howard & Melhuish, 2017); EF Touch (Willoughby & Blair, 2016); N-back task (Drollette et al., 2016); NEPSY-II – neuropsychological assessment, 2nd edition (Korkman et al., 2007); one-back task – Cogstate brief battery (Maruff et al., 2009); fruit Stroop task (Archibald & Kerns, 1999); SST – stop signal task (Oosterlaan et al., 1998); conflict task (Beck et al., 2011).

Method of Quality Appraisal

To assess the methodological quality of the studies, two of the reviewers independently rated each study using a 12-item quality assessment tool (Law et al., 1998) (see Table 2). Each item within each study was rated as *positive* when the item was explicitly described and present; and *negative* when the item was inadequately described or absent. Each of the studies was scored separately by the two reviewers to ensure the consistent scoring of the quality assessment. In the event of disagreements between the two reviewers, unresolved differences were evaluated by a third reviewer. Lastly, the final score for each study was calculated by adding all the positive scores. A study was considered to be of high methodological quality if it received a score above 9; of medium methodological quality if it received a score between 6 and 9; and of low methodological quality if it received a total score below 6.

Table 2

Methodological Quality of the Reviewed Studies

Studies	Questions* 1	2	3	4	5	6	7	8	9	10	11	12	Score
Aadland et al. (2017)	+	+	+	-	+	+	+	+	+	-	+	+	10
Augustijn et al. (2018)	+	+	+	-	+	+	+	+	-	+	+	+	10
Becker et al. (2014)	+	+	+	-	+	+	+	+	+	-	+	+	10
Cameron et al. (2012)	+	+	+	-	+	+	+	+	+	-	+	+	10
Chang & Gu (2018)	+	+	+	+	+	+	+	+	-	+	+	+	11
Cook et al. (2019)	+	+	+	+	+	+	+	+	+	-	+	+	11
Fang et al. (2017)	+	+	+	-	+	+	+	+	+	-	+	+	10
Gashaj et al. (2019)	+	+	+	+	+	+	+	+	+	+	+	+	12
Geertsen et al. (2016)	+	+	+	-	+	+	+	+	+	+	+	+	11
Houwen et al. (2017)	+	+	+	-	+	+	-	+	+	+	+	+	10
Hudson et al. (2020)	+	+	+	-	+	+	+	+	+	-	+	+	10
Lehmann et al. (2014)	+	+	+	-	+	+	+	+	+	+	+	-	10
Livesey et al. (2006)	+	+	+	-	-	+	+	+	+	-	+	-	8
Ludyga et al. (2019)	+	+	+	-	+	+	+	+	+	+	+	+	11
MacDonald et al. (2016)	+	+	+	-	+	+	+	+	+	-	+	+	10
Martins et al. (2020)	+	+	+	+	+	+	+	+	+	-	+	-	10
Maurer & Roebers (2019)	+	+	+	+	+	+	+	+	+	-	+	+	11
Michel et al. (2016)	+	+	+	-	+	+	+	+	+	+	+	+	11
Michel et al. (2019)	+	+	+	-	+	+	+	+	+	+	+	+	11
Obeid & Brooks (2018)	+	+	+	+	+	+	+	+	+	+	+	+	12
Oberer et al. (2017)	+	+	+	-	+	+	+	+	+	-	+	+	10
Piek et al. (2008)	+	+	+	+	+	+	+	+	+	+	+	-	11
Policastro et al. (2018)	+	+	+	-	+	+	+	+	+	-	+	+	10
Rigoli et al. (2013)	+	+	+	-	+	-	+	+	+	+	+	-	9
Roebers & Kauer (2009)	+	+	+	-	+	+	+	+	+	-	+	+	10
Roebers et al. (2014)	+	+	+	-	+	+	+	+	+	+	+	+	11
Stein et al. (2017)	+	+	+	-	+	+	+	+	+	+	+	+	11
Stöckel & Hughes (2016)	+	+	+	-	-	+	+	+	+	-	+	+	9
Stuhr et al. (2020)	+	+	+	-	+	+	+	+	+	+	+	+	11
van der Fels et al. (2019)	+	+	+	+	+	+	+	+	+	+	+	+	12
van der Veer et al. (2020)	+	+	+	-	+	+	+	+	+	+	+	+	11
Wu et al. (2017)	+	+	+	+	+	+	+	+	+	-	+	+	11

Note. "+" indicates positive (explicitly described and present in detail); "–" indicates negative (inadequately described and absent)

* *Questions*: (1) Was the study purpose stated clearly? (2) Was relevant background literature reviewed? (3) Was the research design appropriate? (4) Was the sample described in detail? (5) Was the sample size justified? (6) Was informed consent obtained? (7) Were the outcome measures reliable? (8) Were the outcome measures valid? (9) Were results reported in terms of statistical significance? (10) Was clinical importance reported? (11) Are there any implications of the results of the study? (12) Were the limitations of the study described?

Data Analysis

The present meta-analysis was conducted using Comprehensive Meta-Analysis software (V.3.3.070, November 2014, Biostat, Englewood, USA). Publication bias was investigated in all studies by creating funnel plots. The effect sizes of the included studies were plotted against the standard error associated with each study. In case of an asymmetrical funnel plot, we used Duval and Tweedie's (2000) trim-and-fill procedure to identify the number of missing studies. In addition, Rosenthal's fail-safe number (FSN) was calculated to indicate the robustness of the findings. In the event of a robust effect, the FSN exceeds the critical value—that is, $5k + 10$, where k is the number of contrasts included (Rosenthal, 1979). The Pearson product-moment correlation coefficient (Pearson's r) was chosen as the effect size metric in the analysis. The effect size was considered to be small, medium, or large if the r value was around 0.1, 0.3, or 0.5 or above, respectively (Cohen, 1988). To minimize the unbiased estimate of the overall relationship between motor skills and EFs, multiple r values from the same study were transformed to Fisher's z (Hedges & Olkin, 1985), which was then averaged and back-transformed to r to facilitate the interpretation of results. Two different levels of meta-analysis were then employed to investigate the research questions regarding the global and specific associations between the different components of motor skills and EFs. A random effects model (DerSimonian & Laird, 1986) was chosen, based on the assumption that a distribution of effects exists, which results in heterogeneity among the study results—that is, the effect sizes expected from each study differ across the studies. To evaluate heterogeneity among effect sizes, we used the Q and I-square (I^2) statistics. A significant Q test shows heterogeneity, which suggests that the differences in effect sizes were due to sources other than sampling errors, such as the different characteristics of the studies (Lipsey & Wilson, 2001). In the case of the I^2 statistic, values of 25%, 50%, and 75% or above corresponded to low, moderate, and high levels of heterogeneity, respectively (Higgins et al., 2003). Finally, a moderator analysis of age was performed using meta-regression with the random effects model.

Results

Sample and Study Characteristics

The 32 studies examined in the present meta-analysis provided data on 4,866 participants, with sample sizes ranging from 33 to 732. The mean age of the participants across the studies was 6 years (with a range from 3 to 12 years). All except five of the studies reported gender composition (*n* = 27), with a preponderance of males (51%) over females. Twenty-seven of the 32 studies were cross-sectional in design, while the others had a longitudinal (*n* = 4) or interventional (*n* = 1) design. In all the studies, performance on EFs and motor skills was assessed concurrently. Most of the studies measured motor skills and EFs by taking into account their separate components: balance (*n* = 10), manual dexterity (*n* = 21), locomotor skills (*n* = 8), object control skills (*n* = 11), response inhibition (*n* = 24), working memory (*n* = 25), and cognitive flexibility (*n* = 17). A few of the studies measured the global domain of motor skills (*n* = 7) and the EF composite (*n* = 3). The highest numbers of studies were conducted in the United States (*n* = 6), Switzerland (*n* = 6), and Germany (*n* = 6), followed by the Netherlands (*n* = 4), Australia (*n* = 3), China (*n* = 2), South Africa (*n* = 1), Belgium (*n* = 1), Norway (*n* = 1), Italy (*n* = 1), and Brazil (*n* =1). In terms of their methodological quality, 29 studies received an overall rating of high quality, while the other three studies received an overall rating of medium quality.

Measurement Protocol

Various instruments were used to measure motor skills and EFs. The test most commonly used to measure motor skills was the movement assessment battery for children, 2nd edition (MABC-2) (Brown & Lalor, 2009) (*n* = 15), followed by the Körperkoordinationstest für Kinder

(KTK) (Kiphard, 1974) (*n* = 3); the test of gross motor development, 2nd edition (TGMD-2) (Ulrich, 2000) (*n* = 2); the Beery-Buktenica developmental test of visual-motor integration, 6th edition (Beery VMI-6) (Beery et al., 2010) (*n* = 2); the McCarron assessment of neuromuscular development (MAND) (McCarron, 1997) (*n* = 2); the Bruininks-Oseretsky test of motor proficiency, 2nd edition (BOT-2) (Bruininks & Bruininks, 2005) (*n* = 2); the Bayley scales of infant and toddler development, 3rd edition (BSID-3) (Bayley, 2006) (*n* = 1); the movement assessment battery for children (MABC) (Henderson & Sugden, 1992) (*n* = 1); the Peabody developmental motor scales, 2nd edition (PDMS-2) (Folio & Fewell, 2000) (*n* = 1); PE Metrics™ (NASPE, 2010) (*n* = 1); the visuomotor accuracy-tracking task (VAT) (Thomas et al., 2016) (*n* = 1); basic motor competencies for the fifth grade (MOBAK-5) (Herrmann & Seelig, 2017) (*n* = 1); the grooved pegboard test (Ruff & Parker, 1993) (*n* = 1); the Purdue pegboard test (Tiffin & Asher, 1948) (*n* = 1); the star excursion balance test (SEBT) (Gray, 1995) (*n* = 1); and the early screening inventory, revised edition (ESI-R) (Meisels et al., 1997) (*n* = 1).

Executive functions were measured with the help of performance-based tests (*n* = 30) and rating scales (*n* = 2). In the present study, the behaviour rating inventory of executive function–preschool version (BRIEF-P) (Sherman & Brooks, 2010) was the only assessment tool that mapped onto the different EF components—that is, response inhibition (*n* = 2), working memory (*n* = 2), and cognitive flexibility (*n* = 2). In addition, multiple tests were used to assess each of the EF components. The test most commonly used to measure response inhibition was the day/night Stroop task (DNS) (Berlin & Bohlin, 2002) (*n* = 5), followed by the flanker task (Eriksen & Eriksen, 1974) (*n* = 5), the go/no-go task (Hasselhorn et al., 2012) (*n* = 4); the animal Stroop task (AS) (Wright et al., 2003) (*n* = 1); the Simon says task (Carlson & Wang, 2007) (*n* = 1); the hearts and flowers test (Davidson et al., 2006) (*n* = 1); the Cambridge neuropsychological test automated battery (CANTAB) (Luciana & Nelson, 2002) (*n* = 1); the Stroop color and word test (Golden, 1978) (*n* = 1); the developmental neuropsychological assessment, 2nd edition (NEPSY-II) (Korkman et al., 2007) (*n* = 1); the fruit Stroop test (Archibald & Kerns, 1999) (*n* = 1); and the stop signal task (SST) (Oosterlaan et al., 1998) (*n* = 1). Working memory was measured using the backward color recall test (Zoelch et al., 2005) (*n* = 6), followed by the Corsi block-tapping test (CBT) (Kessels et al., 2000) (*n* = 4), the digit span test (Wechsler, 1991; Wechsler, 2003) (*n* = 3); the working memory span task (Willoughby et al., 2010) (*n* = 1); the self-ordered pointing task (Petrides & Milner, 1982) (*n* = 1); the pictorial updating task (Lee et al., 2011) (*n* = 1); the one-shape array memory task (Cowan et al., 2011) (*n* = 1); the list sorting working memory test (Tulsky et al., 2014) (*n* = 1); the Woodcock-Johnson working memory subtest (Woodcock et al., 2001) (*n* = 1); the Cambridge neuropsychological test automated battery (CANTAB) (Luciana & Nelson, 2002) (*n* = 1); the Mr. Ant task (Howard & Melhuish, 2017) (*n* = 1); the n-back task (Drollette et al., 2016) (*n* = 1); and the one-back task – Cogstate brief battery (Maruff et al., 2009) (*n* = 1). Cognitive flexibility was measured using the mixed flanker task (Diamond et al., 2007) (*n* = 4), followed by the dimensional change card sort task (DCCS) (Zelazo, 2006) (*n* = 3); the cognitive flexibility task (Zimmermann et al., 2002) (*n* = 2); the hearts and flowers task (Davidson et al., 2006) (*n* = 1); the Wisconsin card sorting test (WCST) (Heaton et al., 1993) (*n* = 1); the Cambridge neuropsychological test automated battery (CANTAB) (Luciana & Nelson, 2002) (*n* = 1); the verbal fluency test (Spreen & Strauss, 1998) (*n* = 1); the trail-making test (TMT) (Spreen & Strauss, 1998) (*n* = 1); the developmental neuropsychological assessment, 2nd edition (NEPSY-II) (Korkman et al., 2007) (*n* = 1); and the conflict task (Beck et al., 2011) (*n* = 1). In addition, the EF composite was measured using the head-toes-knees-shoulders task (HTKS) (Ponitz et al., 2009) (*n* = 2); and EF Touch (Willoughby & Blair, 2016) (*n* = 1).

Effect Size for the Relationship between the Global Domains of Motor Skills and Executive Functions

Taking all the studies together, the strength of the relationship between the global domains of motor skills and EFs in typically developing children was $r = .18$ (95% CI [.126– .246]) using the random effects model (Table 3). The effect size was considered to be small, although the association was found to be statistically significant ($p < .001$). The forest plot for this analysis is shown in Figure 4. This was a heterogeneous effect, as indicated by the Q statistic, Q (31) = 127.25, $p < .001$, and the I^2 index of 75.63 (Higgins et al., 2003). On assessing publication bias, we found reasonable symmetry in the funnel plot (Fig. 5). The FSN was 1109, which exceeds Rosenthal's (1995) critical value (i.e., 170), suggesting that the results can be considered robust against publication bias.

Table 3

Effect Size for Overall Relationship between Global Domains of Motor Skills and Executive Functions

Overall	K	N	r	95% CI	Q (df)	I^2(%)
	32	4,866	.18***	.127 – .247	127.25(31)***	75.63

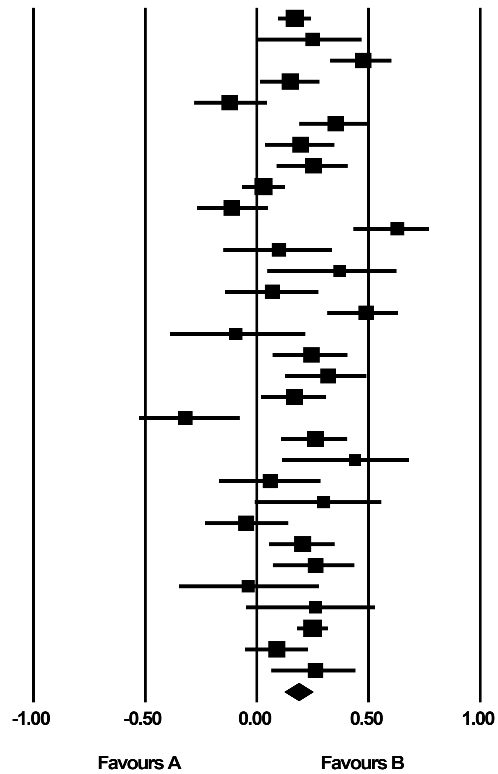
Note. *$p < .05$. **$p < .01$.***$p < .001$

Figure 4.

Forest Plot of All Studies Included in the Meta-Analysis

Study name	Correlation	Lower limit	Upper limit	Z-Value	p-Value
Aadland et al (2017)	0.170	0.097	0.241	4.522	0.000
Augustijn et al (2018)	0.250	0.004	0.467	1.995	0.046
Becker et al (2014)	0.477	0.330	0.601	5.780	0.000
Cameron et al (2012)	0.150	0.016	0.279	2.190	0.029
Chang & Gu (2018)	-0.121	-0.279	0.043	-1.449	0.147
Cook et al (2019)	0.353	0.192	0.496	4.141	0.000
Fang et al (2017)	0.197	0.038	0.346	2.428	0.015
Gashaj et al (2019)	0.254	0.089	0.405	2.995	0.003
Geertsen et al (2016)	0.030	-0.066	0.125	0.615	0.539
Houwen et al (2017)	-0.112	-0.266	0.048	-1.377	0.168
Hudson et al (2020)	0.630	0.434	0.769	5.243	0.000
Lehmann et al (2014)	0.099	-0.148	0.335	0.782	0.434
Livesey et al (2006)	0.371	0.048	0.624	2.238	0.025
Ludyga et al (2018)	0.070	-0.140	0.274	0.650	0.516
MacDonald et al (2016)	0.490	0.317	0.631	5.057	0.000
Martins et al (2020)	-0.094	-0.387	0.216	-0.589	0.556
Maurer & Roebers (2019)	0.245	0.072	0.404	2.751	0.006
Michel et al (2016)	0.320	0.128	0.489	3.198	0.001
Michel et al (2019)	0.168	0.019	0.309	2.211	0.027
Obeid & Brooks (2018)	-0.320	-0.526	-0.078	-2.569	0.010
Oberer et al (2017)	0.263	0.110	0.403	3.331	0.001
Piek et al (2008)	0.440	0.114	0.681	2.587	0.010
Policastro et al (2018)	0.060	-0.169	0.283	0.510	0.610
Rigoli et al (2013)	0.300	-0.008	0.556	1.908	0.056
Roebers & Kauer (2009)	-0.047	-0.231	0.140	-0.491	0.623
Roebers et al (2014)	0.206	0.057	0.346	2.693	0.007
Stein et al (2017)	0.263	0.072	0.435	2.680	0.007
Stöckel & Hughes (2015)	-0.039	-0.346	0.276	-0.237	0.812
Stuhr et al (2020)	0.263	-0.049	0.528	1.660	0.097
Van der Fels et al (2019)	0.250	0.181	0.317	6.896	0.000
Van Der Veer et al (2020)	0.090	-0.052	0.228	1.244	0.214
Wu et al (2017)	0.263	0.066	0.440	2.597	0.009
	0.187	0.127	0.247	5.959	0.000

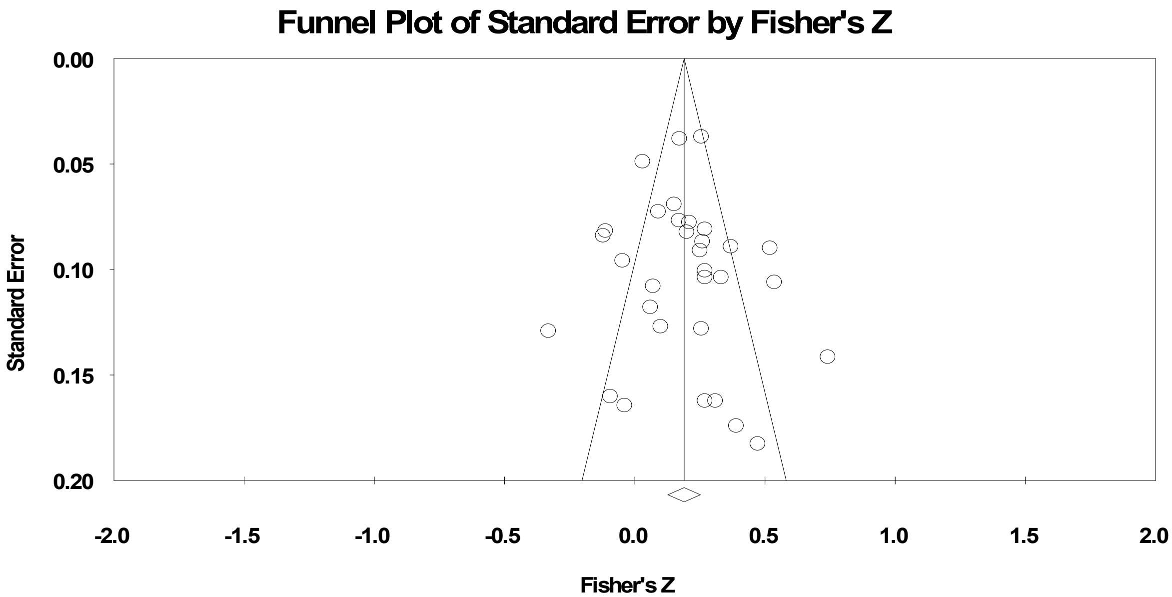
Correlation and 95% CI



Meta Analysis

Figure 5.

Funnel Plot of Standard Error by Fisher's Z for all Studies Included in the Meta-Analysis



Effect Size for the Relationship between the Different Components of Motor Skills and Executive Functions

Several significant associations of small effect sizes were found between the various components of motor skills and EFs using the random effects model (Table 4).

Balance and EF components: A significant small effect size was found between balance and the EF components of response inhibition ($r = .20$, $p < .001$), working memory ($r = .18$, $p < .01$), and cognitive flexibility ($r = .12$, $p < .05$). The effect sizes were observed to be heterogeneous in the case of all three EF components under consideration, Q(8) = 20.94, $p <.01$, $I^2 = 61.79$; Q(7) = 24.90, $p < .001$, $I^2 = 71.90$; Q(7) = 20.34, $p < .01$, $I^2 = 65.58$. When assessing publication bias, we found asymmetrical plots for balance and RI. The Duval and Tweedie's (2000) trim-and- fill procedure was used to find out the missing studies. Using the random-effects model to look for missing studies to the left and right of the means, one missing study to the right of the mean was identified. The FSN was 81, which exceeds Rosenthal's critical value of 55, suggesting a robust effect. An asymmetrical plot was observed for balance and WM. The Duval and Tweedie's trim and fill analysis estimated 2 missing studies to the left of the mean. The FSN was 44 and the Rosenthal's criterion was 50, indicating that these findings should be interpreted with caution. A symmetrical plot was noticed for balance and CF. However, the FSN 21, was under the critical value of 50, which does not imply a robust effect.

Manual dexterity and EF components: A significant small effect size was found between manual dexterity and the EF components of response inhibition (r = .19, p = < .001), working memory (r = .21, p < .001), and cognitive flexibility (r = .17, p < .01). The effect sizes were observed to be heterogeneous in the case of all three EF components under consideration, Q(15) = 58.86, p <.001, I^2 = 74.51; Q(16) = 114.53, p < .001, I^2 = 86.03; Q(11) = 58.01, p < .001, I^2 = 81.04. When assessing publication bias, we observed a symmetrical plot for manual dexterity and RI. The FSN was 253, which exceeds Rosenthal's critical value of 90, indicating a robust effect. Asymmetrical plots were found for manual dexterity and EF components of WM and CF. The Duval and tweedie's trim-and-fill procedure identified 3 missing studies to the left of the mean for both manual dexterity and WM as well as for manual dexterity and CF. The FSN was 354 against Rosenthal's critical value of 95 for manual dexterity and WM; and FSN was 116, which exceeds Rosenthal's criterion of 70 for manual dexterity and CF, implying robust effects.

Locomotor skills and EF components: A significant small effect size was found between locomotor skills and working memory (r = .19, p < .01). This was a heterogeneous effect, Q(6) = 39.39, p < .001; I^2 = 84.78. No significant effects were found between locomotor skills and the EF components of response inhibition and cognitive flexibility (r = .07, p = .42; r = .06, p = .39).

When assessing publication bias, asymmetrical plots were observed for locomotor skills and EF components of RI and CF. The Duval and tweedie's trim-and-fill procedure identified 1 missing study to the right of the mean for both locomotor skills and WM as well as for locomotor skills and CF. The FSN was 11 which was under the critical value of 50 for locomotor skills and RI and FSN 5, was under the critical values of 45 for locomotor skills and CF, implying that these findings must be interpreted with precaution. A symmetrical plot was observed for locomotor skills and WM. The FSN was 73 which exceeds the critical value of 45, indicating robust effect.

Object control skills and EF components: No significant effect was observed between object control skills and the three EF components under consideration ($r = .08$, $p < .10$; $r = .08$, $p < .16$; $r = .06$, $p < .26$). When assessing publication bias, an asymmetrical plot was observed for object control skills and RI. The Duval and tweedie's trim-and-fill procedure identified 3 missing studies to the left of the mean. The FSN 37, was under the critical value of 65 which does not imply a robust effect. Symmetrical plots were observed for object control skills and EF components of WM and CF. The FSN 16, was under the critical value of 50 for object control skills and RI and FSN was 0 for object control skills and CF, indicating that these findings should be interpreted with caution.

Table 4

Effect Size Between Different Components of Motor Skills and Executive Functions

Between motor skills & EF components	K	N	r	95% CI	Q (df)	I^2(%)
Balance						
Response inhibition	9	1160	.20***	.098 - .301	20.94(8)**	61.79
Working memory	8	946	.18**	.052 - .298	24.90(7) ***	71.90
Cognitive flexibility	8	1005	.12*	.014 - .230	20.34(7)**	65.58
Manual dexterity						
Response inhibition	16	1872	.19***	.100 - .280	58.86(15)***	74.51
Working memory	17	2263	.21***	.104 - .324	114.53(16)***	86.03
Cognitive flexibility	12	1573	.17**	.052 - .278	58.01(11)***	81.04
Locomotor skills						
Response inhibition	8	1529	.07	-.112 - .262	79.75(7)***	91.22
Working memory	7	1487	.19**	.047 - .328	39.39(6)***	84.78
Cognitive flexibility	7	1487	.06	-.092 - .227	48.34(6)***	87.58
Object control skills						
Response inhibition	11	1857	.08	-.034 - .202	55.41(10)***	81.95
Working memory	8	1679	.08	-.019 - .189	26.90(7)***	73.98
Cognitive flexibility	9	1779	.06	-.052 - .186	44.15(8)***	81.89

Note. *$p < .05$. **$p < .01$. ***$p < .001$

Moderator Analysis of Age

The results of the meta-regression (Table 5) using the random effects model revealed no significant ($p = .30$) age effects for the relationship between the global domains of motor skills and EFs (Fig. 6). However, among the relationships between the different components of motor skills and EFs, a significant age effect was observed in the case of balance and response inhibition ($p < .01$) (Fig. 7).

Table 5

Results on Meta-regression of Age using Random-effects Model

Covariate	Coefficient	Standard Error (SE)	p-value
Model 1: Overall motor skills and executive functions			
Intercept	.2902	.1023	.0045
Age	-.0164	.0159	.3001
Model 2: Balance and response inhibition			
Intercept	-.2689	.1311	.0402
Age	.0896	.0238	.0002**
Model 3: Balance and working memory			
Intercept	-.2712	.2461	.2705
Age	.0841	.0456	.0652
Model 4: Balance and cognitive flexibility			
Intercept	-.0332	.2353	.8879
Age	.0284	.0410	.4884
Model 5: Manual dexterity and response inhibition			
Intercept	-.0394	.2038	.8467
Age	.0427	.0362	.2378
Model 6: Manual dexterity and working memory			
Intercept	.5382	.2223	.0155
Age	-.0550	.0371	.1385
Model 7: Manual dexterity and cognitive flexibility			
Intercept	-.0213	.2801	.9394
Age	.0333	.0477	.4848
Model 8: Locomotor skills and response inhibition			
Intercept	.4208	.3245	.1946
Age	-.0519	.0465	.2641
Model 9: Locomotor skills and working memory			
Intercept	.0313	.2897	.9140
Age	.0237	.0400	.5534
Model 10: Locomotor skills and cognitive flexibility			
Intercept	.2063	.3200	.5191
Age	-.0198	.0441	.6545
Model 11: Object control skills and response inhibition			
Intercept	.1628	.1908	.3934
Age	-.0125	.0292	.6679
Model 12: Object control skills and working memory			
Intercept	.0144	.1659	.9308
Age	.0106	.0106	.6669
Model 13: Object control skills and cognitive flexibility			
Intercept	.1032	.2002	.6062
Age	-.0134	.0296	.6498

Note. $^{**}p < .01$.

Figure 6.

Scatterplot for Meta-Regression of Age on the Relationship Between Global Motor Skills and Executive Functions.

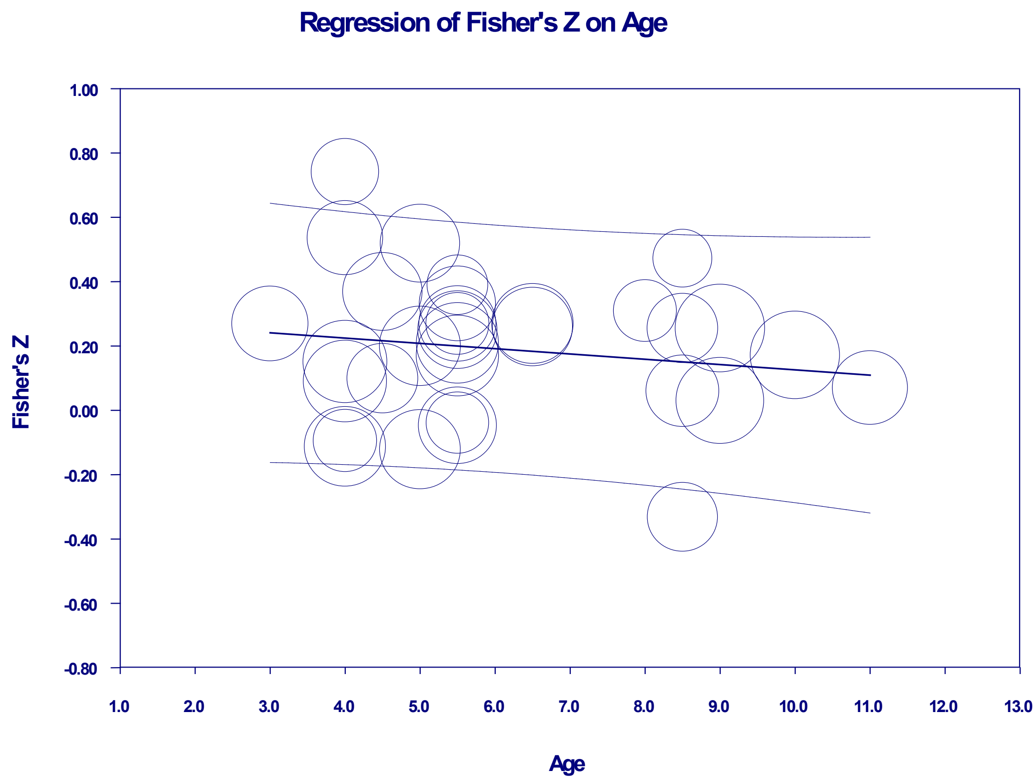
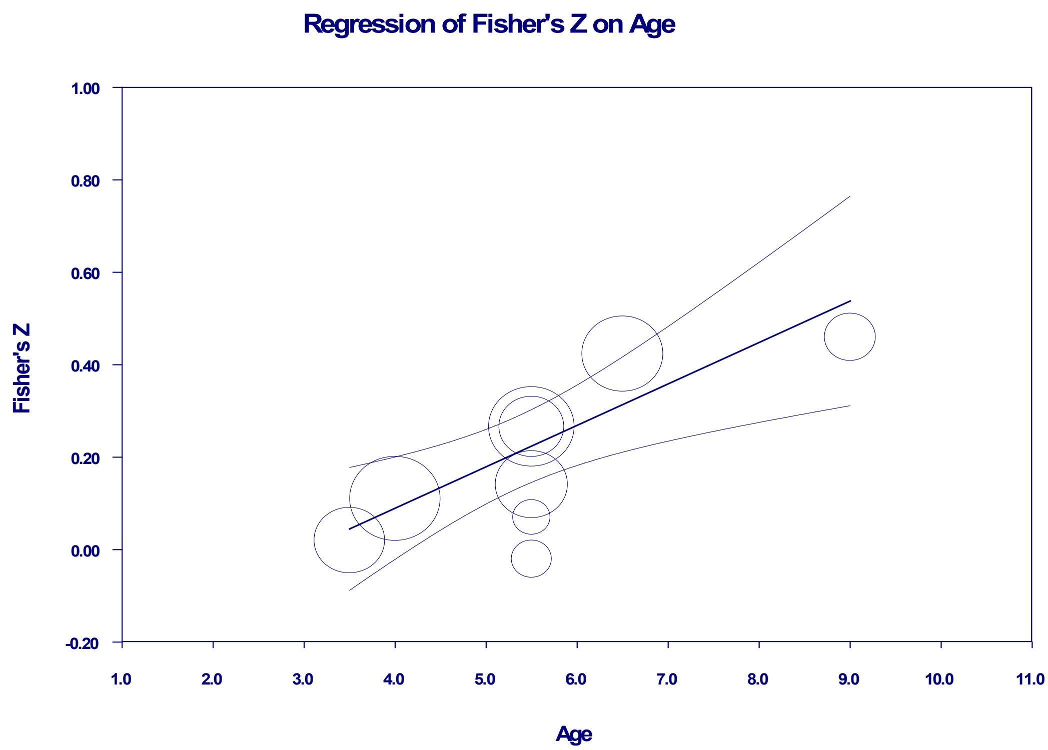


Figure 7.

Scatterplot for Meta-Regression of Age on the Relationship Between Balance and Response Inhibition



Discussion

The association between motor skills and EFs in children is increasingly being recognized. Although previous research (Jongbloed-Pereboom et al., 2012; Wilson et al., 2013) has provided substantial evidence of a relationship between motor skills and EFs in atypically developing children, there is no conclusive evidence for this association in typically developing children. In view of this, the purpose of the present meta-analytic study was to provide a better understanding of the nature of this relationship by systematically evaluating the global as well as the specific associations between the various components of motor skills (balance, manual dexterity, locomotor skills, and object control skills) and EFs (response inhibition, working memory, and cognitive flexibility) in typically developing children. A total of 32 studies, involving 4,866 participants, were included in the meta-analysis. The results indicated significant positive associations of small effect size ($r = .18$) between the global domains of motor skills and EFs (i.e., across all the components of motor skills and EFs). These findings confirm the theoretical notion of reciprocal relationships between motor skills and EFs and support the general idea that both motor skills and executive functioning are subserved by overlapping neural networks (Diamond, 2000; Ito, 2008; Leisman et al., 2016; Sergeant, 2000).

With respect to the specific relationships between the different components of motor skills and EFs, balance and manual dexterity were found to be significantly associated with all the EF components (response inhibition, working memory, and cognitive flexibility), unlike locomotor and object control skills. Balance and manual dexterity can thus be interpreted as less automatized and as motor tasks that are difficult for children in that they engage all three EF components almost to the same extent (Best et al., 2009). The identification of an association between manual dexterity and EFs is consistent with an earlier correlational study that found a stronger relationship in the case of fine motor skills, compared to other motor skills, with cognitive skills in children (van der Fels et al., 2015). Manual dexterity tasks, such as inserting coins into a slot, can indeed be cognitively challenging in several ways. For instance, successful performance on this task requires the child to choose the appropriate motor response (i.e., precise movements of the hands), to hold a mental representation of the task sequence throughout its implementation (i.e., to hold the box with one hand and to insert the coins as quickly as possible), and to switch between thinking regarding the correct order in which the coins need to be inserted. Balance-related tasks, on the other hand, also demand the extensive implementation of higher-order cognitive strategies, such as interference control, for optimal performance (Woollacott & Shumway-Cook, 2002; Kearney et al., 2013). These findings are supported by neuroimaging studies that have shown stronger activation of the cerebellum and prefrontal cortex during the execution of complex motor or cognitive tasks (Diamond, 2000; Serrien & Swinnen, 2006).

Locomotor skills appeared to be associated uniquely with working memory out of all the EF components. This suggests that tasks such as galloping, sliding, skipping, and leaping are not sufficiently automatized in children and therefore require additional movement coordination, meaning a greater emphasis on information activation and sequencing, which involves the working memory (Alesi et al., 2016). These findings can also be corroborated with recent aerobic-based intervention studies, which showed that motor exercises involving bilateral coordination and spatial orientation improved working memory performance in children (Alesi et al., 2016; Koutsandreou et al., 2016).

In the present study, non-significant relationships were found between object control skills and all three EF components, indicating that these skills are largely automatic in children and require minimal higher-level cognitive inputs. This may be due to children's increased familiarity with, and extensive practice of, object control tasks, such as throwing, aiming, and catching (Davis et al., 2011).

Moderator analysis was undertaken to identify whether the relationship between the global domains of motor skills and EFs becomes stronger or weaker with age. The results revealed no significant age effect, indicating that the motor skills–EFs link remains stable throughout childhood and is not influenced by the child's developmental stage. These findings does not support the idea that the strength of the relationship between motor skills and EFs will decrease with age, due to automaticity of motor skills with practice (Ackerman, 1988; Ben-Sasson & Gill, 2014; Libertus & Hauf, 2017).

With respect to the specific relationship between the individual components of motor skills and EFs, the only components that were found to show significant age-related change (improvement) were balance and response inhibition. One possible explanation for this age effect is that the execution of balance control tasks does not become automated with age and requires persistent cognitive efforts in the form of significant inhibitory control capacity for successful task performance (see Woollacott & Shumway-Cook, 2002, for a review). However, these results are not conclusive and should be interpreted with caution as the meta-regression for this component relationship was performed on an inadequate number of studies (n = 9) (Borenstein et al., 2010).

Taken together, the findings of the present study show a significant relationship between motor skills and EFs both at the global domain level as well as between the underlying components of motor skills and EFs, with the strongest independent associations occurring between the motor skills balance and manual dexterity with all three EF components. The results of this meta-analysis are important in the context of intervention programs aimed at promoting motor skills and EFs in children, as they support the idea that interventions in one domain may facilitate the development of both motor skills and EFs in children (Westendrop et al., 2014). In addition, the results highlight the importance of including difficult motor skills, such as balance and manual dexterity, in motor intervention programs designed to improve EFs in children.

While the present meta-analysis enhances our understanding of the multilevel nature of the relationship between motor skills and EFs in typically developing children, there are some limitations that should be borne in mind when interpreting the findings. First, a considerable degree of heterogeneity, as indicated by an $I^2 < 60\%$, was observed across the 32 studies. This amount of dispersion might be attributable to the fact that the same standardized measures were not used consistently to assess motor skills and EFs in the studies included in the meta-analysis. Second, the majority of the studies included in the review (n = 27) used a cross-sectional research design, thereby limiting our understanding of the causality between motor skills and EFs. In future research, the longitudinal examination of the motor skills–EFs link would be valuable in establishing the causal direction between the two domains. Third, there were an insufficient number of studies that investigated the relationship between certain components of motor skills and EFs (e.g., object control skills with working memory and cognitive flexibility; and locomotor skills with response inhibition and cognitive flexibility). Future research should therefore explore the correlation between these specific components in order to gather substantial evidence for or against these relationships. Fourth, the meta-analysis was not able to examine the potential contribution of factors such as the participants' socioeconomic status, race, and ethnicity on the relationship between motor skills and EFs. Although these factors were considered as moderators when the meta-analytic study was set up, there was insufficient information available in the studies to conduct these analyses. Finally, the findings of our study are applicable exclusively to typically developing children. In future studies, it would be worth comparing the strength of the relationship between motor skills and EFs in typically and atypically developing children, and the level of evidence for it, so as to ascertain the underlying causes of the relationship.

Conclusion

Based on a systematic examination of the existing literature, the present meta-analytic study provides evidence, although of a small effect size, for the interrelationship between motor skills and EFs at both the global level as well as at specific levels of analysis. These findings are of interest in the context of training programs aimed at promoting motor skills and/or EFs in children.

Declaration of Competing Interests

The authors report no competing interests.

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4.2. Study II

An Exploratory Study of the Relationship between Motor Skills and Indicators of Cognitive and Socioemotional Development in Preschoolers

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Abstract

Motor skills develop rapidly during early childhood and are considered important for optimal child development. However, little is known about the relationship of motor skills with indicators of cognitive and socio-emotional development in typically developing preschoolers. In view of this, the present study examined the association of gross motor and fine motor skills with executive functions and prosocial behaviour in preschoolers. The study sample consisted of 111 participants between 3 and 5 years of age, who were assessed using the short version of the Bruininks-Oseretsky Test of Motor Proficiency, second edition (BOT-2); the head-toes-knees-shoulders task; the Corsi block-tapping test (CBTT); the dimensional change card sort test (DCCS); and a teacher-rated prosocial behaviour questionnaire (PBQ). The results revealed significant positive associations between motor skills and executive functions as well as prosocial behaviour. Specifically, fine motor skills were twice as strong as a predictor for response inhibition compared to gross motor skills whereas gross motor skills dominated over fine motor skills in predicting prosocial behaviour. The findings of the study highlight the need to promote motor skills during early years of development.

Introduction

Early childhood is considered to be a critical period in terms of children's overall growth and development. During this period, motor skills develop markedly, laying the foundations for success in a number of other developmental areas, including language, cognition, physical and social development (Bar-Haim & Bart, 2006; Campos et al., 2000; Diamond, 2007; Iverson, 2010; Rosenbaum et al., 2001). Motor skills, which are defined as observable, "goal-directed movement patterns" (Burton & Miller, 1998, p.44), can be broadly classified as gross motor skills and fine motor skills. Gross motor skills refer to the ability to effectively move through space using the large, force-producing muscles of the body (Haywood & Getchell, 2009), while fine motor skills involve the coordination of small muscle movements in the fingers, hands, and wrists to efficiently manipulate objects (Clark & Whitall, 1989). Together, these motor skills give children the opportunity to explore and interact with their environment in an increasingly complex way (Piaget & Inhelder, 1966). The child's interaction with their environment in turn allows them the opportunity to acquire cognitive and socio-emotional skills (Bushnell & Boudreau, 1993; Campos et al., 2000). This idea is reinforced in the embodied cognition perspective, in which cognition is considered to take place in the context of the sensory–motor interactions of the individual's body with their physical, as well as with their social environment (Barsalou, 1999; Gibbs, 2005; Smith & Gasser, 2005). This theoretical notion is supported by empirical studies (Ludyga et al., 2019; Oberer et al., 2017; Piek et al., 2008; Policastro et al., 2019; Roebers & Kaurer, 2009; van der Fels et al., 2019) that have demonstrated a positive relationship between motor skills and higher cognitive processes such as response inhibition (RI), working memory (WM), and cognitive flexibility (CF), which are collectively known as executive functions (EFs) (Miyake et al., 2000). Previous studies investigating this relationship in typically developing children have yielded inconsistent findings regarding the strength and nature of the association, and while many of the studies examined the association between motor skills and EFs in school children, the extent to which the results can be generalized to preschoolers is still unclear (Cameron et al., 2012; Houwen et al., 2017; Oberer et al., 2017). Moreover, the studies that did involve preschoolers did not include both gross motor and fine motor skills simultaneously (Becker et al., 2014; de Lucena Martins et al., 2020; Wu et al., 2017; van der Fels et al., 2015) and selectively focused on only one or two components of EFs (Livesey et al., 2006; Piek et al., 2004; Rigoli et al., 2012). Therefore, more research is needed to gain a better understanding of the possible relationship between motor skills and the core components of executive functioning in preschool children. Such knowledge can help in developing innovative intervention programs that include motor components in order to promote young children's cognitive development.

Alongside cognition, motor skills also play a crucial role in a child's social and emotional functioning (Cairney et al., 2013; Cummins et al., 2005; Piek et al., 2015). An important component of socio-emotional development in childhood that has been relatively less studied in conjunction with motor skills is prosocial behaviour. Prosocial behaviour is considered to be a key element in the healthy adjustment of the child (Eisenberg & Fabes, 1990) and is defined as an intentional or voluntary act in which an individual engages in order to benefit another person (Eisenberg et al., 2006). Like motor skills, prosocial behaviour develops rapidly between 3 and 5 years of age (Cassidy et al., 2003) and is typically demonstrated by preschoolers in the form of cooperation, sharing, helping, and comforting acts. Much of the existing work on the developmental origins of prosocial behaviour in preschoolers has focused on the child's early socialization processes (Hay, 1994; Eivers et al., 2012), cognitive maturity (Aguilar-Pardo et al., 2013), and emotional regulation (Laible et al., 2014; Miller et al., 1996), while the role of motor skills has been largely ignored. To date, the only study that has examined the direct link between gross motor, fine motor skills, and helping behaviour has been conducted on 16-month-old infants (Köster et al., 2019). The results of this study showed that the qualitative changes in infants' social abilities that are brought by their accompanied increased competence in motor skills supported their helpful behaviour. However, more research is needed to explore the possible relationship between motor skills and prosocial behaviour in preschool children, as the current evidence base is limited.

In the above context, the present study was undertaken to address some of the gaps in the existing literature, with the following objectives in mind: (a) to examine the relationship between specific motor skills (i.e., gross motor and fine motor skills) with the different components of EFs (i.e., RI, WM, and CF); and (b) to examine the relationship between motor skills and prosocial behaviour in typically developing preschoolers.

Method

Participants

The participants were 111 children aged between 3 and 5 years (*M* = 4.09 years, *SD* = 0.78), of whom 53% were girls and the remaining 47% boys. The participants were selected randomly from two public kindergartens in Budapest, Hungary. Although no formal testing was done to exclude intellectual disability, there were no children with mental retardation or sensory-motor disorders in the sample according to the records and information provided by the children's caretakers. All the children had similar socioeconomic backgrounds.

Assessments

Motor Skills

The children's motor skills were assessed using the short version of the Bruininks-Oseretsky Test of Motor Proficiency, second edition (BOT-2) (Bruininks & Bruininks, 2005). The reliability and validity of the BOT-2 short form are well established (Bruininks & Bruininks, 2005). In the present study, all 12 items of the test measuring gross motor skills (touching nose with index fingers eyes closed; pivoting thumbs and index fingers; walking forwards on a line; one-legged side hopping; and push-ups) and fine motor skills (coloring a star; drawing a line through a path; stringing blocks; copying overlapping circles; copying a diamond; catching a ball with one hand; dribbling a ball using alternate hands) were utilized. Prior to each test item, the children received verbal explanation and demonstration about the specific test procedure. They were also encouraged by the examiner to perform all the test items to the best of their abilities. Regarding the scoring of the test, raw scores were used because norm-referenced scores were not appropriate for children who were younger than 4 years of age in our sample. The raw scores for each test item were converted to point scores. The point scores for the five gross motor skills items and seven fine motor skills items were summed to obtain a total score for gross motor and fine motor skills. It is important to note that the total motor score and standard scores were used only for the purpose of identifying participants with motor difficulty. None of the participants were found to have abnormal (standard score ≤ 40) motor performance.

Cognitive Development

In the present study, the core components of EFs—namely, RI, WM, and CF—were used as indicators of cognitive development.

Response Inhibition. Response inhibition, which is defined as the ability to suppress an automatic response in favor of a more appropriate subordinate response (Miyake et al., 2000) was measured using the head-toes-knees-shoulders (HTKS) task (Ponitz et al., 2009). Studies have demonstrated HTKS to have high interrater reliability (92.3%) and adequate construct validity (McClelland et al., 2007; Ponitz et al., 2009). In this test, children were instructed to do the opposite of what the examiner told them to do. For instance, when asked to touch a particular part of the body (i.e., head, toes, knees, or shoulders), the children were instructed to touch the opposite part of the body instead (e.g., toes rather than head, and shoulders rather than knees). After practicing a few items, the children were given 20 randomly ordered commands to touch their head, toes, knees, or shoulders. Correct responses on all items received a score of 2; self-corrects (i.e., discernible motion towards an incorrect response with the final response given correctly) received a score of 1; and incorrect responses received a score of 0. The maximum possible score was 40.

Working Memory. Working memory, which refers to the ability to temporarily hold information in mind and mentally work on it (Garon et al., 2008) was measured using the Corsi block-tapping test (CBTT) (Corsi, 1972) under forward and backward conditions. CBTT have been found to have good test-rested reliability (r = .81, r = .89; Alloway et al., 2006) in preschoolers. We used nine cubes that were placed asymmetrically on a 25 × 30 cm board. The examiner started the test by creating a sequence pattern by tapping on different blocks at the rate of one block per second. The participant then imitated the same pattern by tapping on the blocks. The number of blocks was increased with each trial. Participants were given two attempts at each trial. The task ended when the participants could no longer memorize the sequence. In the backward condition, the participant had to repeat the sequence backwards. The scores for each of the forward and backward conditions ranged from 2 to 9. In the present study, the scores for the forward and backward conditions were summed to obtain a global score for working memory.

Cognitive Flexibility. Cognitive flexibility, which is defined as the ability to switch between mental sets (Miyake et al., 2000) was measured using the dimensional change card sort (DCCS) test (Zelazo et al., 1996). The DCCS test is a well-established measure (Zelazo et al., 2013) that requires children to shift their attention between two rule sets in order to perform it correctly. In the standard DCCS task, participants were presented with two target cards (i.e., blue rabbit or red boat) and were instructed to sort the cards according to the color of the object. After seven trials, the participants proceeded to the post-switch phase, in which they were asked to sort the next seven cards according to shape. Their score was the sum of the total number of cards correctly sorted (1 = correct, 0 = incorrect) and ranged from 0 to 14. In the advanced version of the DCCS task, if there was a border on the card the child had to sort it by color, but if there was no border the child had to sort it by shape. The score in this case was the sum of the total number of cards correctly sorted (1 = correct, 0 = incorrect) and ranged from 0 to 12. In the present study, the scores for the standard and advanced versions of the DCCS task were summed to obtain a global score for cognitive flexibility.

Socio-emotional Development

Prosocial behaviour was used as an indicator of socio-emotional development in the current study. It was assessed using the teacher-rated prosocial behaviour questionnaire (PBQ) (Weir et al., 1980). The PBQ comprises 20 test items that assess a large class of prosocial behaviours such as comforting, helping, sharing, and cooperating. For each child, these items were rated by their class teacher on a 3-point Likert scale (*rarely applies*, *applies somewhat*, or *certainly applies*). The scores ranged between 0 and 40, with a higher score indicating a higher level of prosocial behaviour.

Procedure

The study was conducted after being given ethical approval by the review committee of the author's university. An agreement form was sent to the head of the kindergarten and the parents of the participants requesting their written consent to carry out the research. The data were then collected from the children on two separate occasions. The children's motor proficiency was assessed on the first occasion, while their EFs were measured a few days later. The tests of EFs were administered in the following order: (1) CBTT; (2) HTKS; and (3) DCCS. Children were tested individually in a quiet room located in the vicinity of their kindergarten, after the instructions had been explained to them. A few standard practice trials were done to ensure that each child clearly understood the instructions. This procedure was followed for the entire sample of participants, with each testing session lasting up to 40 minutes. The PBQs, which were distributed to the classroom teachers at the beginning of the data collection phase, were collected from them once the data collection from the children was completed. It is important to note that the above tests were translated from English to Hungarian through the process of forward and backward translation.

Data Analysis

The exploratory analysis began by computing the descriptive statistics followed by examination of all the variables for normality of score-distributions using Shapiro-Wilks's test. Spearman's rank order correlation was utilized for determining the interrelation of motor skills with the indicators of cognitive and socio-emotional development, as the latter variables were found to be non-normally distributed (Table 6). Further, we carried a series of linear regression analyses to find out which type of motor skills (gross or fine) were a stronger predictor of EFs and prosocial behaviour. Before conducting the linear regression, its assumptions were checked. In all the models presented below, there was no multicollinearity in our data according to variation inflation factor (VIF) and tolerance scores, and the assumption of homoscedasticity was met as well. As for the linear relationship between independent and dependent variables, it was violated in case of cognitive functions and prosocial behaviour, therefore the results of linear regression need to be treated carefully. The data analysis was carried out using IBM SPSS Statistics 26 software.

Results

Descriptive statistics, comprising of means, standard deviations, observed range of scores and test of normality for each of the key variables in the study are presented in Table1. The results of the Spearman's correlation indicated significant positive association for gross motor and fine motor skills with all the three components of EF. Also, the majority of the correlations between motor skills and EFs were found to have moderate strength (Table 7). Concerning the correlations with prosocial behaviour, significant positive correlation of medium to high magnitude was found for both gross motor and fine motor skills (Table 8). Lastly, the results of multiple linear regressions (Table 9) demonstrated that all four models were significant, with RI and prosocial behaviour prediction models having the best variance explained by fine motor and gross motor skills.

Table 6

Descriptive Statistics of the Included Variables on Total Sample (N= 111)

Variables	M	SD	Observed range	Shapiro-Wilk Sig.
Motor skills				
Total Fine motor composite	16.94	7.95	34	.088
Total Gross motor composite	15.14	6.05	26	.117
Total Motor composite	32.03	12.27	54	0.94
Standard score for the total composite score	67.86	11.22	39	.000
Cognitive skills				
Response Inhibition	24.32	11.78	40	.000
Working memory	4.18	1.87	9	.000
Cognitive flexibility	18.86	4.82	26	.000
Prosocial behaviour	23.89	8.82	38	.013

Note. * The total motor score and standard scores were used to identify participants with motor difficulty.

Table 7

Correlation between Motor Skills and Executive Functions

	Response Inhibition	Working memory	Cognitive flexibility	Gross motor skills	Fine motor skills
Response inhibition	1	.510**	.486**	.461**	.667**
Working memory	.510**	1	.346**	486**	.494**
Cognitive flexibility	.486**	.346**	1	.479**	.398**
Gross motor skills	.461**	.486**	. 479**	1	.540**
Fine motor skills	.667**	.494**	.398**	.540**	1

Note. **: Correlation is significant at the p ≤ .01 level.

Table 8

Correlation Between Motor Skills and Prosocial Behaviour

	Gross motor skills	Fine motor skills	Prosocial behaviour
Gross motor skills	1	.540**	.709**
Fine motor skills	.540**	1	.607**
Prosocial behaviour	.709**	.607**	1

Note. **: Correlation is significant at the p < .01 level

Table 9

Multiple Linear Regression Models for Response Inhibition, Working Memory, Cognitive Flexibility and Prosocial Behaviour Based on the Following Predictors: Gross Motor and Fine Motor Skills.

	Predictor	B	T	Sig.	β	Model R^2	Model F	Model sig.
Response inhibition	Gross motor skills	.40	2.475	.015	.20			
	Fine motor skills	.81	6.658	< .001	.55	.45	44.1	< .001
Working memory	Gross motor skills	.07	2.457	.016	.24			
	Fine motor skills	.07	3.249	.002	.32	.23	16.2	< .001
Cognitive flexibility	Gross motor skills	.32	4.374	< .001	.40			
	Fine motor skills	.16	2.936	.004	.27	.33	26.7	< .001
Prosocial behaviour	Gross motor skills	.78	7.244	< .001	.53			
	Fine motor skills	.36	4.424	< .001	.33	.56	68.5	< .001

Discussion

The present study sought to gain a better understanding of the association of motor skills with indicators of cognitive and socio-emotional development in preschool children. Specifically, the study examined the relationship of gross motor and fine motor skills with core components of EFs (i.e., RI, WM, and CF) and prosocial behaviour in a sample of 111 typically developing preschoolers. The results demonstrated that motor skills were positively related to EFs. These associations can be explained as a result of similar developmental timetables with respect to the motor and cognitive domains during early childhood years—that is, between the ages of 3 and 5 (Anderson, 2002; Carson et al., 2015). Furthermore, parallel increases in motor skills and EFs could be due to the coactivation of certain brain structures (prefrontal cortex, cerebellum, and basal ganglia) underlying performance on tasks involving motor skills and EFs (Diamond, 2000; Diamond, 2015; Ridler et al., 2006).

The results of our study also revealed that the strength of the relationship varied between the different components of motor skills and EFs. Both, gross motor and fine motor skills showed moderately strong to strong positive associations with RI and CF while WM was found to be moderately related with both gross motor and fine motor skills. Compared to other studies (Cook et al., 2019; Oberer et al., 2017), this is the first study to provide substantial evidence for a positive association between gross motor skills and cognitive flexibility in preschoolers. A possible explanation for this finding could be that the tasks used in the current study to assess gross motor skills were less familiar to the children, thus requiring them to pay considerable attention to switching rapidly between simultaneous goals for successful task performance (Anderson, 2002). For instance, touching the nose with the index fingers with eyes closed can be cognitively challenging in several respects. Successful performance on this task requires the child to choose the appropriate motor response (i.e., to touch the nose with the index finger while the other fingers are tucked in), to hold a mental representation of the task sequence throughout its implementation (i.e., to stand with both arms straight out to the sides and to touch the index fingers to the nose with continuous movements while the eyes are closed), and to switch between thinking with respect to alternating arms with each touch.

The findings regarding the link between fine motor skills and RI are consistent with previous studies (Livesey et al., 2006; Röthlisberger et al., 2012; Stöckel & Hughes, 2016) and indicate that children of preschool age may not yet have practiced fine motor skills sufficiently for them to have become automated (Maurer & Roebers, 2019), thus performance on fine motor skills tasks required greater involvement of cognitive resources, especially RI.

Lastly, our analysis showed that both gross motor and fine motor skills were positively related to WM in similar strength. These findings extend their support to other studies that demonstrated, both better whole body coordination and manual dexterity were positively associated with better recall of items in WM tasks (Niederer et al., 2011; Piek et al., 2008; Roebers & Kauer, 2009; Wassenberg et al., 2005). Evidence derived from neuroimaging studies provides some explanation for this relationship, in the form of an overlap in the neural networks that are important for gross motor skills, fine motor skills, and WM (Diamond, 2000; Leisman et al., 2016). However, further studies are needed to identify the plausible mechanisms related to motor skills especially fine motor skills and working memory.

With respect to the indicator of socio-emotional development, the results showed positive associations between motor skills and prosocial behaviour, although the extent of this relationship differed in the case of gross motor and fine motor skills. In particular, prosocial behaviour was related more strongly to gross motor than to fine motor skills. These findings suggest that having gross motor skills may facilitate prosocial behaviour in preschoolers by providing them with opportunities to engage in social interactions with their peers (Bar-Haim & Bart, 2006; Zimmer-Gembeck et al., 2005). For instance, children with better motor skills are more likely to participate in active play with their peers, which in turn promotes and stimulates social interaction and helps these children develop a positive attitude toward their peers, which is a key component of prosocial behaviour (Caputi et al., 2012; Layous et al., 2012; Pellegrini & Smith, 1998). These findings can be corroborated with previous studies in which motor difficulties were recognized as a contributing factor for poor socio-emotional competence in children with developmental coordination disorder (DCD) (Cummins et al., 2005; Piek et al., 2008).

Taken together, our findings provide evidence for a positive association between motor skills and indicators of cognitive and socio-emotional development in a relatively large sample of preschoolers with fairly equal gender representation. It is, however, important to note that the present study is not without limitations. First, the study used a cross-sectional design, which limits causal inferences. Second, although the participants of this study were attending the mainstream kindergarten and did not have intellectual disability or any other developmental disorders based on the kindergarten's record, however this was not confirmed by a formal measure of IQ or other developmental screeners. Third, there is a possibility that the relationship between motor skills and executive functions may have been influenced by the choice of tests used. For instance, the motor component involved in each of the three EFs tests employed in the study, might have confounded the nature and the strength of this relationship. It is therefore recommended for future studies to replicate the current findings by employing different measures of EFs. Fourth, we did not use an age-appropriate, objective performance-based measure of prosocial behaviour in children, thus there is a possibility that the results were influenced by the personal bias of the teacher towards the children. Finally, in attempting to interpret the results, it is important to note that the findings relating to socio-emotional development is limited to only prosocial behaviour and does not generalize to its other elements such as self-awareness and emotion regulation.

In conclusion, our study suggests that during preschool years, motor skills are positively related to other developmental domains, especially cognitive and socio-emotional development. Therefore, it is highly recommended that the development and promotion of motor skills be considered as an integral part of early childhood development programs.

4.3. STUDY III

Age differences in Executive Functions among Hungarian Preschoolers

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Abstract

Executive functions (EFs) undergo dramatic changes during preschool years and show differential age-related effects. In view of this, the present study examines the developmental pathways of EF components among Hungarian preschoolers. The study sample consisted of 136 participants aged between 3 and 6 years old, who were assessed using the head-toes-knees-shoulders test (HTKS), the Corsi block-tapping test, and the dimensional change card sort test (DCCS). The analysis revealed significant age effect on performance in all EF tests, with a trend towards better performance with age. In general, the results for most EF tasks were similar to those reported by studies conducted in other countries, indicating consistency in the structure of EFs. Moreover, superior performance on cognitive flexibility tasks by younger participants draws attention to the potential influence of early childhood education, via child-rearing beliefs and practises, on the promotion of EF skills.

Introduction

Preschool years have been considered a critical period of transition for executive functions (EFs) due to rapid development of the prefrontal cortex, a brain region underlying EFs (Best & Miller, 2010; Röthlisberger et al., 2013). Executive functions refer to higher-order cognitive processes that enable individuals to interact with their environment in an adaptive manner (Diamond, 2013). Over the past few years, there has been a growing focus on young children's EFs as an important developmental factor, since EFs contribute to children's school readiness, academic success, socioemotional competence, and mental health (J. A. Welsh et al., 2010; Kraybill & Bell, 2013; Schoemaker et al., 2012). Executive functions in preschoolers have also been found to play a significant role in predicting the retrieval of specific autobiographical memories (Nieto et al., 2018), a key element of human experience that serves several important functions, including the formation of a stable sense of self or identity (Bluck et al., 2005). Lastly, an in-depth understanding of EF during preschool years can also facilitate early identification and subsequent intervention of neurodevelopmental disorders such as ADHD and ASD which have executive dysfunctions as central to its aetiology (Roselli et al., 2008). The myriad of positive outcomes associated with EFs, and the rapid brain maturation processes that take place during this developmental period make it an ideal time for a thorough investigation of the nature and factors influencing the development of EFs. Executive functions in preschool children can be divided into three interrelated yet distinct components – namely, response inhibition (RI), working memory (WM), and cognitive flexibility (CF) (or set shifting) (Miyake et al., 2000; M. C. Welsh et al., 1991). Each of these EF components undergoes significant development during early childhood years and shows a distinct developmental pattern, with some components reaching maturity more quickly than others (Best & Miller, 2010; Lerner & Lonigan, 2014; Lonigan et al., 2016; Nieto et al., 2016). Response inhibition, which refers to the ability to override an automatic response in favour of a more appropriate subordinate response, is the first component to emerge and is considered to be the foundation of EF (Miyake et al., 2000). Developmental differences have been noted on several RI-based tasks. For instance, Carlson (2005), in her cross-sectional study on delay gratification tasks, demonstrated that 3-year-olds have difficulty delaying the urge to eat a treat beyond 1 minute, whereas 4-year-olds are able to resist eating a treat for 5 minutes, thus indicating that inhibitory control improves with age. Similar developmental profiles, where considerable improvement in inhibition is attained between 3 and 5 years of age, have been noted on go/no-go tasks (Carlson, 2005; Van den Wildenberg & Van der Molen, 2004) as well as on complex response inhibition tasks (Carlson & Moses, 2001; Diamond & Taylor, 1996; Gerstadt et al., 1994; Ponitz et al., 2009). The development of working memory, like response inhibition, has been studied using wide-ranging tasks that require temporarily holding information in mind and mentally working on it (Baddeley et al., 1986; Garon et al., 2008). A sequential improvement in performance has been noted in children between 3 and 6 years of age across several memory span tasks, such as the forward digit span task (Carlson, 2005), the backward digit span task (Unsworth & Engle, 2007), the spatial memory scanning task (Davis & Pratt, 1995; Gathercole, 1998; Perner & Lang, 2000), the missing scan task (Roman et al., 2014), and the count and label task (Stievano & Valeri, 2013). Cognitive flexibility, or set shifting, is the last component to develop, as it builds on response inhibition and working memory (Miyake et al., 2000). Typically, a rudimentary ability to rapidly switch between mental sets appears from the age of 3 years and continues to be refined from the ages of 4 to 5 years and beyond. For instance, Zelazo (2006) demonstrated a significant age-related difference in performance between 3-, 4-, and 5-year-old children on the dimensional change card sort test (DCCS), which is one of the most widely used tasks for measuring cognitive flexibility. Specifically, most 3-year-olds succeeded in the first phase of the task, which requires them to sort cards according to a specific dimension (colour), but they struggled to switch to the new rule for sorting the cards (by shape) and showed a tendency to perseverate on the previous dimension. In contrast, most 4- and 5-year-olds were able to successfully switch dimensions (Kirkham et al., 2003; Kloo & Perner, 2005; Zelazo et al., 1996). Unlike standard DCCS, the majority of children aged between 5 and 6 years old struggled on the advanced DCCS, which required them to sort the cards based on an additional dimension (Zelazo et al., 2003). Taken together, the existing evidence suggests that EFs expand from 3 years of age, with the development of response inhibition, working memory, and cognitive flexibility becoming more pronounced at around 5 years of age. The growth of EF during this period is mirrored by rapid brain maturation processes, such as increased myelination, synaptic pruning, and the formation of neural networks in the prefrontal cortex (Casey et al., 2005; Kagan et al., 2005; Thompson & Nelson, 2001). Besides biological influences, the development of EFs is also related to broader environmental influences on children, including early childhood education and care (also known as preschool education). A growing body of research suggests that early learning opportunities through preschool education are positively associated with a child's cognitive and intellectual performance (Anderson et al., 2003; Burger, 2010; Currie, 2001; Karoly et al., 2005). One potential explanation of these outcomes is exposure to an enriched learning environment that allows children to optimize their creative thoughts through free exploration and pretend play. This kind of learning environment, provided through the preschool curriculum, has also been linked to an improvement in children's working memory, inhibitory control, and set shifting skills (Bierman et al., 2008). Another promising avenue via which early childhood education can exert an influence on EF skills is child-rearing beliefs and practises (Imada et al., 2013). It has been consistently demonstrated by numerous studies that Asian preschoolers exhibit greater attentional control than their Western counterparts (Lan et al., 2011; Oh & Lewis, 2008; Sabbagh et al., 2006). Similarly, Moriguchi et al. (2012) concluded that Canadian preschoolers outperformed

Japanese preschoolers on the social version of the DCCS task. These findings suggest that EF development is multifaceted and is governed by both biological and environmental factors. Although there are numerous studies on EF improvement as a function of age in multiple countries, including the USA (Best & Miller, 2010; Carlson, 2005; Davidson et al., 2006), Canada (Garon et al., 2008; Zelazo et al., 2003), and the Netherlands (Huizinga et al., 2006), there are very few studies based in Eastern European countries. Moreover, the preschool education system in Eastern European countries, and especially Hungary, has several distinctive characteristics compared to the USA and most Western European countries, which suggests the need for a thorough examination of the development of EF among Hungarian preschoolers. For instance, children in Hungary start preschool education at 3 years of age and spend at least 4 hours per day in kindergarten (Hungarian Government, 2011). As opposed to rote learning and subject knowledge, the educational curriculum of kindergartens in Hungary (Ministry of Culture and Education, 1997) places a strong emphasis on fostering children's imagination and ability to think flexibly by introducing them to a variety of activities such as music, art, movement, and handicrafts. This kind of creative curriculum, which gives children equal exposure to the arts and the sciences, in a preschool environment that is characterized by social connectedness as an important child rearing practise (Brayfield & Korintus, 2011) has been found to have a positive outcome on children's literacy skills, such as reading and writing (Podlozny, 2000). However, its impact on children's executive functions is not yet known. In light of this, the present study uses a sample of Hungarian preschoolers to investigate age-related difference in EFs, including response inhibition, working memory, and cognitive flexibility.

Method

Participants

The participants comprised 136 children aged between 3 and 6 years (M = 4.87 years and SD = 0.98), of whom 51% were girls and the remaining 49% boys. The participants were chosen randomly from two public kindergartens in Hungary. Almost all the children had been enrolled in kindergarten at 3 years of age. Although no formal testing was done to exclude intellectual disability, there were no children with mental retardation or other sensory disorders in the sample, based on the records and information provided by the children's caregivers. The socioeconomic backgrounds of the children were determined based on the location of the kindergartens. The kindergartens were situated in average SES neighbourhood in Budapest.

Assessments

Working Memory

Working memory (WM) was measured using the Corsi block-tapping test (Corsi, 1972) under forward and backward conditions. A total of nine cubes were used, which were asymmetrically placed on a 25 × 30 cm board. The examiner started the test by tapping a sequence of blocks at the rate of one block per second. The participant then imitated the pattern by tapping the blocks. The number of blocks tapped was increased with each round, and the participant was given two attempts at each sequence. The task ended when the participant could no longer memorize the sequence. In the backward test, the participant had to repeat the sequence backwards. The scores for both the forward and backward tests ranged from 2 to 9.

Response Inhibition

Response inhibition was measured using the head-toes-knees-shoulders task (HTKS) (Ponitz et al., 2009). In this test, the children were instructed to do the opposite of what the examiner told them to do. For instance, when asked to touch a particular part of the body (i.e., head, toes, knees, or shoulders), the children were instructed to touch the opposite parts of the body instead (e.g., toes rather than head, and shoulders rather than knees). After practising a few times, the children were given 20 commands, in random order, to touch their head, toes, knees or shoulders. A correct response on each occasion received a score of 2; self-corrects (i.e., a discernible motion towards an incorrect response, with the final response given correctly) received a score of 1; and incorrect responses received a score of 0. The maximum possible score was 40.

Cognitive Flexibility

Cognitive flexibility was measured using the dimensional change card sort task (DCCS) (Zelazo et al., 1996). The DCCS is a non-verbal task that requires children to shift their attention between two sets of rules in order to perform the task correctly. In the standard DCCS, participants were presented with two target cards (i.e., a blue rabbit and a red boat) and were then instructed to sort the cards according to the colour of the object featured on them. After seven rounds, participants proceeded to the post-switch phase, in which they were asked to sort the next seven cards according to shape. Their score was the sum of the total number of cards correctly sorted (1 = correct, 0 = incorrect) and ranged from 0 to 14. In the advanced version of DCCS, if the card featured a border the child had to sort it by colour, but if there was no border, the child had to sort it by shape. The score here was the sum of the total number of cards correctly sorted (1 = correct, 0 = incorrect) and ranged from 0 to 12.

Procedure

The study was conducted after it was cleared for ethical aspects by the review committee of the author's university. A consent form was sent to the head of the kindergartens and to the parents of the participants, requesting their written consent to the research. Data collection began with the administration of EF tests on the children in the following order: (1)

the Corsi blocktapping test; (2) the head-toes-knees-shoulders test (HTKS); and (3) the dimensional change card sort test (DCCS). The children were individually tested in a quiet room located within their kindergarten, and a single session lasted up to 40 minutes. Testing was started only after the examiner had explained the instructions and performed a few standard practise rounds in order to make sure that the child had fully understood the instructions.

Data Analysis

The analysis of the age-related differences in the EF tests began by evaluating the normality of data distribution with the help of the Shapiro–Wilk test. Taking into account the results of the Shapiro–Wilk test, we concluded that the data were not normally distributed across the population. Therefore, a nonparametric independent samples Kruskal– Wallis test was used to track the differences across age groups with respect to EFs, including the head-toes-knees-shoulders test (HTKS), forward working memory (FWM), backward working memory (BWM), standard dimensional change card sort (SDCCS), and advanced dimensional change card sort (ADCCS). As an independent variable, age was divided into four categories: 3, 4, 5, and 6 years old. After performing the Kruskal– Wallis test, a pairwise comparison was made using Bonferroni's correction method to determine which exact pair(s) of age groups had a significant difference in terms of EF performance. The level of confidence was set at.05 for all comparisons. IBM SPSS Statistics 26 software was used for the data analysis.

Results

The results (Table 10) show a clear trend towards better performance with an increase in age in all the EF tests. In particular, performance across all the EF tests was found to be pronounced at the age of 5 years (Fig. 8), with children aged between 4 and 5 years old showing superior performance compared to other neighbouring age groups. A significant age effect was also found on all EF tests: HTKS, $\chi 2$ (3) = 42.695, p = .001; FWM, $\chi 2$ (3) = 26.924, p = .001;

BWM, χ 2 (3) = 32.768, p = .001; SDCCS, χ 2 (3) = 12.591, p = .006; ADCCS, χ 2 (3) = 16.040, p = .001). Post hoc analyses using Bonferroni's correction method revealed significant differences among several age groups on all the tests. Regarding HTKS, a significant difference was noted between the 3-year-olds age group (mean rank HTKS performance of 38.92) and the 5-year-olds (90.55) and 6-year-olds (92.61) age groups; and between the 4-year-olds age group (53.24) and the 5-year-olds (90.55) and 6-year-olds (92.61) age groups. With respect to FWM and BWM, the significant pairs were the same as in HTKS, but with different mean ranks: FWM (3 [mean rank FWM performance of 43.22], 4 [60.23], 5 [81.06], 6 [90.91]); and BWM (3 [mean rank BWM performance of 53.42], 4 [54.05], 5 [79.18], 6 [96.11]). Significant differences were also noted between the 3-year-olds age group (mean rank SDCCS performance of 55.0) and the 5-year-olds (74.38) and 6-year-olds (81.82) age groups on SDCCS. Unlike the other EF tests, an increase in performance on ADCCS was found at the age of 6 years, with significant differences between the 3-year-olds age group (mean rank ADCCS performance of 49.74) and the 6-year-olds age group (92.84), and between the 4-year-olds age group (63.32) and the 6-year-olds age group (92.84).

Table 10

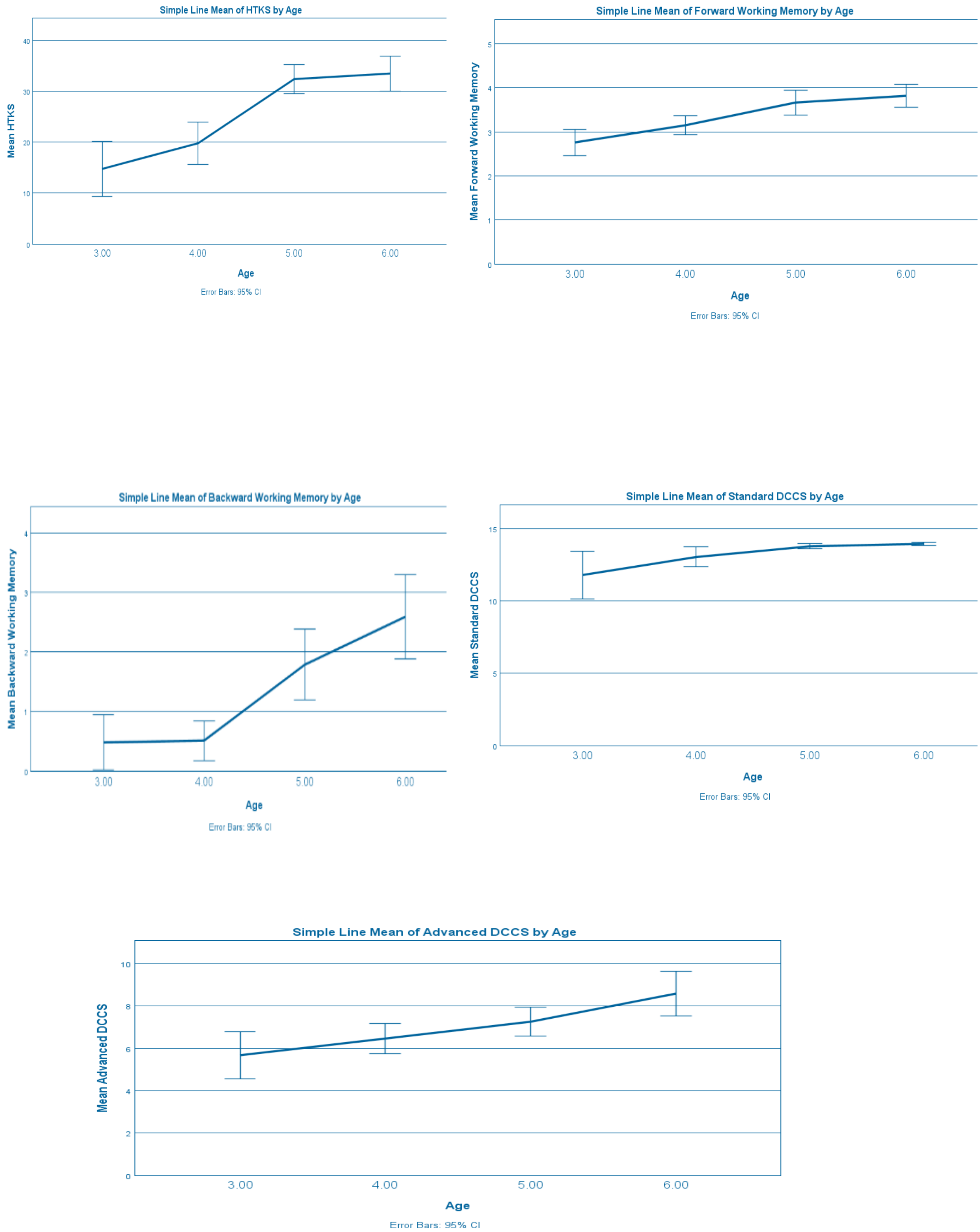
Means and Standard Deviations for EF Measures as a Function of Age

	Age (years)					
	3 (N=25)	4 (N=47)	5 (N=42)	6 (N=22)	Kruskal-Wallis χ^2	[a] Post hoc Mann-Whitney *U*
HTKS	14.76 (13.17)	19.81 (14.13)	32.4 (9.14)	33.5 (7.79)	42.695 (p < .001)	3 < 5, 6; 4 < 5, 6
Forward WM	2.76 (.723)	3.15 (.751)	3.67 (.902)	3.82 (.588)	26.924 (p < .001)	3 < 5, 6; 4 < 5, 6
Backward WM	.48 (1.12)	.51 (1.14)	1.79 (1.9)	2.59 (1.59)	32.768 (p < .001)	3 < 5, 6; 4 < 5, 6
Standard DCCS	11.8 (4)	13.04 (2.35)	13.79 (.56)	13.95 (.213)	12.591 (p = .006)	3 < 5, 6
Advanced DCCS	5.68 (2.67)	6.47 (2.42)	7.26 (2.22)	8.59 (2.4)	16.040 (p = .001)	3 < 6; 4 < 6

[a] Provided pairs have shown significant differences

Figure 8.

Performance on EF Tests as a Function of Age.



Discussion

The aim of the present study was to gather initial data on the performance of EF tests across different age groups within a sample of Hungarian preschoolers. The results showed age to have a significant effect on the performance of all EF tests. Moreover, we observed a trend of progressive performance with increasing age on all EF tests. However, the pattern of development differed for the different EF components, and a slight difference between age groups was found, with the highest performance shift noticed at around 5 years of age. This peak in EF performance reflects the accelerated growth of neural connections in the frontal lobes that takes place at this age. In addition to the brain maturation processes, early exposure to preschool education (it is mandatory for children to start kindergarten at 3 years of age according to the Hungarian Government, 2011) appears to contribute to this leap in performance during later preschool years. Early exposure to the academic structure of the kindergarten, which entails repeated practise in areas such as memory skills, deductive reasoning, and different learning strategies, can nurture a child's ability to make use of strategies and skills to efficiently solve problems, which may later be reflected in their improved performance on all EF tasks. The pattern of differences in performance on response inhibition tasks, as measured by the HTKS test, showed that inhibitory abilities improved with each passing year. These findings are in keeping with earlier research on RI developmental trends (Carlson, 2005; Garon et al., 2008; Isquith et al., 2004) and can partly be explained by the structural changes and functional organization of the prefrontal cortex (Best & Miller, 2010; Blair, 2002). Increased efficiency in handling cognitive demands with age may also result in an increased capacity to resist interference from internal as well as external stimuli (Brainerd et al., 2008). A similar developmental pattern, with a linear increase in both forward and backward working memory capacity, was observed in the Corsi blocktapping task. The number of items that the children were able to remember forwards and backwards improved between the ages of 3 and 6 (from 2.76 items to 3.82 items, and from 0.48 items to 2.59 items, respectively). This developmental progress in working memory capacity is consistent with other studies (Carlson, 2005; Carlson & Moses, 2001; Davis & Pratt, 1995; Gathercole, 1998; Perner & Lang, 2000) and reflects the increased capacity of the visuospatial sketchpad to hold material in visual form, as well as the increased use of non-visual strategies that rely on both the phonological loop and the central executive to supplement memory performance (Baddeley & Hitch, 2000). With respect to cognitive flexibility, as measured by standard and advanced DCCS, superior performance was observed among older preschoolers compared to younger ones. Unlike previous studies (Carlson, 2005 Zelazo et al., 1996), most of the 3-year-olds were able to sort the cards according to the new rule in the post-switch phase in the standard DCCS test (M = 11.8), although not as efficiently as children aged 4 (M = 13.04) and above. This striking finding may partly be due to the child-rearing values prevalent in Hungary. Child-rearing practises in Hungary are characterized by a strong emphasis on cultivating social relationships, in the form of maintaining cooperative relations with others, being sensitive to social cues, and displaying behaviours that affirm relatedness to others (Brayfield & Korintus, 2011). These values foster a high tendency towards context sensitivity, which has been implicated in the successful performance of the DCCS task, which requires reflecting on multiple features of stimuli at the same time (e.g., colour and shape) and responding to a broader construal of the current context rather than focusing narrowly on specific features of the stimulus (Zelazo, 2006). Unlike on the standard DCCS, most children, including the older preschoolers, struggled on the advanced DCCS, which required them to sort the cards based on an additional dimension. These findings can be linked to the developmental constraints regarding the integration and use of higher-order rules, as proposed in the cognitive complexity and control (CCC) theory of Zelazo and Frye (1997). According to this theory, inability to use these higher-order rules is due to limited working memory capacity, which makes it difficult to overcome the strong mental set regarding the S–R association during the pre-switch phase. This interferes with the reprocessing of information that is required in order to make an appropriate decision regarding the use of the switching principles.

Taken together, our findings provide evidence for the existence of different developmental patterns of EF components among preschoolers and improve understanding of how environmental influences such as early childhood education contribute to the development of certain EF components. It is, however, important to note that the present study is not without limitations. First, the study used a cross-sectional design rather than a longitudinal design, which is more appropriate for studying developmental changes. Second, the limited sample size prevented us from drawing conclusions regarding gender-related differences in the EF developmental trajectory. Finally, our findings regarding the influence of preschool education through child-rearing practises on the set-shifting test need to be validated by other studies.

In conclusion, the findings of the present study suggest that environmental influences, in the form of early childhood education, have the potential to serve as a pathway for promoting EF skills which in turn can lead to a better quality of life. Moreover, the mechanism by which early childhood education has been assumed to influence EFs informs future research to carry out studies regarding international comparisons on child rearing for obtaining a more authentic representation of children's self-regulation.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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4.4. STUDY IV

Fundamental Movement Skills in Children with Autism Spectrum Disorder: A Systematic Review

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Abstract

Fundamental movement skills (FMS) are basic movement skills (i.e. balance, object control, and locomotor skills) that form the foundation for more advanced movement patterns. These skills are a crucial but often an overlooked part of the development process, especially in populations with autism spectrum disorder (ASD). In view of this, the present review was undertaken with the purpose of determining the extent of FMS impairment in children with ASD compared to typically developing children and those with other developmental disorders.

A total of 24 studies that measured FMS competencies; namely locomotor, object control, and balance skills in children with ASD using product- and process-oriented standardized movement assessment batteries were included in the review. The results showed that impairments in FMS are highly prevalent across the ASD spectrum and that children with ASD exhibited greater impairments in FMS competencies especially object control and locomotor skills compared to typically developing children and those with other developmental disorders. Moreover, these impairments in FMS appear to emerge early in life and persist throughout late childhood years in the majority of children with ASD. These findings provide preliminary evidence suggesting that FMS has the potential to be an early motor marker in children with ASD, and that practitioners should therefore be encouraged to consider movement skill evaluations as a routine investigation for children with ASD.

Introduction

Autism spectrum disorder (ASD) is an umbrella term for a group of neurodevelopmental disorders with a clinical presentation predominantly related to deficits in "social communication skills and poor social interaction", accompanied by "restricted, repetitive patterns of behaviour, interest, or activities" (American Psychiatric Association, 2013). Globally, the presence of ASD has increased exponentially, with 1 in 54 children being diagnosed with the disorder (Maenner, 2020). The economic burden related to the care of children with ASD is substantial and includes costs such as health care services, health education, ASD-related therapy, services provided for the families, and the labor costs of caregivers (Lavelle et al., 2014). The increasing prevalence and significant costs associated with ASD are fueling continuous efforts to further understand the biomarkers and symptoms of ASD for early detection and the development of effective interventions.

There is renewed interest in the motor development of young children with ASD due to growing evidence that suggests that impairments in motor skills precede, and even exacerbate, social- communicative symptoms in ASD (Harris, 2017; Leary & Hill, 1996; MacDonald, Lord, & Ulrich, 2014). For instance, a prospective study on infants at high risk of ASD demonstrated that parental concerns regarding children's motor development at six months of age were a significant predictor of ASD diagnosis, whereas parental concerns regarding social communication and repetitive motor behaviours were not predictive of ASD until after 12 months of age (Sacrey et al., 2015). Similarly, a recent longitudinal study using standardized developmental tests on high-risk infants demonstrated that fine and gross motor skills at six months of age were a significant predictor of ASD diagnosis at 24 to 26 months of age (LeBarton & Landa, 2019). These findings, along with the growing research evidence suggesting that motor disturbances are among the earliest detectable signs of ASD (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gowen & Hamilton, 2013; Guinchat et al., 2012), provide new insights and indicate a need to shift the focus from socio-communicative deficits to a motor perspective in order to facilitate early diagnosis of ASD.

One important yet overlooked aspect of motor development in the context of ASD are fundamental movement skills (FMS). These are the observable movement patterns of gross motor skills (GMS) that involve the "large, force-producing muscles of the trunk, arms, and legs" (Gabbard, 2012). Fundamental movement skills are the basis for more advanced skills and comprise object control, locomotor, and balance skills (Gallahue, Ozmun, & Goodway, 2012). Object control skills involve handling and controlling objects with the hand or foot. For example, throwing, catching, dribbling, kicking, underhand rolling, overhand throwing, and striking. Locomotor skills involve engaging the body in movement in different directions. These skills include hopping, galloping, leaping, jumping, sliding, and skipping. Balance skills keep the body in a controlled position during a specific task that is performed in situ or while in motion.

Fundamental movement skills emerge during early childhood years and continue to develop in an orderly manner on a developmental continuum of skills sequences until late childhood (Clark, 1994; Hardy, King, Farrell, Macniven, & Howlett, 2010). It is important to monitor FMS development during maturation, because mastery of FMS is critical for the overall development of the child and contributes to the child's cognitive functioning (Campos et al., 2000; Piek, Hands, & Licari, 2012), language development and communication skills (Bedford, Pickles, & Lord, 2016; Gernsbacher, Sauer, Geye, Schweigert, & Goldsmith, 2008), and adaptive behaviour (Clearfield, 2011; Iverson, 2010; Lubans, Plotnikoff, & Lubans, 2012). The significant impact of FMS on areas that are regarded as the defining characteristics of ASD, along with the current research imperative to identify the definitive motor markers of ASD (Zwaigenbaum et al., 2015), reinforce the importance of using assessment methods that can contribute to our understanding of the specific FMS competencies that are compromised in ASD, and of subsequently developing an individualized intervention plan.

Fundamental movement skills are commonly measured using movement assessment batteries that can be broadly classified into two approaches, i.e. product-oriented and process-oriented assessments (Gabbard, 2012). The former approach, which is also referred to as norm-referenced assessment, measures the outcome of performance, whereas the latter, also known as criterion-referenced assessment, focuses mainly on the technique used to perform a movement (for details, see appendix). These assessment batteries provide a comprehensive evaluation of movement skills and have been found to differentiate well between children with and without motor impairments (reviewed by Cools, De Martelaer, Samaey, & Andries, 2011), resulting in their use in several studies examining FMS in children with ASD (Berkeley, Zittel, Pitney, & Nichols, 2001; Breslin & Rudisill, 2011; Ghaziuddin & Butler, 1998; Green et al., 2002; Green et al., 2009; Hauck & Dewey, 2001; Hilton et al., 2007; Iwanaga, Kawasaki, & Tsuchida, 2000; Jasmin et al., 2009; Landa & Garrett-Mayer, 2006; Liu, Hamilton, Davis, & ElGarhy, 2014; Liu, Breslin, & ElGarhy, 2017; Lloyd, MacDonald, & Lord, 2013; MacDonald et al., 2014; Mache & Todd, 2016; Matson, Mahan, Fodstad, Hess, & Neal, 2010; Pan, Tsai, & Chu, 2009; Paquet, Olliac, Bouvard, Golse, & Vaivre-Douret, 2016; Provost, Lopez, & Heimerl, 2006; Provost, Heimerl, & Lopez, 2007; Staples & Reid, 2010; Van Waelvelde, Oostra, Dewitte, Van Den Broeck, & Jongmans, 2010; Whyatt & Craig, 2012; Zachor, Ilanit, & Itzchak, 2010).

The purpose for undertaking the present review was our limited knowledge about the specific motor markers implicated in ASD. Furthermore, the existing literature on impairments in basic movement skills (e.g. locomotor, object control, and balancing skills) have sampled individuals across broad age groups (Biscaldi et al., 2015; Hannant, Cassidy, Tavassoli, & Mann, 2016; Jansiewicz et al., 2006; Stins, Emck, De Vries, Doop, & Beek, 2015), thus obscuring the extent and developmental trajectory of FMS impairments in children with ASD. There are also gaps in the literature regarding the degree to which FMS impairment is responsible for motor deficiencies in children with ASD compared to typically developing children and children with other developmental disorders. In an attempt to shed light on these concerns, the present review focused on studies that assessed FMS in children with ASD using movement assessment batteries.

Method

Retrieval of Studies

An exhaustive search for studies measuring FMS in children with ASD was undertaken in the following databases: (a) PubMed; (b) Science Direct; and (c) Google Scholar. The search keywords, which were used either individually or in combination, included "assessment," "gross motor skills," "movement competency," "locomotor skills," "balance," "object control skills," "fundamental movement skills," "standardized tests," "product oriented movement batteries," "process oriented movement batteries", "very young children," "school-age children," "autism," "Asperger syndrome", "high-functioning autism", "pervasive developmental disorder–not otherwise specified" and "autism spectrum disorder (ASD)."

The following definitions of certain keywords are used in the present review:

- Very young children: Children less than six years of age.
- School-age children: Children between six and 12 years of age.
- Fundamental movement skills (FMS): Competencies (i.e. locomotor skills, object control skills, and balance) based on the classification by Gallahue et al. (2012).
- Autism spectrum disorder (ASD): Autism or childhood autism, Asperger syndrome (AS), high-functioning autism (HFA), and pervasive developmental disorder–not otherwise specified (PDD-NOS), or atypical autism.

Eligibility Criteria

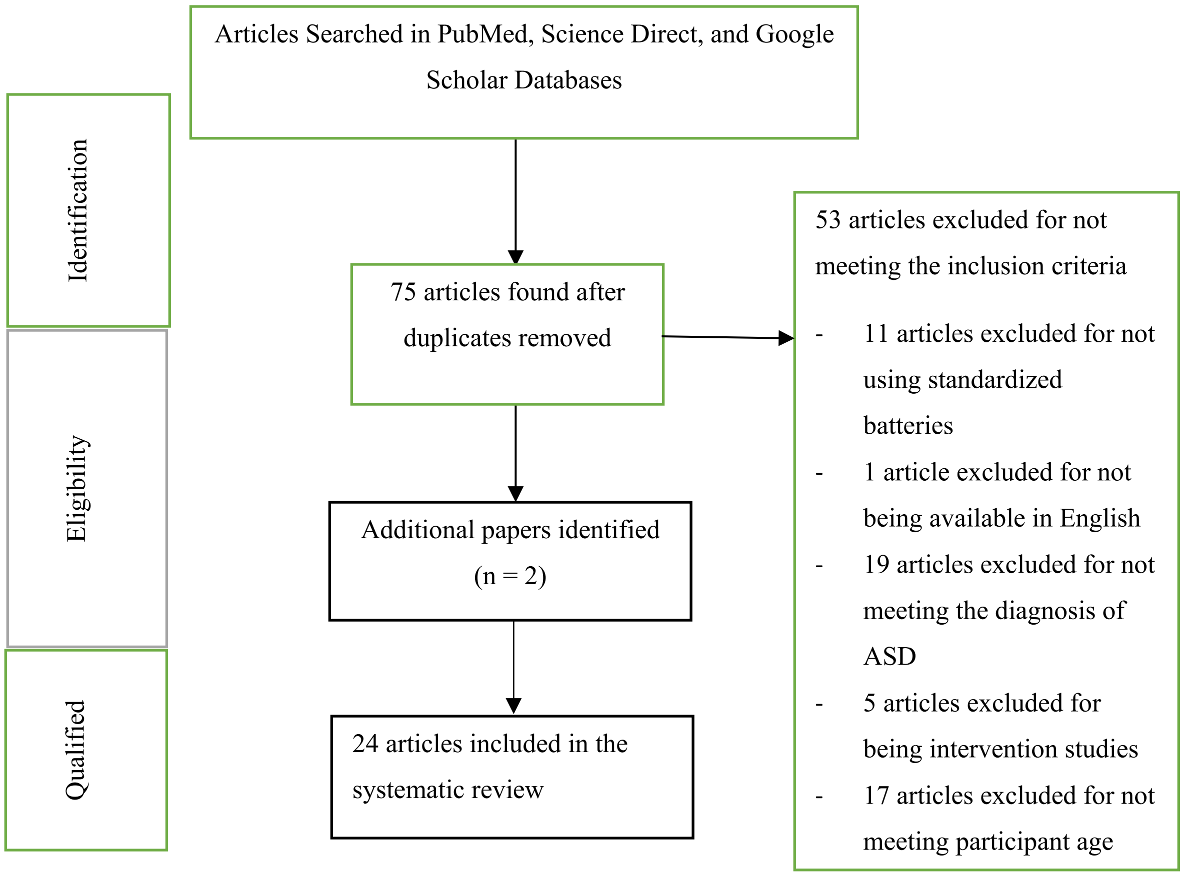
The search for studies across electronic databases was based on the following inclusion criteria: (a) participants diagnosed with ASD; (b) participants not older than 12 years of age; (c) studies that assessed at least one FMS competency i.e. object control, locomotor skills, and balance skills or overall FMS composite; (d) studies that used standardized movement assessment batteries based on a product-oriented and/or process-oriented approach to measure FMS competencies; (e) studies published in a peer-reviewed journal; and (f) studies printed in English. Studies were excluded if: (a) they evaluated FMS using retrospective data or other assessment methods, such as observation, video analysis, and so forth (n = 11); (b) they were intervention studies designed to alter FMS competencies (n = 5); (c) participants did not have a diagnosis of ASD (n = 19).; (d) participants were over the age of 12 (n =17).; and (e) the studies were not published in English (n = 1). The list of excluded studies is available from the corresponding author.

Study Selection and Data Extraction Process

When conducting the search, the authors first screened study title and abstracts for eligibility, followed by a review of the full text of the articles to determine whether they met the inclusion criteria. In order to ensure the reliability of the electronic database search, the author and two co-authors conducted the search independently. A total of 75 articles were identified at this stage, 53 of which did not meet the inclusion criteria. Two additional studies were identified based on the recommendation from an expert in the field. In total, 24 studies were selected for the final review (Fig. 9). After the final selection of 24 studies, information pertinent to the current review was extracted. This included: (a) descriptive information (such as author(s), year of publication, and the country in which the data were collected); (b) sample characteristics (i.e. gender and age of participants, nature of clinical population); (c) study design (whether it was a case study, cross-sectional study, or longitudinal study); (d) comorbid psychiatric or neurological condition; (e) Intelligent Quotient (IQ) score; (f) the FMS competency measured; and (g) the type of FMS assessment used (e.g. product-oriented or process-oriented assessment). In order to ensure the accuracy of the information derived from these studies, five studies were randomly selected and independently coded by two coders. Agreement between the coders ranged from 90% to 95%. The disagreement was resolved via consensus until 100% accuracy was achieved.

Figure 9.

PRISMA Flowchart of Study Selection Process



Method of Quality Appraisal

The methodological quality of the studies was assessed according to the guidelines of Law and Colleagues (1998). Based on this method, the quality of the studies was evaluated using 14 questions that can be broadly classified into the following categories: purpose of the study; background literature; research design; sample; reliability and validity of assessment tools; results; conclusion; study limitations; and clinical implications. Each question was given a score of 1 if it met the criteria, or 0 if it did not meet the criteria (see Table 11). The scores were calculated for each study. A score of 11 or above was considered high methodological quality; a score between 7 and 10 points was considered good methodological quality; and a total score below 7 was considered low methodological quality. Two authors independently assessed the methodological quality of the studies, and in case of disagreement reached a consensus via discussion.

Table 11

Methodological Quality of Reviewed Studies

Studies	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
										*Questions					
Berkeley et al. (2001)	1	1	1	1	1	1	1	1	0	1	1	1	1	1	13
Breslin & Rudisill (2011)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Ghaziuddin and Butler (1998)	1	1	1	1	0	1	1	1	1	1	0	1	1	1	12
Green et al. (2002)	1	1	1	1	1	1	1	1	1	1	1	1	1	0	13
Green et al. (2009)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Hauck & Dewey (2001)	1	1	1	1	1	0	1	1	1	1	0	1	1	1	12
Hilton et al. (2007)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Iwanaga et al. (2000)	1	1	1	1	1	0	1	1	1	1	0	1	1	1	12
Jasmin et al. (2009)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Landa & Garrett-Mayer (2006)	1	1	1	1	1	0	1	1	1	1	0	1	1	1	12
Liu et al. (2014)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Liu et al. (2017)	1	1	1	1	1	0	1	1	0	1	1	1	0	1	11
Lloyd et al. (2013)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
MacDonald et al. (2014)	1	1	1	1	1	0	1	1	1	1	1	1	1	1	13
Mache & Todd (2016)	1	1	1	0	1	1	1	1	1	1	1	1	1	1	13
Matson et al. (2010)	1	1	1	1	1	1	1	1	1	1	0	1	0	0	11
Pan et al. (2009)	1	1	1	1	1	1	1	1	1	1	0	1	1	1	13
Paquet et al. (2016)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Provost et al. (2006)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Provost et al. (2007)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Staples & Reid (2010)	1	1	1	1	1	0	1	1	1	1	1	1	1	1	13
Van Waelvelde et al. (2010)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Whyatt & Craig (2012)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	14
Zachor et al. (2010)	1	1	1	1	1	0	1	1	1	0	1	1	1	0	11

**Questions*: (1) Was the study purpose stated clearly? (2) Was relevant background literature reviewed? (3) Was the research design appropriate? (4) Was the sample described in detail? (5) Was the sample size justified? (6) Was informed consent obtained? (7) Were the outcome measures reliable? (8) Were the outcome measures valid? (9) Were results reported in terms of statistical significance? (10) Were the analysis methods appropriate? (11) Was clinical importance reported? (12) Were the conclusions appropriate? (13) Are there any implications of the results of the study? (14) Were the limitations of the study described?

Results

Study Characteristics

The 24 studies considered in this systematic review provided data on 1,094 participants with ASD. All except ten of the studies reported gender composition (n = 14). There was a preponderance of males (85%) over females. Out of the 24 studies considered, 20 were cross-sectional studies, while the others used a longitudinal (n = 1), combined cross-sectional and longitudinal (n = 1), pre-test and post-test (n = 1), and case study (n = 1) design.

The majority of the studies were from the United States of America (n = 13), while others were conducted in Europe (n = 5), Canada (n = 3), and Asia (n = 3). Out of the total studies, 11 were conducted on very young children diagnosed with ASD. The most frequently used FMS assessment battery for this age group was the Peabody Developmental Motor Scales 2nd edition (PDMS-2) (Folio & Fewell, 1983; Folio & Fewell, 2000) (n = 4), followed by the Mullen Scales of Early Learning (MSEL) (Mullen, 1989, 1995) (n = 3), the Japanese version of the Miller Assessment for Preschoolers (JMAP) (Tsuchida, Sato, Yamada, & Matsushita, 1989) (n = 1), the Bruininks-Oseretsky Test of Motor Proficiency 2nd edition (BOT-2) (Bruininks & Bruininks, 2005) (n = 1), the Bayley Scales of Infant Development 2nd edition (BSID-2) (Bayley, 1993) (n = 1), and the Battelle Developmental Inventory 2nd edition (BDI-2) (Newborg & Riverside Publishing Company, 2005) (n = 1). The remaining 13 studies were carried out on school-age children with ASD. The most commonly used FMS assessment was the Test of Gross Motor Development 2nd edition (TGMD-2) (Ulrich, 2000) (n = 4), followed by the Movement Assessment Battery for Children 2nd edition (MABC-2) (Henderson et al., 2007) (n = 3), the Movement Assessment Battery for Children (MABC) (Henderson & Sugden, 1992) (n = 2), the Bruininks-Oseretsky Test of Motor Proficiency (BOT) (Bruininks, 1978) (n = 1), the Test of Gross Motor Development (TGMD) (Ulrich, 1985) (n = 1), the Test of Gross Motor Development 3rd edition (TGMD-3) (Ulrich, 2013) (n = 1) and the Battelle Developmental Inventory (BDI) (Newborg, Stock, Wneck, Guidubaldi, & Svinicki, 1984) (n = 1).

Results

Fundamental Movement Skills in Very Young Children (Six Months to Six Years Old)

Eleven studies were included in the category of very young children with ASD. All these studies were found to have high methodological quality. The studies included 712 participants with a mean age of 3.5 years. Participants did not have comorbid psychiatric or a neurological condition in any of the studies. Majority of the studies included participants with IQ score of above 70 (n = 5) followed by studies that included participants irrespective of their level of intellectual functioning (n=4) and the remaining studies (n = 2) did not mention about the intellectual level of the participants. Some of the studies evaluated the performance of children with ASD by comparing it with the performance of typically developing children or normative sample on a particular assessment battery (n = 5), while other studies compared the performance of children with ASD to that of children with other developmental disorders (n = 4) and within the spectrum of autism disorders (n = 2). (Table 12).

In comparison to normative sample of typically developing children, majority of very young children with ASD showed below average performance (≤ 15th percentile) on overall FMS composite (Jasmin et al., 2009; Liu et al., 2017; Zachor et al., 2010). Sixty-three percent of the children were found to perform on average 6.4 months behind their chronological age (MacDonald et al., 2014). Moreover, the difference between chronological age and FMS age equivalent was found to increase progressively with age (the 12–24 month age group were on average 3.50 months behind; the 25–30 month group were 5.13 months behind; and children in the 31–36 month group were 9.18 months behind what would be expected for their chronological age), even after controlling for non-verbal IQ (Lloyd et al, 2013). A similar finding was demonstrated by a longitudinal study where it was found that the development trajectory of FMS was slowest between 14 to 24 months for children with ASD (M= 36.21 SD = 9.31) as compared to children with language delay (LD) (M=46.64 SD =12.61) (Landa & Garrett-Mayer, 2006).

Children with ASD also showed poor performance (M = 3.1, SD = 3.8) on FMS compared to the attention deficit hyperactive disorder (ADHD) group (M = 5.6, SD = 3.7), even after controlling for IQ (Van Waelvelde et al., 2010). Their locomotor and object control profiles (M = 5.3, SD = 2.1; M = 5.9, SD = 1.6) were slightly different from children with developmental delays in the motor area (M = 5.7, SD = 2.4; M = 6.4, SD = 1.7) (Provost et al., 2007), although they differed considerably from the profiles of children with non-motor delays (NMD) (children with speech and language delays and social–emotional delays) (M = 8.8, SD = 1.0; M = 9.1, SD = 1.1) (Provost et al., 2006).

Within the ASD spectrum, children with autism were found to have a higher percentage of impairment (16.2%) on overall FMS composite compared to children with PDD-NOS (10.7%) (Matson et al., 2010). Some aspects of motor problems, such as poor standing balance, seemed to be specific for a larger number of children in the AS group (80%) compared to the HFA group (Iwanaga et al., 2000).

Table 12

Summary of Studies Done on Very Young Children (0–6 Years)

Authors	Participant Characteristics	Type of Study	Comorbid Psychiatric/ Neurological condition (ASD group)	Intelligent Quotient (IQ)	FMS Competency	FMS Measure		Results
						Product	Process	
Iwanaga et al. (2000)	n = 25 (males 17, females 8); participants with Asperger syndrome (AS) (n = 10); participants with high-functioning autism (HFA) (n = 15); ages 4 to 6 years old	Cross-sectional study	Absent	IQ above 70	Balance	JMAP		80% of children with AS had poor (< 5th percentile) standing balance compared to children with HFA.
Jasmin et al. (2009)	n = 35 (males 32, females 3); ages 3 to 4 years; participants with ASD	Cross-sectional study	Absent	Range of IQs below and above 70	Locomotor and object control skills (ball skills)	*PDMS-2		a) 63% of children showed lower performance (≤ 2 SD) on FMS compared to the normative sample; b) Definite (< 5th percentile) impairments were found in both, locomotor and object control skills
Landa & Garrett-Mayer (2006)	n = 87 (males 52, females 35); ages 6 months to 2 years; participants with ASD (n = 24); participants with language delay (LD) (n = 11); unaffected participants (n = 52)	Longitudinal study	Absent	Not mentioned	FMS composite	MSEL		ASD group performed worst (M = 36.21, SD = 9.31) at 24 months of age in comparison with LD group (M = 46.64, SD = 12.61) and unaffected group (M = 51.94, SD = 11.02).

Liu et al. (2017)	n = 1 male participant with ASD; age 5 years	Case study	Absent	IQ above 70	Balance, locomotor, and object control skills	1)BOT-2 2)MABC-2	3)TGMD-2 4)*PDMS-2	Below average performance were found on all the assessment batteries.
Lloyd et al. (2013)	n = 162 (males 140, females 22) participants with ASD; ages 1 to 3 years	Cross-sectional and longitudinal study	Absent	Non-verbal IQ above 70	FMS composite	MSEL		Children with ASD were behind their chronological age on FMS at each cross-sectional age point (12–24 months group were 3.50 months behind; 25–30 month group were 5.13 months behind; and 31–36 month group were 9.18 months behind what would be expected), with the delay being significantly ($p < .001$) more pronounced with age.
MacDonald et al. (2014)	n = 159 (gender not mentioned) participants with ASD; ages 1 to 3 years	Cross-sectional study	Absent	Range of IQs below and above 70	FMS composite	MSEL		Children performed 6.4 months behind what would be expected for their chronological age.
Matson et al. (2010)	n = 396 (males 284, females 112); ages 1 to 3 years; participants with autism (n = 116); participants with PDD-NOS (n = 112); participants with atypical development (n = 168)	Cross-sectional study	Absent	Not mentioned	FMS composite	BDI-2		Children with autism (16.2%) had a higher percentage of impairment in movement skills compared to those with PDD-NOS (10.7%).

Provost et al. (2006)	n = 56 (males 42, females 14); ages 1 to 5 years; participants with ASD (n = 19); participants with DD in motor area (n = 19); participants with developmental concerns without motor delay (NMD) (n = 18)	Cross-sectional study	Absent	Range of IQs below and above 70		BSID-2	* PDMS-2	ASD group performance on both locomotor and object control skills (M = 5.7, SD = 2.4; M = 5.9, SD = 1.6) differed considerably from NMD group (M = 8.8, SD = 1.0; M = 9.1, SD = 1.1) but did not differ much from DD group (M = 5.3, SD = 2.1; M = 6.4, SD = 1.7)
Provost et al. (2007)	n = 38 (males 30, females 8); ages 1 to 3 years; participants with ASD (n = 19); participants with DD (n = 19)	Cross-sectional study	Absent	Range of IQs below and above 70	Locomotor and object control skills	*PDMS-2		The majority of children in the ASD and DD groups showed similar performance on the two FMS competencies.
Van Waelvelde et al. (2010)	n = 49 (males 39, females 10); ages 4 to 6 years; participants with or at risk of ASD (n = 15); ADHD (n = 16); no diagnosis (n = 18)	Pre-test and post-test design	Absent	IQ above 70	FMS composite	MABC		Children with ASD showed poorer performance (M = 3.1, SD = 3.8) compared to children with ADHD (M = 5.6, SD = 3.7)
Zachor et al. (2010)	n = 25 (males 24, females 1) participants with ASD; ages 2 to 5 years	Cross-sectional study	Absent	IQ above 70	FMS composite		*PDMS	Children with ASD showed below average performance (≤ 15th percentile) relative to normative sample

JMAP = Japanese version of the Miller Assessment for Preschoolers; PDMS-2 = Peabody Developmental Motor Scales 2nd edition; MSEL = Mullen Scales of Early Learning (the gross motor skills subtest was used); BOT-2 = Bruininks-Oseretsky Test of Motor Proficiency 2nd edition; MABC-2 = Movement Assessment Battery for Children 2nd edition; TGMD-2 = Test of Gross Motor Development 2nd edition; BDI-2 = Battelle Developmental Inventory 2nd edition; BSID-2 = Bayley Scales of Infant Development 2nd edition; MABC = Movement Assessment Battery for Children; PDMS = Peabody Developmental Motor Scales. Note: *PDMS and *PDMS-2 use both product-oriented and process-oriented approach to movement assessment.

Fundamental Movement Skills in School-Age Children (Six to 12 years of Age)

Thirteen studies were included in the category of school-age children with ASD. All these studies were found to have high methodological quality. The studies included 382 participants with a mean age of 9.3 years. Participants did not have comorbid psychiatric or a neurological condition in any of the studies. Most of the studies (n = 5) included participants regardless of their level of intellectual functioning followed by studies that included participants with IQ score of above 70 (n = 4) and the remaining studies (n = 4) did not provide information regarding the intellectual level of the participants. Some of the studies evaluated the performance of children with ASD by comparing it with typically developing children or with the normative sample of typically developing children on a particular assessment battery (n = 9), while other studies compared their performance to children with other developmental disorders (n = 3) and within the spectrum of autism disorders (n = 1) (Table 13).

Compared to the normative sample, the majority of school-age children with ASD showed definite impairments (< 5th percentile) on the overall FMS composite (Breslin & Rudisill, 2011; Green et al., 2009; Hilton et al., 2007; Liu et al., 2014; Paquet et al., 2016). They also exhibited significant impairments in overall FMS composite (< .01) compared to chronological age and mental age matched control groups (Staples & Reid, 2010; Whyatt & Craig, 2012). In terms of specific areas of impairment across the different FMS competencies, between 67% and 80% of children with ASD had definite (< 5th percentile) to borderline (5th–15th percentile) impairments in locomotor skills (Berkeley et al., 2001; Liu et al., 2014; Mache & Todd, 2016); between 53% and 82% of children had definite to borderline impairments in object control skills (Berkeley et al., 2001; Hilton et al., 2007; Liu et al., 2014; Mache & Todd, 2016); and between 33% and 58% of children had definite to borderline impairments in balance (Hilton et al., 2007; Paquet et al., 2016).

In comparison to the clinical groups, children with ASD showed significantly ($p < .01$) lower performance on both locomotor and object control skills compared to children with ADHD, even after controlling for their IQ scores (Pan et al., 2009). Their performance on overall FMS composite was also worse ($M = 42.08$, $SD = 14.40$) than the performance of children with developmental delays ($M = 47.55$, $SD = 14.05$) (Hauck & Dewey, 2001) and those with specific developmental disorder of motor function (SDD-MF) (Green et al., 2002). The ASD group had a higher mean impairments score ($M = 2.91$, $SD = 2.32$) compared to the SDD-MF group ($M = 1.86$, $SD = 1.36$), with a significant difference ($p < .05$) between the two identified groups in terms of object control skills (Green et al., 2002).

Within the ASD group, movement impairments were found to be universal compared to the normative sample, with the AS group showing a lesser degree of impairments in overall FMS composite ($M = 33.1$, $SD = 16.3$) than the PDD-NOS ($M = 29.6$, $SD = 9.3$) and autism ($M = 20$, $SD = 12.5$) groups (Ghaziuddin & Butler, 1998).

Table 13

Summary of Studies Done on School-Age Children (6–12 Years)

Authors	Participant Characteristics	Type of Study	Comorbid Psychiatric/ Neurological condition	Intelligent Quotient (IQ)	FMS Competency	FMS Measure		Results
						Product	Process	
Berkeley et al. (2001)	n = 15 (males 10, females 5) participants with high-functioning autism (HFA); ages 6 to 8 years	Cross-sectional study	Absent	Not mentioned	Locomotor and object control skills	TGMD		53% of children with HFA scored in the severe (< 5th percentile) to borderline (5th–15th percentile) impairments range in object control skills, whereas 80% were between the severe and borderline range on locomotor skills.
Breslin & Rudisill (2011)	n = 22 (males 16, females 6) participants with ASD; ages 3 to 11 years	Cross-sectional study	Absent	Not Mentioned	FMS composite	TGMD-2		63% of children had borderline impairment
Ghaziuddin & Butler (1998)	n = 24 (males 21, females 24); age 11 years old; participants with Asperger syndrome (AS) (n = 12); participants with autism (n = 12); participants with PDD-NOS (n = 12)	Cross-sectional study	Absent	IQ above 60	FMS composite	BOT		All three groups showed poor performance relative to standardized norms with the AS group (M = 33.1, SD = 16.3) found to be relatively less impaired than the PDD-NOS group (M = 29.6, SD = 9.3) and the autism group (M = 20, SD = 12.5).
Green et al. (2002)	n = 20 males; ages 6 to 11 years; participants with AS (n = 11); participants with a specific developmental disorder of motor function (SDD-MF) (n = 9)	Cross-sectional study	Absent	IQ above 70	Object control skills and balance	MABC		The ASD group had higher mean impairment scores (M = 2.91, SD = 2.32) compared to the SDD-MF group (M = 1.86, SD = 1.36). Significant difference ($p < .05$) between the two groups was found on object control skills.

Green et al. (2009)	n = 101 (males 89, females 12) participants with ASD; ages 9 to 10 years	Cross-sectional study	Absent	Range of IQs below and above 70	FMS composite	MABC-2	1) 79% of children with autism had definite motor impairment (<5th percentile), and 10% borderline impairment (5th–15th percentile). 2) Majority (97.1%) of children with a low IQ showed significant impairments than children with a high IQ (69.7%; χ^2 (1) = 10.5, p = .001).
Hauck & Dewey (2001)	n = 20 (males 18, females 2) participants with autism; ages 2 to 7 years; participants with developmental delays (DD) (n = 20)	Cross-sectional Study	Absent	Range of IQs below and above 70	FMS composite	BDI	Poorer performance found in ASD group (M = 42.08, SD = 14.40) compared to DD group (M = 47.55, SD = 14.05)
Hilton et al. (2007)	n = 51 (males 44, females 7) participants with Asperger syndrome; ages 6 to 12 years	Cross-sectional study	Absent	IQ above 70	Object control skills and balance	MABC	65% of children had definite levels of motor impairment, and 25% had borderline motor impairment.Greater impairments were found in object control skills (82%) in contrast to balance (33%).
Liu et al. (2014)	n = 42 (males 30, females 12); participants with ASD (n = 21); typically developing participants (n = 21); ages 5 to 10 years	Cross-sectional study	Absent	Not mentioned	Locomotor and object control skills	TGMD-2	Significant (p < .01) differences were found between children with ASD and typically developing children on both the skills. A greater percentage of impairments were found in locomotor skills (67%) than object control skills (60%).

Mache & Todd (2016)	n = 22; participants with ASD (n = 11); typically developing participants (n = 11); ages 5 to 12 years	Cross-sectional study	Absent	Not mentioned	Locomotor and object control skills	TGMD-3	Significant differences were found between children with ASD and typically developing children on ($p < .001$) locomotor skills and ($p < .05$) object control skills.
Pan et al. (2009)	n = 91 (gender not mentioned); participants with ASD (n = 29); participants with ADHD (n = 28); typically developing participants (n = 34); ages 6 to 10 years	Cross-sectional study	Absent	Above 70	Locomotor and object control skills	TGMD-2	The ASD group performed significantly ($p < .01$) worse than the ADHD group on both locomotor and object control skills.
Paquet et al. (2016)	n = 34 (males 31, females 3) participants with ASD and a reference group of typically developing children; ages 4 to 11 years	Cross-sectional study	Absent	Range of IQs below and above 70	Balance and object control skills	MABC-2	30% and 24% children with ASD scored 1 SD below the reference group on object control skills and balance.
Staples & Reid (2010)	n = 25 (males 21, females 4) participants with ASD: (1) age matched; (2) mental age matched (movement skill matched); ages 9 to 12 years	Cross-sectional study	Absent	Range of IQs below and above 70	Locomotor and object control skills	TGMD-2	Children with ASD performed movement skills similarly to typically developing children half their chronological age. Specific areas of impairment were noted in object control ($p < .01$) and locomotor skills ($p < .01$).
Whyatt & Craig (2012)	n = 18 (males 11, females 7) participants with ASD: (1) receptive vocabulary matched; (2) nonverbal IQ matched; ages 7 to 10 years	Cross-sectional	Absent	IQ above 70	Object control (ball skills) and balance	MABC-2	Children with ASD showed significantly ($p < .001$) lower performance on both the skills compared to the vocabulary matched and nonverbal IQ matched control groups.

TGMD = Test of Gross Motor Development; TGMD-2 = Test of Gross Motor Development 2nd edition; BOT = Bruininks-Oseretsky Test of Motor Proficiency; MABC = Movement Assessment Battery for Children; MABC-2 = Movement Assessment Battery for Children 2nd edition; BDI = Battelle Developmental Inventory.

Discussion

Fundamental movement skills are basic movement skills (i.e. locomotor, object control, and balance skills) that are crucial to childhood development. The purpose of the present study was to review the performance of children with ASD on FMS with the aim of determining the extent of their impairments in these skills compared to typically developing children and children with other developmental disorders. In total, 24 studies involving 1,094 participants who were classified into two groups, i.e. very young children (between six months and six years of age) and school-age children (six to 12 years of age) were included in the review. All the studies measured FMS using either product-oriented or process-oriented standardized movement assessment batteries.

The results showed that children with ASD have widespread impairments in FMS that lasts throughout childhood. Compared to their typically developing peers, a larger number of children in the ASD group demonstrated greater impairments across all the categories of FMS, even after controlling for IQ (Hilton et al., 2007; Staples & Reid, 2010; Whyatt & Craig, 2012). Children with ASD were also found to have delayed developmental trajectories of FMS from an early age (Landa & Garrett-Mayer, 2006; Lloyd et al., 2013; MacDonald et al., 2014), with the delays becoming increasingly pronounced with age: School-age children (aged between nine and 12 years) with ASD performed movement skills similar to typically developing children approximately half their chronological age (i.e. four to six years old) (Staples & Reid, 2010). This widening of the differences in movement delays is indicative of the slow development of FMS in children with ASD, which could possibly be due to severe dysfunctions in cerebellar and basal ganglia circuitry of ASD children (Allen, Müller, & Courchesne, 2004; Mostofsky et al., 2009; Qiu, Adler, Crocetti, Miller, & Mostofsky, 2010). Other factors that may contribute to the slowing of the development of FMS are impairment in imitation and perceptual-motor skills which are inherent characteristics of ASD and play a pivotal role in learning FMS (Vanvuchelen, Roevers, & De Weerdt. 2007).

Children with ASD also demonstrated significant impairments in overall FMS composite across all the clinical groups (Green et al., 2002; Hauck & Dewey, 2001; Van Waelvelde et al., 2010). These findings can be explained by the social symptomatology uniquely seen in ASD. For instance, children with ASD lack interpersonal skills, which can result in limited social interaction, including playing games with their peers, which in turn may limit their opportunities to successfully practice these skills, thus preventing them from developing these competencies (Attwood, 2008; Ming, Brimacombe, & Wagner, 2007).

Across the different FMS competencies, specific areas of impairment were observed in object control and locomotor skills (Green et al., 2002; Pan et al., 2009). Impairments in these competencies were also prevalent among the ASD group compared to their age-matched typically developing peers (Mache & Todd, 2016; Staples & Reid, 2010; Whyatt & Craig, 2012). These findings suggest that children with ASD have significant underlying difficulty on tasks that rely heavily on perceptual-action coupling strategies such as catching a ball (Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Izawa et al., 2012) and those that requires coordinated movements between arms and legs such as jumping and leaping.

Within the ASD group, children at the severe end of the spectrum exhibited greater impairment in movement skills (Ghaziuddin & Butler, 1998; Iwanaga et al., 2000; Matson et al., 2010). These differences could be attributed to the lower levels of cognitive functioning present in children with autism (Baird et al., 2006), which seems to result in decreased or delayed neural pruning during motor activity (Akshoomoff et al., 2002; Ming et al., 2007), thereby leading to severe movement impairments in this group as compared to those on the milder end of the spectrum.

Overall, these studies provide preliminary evidence regarding the pervasiveness of FMS impairments in children with ASD, although the severity of these impairments is rather varied across the different FMS competencies. These findings suggest that clinicians should consider the evaluation of movement skills as a routine investigation in children with ASD. They should also target movement skills especially object control and locomotor skills, as an important focus of early interventions. Movement-based interventions in the form of play and physical activities would not only improve the FMS of children with ASD, but would also indirectly contribute to improving their socio-communication skills by providing them with opportunities for active involvement with other children.

The existing movement assessment batteries are useful in detecting whether a child is showing optimum development of FMS. However, they are limited in terms of their ability to provide sensitive information regarding the factors underlying identified impairments. A further implication would thus be the need for researchers to develop new, user-friendly, technology-based movement assessment methods, such as inertial sensors, that are capable of providing valuable information regarding the subtle variations in the organization and quality of bodily movement that cannot be identified using movement assessment batteries.

Strengths and Limitations

The review shows that FMS impairment is widespread in children with ASD, regardless of their cognitive level. Furthermore, impairment in certain FMS competencies, such as object control and locomotor skills are more prominent in children with ASD. These findings thus provide preliminary evidence suggesting that FMS have the potential to be an early motor marker in children with ASD.

The present review has several limitations that should be taken into consideration. Firstly, the movement assessment batteries that were used to measure FMS in children with ASD were designed primarily for typically developing children and may not provide an absolutely accurate interpretation of FMS impairments in children with ASD. For instance, the verbal method used in these assessment batteries for giving task instructions makes them less acceptable to children with ASD, who have inherent difficulties in communication and social interactions. Secondly, the review included published studies only. Although an attempt was made to search for grey literature, this search was not comprehensive and may have resulted in the omission of relevant studies. Finally, the sample size in the majority of the studies was small, with most of the participants being male, which potentially jeopardizes the generalizability of the results.

Conclusion

The review demonstrates that fundamental movement skills are ubiquitous to childhood development and have the potential to be an early motor marker for the diagnosis of ASD. Moreover, these impairments are present at an early age and persist into late childhood years.

5. GENERAL DISCUSSION

The main goal of the dissertation was to develop a better understanding of the importance of motor skills in early childhood. In this respect, the studies reported in the previous section provide information on the significance of motor skills in the areas of cognitive and socio-emotional functioning. It further demonstrates that fundamental motor skills have the potential to be an early behavioural marker in the diagnosis of autism spectrum disorder (ASD) and suggests that executive functions, an important construct in our dissertation can be improved as a result of early childhood education.

Concerning the first objective of the dissertation about the interrelatedness of motor skills with cognitive development, our meta-analytic study found evidence although small in size (r = .18) for the relationship between motor skills (balance manual dexterity, locomotor skills, and object control skills) and EFs (response inhibition, working memory, and cognitive flexibility). These findings indicate that both motor skills and executive functions are governed by common neural networks (Diamond, 2000; Ito, 2008; Leisman et al., 2016; Sergeant, 2000). Amongst the different components of motor skills, manual dexterity and balance were found to have strongest independent association with all the EF components indicating that these motor skills are less automatized in children and thus require extensive implementation of higher-order cognitive strategies (Best et al., 2009). Manual dexterity tasks, such as inserting coins into a slot, can indeed be cognitively challenging in several ways. For instance, successful performance on this task requires the child to choose the appropriate motor response (i.e., precise movements of the hands), to hold a mental representation of the task sequence throughout its implementation (i.e., to hold the box with one hand and to insert the coins as quickly as possible), and to switch between thinking regarding the correct order in which the coins need to be inserted. Balance-related tasks, on the other hand, also demand the extensive implementation of higher-order cognitive strategies, such as interference control, for optimal performance (Kearney, Harwood, Gladman, Lincoln, & Masud, 2013; Woollacott & Shumway-Cook, 2002). These findings are significant in the context of intervention programs which are aimed at promoting motor skills and EFs in children, as they support the idea that interventions in one domain may facilitate the development of both motor skills and EFs in children (Westendrop et al., 2014) and highlights the importance of including difficult motor skills, such as manual dexterity and balance, in motor intervention programs designed to improve EFs in children.

The dissertation also confirmed and shed clarity over the relationship of different motor skills i.e., gross motor and fine motor skills with the key components of executive functions in preschool aged children by demonstrating that fine motor skills as compared to gross motor skills were twice as strong as a predictor for response inhibition. These findings are consistent with our meta-analytic study (Gandotra et al., 2021) and previous studies (Livesey et al., 2006; Röthlisberger et al., 2012; Stöckel & Hughes, 2016) which showed that children of preschool age may not yet have practiced fine motor skills sufficiently for them to have become automated (Maurer & Roebers, 2019), thus performance on fine motor skills tasks required greater involvement of cognitive resources, especially RI.

Concerning the relationship of motor skills with the indicator of socio-emotional development, the results showed positive associations between motor skills and prosocial behaviour, although the extent of this relationship differed in the case of gross motor and fine motor skills. In particular, prosocial behaviour was related more strongly to gross motor than to fine motor skills. These findings suggest that having gross motor skills may facilitate prosocial behaviour in preschoolers by providing them with opportunities to engage in social interactions with their peers (Bar-Haim & Bart, 2006; Zimmer-Gembeck et al., 2005). For instance, children with better motor skills are more likely to participate in active play with their peers, which in turn promotes and stimulates social interaction and helps these children develop a positive attitude toward their peers, which is a key component of prosocial behaviour (Caputi et al., 2012; Layous et al., 2012; Pellegrini & Smith, 1998). These findings can be corroborated with other studies in which motor difficulties were recognized as a contributing factor for poor socio-emotional competence in children with developmental coordination disorder (DCD) (Cummins et al., 2005; Piek et al., 2008).

The next research objective which was about examining developmental trajectories of executive functions amongst Hungarian preschoolers, our dissertation demonstrated that all the three EF components improved as a function of age with the highest performance shift noticed at around 5 years of age. These findings can be corroborated with previous studies (Best & Miller, 2010; Carlson, 2005; Davidson et al., 2006; Garon et al., 2008; Huizinga et al., 2006; Zelazo et al., 2003). However, unlike other studies, an interesting finding of our dissertation was that most of the 3-year-olds were able to sort the cards according to the new rule in the post-switch phase of the standard DCCS test, although not as efficiently as children aged 4 and above. These findings suggest that besides brain maturation processes such as increased myelination, synaptic pruning, and the formation of neural networks in the prefrontal cortex (Casey et al., 2005; Kagan et al., 2005; Thompson & Nelson, 2001), superior performance on executive functions tasks by younger participants was a result of their early exposure to preschool education. Compared to the USA and other western countries, children in Hungary start preschool education at 3 years of age and spend at least 4 hours per day in kindergarten (Hungarian Government, 2011). Early exposure to the academic structure of the kindergarten, which entails repeated practise in areas such as memory skills, deductive reasoning, and different learning strategies, can nurture a child's ability to make use of strategies and skills to efficiently solve problems, which may later be reflected in their improved performance on all EF tasks. These findings improve our understanding of how environmental influences such as early childhood education contribute to the development of certain EF component and suggest that environmental influences, in the form of early childhood education, have the potential to serve as a pathway for promoting EF skills.

Lastly, our dissertation also showed that impairments in motor skills especially fundamental movement skills (FMS) are fairly prevalent in majority of children with autism spectrum disorder (ASD). Compared to their typically developing peers, a larger number of children in the ASD group were found to have greater impairments across all the categories of FMS (i.e., object control, locomotor skills, and balance skills or overall FMS composite), even after controlling for IQ scores, indicating that cognitive abilities alone cannot explain movement skills difficulties among children with ASD (Hilton et al., 2007; Staples & Reid, 2010; Whyatt & Craig, 2012). Children with ASD also demonstrated significant impairments in overall FMS composite across all the clinical groups indicating that impairments in FMS are specific to ASD. Across the different FMS competencies, specific areas of impairment were observed in object control and locomotor skills (Green et al., 2002; Pan et al., 2009). These findings suggest that children with ASD have significant underlying difficulty in performing tasks that rely heavily on perceptual-action coupling strategies, such as ball catching (Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Izawa et al., 2012) and tasks that requires coordinated movements between arms and legs, such as jumping and leaping. The findings with respect to locomotor skills impairments are further supported by a recent review (Kindregan et al., 2015) that demonstrated marked variability in gait parameters such as increased step width, reduced step length, higher cadence (steps per minute) and reduced range of motion in children with ASD. Within the ASD group, almost all the children regardless of their specific diagnosis (of autism, AS and PDD-NOS) demonstrated impairments in FMS compared to the normative sample. However, children at the severe end of the spectrum exhibited greater impairments in movement skills (Ghaziuddin & Butler, 1998; Iwanaga et al., 2000; Matson et al., 2010). These differences can be attributed to the lower levels of cognitive functioning in children with autism (Baird et al., 2006), which appears to result in decreased or delayed neural pruning during motor activity (Akshoomoff, Pierce, & Courchesne, 2002; Ming et al., 2007), thereby leading to severe movement impairments in this group as compared to children at the milder end of the spectrum. These findings suggests that FMS have the potential to be an early motor marker in ASD and strongly recommends clinicians to consider the evaluation of movement skills as a routine investigation in children with ASD. It also highlights that movement skills especially object control and locomotor skills, should be targeted as an important focus of early intervention.

6. EVALUATION OF THE DISSERTATION

6.1. Strengths and Implications

- The purview of the dissertation is broad as it tries to provide us with an in-depth understanding of the nature of the relationship of motor skills with other developmental domains, namely, cognitive and socio-emotional development.
- It enhances our understanding of the multilevel nature of the relationship between motor skills and EFs in typically developing children. This knowledge in turn can be valuable to child care practitioners when designing intervention programs aimed at improving motor skills and/or EFs in children.
- It also draws our attention to the potential influence of early childhood education, via child-rearing beliefs and practises, on the promotion of EF skills. It specifically emphasises the inclusion of creative activities such as music, art, movement and handicrafts in the educational curriculum of kindergartens for the promotion of executive functions especially cognitive flexibility.

- The dissertation also demonstrates that FMS has the potential to be an early motor marker in children with ASD, and that practitioners should therefore be encouraged to consider movement skill evaluations as a routine investigation for children with ASD.
- It also lays the groundwork for future research to investigate the role of motor skills in various neurodevelopmental disorders.
- Finally, the cross-sectional studies that are included in the dissertation utilized standardized and age-appropriate measures to collect the data on the various study variables i.e., fine motor skills, gross motor skills, executive functions (response inhibition, working memory and cognitive flexibility), and prosocial behaviours.

6.2. Limitations and Future Direction

- Due to the exploratory nature of the study, it is important to interpret the findings on the association between motor skills with the indicators of cognitive and socio-emotional development with precaution.
- It cannot be ruled out that the relationship between motor skills and executive functions may have been influenced by the choice of tests used. For instance, the motor component involved in each of the three EFs tests employed in the study, might have confounded the nature and the strength of this relationship. It is therefore recommended for future studies to replicate the current findings by employing different measures of EFs.
- The present findings on the association between motor skills and indicators of cognitive development are based on a cross-sectional investigation and causal relationships cannot be inferred. Studies with a longitudinal research design are therefore required to confirm the underlying neural mechanism related to motor skills and executive functions.

- The findings relating to socio-emotional development is limited to only prosocial behaviour and does not generalize to its other elements such as self-awareness and emotion regulation. It would be therefore highly suggested for the future studies to reflect more light on these elements in conjunction with motor skills.
- Although our study shows that environmental influences in the form of early childhood education have the potential to serve as a pathway for promoting EF skills. However, the mechanism by which early childhood education has been assumed to influence EFs informs future research to carry out studies regarding international comparisons on child rearing for obtaining a more authentic representation of children's self-regulation.
- Due to the time-bound nature of the study and logistic reasons, the coverage of empirical studies was limited to typically developing children. In future studies, it would be worth comparing the strength of the relationship between motor skills and EFs in typically and atypically developing children, and the level of evidence for it, so as to ascertain the underlying causes of the relationship.

7. CONCLUSION

Our dissertation fills an important gap in the literature by demonstrating the importance of motor skills as critical for healthy child development. It contributes to a better understanding of the interrelation between motor skills with other components, namely cognitive and socio-emotional aspects of development especially in preschool aged children. These findings can inform and guide researchers, practitioners and policymakers on best practices and emphasizes the importance and need for promoting motor skills during early child development. Additionally, these findings encourage child care practitioners to routinely assess motor skills in children with neurodevelopmental disorders especially ASD.

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