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Interlinking Developmental Domains:

Low Motor Skills in Typically Developing Children are Related to Intelligence, Executive Functions, and Behavior

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Stephanie Klupp

aus Basel, BS

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Prof. Dr. Alexander Grob

Prof. Dr. Sakari Lemola

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ABSTRACT

Children develop rapidly over their first decade of life across the three main domains of motor, cognitive, and social-emotional development. The interlink between children's developmental domains is considered as important for children to develop as a whole. Developmental theories support the notion that motor, cognitive, and social-emotional development are each bidirectionally related. Furthermore, changes through movement in relations to individuals and objects enables interactions which facilitates development. With focus on motor development, children and adolescents often do not reach the recommended amount of daily physical activity. Consequently, restrictions in motor skills may in turn hinder engagements with the environment and social interactions with individuals, which therefore reduce learning opportunities in addition to impacting other developmental processes.

To increase the in-depth understanding of these relations, the aim of the current dissertation is to contribute to a more comprehensive understanding of how the development of children in one developmental domain (i.e., motor) relates to their development in the other domains (i.e., cognitive and social-emotional). For this, three studies were conducted assessing standardized test batteries in typically developing children between the ages of 7 to 13 years. The associations between (1) fine motor skills and intelligence, (2) motor skills as well as aerobic fitness and executive functions, and (3) gait and social-emotional behavior were analyzed. Furthermore, the overarching focus was to highlight the dimensional perspective of children who fall within the low end of the typically developing motor ability range, as this dissertation is relevant for considerations in future interventions.

To investigate interlinks between developmental domains, hierarchical regressions were conducted in studies 1 and 2 and a multilevel modeling approach was used in study 3. Results of study 1 demonstrated that lower performances in fine motor skills are associated with lower scores in full-scale IQ, perceptual reasoning, and processing speed. Study 2 revealed that lower fine motor skills and lower aerobic fitness were significantly related to lower scores in switching and updating. Furthermore, it was shown that fine motor skills explained additional variance in executive functions above and beyond aerobic fitness. Lastly, study 3 indicated that children with a higher variability in stride length as well as stride velocity showed significantly less prosocial behavior, had more emotional symptoms and demonstrated less risk-taking behavior.

In summary, this cumulative dissertation offers new insights on a differentiated view of the interlink between fine and gross motor skills and their associations to intelligence, executive functions and behavior in typically developing children. In addition, this dissertation connects multiple studies for an overarching view of the three core domains of child development. The outlook highlights the theoretical and practical value of physical education in school and after school activities which should be preserved and supported. Lastly, the results suggest that typically developing children with low motor skills will not likely outgrow their deficits but are in need of support in the future.

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Introduction

According to the World Health Organization (2020), children and adolescents are recommended 60 minutes of daily physical activity. Notably, 11% of Swiss children under the age of 10 years of age and 61% of children above 10 years do not meet this recommendation (Bringolf-Isler et al., 2016). This finding does not only highlight the relevance of investigating children’s motor development but also demonstrates how the amount of physical activity changes across childhood and adolescence. Development is generally defined as “the progressive series of changes in structure, function and behavior that occur over the lifespan of a human being”. Specifically, child development focuses on these changes from conception through adolescence (American Psychological Association, 2015, p. 304). Child development is often separated into three core domains which overlap and interact closely: physical development or motor development, cognitive development, and social-emotional development (Berk, 2018). Furthermore, development is seen as a lifelong process that is multidimensional, multicausal, and multidirectional (Baltes, 1987; Berk, 2018).

Motor development includes aspects of human movement which are integral for everyday life and strongly connected to human health (Hillman et al., 2008; Khan & Hillman, 2014). In addition to relations within the same domain, motor development is of relevance for cognitive as well as social-emotional development (Mancini, Rigoli, Heritage, et al., 2016; Pesce et al., 2016). In previous infant research, motor development has been identified as crucial for children’s understanding of the world, and learning is built on interactions with infants’ environment (Libertus & Hauf, 2017). For example, infants’ interactions with objects and individuals (e.g., obtaining distal objects, carrying objects, and bringing caregivers objects) are linked to motor milestones such as walking (Berger, 2010; Karasik et al., 2011). In order to understand the development within and the interplay between these three developmental domains, few theoretical frameworks (e.g., embodied cognition theory) have considered their bidirectionality and reciprocity (McClelland & Cameron, 2019). However, developmental processes are often studied separately within one developmental domain.

The present dissertation aims to target this gap in the literature by providing an overview of how children’s motor development relates to their cognitive as well as social-emotional development. Specifically, the current studies investigate associations between fine and gross motor skills and intelligence, executive functions, and social-emotional behavior. Overall, the examined constructs are foundational skills which develop considerably across early and middle childhood and well into adolescence. Adopting a dimensional perspective onto development, the studies of this dissertation are mainly focusing on typically developing children who perform in the low range of motor skills, yet without reaching the clinical cut-off values for developmental disabilities. They are referred to as children with low motor skills whose population is quite rarely examined.

In the following section of this cumulative dissertation, I provide an overview of the theoretical background and current state of research within the three core domains of child development. Based on this theoretical background I summarize the research questions underlying each of the studies. Subsequently, I present the methods of my three studies as well as a synopsis of the results. Lastly, I conclude the dissertation with a general discussion and provide an outlook for practical values and future research.

Theoretical Background

Domains of Child Development

Motor Development

Motor development can be defined as the “the development and deterioration of muscular coordination and control” (American Psychological Association, 2015, p. 671; Berk, 2018). Motor skills are complex constructs that are often separated into fine motor skills and gross motor skills (Gandotra et al., 2021; Henderson et al., 2007).

Fine motor skills involve the ability to execute precise small muscle movements through hand-eye coordination (Clark & Whitall, 1989; Magill, 1996). To highlight some fine motor milestones: in the first two years of life, toddlers gradually improve the action of reaching and grasping for objects, followed by an improvement in the control of fingers and hands which leads to self-sufficient dressing, feeding, drawing, and cutting in early childhood (Berk, 2011). Subsequently, in middle childhood, fine motor skills are further refined and children’s drawings and handwriting become clearer and more detailed (Berk, 2018), enabling children to learn essential cultural techniques such as writing in school.

Gross motor skills encompass balance skills, object control skills, and locomotion, which are of importance to general motor development. While balance skills require the control of equilibrium in static and dynamic movements, object control skills demand the control of limbs in interaction with objects, for instance when kicking, catching or throwing (Caspersen et al., 1985; Clark & Whitall, 1989; van Capelle et al., 2017). Locomotion is the act of movement between two places, such as walking (i.e., gait), running or jumping, which requires the coordination of lower limbs with neural control systems (Adolph & Berger, 2006; Clark & Whitall, 1989; van Capelle et al., 2017). Within the first year of life, children achieve the gross motor milestones of sitting, crawling, standing and eventually walking (Berk, 2011; World Health Organization, 2006). In early childhood, these gross motor skills improve through the continuous development of balance and coordination, which are cornerstones for gains in agility, flexibility and strength in middle childhood (Berk, 2018). With respect to children’s walking, studies have shown that around the age of seven years, children attain a mature and stabilized gait pattern, while certain variables (i.e., gait variability) continue to develop progressively into adolescence (Adolph et al., 2003; Danion et al., 2003; Hagmann-von Arx et al., 2016).

Motor skills are required to execute activities which require physical fitness. Physical fitness describes an individual’s capacity of respiratory and cardiovascular systems to utilize oxygen, as well as the ability to perform lengthy vigorous movements (Esteban-Cornejo et al., 2019; Ortega et al., 2008). Physical fitness can be divided into health-related components such as cardiorespiratory endurance (i.e., aerobic fitness), flexibility, muscular endurance, and muscular strength, as well as skill-related components such as agility, balance, coordination, speed, and power (Caspersen et al., 1985; Pettee Gabriel et al., 2012). Previous research has shown that children with higher physical fitness have larger subcortical brain structures and more brain activation compared to children with lower physical fitness, supporting the associations between motor and brain development (Haapala, 2013). In the first years of life, the brain grows fast, the number of neurons and synapses increases dramatically as well as myelinization proceeds, which in turn enhances children’s learning capacity as well as motor coordination (Berk, 2018). Important components in brain development are the prefrontal cortex for complex thought (i.e., executive functions), the hippocampus for memory and spatial awareness, and the amygdala for processing novel information and emotions (Berk, 2018; McClelland & Cameron, 2019).

In summary, motor development is the improvement of the abilities to move in and engage with the surroundings. Moreover, brain development is not only vital for the effective functioning of the motor domain but for all other developmental domains as well such as the cognitive domain.

Cognitive Development

The second developmental domain, cognitive development, comprises of “the growth and maturation of thinking processes, including perceiving, remembering, concept formation, problem solving and reasoning” (American Psychological Association, 2015, p. 203). Cognitive development includes concepts such as intelligence and executive functions (Berk, 2018) — important constructs within the present dissertation.

As of today, intelligence is defined by 52 experts as “a general mental capability that involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience” (Gottfredson, 1997, p. 13). Similar to other cognitive constructs, intelligence is not directly observable and therefore standardized test batteries are used to assess intelligent behavior (Grob & Hagmann-von Arx, 2018). A more fine-grained view of subcomponents of intelligence can be achieved by distinguishing between verbal comprehension as the understanding of verbal information, perceptual reasoning as the understanding of visual information to solve abstract problems, working memory as the ability to hold and manipulate verbal information, and processing speed as the mental speed of processing and solving problems (Groth-Marnat, 2009). In early childhood, intelligence can be assessed through verbal and nonverbal tasks in intelligence tests, which are predictive of later intelligence and academic achievement (Berk, 2018). Across middle childhood, intelligence becomes more stable and is closely connected to other cognitive constructs such as executive functions (Berk, 2018). One reason may be that intelligence and executive functions partially assess similar constructs (e.g., problem solving). Thus, research has suggested that intelligence may relate differently to specific components of executive functions (Ardila, 2018).

Executive functions are relevant in children’s everyday school participation. Children need to able to focus on their work while blending out surrounding distraction. For example, when the teacher says something, they have to be able to shift between listening and their work, while also continuing to update the tasks they are required to do (Diamond, 2013). Executive functions are cognitive top-down control processes that facilitate goal-directed behavior and are comprised of three core components which are connected yet distinguishable (for a review, see Diamond & Ling, 2019; Miyake et al., 2000). These components refer to inhibition as the ability to deliberately suppress an automated and predominant response, switching as the cognitive flexibility to change perspectives or demands, and updating as the ability to manipulate information by replacing old, no longer relevant information with newer, more relevant information (Baddeley et al., 1997; Diamond, 2013; Miyake et al., 2000). In early childhood, children improve in inhibition, switching, and updating capacity, resulting in an increased ability to solve complex tasks across middle childhood and into adolescence (Berk, 2018). Notably, through increasing differentiation, the structure of executive functions develops from a unitary construct into the diverse postulated three-factor model across childhood (Shing et al., 2010; Wiebe et al., 2011). The diversity of executive functions is also supported by different developmental trajectories for the three components. More concretely, findings indicated that out of the three core components, inhibition appears to emerge and develop at a younger age compared to switching and updating (Best & Miller, 2010; Huizinga et al., 2006).

In summary, cognitive development is an important aspect of child development as it includes versatile thinking processes. Besides the central function of intelligence and executive functions within cognitive processes, these constructs also interact with children's social-emotional development (McClelland & Cameron, 2019). For example, executive functions support the regulation of attention, emotion, and behavior across development (Zelazo et al., 2016).

Social-Emotional Development

The third developmental domain, social-emotional development, combines the "acquisition of interpersonal skills, relationships, behavior and attitudes that enable the individual to interact with others" with "the capacity to experience, express, interpret and cope with the full range of emotions" (American Psychological Association, 2015, pp. 363, 994). Social-emotional development includes concepts of social interactions, emotions and behavior, which are partly covered within this dissertation.

Children grow up in an environment with different types of interactions to parents, siblings, caretakers, and peers (Damon et al., 2006). Havighurst's theory of developmental tasks in childhood includes self-control, social cooperation, as well as the development of conscience, attitudes, and socially responsible behavior (Havighurst, 1956; Manning, 2010). In early childhood, social interactions develop as nonsocial activities decrease and cooperative play increases (Berk, 2018). In addition, empathy increases across childhood, leading to more sympathy, more prosocial behavior, a higher sensitivity towards others, and less physical aggression, which is at the same time influenced by temperament and parenting styles (Siegler et al., 2016). Temperament is expressed early in life, and is assumed as being stable within individuals yet varying between children (Siegler et al., 2016). Children's temperament is highly related to their emotion regulation, which is the ability to manage emotions for a positive outcome. Emotion regulation develops considerably across early and middle childhood, and by the age of 10 years, most children are capable of adapting between problem- or emotion-focused coping (Berk, 2018).

Behavior is elicited by social interactions as well as emotions, as individuals respond to external or internal stimuli (Siegler et al., 2016). Behavior includes favorable ones such as prosocial, considerate and patient behaviors, and less favorable behaviors such as lying, bickering, and stealing as well as other behaviors such as risk-taking and deferred gratification (Berk, 2018).

In summary, social-emotional development refers to a child's understanding and regulation of their emotions as well as their ability to build and maintain social relationships by exploring and interacting with their environment. Besides the importance of the development within the domain, social-emotional development is also closely interlinked to motor development, as for example demonstrated in the association between social exchanges with crawling and walking (Karasik et al., 2011; Mancini, Rigoli, Heritage, et al., 2016). Following these studies, the time is ripe to more closely investigate the bidirectionality between these core developmental domains (McClelland & Cameron, 2019), with the ultimate goal to achieve a more unified, holistic view of children's development.

Mechanisms Interlinking Motor Development and Cognitive Development

Cognitive and motor skills have often been associated in psychological theories. Historically, some explanations have been based on Piaget's theory of cognitive development, which postulates that within the sensorimotor stage infants develop their understanding of the environment through the integration of movements and sensations (Piaget & Cook, 1952). Furthermore, infants initiate their own learning opportunities and facilitate cognitive development through self-directed actions (Piaget, 1947). Therefore, motor development is significant for the acquisition of new motor abilities (Leonard, 2016), which enable new learning opportunities in children's environments. Specifically, motor milestones such as crawling and walking change infants' perspectives and distances to objects or individuals (Adolph & Joh, 2007; von Hofsten, 2009). Piaget's indications of movement playing a central role in cognitive development, was refocused within the perspective of embodiment (Barsalou, 1999). The embodied cognition theory suggests that motor abilities enable interactions and engagements with the environment as well as with other people and thus create more opportunities for cognitive development and facilitate cognitive processes (Gibbs, 2005; Gottwald et al., 2016; Harbourne & Berger, 2019; Leonard, 2016; Loeffler et al., 2016; Oudgenoeg-Paz et al., 2012; Pesce et al., 2016; Smith & Gasser, 2005).

In addition to actively exploring their environment, children develop through interactions with the environment and individuals (McClelland & Cameron, 2019). This dynamic systems approach supports the view of a dynamic relationship between children's motor and cognitive skills as well as development being interactive and bidirectional (Thelen & Smith, 1996). This bidirectionality between motor and cognition is expressed when considering that motor abilities drive cognitive development, while at the same time, cognitive skills determine motor development (Adolph & Joh, 2007). For example, to acquire and perform movements, humans require cognitive resources such as executive functions, planning and intention (Adolph & Franchak, 2017). Furthermore, the dynamic systems approach contributes to describing the interaction between motor and cognitive development through processes such as automaticity and reciprocity (McClelland & Cameron, 2019). When a motor ability becomes more automatic through repetition, this automatization corresponds with a reduction in cognitive resources or engagement (Fitts & Posner, 1967; Maurer & Roebers, 2019; Yogev-Seligmann et al., 2008), which in turn enables to attend to more complex tasks (Best, 2010; Ludyga et al., 2020; Pesce, 2012). The concept of reciprocity in this context refers to the co-development of motor and cognitive skills in the sense that gains in one domain go alongside gains in the other domain (McClelland &

Cameron, 2019). Taken together, these theoretical perspectives contribute to our understanding of the interactions between motor and cognitive development.

Furthermore, motor and cognitive performance also co-develop on a structural and functional level within the brain (Diamond, 2000). More precisely, both domains show a similar accelerated development in childhood, with a lengthy developmental trajectory into adolescence as well as a co-activation of neural areas like the cerebellum and prefrontal cortex in certain tasks (Diamond, 2000; Houwen et al., 2016; Roebers & Kauer, 2009). In addition to this co-activation, many motor tasks showed to increase brain volume and blood flow, which in turn resulted in enhanced cognitive performance (Ratey & Loehr, 2011). Here, it is important to differentiate between short- and long-term physiological alterations in the brain following either acute or chronic physical fitness (Verburgh et al., 2014). These physiological changes include the increase of brain-derived neurotrophic factors that enable synaptic plasticity, assist neuron growth and facilitate cognitive functions such as learning and memory (Kramer & Erickson, 2007; Phillips, 2017; Voss et al., 2010). These findings are further supported by acute and chronic invention studies which have been shown to improve executive functions (Liu et al., 2020).

In summary, these changes in the brain explain the observable associations found between motor and cognitive development. Open questions refer to how specific constructs are associated with theory development and targeted interventions. Within the motor domain, two main subcomponents of fine and gross motor skills (Gandotra et al., 2021), as well as physical fitness can be differentiated (van Waelvelde et al., 2019). Within the cognitive domain, intelligence is the most investigated construct within psychology (Rost, 2009). Moreover, executive functions are seen as crucial prerequisite for learning (McClelland & Cameron, 2019). Thus, their relation to motor development was investigated in greater detail.

Previous Research Linking Fine Motor Skills with Intelligence and Executive Functions

Children’s fine motor skills play an important role for their cognitive development. For example, during early childhood, fine motor skills are required in block building activities or puzzle play, while in middle childhood it facilitates learning processes (Marr et al., 2003). Since fine motor skills are viewed as a prerequisite of learning, they also contribute to children’s academic achievement (McClelland & Cameron, 2019). Previous research supports that children’s fine motor skills contribute significantly to their kindergarten readiness and later to reading and mathematical achievement (Cameron et al., 2012; Grissmer et al., 2010). In addition to academic achievement, learning abilities are also interrelated with intelligence (Dandagal & Yarriswami, 2017). A systematic review including the relation between fine motor skills and intelligence, demonstrated weak-to-moderate correlations based on a few studies (van der Fels et al., 2015).

In more detail, previous research investigated children aged 4-11 years and demonstrated that fine manual control and motor coordination were significantly correlated to short term memory, visual processing, and fluid reasoning, while fine manual control was additionally correlated to long-term memory and crystallized ability (Davis et al., 2010; Davis et al., 2011). Furthermore, another study demonstrated significant correlations between a fine motor composite and general knowledge, vocabulary and comprehension in 3- and 4-year-olds

(Cameron et al., 2012). In addition, a study with 5- and 6-year-old children demonstrated significant correlations between fine motor skills and non-verbal intelligence (Roebers et al., 2014). Another study examining 4- to 6-year-old children reported significant correlations between fine motor skills and reasoning and processing speed (Martzog et al., 2019). Lastly, a study investigating the complexity of motor tasks, including fine motor elements, demonstrated that intelligence was correlated to the complex motor task but not to the simple motor task, indicating that the complexity of the task matters (Martin et al., 2010). Contrary to previous studies, a study with 12- to 16-year-old children examined fine motor skills with verbal comprehension and working memory and found no significant correlation (Rigoli et al., 2012b).

In summary, research examining the relation between fine motor skills and intelligence is rather scarce, partially inconclusive, and has mainly investigated children in early and middle childhood. This is rather surprising as the literature suggests that both domains show comparable developmental trajectories well into adolescence (Diamond, 2000). In addition, previous studies often examined the construct of intelligence by considering a specific subcomponent (i.e., reasoning) rather than a complete examination of the full construct including all possible subcomponents of a standardized intelligence test.

Besides the connection between fine motor skills and intelligence, the relation to executive functions is also of importance. A review revealed insufficient, due to too few publications, yet weak-to-moderate correlations between fine motor skills and executive functions in typically developing children (van der Fels et al., 2015). More specifically, a study found significant associations between fine motor skills and inhibition in 5- and 6-year-olds (Livesey et al., 2006). Another study in 12- to 16-year-olds showed no significant relation between fine motor skills and updating or the inhibition subtest (Rigoli et al., 2012a). In addition, 3- and 4-year-olds' inhibition correlated significantly with fine motor skills (Cameron et al., 2012). Another study examined 5- and 6-year-old children and demonstrated significant correlations between fine motor skills and all three core executive functions (Roebers et al., 2014). After van der Fels et al.'s review was published in 2015, there has been an increase in studies that further explored the association between fine motor skills and executive functions and revealed more significant associations (e.g., Oberer et al., 2017; Stockel & Hughes, 2016). Moreover, a recent meta-analysis confirmed this significant relation with robust effects to all three executive function components (Gandotra et al., 2021). However, when looking at the studies which were included in this meta-analysis, it becomes clear that the majority of research again mainly examined children up to 6 years of age, while fewer studies examined children older than 7 years. In addition, the few studies that focused on participants older than 7 years have rarely investigated all three core components in a single design.

Previous Research Linking Gross Motor Skills and Fitness with Executive Functions

Similar to the increased number of studies investigating fine motor skills mentioned above, several recent studies have begun to examine the relationship between gross motor skills and executive functions (Gandotra et al., 2021; van der Fels et al., 2015). The review from van der Fels et al. (2015) summarized studies as showing no-to-weak evidence between executive functions and gross motor skills (i.e., jumping, walking, sprinting, strength, agility, flexibility and balance); and reported insufficient evidence indicating no-to-moderate correlations for object control (van der Fels et al., 2015). More specifically, a study revealed correlations between jumping and inhibition as well as switching, and between postural flexibility and inhibition as well as updating in 7-year-old children (Roebers & Kauer, 2009). In addition, another study in 12- to 16-year-old children found significant correlations between object control skills and switching as well as updating (Rigoli et al., 2012a, 2012b). However, studies have also demonstrated no significant relations between gross motor skills such as objection control and balance to inhibition in 3- to 6-year-old children (Cameron et al., 2012; Livesey et al., 2006) as well as balance to switching and updating (Rigoli et al., 2012a, 2012b). Yet another recent study published after this review, demonstrated significant relations between gross motor skills, such as jumping, balance and ball skills and inhibition as well as updating (van der Fels et al., 2019). Furthermore, significant relations between strength and speed were found to updating but not to inhibition or switching (Stuhr et al., 2020). A recent meta-analysis helps understanding and summarizing these recent studies. This meta-analysis revealed significant and robust effects between balance skills and inhibition as well as between locomotion and updating according to Rosenthal's fail-safe-N (Gandotra et al., 2021). However, significant relations between balance skills and switching and updating were not robust; and the relations between locomotion and inhibition and switching as well as the relation between object control and all three executive functions were non-significant (Gandotra et al., 2021). Overall, this analysis supports the notion of insufficient and inconclusive evidence regarding the relation between gross motor skills and executive functions and most studies examining this relation have investigated children in early childhood.

As motor skills are required to execute aerobic fitness, previous research has examined this more specific relation between aerobic fitness and executive functions (Khan & Hillman, 2014). According to a recent review, children with greater aerobic fitness performed higher on executive function tasks (van Waelvelde et al., 2019). More specifically, the majority of research found significant associations with inhibition (e.g., Buck et al., 2008; Hillman et al., 2009), switching (e.g., van der Niet et al., 2014), and updating (e.g., Geertsen et al., 2016; Scudder et al., 2014). However, some studies were not able to demonstrate this association to inhibition (e.g., Pindus et al., 2016), switching (e.g., Nieto-Lopez et al., 2020), and updating (e.g., Schmidt et al., 2015). A possible explanation for these inconsistent findings may refer to methodological differences used when examining the constructs of aerobic fitness and executive functions. Overall, the majority of previous research supports the relation between gross motor skills and executive functions. However, most research has focused on only one or two executive function tasks and studies have rarely examined all three executive function components to enable an overarching view (for an overview, see van Waelvelde et al., 2019).

Mechanisms Linking Motor Development and Social-Emotional Development

One foundational mechanism underlying relations between motor and social-emotional development may refer to information processing, by which situational information is cognitively perceived, processed and movement is generated as a response (Kenny et al., 2016; Singer et al., 1979). Therefore, in order to develop socially and emotionally, movement precision and coordination are imperative (Mancini et al., 2019; Piek et al., 2006). As soon as infants are able to crawl, they receive social-emotional signals from their caretakers which are suggested to be the foundation of social referencing (c.f., the visual cliff, Gibson & Walk, 1960). Social references such as parental facial expressions or tone, guide infants' movements and exploration behavior (Campos et al., 2000). Furthermore, motor development contributes to an infant's ability to interact with their social environment (Leonard, 2016) and act autonomously. In line with the embodied cognition theory, motor skills also enable more self-initiated interpersonal interactions (Harbourne & Berger, 2019). For example, gross motor skills such as gait enable children to navigate through the world, change their relations to objects and people, and allow them to initiate interactions with learning materials and participate in play activities (Iverson, 2010; McClelland & Cameron, 2019). This novel motor behavior creates a building block for acquiring social-emotional skills and these opportunities and peer play enhance the development of children's social skills as well as their behavioral outcomes (Karasik et al., 2011; Mancini et al., 2019).

Therefore, motor development can be seen as closely related to social-emotional development, with gait acting as a facilitator for the engagement with the environment.

Previous Research Linking Gait with Social Interactions, Emotions and Risk-Taking Behavior

In the last decade, some studies have been published which investigated the associations between children's gait and their social-emotional behavior, however, research is still scarce. This research has emerged in response to several adult studies in which a decreased gait speed was associated with depressive symptoms (Lemke et al., 2000; Michalak et al., 2009), as well as anxiety (Zhao et al., 2019). Furthermore, studies have indicated that human gait reflects emotions. For example, a study found significant associations between increased gait speed and joy as well as anger (Gross et al., 2012). This was further supported by research showing increased brain activity when performing happy movements (Atkinson et al., 2012), as well as when undertaking negative (i.e., angry) emotional walks (Schneider et al., 2014). The only study examining this relation in children is a recent study which demonstrated that 13-year-old children with higher emotional symptoms and behavioral difficulties walked with shorter steps in a higher cadence (Mansoubi et al., 2020). Regarding social interactions, a recent study in adults has demonstrated an association between vulnerable gait cues (i.e., less synchronous, less fluid, long or short strides) and self-reported experiences in victimization (Blaskovits & Bennell, 2019; Grayson & Stein, 1981). Furthermore, a recent meta-analysis of adolescents and adults has found that synchronous movements are associated with prosocial behavior, perceived social bonding, social cognition, and positive affect (Mogan et al., 2017).

Overall, these results provide first insights into how children's gait relates to their social-emotional behavior. However, research regarding the association between gait and emotions is scarce. Further research is required, using wider age spans in children and investigating emotional symptoms and problem behavior. In addition, studies exploring the relationship of gait and social development are rare in children and research with risk-tasking behavior is lacking completely.

Examining Low Motor Development in Relation with Cognitive and Social-Emotional Development

Within research of typical development, the focus is often placed on well-developed motor skills and why these are important. Thereby, it is frequently assumed that motor skills develop innately, however, research has indicated that many children show only weak motor skills (Goodway & Branta, 2003; Stodden et al., 2008). Considering the bidirectionality between children's developmental domains, delays or difficulties in motor skill development may be a risk factor and negatively impact children's cognitive and social-emotional development (Hagmann-von Arx et al., 2016; Libertus & Hauf, 2017; Mansoubi et al., 2020). To revisit the theory of embodied cognition, difficulties in motor skills may hinder crucial interactions with others and engagements with the environment and therefore reduce learning opportunities (Martí, 2020). Moreover, children with low motor skills may experience negative situations such as social exclusion, which may lead them to avoid these situations as a coping strategy for disengagement (Bouffard et al., 1996; Stodden et al., 2008). Avoidance in turn initiates a vicious circle, as this refrainment depletes possibilities to practice motor skills and as a result, difficulties in motor skills may increase (Cairney et al., 2013; Skinner & Piek, 2001). This negative spiral reduces social participation so that these children might additionally be at greater risk for emotional and behavioral problems as well (Schoemaker & Kalverboer, 1994; Zwicker et al., 2012). This is also supported by the theoretical framework the Environmental Stress Hypothesis, which conceptualizes poor motor skills in clinical samples as a primary stressor to contribute to the experience of intra- and interpersonal conflicts and to the risk of developing internalizing problems such as anxiety and depression (Blank et al., 2019; Cairney et al., 2013; Mancini, Rigoli, Cairney, et al., 2016).

Previous longitudinal research with preterm and typically developing children has demonstrated that variability in gross motor development within the first four years of life predicted more parental-reported emotional symptoms (i.e., anxiety and depression) in middle childhood (Piek et al., 2010). Furthermore, previous research applied the term poor motor skills to characterize a diverse range of uncoordinated or clumsy behavior (Bejerot et al., 2013). This line of research is situated predominantly in clinical research as children were identified with "poor motor skills" when being diagnosed with a developmental coordination disorder (e.g., American Psychiatric Association, 2013) or when scoring below a certain cut-off value in a standardized motor assessment or standardized parental questionnaire (e.g., Henderson et al., 2007; Wilson et al., 2009). Studies found significant associations between poor motor skills and lower prosocial skills as well as peer relations, such as less sociable behavior and interactions, higher loneliness, fewer friends, less social support, and more exclusion from peer play (Engel-Yeger & Hanna Kasis, 2010; Leonard, 2016; Lingam et al., 2012; Mancini et al., 2019; Poulsen et al., 2008; Smyth & Anderson, 2000; Zwicker et al., 2012). In addition to experiencing more exclusion, children with poor motor skills are also frequently victims of social ostracism and bullying (Bejerot et al., 2013; Campbell et al., 2012; Missiuna & Campbell, 2014; Piek et al., 2005).

Overall, studies with clinical samples support the associations between poor motor skills and children's social-emotional development (Bouffard et al., 1996; Cantell et al., 1994; Mancini et al., 2019; Skinner & Piek, 2001). However, research with typically developing children is scarce as of today. In the following thesis, the term "low motor skills" is used for motor competences which fall within the lower end of the range of typical development. Therefore, to consider a more dimensional view, through using continuous rather than categorical perspectives of motor skills, typically developing children with low motor skills may similarly demonstrate an impact on their cognitive as well as social-emotional development. Such a finding would highlight the relevance and importance of more inclusive interventions and support structures.

Research Questions

In the present studies, the interplay between the three developmental domains motor, cognitive, and social-emotional development is investigated. Typically developing children between 7- and 13 years of age are the overarching focus of this dissertation. Within three studies, I investigated the main research question of the current dissertation: *How are low motor skills interlinked to cognitive development (i.e., intelligence and executive functions) and social-emotional development (i.e., prosocial behavior, hyperactivity, emotional symptoms, conduct and peer problems, and risk-tasking)?* For an overview of the studies see Table 1.

Study 1 (Klupp, Möhring, Lemola, & Grob, 2021): *How are fine motor skills and intelligence subcomponents related in typically developing children?* Previous research was extended by (a) examining this relation in childhood into early adolescence and therefore extending research of kindergarten or transition to school, (b) considering all four subcomponents of intelligence (perceptual reasoning, verbal comprehension, working memory, and processing speed), in addition to the full-scale IQ, and (c) generating a more comprehensive and detailed insight into this relation.

Study 2 (Klupp, Grob, & Möhring, 2022a): *How are fine motor skills, gross motor skills, and fitness related to all three core executive functions inhibition, switching, and updating?* Previous research is extended by (a) investigating all three core components to enable a comparison across executive function components, (b) exploring this relation separately as well as simultaneously to determine the relative contribution above one another, and (c) controlling for multiple relevant control variables.

Study 3 (Klupp, Grob, & Möhring, 2022b): *How gross motor skills (i.e., gait) related to social-emotional and risk-taking behavior?* Previous research is extended by (a) utilizing a novel indicator of children's motor ability such as gait variability, (b) investigating various subcomponents of social-emotional behavior as well as exploring this relation to risk-taking behavior, and (c) extending clinical findings by assessing a large sample of typically developing children.

Methods

Samples

The present research questions were investigated with data that we collected in the research project "Cognitive and Motor Development" in the Department of Developmental and Personality Psychology at the University of Basel in Switzerland. We recruited the majority of children from local schools. Inclusion criteria for all three studies composed of (a) sufficient German language skills, (b) no intellectual impairment as confirmed by the Wechsler Intelligence Scale for Children fourth edition (WISC-IV, intelligent quotient > 70; Petermann & Petermann, 2011); and (c) no gait related or developmental or psychopathological disorders (e.g., Developmental Coordination Disorder) as confirmed by the diagnostic history through a parental questionnaire as well as the assessment of the Movement Assessment Battery for Children second edition (MABC-2 ≥ 16th percentile; Henderson et al., 2007).

Study 1. In the first study, we included data of children aged 7–13 years which was collected between May 2013 and July 2014. After excluding participants with missing data in the key variables the final sample consisted of N = 139 typically developing children (63 females; M_{age} = 10.06 years; SD_{age} = 1.45 years).

Study 2. In the second study, we included data that we collected between March 2017 and September 2018 of typically developing children aged 8–13 years. The final sample consisted of N = 129 children (58 females; M_{age} = 10.73 years; SD_{age} = 1.60 years).

Study 3. For the third study, the datasets from Study 1 and Study 2 were combined, as the variables of interests were examined in both subsamples and to examine the largest possible number of participants. The final sample consisted of N = 221 children (104 females; M_{age} = 10.54 years; SD_{age} = 1.57 years).

Measures and Procedures

We assessed the relations between different aspects of human movement (motor skills, aerobic fitness and gait) and various cognitive and social-emotional constructs (intelligence, executive functions, and social-emotional and risk-taking behavior). All three studies were part of our larger cross-sectional design which examined cognitive and motor single- and dual task situations that are described elsewhere in more detail (cf., Hagmann-von Arx et al., 2016; Hagmann-von Arx et al., 2015; Manicolo et al., 2019; Manicolo et al., 2017; Manicolo et al., 2016; Möhring et al., 2018; Möhring et al., 2020; Möhring et al., 2021). For all three studies, we tested children with a battery of widely acknowledged and standardized tasks at the laboratory of the University of Basel.

Study 1. In the first study, we examined the constructs of intelligence and fine motor skills with two age-standardized test batteries in order to ensure comparability between participants of different ages and across measurements. We measured intelligence with the standardized, reliable, and valid assessment WISC-IV (Petermann & Petermann, 2011), which is composed of four indices: (a) verbal comprehension as the ability to understand language; (b) perceptual reasoning as the ability to understand visual information and solve abstract problems; (c) working memory as the ability to hold, organize, and manipulate verbal information; and (d) processing speed as the ability to process information (Groth-Marnat, 2009). The full-scale IQ as well as the four age-standardized index scores were computed for the analyses.

The MABC-2 is a standardized, reliable, and valid assessment of children's general motor abilities based on performance in the three motor subcomponents: (a) manual dexterity indicating fine motor skills; (b) balance including static and dynamic balance as well as locomotion; and (c) aiming and catching also referred to object control skills (Henderson et al., 2007). Due to previous studies suggesting stronger relations between intelligence and fine motor skills as compared to gross motor skills (van der Fels et al., 2015), we focused exclusively on fine motor skills in the first study. The analyses included solely children's performance assessing manual dexterity, consisting of three subtests: a one-handed posting task, a bimanual assembly task, and a trail-drawing task. Raw scores of the subtests were computed into an age-standardized fine motor subcomponent score.

Study 2. In the second study, we examined motor skills as well as aerobic fitness in relation to executive functions. In addition to fine motor skills, balance skills and object control skills were investigated and therefore all three subcomponents of the MABC-2 were included (Henderson et al., 2007). Fine motor skills were measured using the manual dexterity subcomponent described above. Further, the subcomponent balance skills is measured by three subtests: a board balance task, a walking balance task and a jumping task. Lastly, the two subtests catching a ball and aiming at a target compile the subcomponent object control skills. Similar to the previous procedure, we converted the raw scores into age-standardized subcomponent scores.

Additionally, in this respective study we investigated aerobic fitness with the Progressive Aerobic Cardiovascular Endurance Run (PACER; Léger et al., 1988). This is an established, reliable and valid measure in children (Carrel et al., 2012; Olds et al., 2006; van Waelvelde et al., 2019). The aim of this shuttle run is to jog back and forth between two boundaries as long as possible. An audio signal determines the speed and increases gradually. Based on the number of completed runs, a higher score indicates greater aerobic fitness.

Besides the motor tasks, children completed an inhibition, a switching and an updating task. Each executive function task included a total of 96 items from which we assessed the number of errors. Trials were visually presented and children answered verbally to avoid any confounding involvement from motor activity (i.e., as compared to button press). To increase the comparability and control for differences among individual children’s baseline performance, we adjusted the tasks by equating the difficulty (cf., Saxena et al., 2017). Participants completed three executive function tasks: an animal Stroop task as a measure of inhibition (Grob & Hagmann-von Arx, 2018; Stroop, 1935), a local-global task as a measure of switching (Navon, 1977), and a 2n-back task as a measure of updating (Dobbs & Rule, 1989).

Study 3. In the third study, we examined relations between gait and social-emotional behavior. We assessed children’s normal walking (i.e., straight forward walking at their self-selected pace) with the objective, reliable and valid electronic carpet system GAITRite (CIR Systems, New Jersey USA; Dusing & Thorpe, 2007). The GAITRite consists of 7 m active carpet containing more than 23’000 embedded sensors and additional inactive sections at both ends of 1.25 m to account for acceleration and deceleration. The gait analysis focused on children’s stride-to-stride fluctuations (i.e., gait variability) which is expressed by the coefficient of variation (CV; Yogev et al., 2005). These included three different gait measures: temporal (CV stride time), spatial (CV stride length) and spatial-temporal parameters (CV stride velocity).

Further, parents completed the standardized, reliable and valid Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997) to report about their children’s behavior on the five subscales: prosocial behavior, hyperactive and inattentive behavior, emotional symptoms, conduct problems, and peer problems. In addition, parents also answered an adapted version of the Tridimensional Personality Questionnaire (TPQ; Brandau & Daghofer, 2010; Cloninger et al., 1991) to asses children’s risk behavior reliable and valid on the three subscales: novelty seeking, risk-taking, and reward dependence.

Statistical Analyses

All three studies follow a cross-sectional design in which a variety of variables was collected at one time point. Further, as children cannot be randomly assigned to ability levels or development, the information was gathered from natural life circumstances and natural changes without manipulating their experiences and supporting ecological validity (e.g., Berk, 2018). In the present studies, we analyzed relations between participants' characteristics through hierarchical regressions and multilevel modeling approaches in SPSS 26 to examine how variables are associated with one another.

Study 1. To examine the relation between fine motor skills and several aspects of intelligence, we conducted a series of hierarchical regressions analysis. The full-scale IQ as well as the four subcomponents of intelligence (verbal comprehension, perceptual reasoning, working memory, processing speed) served as our dependent variables. In the first step, we entered the control variables sex and maternal education. As age-standardized values were used, age was not again controlled for. In the second step, we added fine motor skills as independent variable.

Study 2. We conducted a series of hierarchical regressions to examine the relative importance of motor skills and aerobic fitness for children's executive functions. By considering the order of variable inclusion into the model, we explored whether motor skills and aerobic fitness explain variance in executive functions above and beyond each other. We computed the hierarchical regressions separately for each of the three dependent variables of executive functions (inhibition, switching, updating). In the first step, we entered the control variables age, sex, body mass index, intelligence and parental education based on previous research suggesting potential influences (e.g., refs). In the second step, we added aerobic fitness, followed by fine motor skills in the third, balance skills in the fourth, and object control skills in the fifth step as predicting variables. As mentioned above, the hierarchical regressions were repeated in reverse order. In the second set of hierarchical regressions, control variables were entered in the first step, fine motor skills in second, balance skills in third, object control in forth, and lastly aerobic fitness in fifth step.

Study 3. To examine the relation between children's gait and their intra- and interpersonal characteristics, we utilized a multilevel modeling approach. This allowed us to take the nested data structure and individual interdependence of children's strides on the gait assessment system into account as well as to analyze the maximum number of children's strides. The two-level approach used gait variability across individual walks (CV stride time; CV stride length; CV stride velocity) on level 1. The level 2 comprised of the child's characteristics which included the control variables (age, sex, and intelligence) as well as the parental reports on behavior (SDQ and TPQ). For each gait variability measure we conducted a separate model. The null model contained the control variables and was compared to the full model in which the child's behavior was added.

Synopsis of the Results

Study 1. The findings of the first study suggest a significant association between fine motor skills and several aspects of intelligence in typically developing children. Specifically, significant relations between fine motor skills and full-scale IQ, perceptual reasoning, and processing speed as well as a tendency in working memory were found even after controlling for sex, age, and maternal education. However, relations to verbal comprehension were not significant. This demonstrates that lower levels of fine motor skills are associated with lower intelligence scores, thereby supporting a general association between motor and cognitive skills.

Study 2. The findings of the second study suggest significant associations between aerobic fitness and fine motor skills with switching and updating, however, relations to inhibition were non-significant. Furthermore, balance and object control skills were unrelated to inhibition, switching and updating. Regarding the relative importance of motor skills and aerobic fitness, it was found that fine motor skills explained additional variance above children’s aerobic fitness in switching and updating skills. The reverse could not be confirmed as the explained variance of aerobic fitness on children’s switching and updating ability changed to a non-significant effect when fine motor skills were simultaneously accounted for. This indicates that especially lower levels of fine motor skills, but also lower levels of aerobic fitness are associated with lower switching and updating performances.

Study 3. The findings of the third study suggest significant associations between gait variability and children’s facets of intra- and interpersonal characteristics. Specifically, results indicated that children with higher gait variability in their stride length and stride velocity demonstrated fewer prosocial skills and a higher frequency of reported emotional symptoms. Moreover, gait variability was not associated with the subscales measuring hyperactivity, conduct problems, and peer problems. Furthermore, children who showed a higher gait variability were reported to be less risk-taking and therefore more cautious, while gait variability was not associated with the subscales measuring novelty seeking and reward dependence. This demonstrates that higher gait variability is associated to fewer prosocial skills, more emotional symptoms and less risk-taking.

Discussion

Motor development has shown close relations to the other two main developmental domains of cognitive and social-emotional development. The three studies within this dissertation aimed to increase the in-depth understanding of these relations by examining developmental domains in relation to one another as well as examining motor skills of typically developing children with a continuous perspective to highlight low motor performances. Firstly, the following section includes a summary and discussion of the acquisition on how children’s development in the motor domain relates to their development in the cognitive as well as the social-emotional developmental domain. Secondly, the insights of the overarching focus on low motor skills in typically developing children are summarized and discussed. Thirdly, the strengths and limitations as well as a future outlook were considered, followed lastly by an overall conclusion.

Beyond the Relationship Between Developmental Domains

The significant associations in Study 1 add to previous findings (e.g., Cameron et al., 2012) and support the notion of fine motor skills being related to intelligence throughout childhood and well into adolescence. Specifically, the intelligence subdomains of perceptual reasoning and processing speed were significantly associated with fine-motor skills, while working memory yielded a tendency and verbal comprehension was non-significant. These results indicate that especially fluid aspects of intelligence are related to fine motor skills, in contrast to aspects reflecting crystallized intelligence in line with previous conclusions (van der Fels et al., 2015). Study 1 highlighted that the significant associations were found above age effects suggesting that maturation alone would not account for these relations. In addition, these results have demonstrated the additional value of examining the subcomponents of a construct, such as intelligence, as specific associations can be detected. In summary, the correlative results of the present study are in line with the embodied cognition theory which suggests that fine motor skills facilitate cognitive development, as well as the dynamic systems approach which highlights the bidirectionality between cognitive and motor skills (Adolph & Joh, 2007; Harbourne & Berger, 2019).

The significant associations in Study 2 between aerobic fitness and fine motor skills with switching and updating are consistent with previous research (Gandotra et al., 2021; van der Fels et al., 2015; van Waelvelde et al., 2019). Furthermore, fine motor skills explained additional variance above aerobic fitness in switching and updating while aerobic fitness did not significantly explain any additional variance in children's switching and updating performance when simultaneously accounting for fine motor skills. These results further support the association between motor and cognitive development. However, these relations were not confirmed for inhibition, nor balance and object control skills. Possible explanations could be the variety of tasks used in previous research or the perceived difficulty within the present tasks. The present study took a crucial first step to investigate the in-depth relation between motor and cognitive development by including multiple facets of motor skills and executive functions simultaneously. Given that the findings suggested that aerobic fitness and fine motor skills differ in their relation to executive function (Haapala, 2013), it seems important to examine different aspects of these constructs in future research. In addition, previous research seldomly included all three executive functions (van Waelvelde et al., 2019), which is important as the three components show different developmental trajectories (Huizinga et al., 2006). Ideally, multiple varying assessments should be included to form latent constructs of motor as well as cognitive components. In summary, taking multiple components of human movement into account is critical for achieving an overarching and comprehensive understanding of the interplay between the motor and cognitive developmental domains.

The significant associations between gait variability and prosocial behavior, emotional symptoms and risk-tasking in Study 3 are in line with previous research demonstrating that intra- and interpersonal behaviors are associated with human movement (Mansoubi et al., 2020; Simpson et al., 1993; Smyth & Anderson, 2000). Specifically, it was found that children with fewer prosocial skills, more reported emotional symptoms, and less risk-taking behavior showed higher gait variability in their stride length and stride velocity. The last association can be regarded as unexpected, as some would expect children who walk more cautiously to walk more regularly. However, this relation can on one side be explained through children who engage in riskier behavior often seek out challenging situations to explore their boundaries. As children develop various aspects of their motor skills in these situations, their gait variability may decrease. On the other side, children with higher gait variability might hold back on risky behaviors, as they are able to adapt and identify their difficulties. Overall, this study contributes to our understanding of how walking may reveal information about psychosocial behavior and further support the research of the association between motor and social-emotional development. There are two points to highlight from this study. Firstly, regarding the vicious circle of disengagement as a copying strategy, Study 3 highlights that children with fewer prosocial skills, children who tend to be more nervous, anxious or sad, or children which are more cautious and potentially shyer are at risk for social-emotional skills (Cairney et al., 2013). Therefore, the negative spiral involving social participation is not only evident in motor but social-emotional development as well (Bouffard et al., 1996; Zwicker et al., 2012). Secondly, the research examining gait in children often takes place before the age of 7 years due to the important milestones achieved during this period (Adolph et al., 2003; Hagmann-von Arx et al., 2016). However, when investigating the development of gait after the completion of a mature gait pattern, it is still well possible to detect differences in gait due to the lengthy developmental progression of gait variability (Van Emmerik et al., 2005). It is therefore important to conduct assessments with sensitive measuring instruments which can identify gait variability. In summary, this transfers to the general examination of motor skill development within children as well as the assessment of cognitive and social-emotional development, as sensitive and age-appropriate measures are vital to detect variability in development and to identify children at risk.

Furthermore, across the three studies several control variables were included in the statistical approaches to examine and account for possible interferences. These included age, sex, and maternal education, which are important for interpreting the assessed associations. Firstly, all three studies controlled for age by either using age-standardized scores or including age in the statistical model. The significant associations between motor skills and the cognitive as well as social-emotional domain are indicative of an interplay between these domains above simple age effects. Therefore, explanations along the line of the maturational hypothesis, which suggests that older children demonstrate higher performance on all types of tasks compared to younger children, are unlikely (Cameron et al., 2012; Suggate & Stoeger, 2014). Secondly, the present studies controlled for sex effects. The majority of the results display no significant sex effects within the associations between fine motor skills and intelligence, switching and updating as well as for aerobic fitness and switching and updating. However, females were found to make less errors in the inhibition task and walking more regularly, which is in line with some previous studies (Mileva-Seitz et al., 2015; Singh et al., 2022). A recent meta-analysis indicated no significant sex difference in inhibition (Gaillard et al., 2021). Lastly, maternal education an indicator of the social economic status was included in the statistical models, to also address the question of the socioeconomic hypothesis, which suggests that relations between developmental domains may reflect differences in the socioeconomic background, as disadvantaged children may have fewer opportunities to enhance their skills (Grissmer et al., 2010). The analyses demonstrated ambiguous results. While maternal education was significant within Study 1, it was not significant in the majority of analyses in

Study 2. Therefore, one possible conclusion is that the socioeconomic hypothesis does not explain the significant association between the developmental domains and that the effects go beyond the socioeconomic status.

Low Motor Skills and Implications

The second focus of this dissertation was to examine children between 7 and 13 years of age with a dimensional approach. The studies also show the high end of motor ability, however, due to implications the focus was set on children falling within the low end of typically developing motor ability range, yet not fulfilling the clinical cut-off values. Thus, the three studies within this dissertation provided a more dimensional perspective of low motor skills and the relation to lower cognitive performance as well as to social-emotional difficulties. Children with lower fine motor skills scored lower on the intelligence battery within Study 1 as well as lower on executive function tasks in Study 2. Furthermore, Study 2 also revealed that children with lower aerobic fitness demonstrated lower executive function performance. In addition, Study 3 provided evidence that children who walked less regularly showed less prosocial behavior and more emotional symptoms.

Highlighting the dimensional perspective on the results of children at the low end of the motor ability range is especially important for future interventions. Children with clinically relevant motor difficulties, such as a diagnosis for a developmental coordination disorder according to the Diagnostic and Statistical Manual are more likely to receive support in form of motor interventions (Zwicker et al., 2012). This is also the case for children who meet certain cut-off values in clinically relevant questionnaires such as the Developmental Coordination Disorder Questionnaire or perform below the 16th percentile in the M-ABC-2 (Sartori, 2019). However, the current findings support a more dimensional perspective of motor development, indicating that even when children do not meet these cut-off criteria and are classified within the typically developing spectrum of motor skills, they do not only demonstrate below average motor skills but also significantly lower cognitive performances as well as social-emotional difficulties. In conclusion it seems that children with low motor skills would be similarly designated for intervention and support.

Furthermore, returning to the embodied cognition theory, interventions focus on the opportunity for engagement with motor skills. On one side, the motor skill development provides the basis required for later and advanced movement. On the other side, motor skills create movement exposure to counteract the emergence of the vicious circle and therefore promote physical activity, social interactions, and health. Therefore, although interventions in research in child development often focus on a specific domain, improvements in other domains can also be recorded during development in childhood as skills are malleable to change (McClelland & Cameron, 2019). For example, a recent meta-analysis of children with developmental coordination disorder reported a significant improvement after an intervention in motor performance as well as for cognitive and emotional functions (Yu et al., 2018). However, this meta-analysis also mentions certain limitations as the majority of interventions focus on gross motor skills. Thus, fine motor skill interventions are rare. Moreover, the studies regarding cognitive and emotional outcomes were limited. Although the majority of studies with motor skills intervention focus on clinical samples, some studies have investigated intervention effects on typically developing children. Previous research has shown that increasing opportunities for physical activity improves aerobic fitness (Ferguson et al., 2015) and object control skills (Yu et al., 2016) in typically developing children. Overall, these intervention studies suggest that training is essential and beneficial for various facets of child development.

Strengths, Limitations, and Future Research

To integrate and contextualize the insights gained within the present dissertation, it is important to keep the strengths and limitations in mind. The examined age range of 7- to 13-year-olds encompasses not only a relevant time in child development from theoretical perspective, but covers the entire primary school which is also relevant from a practical perspective before moving into secondary school. When planning the study design, we were mindful of selecting standardized test batteries wherever possible and established, reliable, and valid measurements for the other constructs. In addition, the studies embraced an integrated and differentiated approach by considering well-accepted subcomponents of children's intelligence and executive functions. Moreover, within the statistical approaches of all included studies, we accounted for control variables such as age, sex, and maternal or parental education. Additionally, Study 2 analyzed the relative importance by exploring all possible orders within the hierarchical regression to determine the explained variance beyond each variable. Within Study 3, it should be highlighted that the interdependence between walks was taken into account. From a global perspective, the strengths of the present dissertation include the contemplation of the interplay between the three main developmental domains with a focus on low motor skills. Moreover, the consideration of various motor skills measurement contributes to a multifaceted examination. Lastly, the cross-sectional design across the studies is advantageous with regard to eliminating the problems of drop-out and practice effects hereby.

However, due to the correlational design of the three included studies, indications of causality and direction of the associations through regressions are impossible. The observation of intra-individual development is also not possible. In addition, several constructs within the three studies have been measured with only one task or questionnaire due to the feasibility of the study and to minimize subject (and family) burden. Another challenge within the assessments was the problem of task impurity, as for example some cognitive tasks partially require aspects of motor skills and vice versa (Best & Miller, 2010; Loh et al., 2011). Within our studies, we have addressed this problem by using established measures and preferring verbal response formats over for example key presses wherever possible. Furthermore, the limitations of the present dissertation include no examination between the interlink of the cognitive and social-emotional domain. As this connection is also beyond the scope of the current dissertation, future research should try to assess the interlinks between all three main developmental domains.

In addition, this dissertation considered various motor skills assessments whereas cognitive and social-emotional constructs were measured by a single assessment, yet we included all subcomponents. However, conducting different tasks for the same construct enables validation and latent modelling approaches. Therefore, future studies should consider multimethod approaches for all included constructs. Furthermore, first research interventions were able to show positive effects of motor interventions especially in children with developmental coordination disorder but also in typically developing children (e.g., Cohen et al., 2015). Future research should investigate the effects of interventions with children showing low motor skills and between group comparisons in more detail, especially regarding fine motor skill interventions which are scarce as of today. In addition, previous research in a clinical sample has demonstrated mixed results regarding follow-up effects of intervention studies (Yu et al., 2018). This suggests that although training motor skills over a short period (e.g., two-to-three months) seem to be effective, it is important to continue assessing motor skills engagement, leading to the importance of the establishment of long-term programs available outside the research context and put into practice to examine sustainability.

Conclusion

By interlinking the domains of motor, cognitive, and social-emotional development, the present dissertation provides new insights which strengthen and extend previous research within developmental psychology. Through the overarching focus across different developmental domains, three conclusions can be inferred from the present dissertation. Firstly, integrating several studies within a single line of research in form of the present dissertation enables to see and discuss the bigger picture. While single research papers are often narrow and focused on examining the specific relation between specific constructs, the novelty within the present dissertation lies in the prospect to discover the child in its entirety and to highlight how the three core domains of child development contribute within and across domains. Secondly, the present studies extend the kindergarten and school readiness research to a larger age span, namely the entirety of primary school. The current results suggest significant associations above the maturational hypothesis suggesting that children will not likely outgrow their low motor skills but may be in need of support. Thirdly, there have been several discussions within politics and policy makers which continuously discuss physical education as subject in school and whether to reduce these hours in favor of other academic subjects. However, research has shown the importance of the association between motor development and cognitive as well as social-emotional development and society is encouraged to implement this knowledge and to promote motor skills.

Ultimately, this dissertation adds to a more holistic view of child development by considering different components of motor skills, intelligence, executive functions, and social-emotional behavior. Furthermore, the dimensional perspective increases the awareness of children’s low motor performances and path the way toward early identification in and interventions for children at risk in all developmental domains.

Table 1

Overview of the studies included in the present dissertation

	Study 1 **(Klupp, Möhring, Lemola, & Grob, 2021)**	**Study 2** **(Klupp, Grob, & Möhring, 2022a)**	**Study 3** **(Klupp, Grob, & Möhring, 2022b)**
Child Development Domains	Motor and cognitive	Motor and cognitive	Motor and social-emotional
Research Question	How are fine motor skills and intelligence subcomponents related in typically developing children?	How are fine motor skills, gross motor skills, and fitness related to all three core executive functions inhibition, switching, and updating?	How are gross motor skills (i.e., gait) related to social-emotional and risk-taking behavior?
Sample	N = 139 n = 63 females $Range_{age}$ = 7–13 years M_{age} = 10.06 years SD_{age} = 1.45 years	N = 129 children n = 58 females $Range_{age}$ = 8–13 years M_{age} = 10.73 years SD_{age} = 1.60 years	N = 221 children n = 104 females $Range_{age}$ = 7–13 years M_{age} = 10.54 years SD_{age} = 1.57 years
Statistical Analysis	Hierarchical regressions analysis	Hierarchical regressions analysis	Multilevel Modeling
Motor Variables	Fine motor skills (MABC-2)	Fine and gross motor skills (MABC-2) - Fine motor skills - Balance skills - Object control skills Aerobic fitness (PACER)	Gross motor skills (GAITRite) - normal walking, i.e., gait
Second Domain Variables	Intelligence (WISC-IV) - Verbal comprehension - Perceptual reasoning - Working memory - Processing speed	Inhibition (animal Stroop task) Switching (local-global task) Updating (n-back task)	Social-emotional behavior (SDQ) - Prosocial behavior - Hyperactive and inattentive - Emotional symptoms - Conduct problems - Peer problems Risk Taking Behavior (adapted TPQ)
Main Finding	Lower levels of fine motor skills are associated with lower intelligence scores.	Lower levels of fine motor skills, but also lower levels of aerobic fitness are associated with lower switching and updating performances.	Higher gait variability is associated to fewer prosocial skills, more emotional symptoms and less risk-taking behavior.

Note. MABC-2 = Movement Assessment Battery for Children second edition. PACER = Progressive Aerobic Cardiovascular Endurance Run. SDQ = Strengths and Difficulties Questionnaire. TPQ = Tridimensional Personality Questionnaire. WISC-IV = Wechsler Intelligence Scale for Children fourth edition.

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APPENDIX A: STUDY 1

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Relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder

Stephanie Klupp[*,a], Wenke Möhring[a], Sakari Lemola[b], Alexander Grob[a]

* **Corresponding author:** Stephanie Klupp, University of Basel, Department of Psychology, Missionsstrasse 62, 4055 Basel, Switzerland; Email: stephanie.klupp@unibas.ch

[a] University of Basel, Department of Psychology, Switzerland.

[b] University of Bielefeld, Germany.

Authorship Statement

A. Grob and S. Lemola substantially contributed to the conception and design of the study. S. Lemola substantially contributed to the acquisition of data. W. Möhring and S. Klupp substantially contributed to the analyses of the present manuscript. All authors contributed to the interpretation of data. S. Klupp drafted the manuscript. All authors critically revised the article and approved the final version to be published.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest.

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Abstract

Background: The embodied cognition hypothesis implies a close connection between motor and cognitive development. Evidence for these associations is accumulating, with some studies indicating stronger relations in clinical than typically developing samples. *Aims:* The present study extends previous research and investigates relations between fine motor skills and intelligence in typically developing children (n = 139, 7–13 years) and same-aged children with attention deficit hyperactivity disorder (ADHD, n = 46). In line with previous findings, we hypothesized stronger relations in children with ADHD than in typically developing children.

Methods and procedure: Fine motor skills were assessed using the standardized Movement Assessment Battery for Children. Intelligence was measured with the standardized Wechsler Intelligence Scale for Children.

Outcomes and results: Regression analyses indicated significant relations between fine motor skills and full-scale IQ, perceptual reasoning, working memory, and processing speed. Moderation analyses identified stronger relations between fine motor skills and full-scale IQ, perceptual reasoning, and verbal comprehension in children with ADHD compared to typically developing children.

Conclusions and implications: Results suggest a close relation between fine motor skills and intelligence in children with and without ADHD, with children diagnosed with ADHD showing stronger relations. Findings support combined motor-cognitive interventions in treating children with ADHD.

Keywords: fine motor skills, intelligence, children, attention deficit hyperactivity disorder, ADHD

What this paper adds

The current study investigated relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder (ADHD). Previous research has examined small and heterogenous clinical samples, including children with multiple developmental disabilities. By contrast, the present study used a large homogeneous sample of children with ADHD which allows specific implications. Furthermore, recent studies have mainly investigated samples of typically developing children at the age of kindergarten and their transition to school. The present sample extends these studies by examining the association between fine motor skills and intelligence across childhood to early adolescence. Analyses of intelligence considered the full-scale IQ as well as the four subcomponents (perceptual reasoning, verbal comprehension, working memory, and processing speed) for detailed insight and specific conclusions. Results have high theoretical and practical value for creating effective motor-cognitive interventions in treating children with ADHD.

Introduction

Motor and cognitive abilities are often assumed to be deeply connected. Whereas some researchers have proposed that motor skills are linked with developmental changes in cognition (e.g., Adolph & Joh, 2007), others named motor skills as foundation for cognitive development (e.g., von Hofsten, 2009). Explanations historically refer to Piaget's theory, who proposed that the sensorimotor stage is the initial stage of adaptation in cognitive development: infants create learning opportunities through self-initiated actions (Piaget, 1947). More recently, the embodied cognition perspective attempted to explain the link between motor and cognitive abilities beyond simple age-related changes (Barsalou, 1999; Gibbs, 2005). According to this theory, executing a new motor skill facilitates cognitive processes in infants and children as they discover new aspects in their environment which helps shaping their perception, and enables new opportunities to interact with objects and people (Gottwald et al., 2016; Harbourne & Berger, 2019).

In line with this embodied cognition account, correlational studies showed associations between infants' motor development and concurrent spatial abilities (e.g., Schwarzer et al., 2013), later language (e.g., Oudgenoeg-Paz et al., 2012) and categorization skills (e.g., Murray et al., 2006). In addition, experimental studies point to the causal relation between infants' motor experience and object exploration skills (e.g., Libertus et al., 2016), spatial abilities (e.g., Möhring & Frick, 2013), and executive functioning (e.g., Berger, 2010). Importantly, these effects are not restricted to infancy but seem to continue into childhood and adulthood (for reviews, see Berger et al., 2018; Frick et al., 2014; Kontra et al., 2012).

Further evidence for a close link between motor and cognitive skills comes from their similar developmental trajectories and an overlap of activated neural areas (e.g., cerebellum, dorsolateral prefrontal cortex; Diamond, 2000). The majority of research investigating this topic has focused on typically developing children (Frick & Möhring, 2016; Piek et al., 2008; Piek et al., 2004; Rigoli et al., 2012; Roebers & Kauer, 2009; Wassenberg et al., 2005), with evidence from clinical populations being less well studied. Some of this research with clinical samples has indicated that children with developmental disorders that are predominantly associated with attention deficits often show co-morbidities with motor problems (cf. Diamond, 2000). For example, many children with attention deficit hyperactivity disorder (ADHD) do not only show attention deficits but also impaired motor skills (for a review, see Kaiser et al., 2015). In particular, 30–50% of children with ADHD meet the diagnostic criteria of a comorbid Developmental Coordination Disorder (Fliers et al., 2008; Kadesjo & Gillberg, 1998; Sergeant et al., 2006).

Based on these latter studies, it seems likely that motor and cognitive skills are related in typical and clinical populations. To date, only few studies have investigated these relations in typical and clinical samples in a single unified approach (e.g., Smits-Engelsman & Hill, 2012). Crucially, these studies demonstrate that associations between motor and cognitive skills seemed to be stronger in clinical groups as compared to typically developing children. For example, Dyck et al. (2006) investigated relations between motor coordination and language skills in children aged 6–15 years with autism spectrum disorder (ASD) and controls and found stronger relations in the clinical sample. Likewise, another study examined 1- to 10-year-old children with intellectual and developmental disabilities (e.g., children with Down syndrome) and showed stronger correlations among motor, cognitive, and language measures as compared to typically developing children matched for developmental age (Houwen et al., 2016). With respect to explanations for these differential patterns, several authors suggested an unusual interdependence among neurocognitive processes in children with developmental disabilities (Dyck et al., 2006; Houwen et al., 2016). This explanation is supported by findings showing that movement problems in children with ADHD have been associated with a disbalance of basal ganglia neurocircuitries (Archer & Beninger, 2007).

Further evidence for different relations between motor performance and intelligence in clinical populations as compared to controls was investigated in children with acquired and congenital disorders (e.g., traumatic brain injury, ADHD) and healthy, typically developing children (Martin et al., 2010). Participants were examined with a standardized intelligence measure and a simple repetitive and a more complex sequenced motor task. Results demonstrated that in both samples, higher intelligence was related to better performance in the complex motor task. However, intelligence and performance in the simple motor task was only correlated in the clinical sample but not in typically developing children. The authors suggested that atypical neurodevelopmental processes in the clinical sample caused this pattern of results. In accordance with the model of motor learning (cf. Fitts & Posner, 1967), motor skills become increasingly automatized across development and thus, require less cognitive resources. In light of this model, findings of Martin et al. (2010) could also be explained by assuming that motor control required a high level of cognitive resources for the complex motor task in both samples, but may have been more automatized in case of the simple motor task in typically developing children. As a consequence, typically developing children may have shown lower interindividual variability in the simple motor task of this respective study, providing less shared variance with the intelligence measure.

The studies investigating different relations between cognitive and motor skills in typical and clinical samples (Houwen et al., 2016; Martin et al., 2010) have mainly used very heterogenous samples including children with various diagnoses (with the exception of Dyck et al., 2006 who examined children with ASD). Even though such an approach is informative, it precludes the possibility to make specific conclusions for children with particular developmental disabilities. The current study aimed at extending previous research and investigated relations between cognitive and motor skills using a large, homogenous sample of children diagnosed with ADHD. It is of particular interest to investigate this specific clinical sample because ADHD is one of the most prevalent diagnosed developmental disorders in childhood affecting many children (Willcutt, 2012), and children with ADHD have difficulties in attention and often co-occurring motor problems (Kaiser et al., 2015).

Considering that previous research suggests that fine motor skills showed stronger relations to cognition as compared to gross motor skills (van der Fels et al., 2015), the present study focused specifically on this set of skills. Fine motor skills are defined as the ability to control small muscle movements to accomplish a task using hand-eye coordination, fine motor precision, and integration (Luo et al., 2007; Magill, 1996). Evidence for associations between fine motor and cognitive skills comes mainly from research with typically developing kindergarteners. For example, cross-sectional and longitudinal studies showed that fine motor skills significantly contributed to children's kindergarten achievement (Cameron et al., 2012), as well as reading and mathematical achievement (Grissmer et al., 2010). Additionally, research demonstrated relations between fine motor skills and intelligence in typically developing children aged 4–11 years (Davis et al., 2010; Davis et al., 2011; Roebers et al., 2014). However, considering that fine motor skills develop well into adolescence (Diamond, 2000), it is rather surprising that only few studies focused on older children. The current study begins to fill this gap by focusing on children up to adolescence.

The current study investigated relations between fine motor skills and intelligence in typically developing children and children with ADHD. Fine motor skills and intelligence were assessed with standardized instruments to enable comparability with previous research (e.g., Roebers et al., 2014). Additionally, investigating aged-normalized values enables to examine the relations between fine motor skills and intelligence beyond simple age effects. Analyses were conducted for full-scale IQ as well as for the four subcomponents of intelligence (verbal comprehension, perceptual reasoning, working memory, and processing speed), thus looking at specific associations between aspects of intelligence and fine motor skills. Additionally, to determine whether children with ADHD show stronger relations between fine motor skills and intelligence as compared to typically developing children, a series of moderated regression analyses was conducted.

Methods

Participants

Two-hundred and twenty children aged 7–13 years participated in the present study. Participants with missing data in the key variables were excluded (*n* = 35). Therefore, the final sample consisted of *n* = 185 children, of which 139 were typically developing children and 46 were children diagnosed with ADHD (for sample characteristics, see Table 1). The majority of participants came from Switzerland (94%), other European countries, American and African countries. Typically developing children were recruited from local schools. Children were included in the study when showing sufficient German language skills and when the parental questionnaire confirmed that they did not have any developmental or psychopathological diagnosis. Children with ADHD were recruited from the University Children's Hospital in Basel or local pediatricians after being diagnosed with ADHD according to criteria of the DSM-IV or ICD-10. The majority of children with ADHD (*n* = 33) was treated with stimulant medication such as methylphenidate and discontinued their medication 24 hours before the assessment (cf. Thompson, 2007). Results of the parental questionnaire asking for other developmental disorders in addition to ADHD revealed that some children with ADHD had co-occurring disorders of speech and language (*n* = 3), disorders of scholastic skills (*n* = 2), and other developmental disorders (e.g., delayed emotional development, *n* = 4). Parents of two children with ADHD reported a co-morbid developmental coordination disorder. No other co-occurring diagnoses with motor characteristics (e.g., tic disorders) were reported. Furthermore, no child with or without ADHD had to be excluded due to a potential intellectual impairment (IQ < 70), assessed with the German version of the Wechsler Intelligence Scale for Children fourth edition (WISC-IV; Petermann & Petermann, 2011). The ethics committee in Northwestern and

Central Switzerland (EKNZ) approved the current study (Nr. 386/11). Parents gave written informed consent; children assented verbally.

Previous research investigating similar relations between fine manual control and cognitive abilities showed moderate effect sizes with the smallest correlation being $r = .265$ (cf. Davis et al., 2011). A priori power analyses with G-Power 3.1, based on this correlation, assuming a power of .80, and significance levels of $p < .05$, revealed a minimum sample size of 141 children to detect a relation between two variables in a hierarchical regression with five predictors. Therefore, the present study is assumed to be adequately powered for computing these correlational analyses. The present study is also adequately powered for comparing motor and cognitive performance between the two groups (children with and without ADHD). As previous effect sizes of $\eta^2 = .10$ were found for differences in children's fine motor skills between children with and without ADHD (cf. Bünger et al., 2019), another power analysis based on this effect size revealed a total sample size of 138 children, assuming a power of .80 and significance levels of $p < .05$.

Procedure and measures

Children were tested at the University with a battery of tasks including the Movement Assessment Battery for Children (M-ABC-2; Henderson et al., 2007) and the WISC-IV (Petermann & Petermann, 2011). Age-standardized measures were chosen to ensure comparability between different-aged participants and across measurements. The M-ABC-2 measures general motor ability in children between 3;0 to 16;11 years based on performance in three motor subcomponents: manual dexterity, aiming and catching, and balance. The M-ABC-2 shows a high retest-reliability with coefficients between 0.73 and 0.84 and high inter-rater reliability with coefficients between .92 and 1.00 (cf. the M-ABC-2 manual; Henderson et al., 2007, p. 139). Given that the present study focused exclusively on fine motor skills (cf. van der Fels et al., 2015), only children's performance on the manual dexterity subcomponent was included which reflect typical measures of children's fine motor skills (e.g., Roebers et al., 2014). The manual dexterity tasks differ slightly for the two age bands of 7–10 years and 11–16 years and consist of three subtests: a one-handed posting task, a bimanual assembly task, and a trail-drawing task. The younger age group had to place pegs into a board, thread a lace, and draw a line through a trail; the older age group had to turn the pegs on the board, construct a triangle with nuts and bolts, and draw a line through a narrower trail. For the first two subtests, times of completion were measured; for the third subtest, errors were assessed. Scores of these subtests were added and standardized to compile an age-standardized score for fine motor skills ($M = 10$, $SD = 3$, range = 1–19).

Intelligence was measured with the standardized WISC-IV (Petermann & Petermann, 2011). This test is widely used and the internal consistency reliability coefficients range between 0.87 and 0.97 (cf. HAWIK-IV manual; Petermann & Petermann, 2011, p. 115). The full-scale IQ is measured based on four indices: (a) verbal comprehension (understanding and conceptualizing of verbal information); (b) perceptual reasoning (non-verbal, fluid reasoning and the understanding of visual information and solving abstract visual problems); (c) working memory (the ability to hold, organize, and manipulate verbal information); and (d) processing speed (the mental speed with which information is processed and nonverbal problems are solved; Groth-Marnat, 2009). For each of the ten core subtests of the WISC-IV, an age-standardized score is computed (*M* = 10, *SD* = 3, range = 1-19) and the respective subtest scores are added to compute the four index scores. Notably, responding to some subtests of the indices perceptual reasoning and processing speed index requires hand-eye coordination skills (e.g., Loh et al., 2011). Conversely, performances on the indices working memory and verbal comprehension can be evaluated independently from motor skills as their subtests do not include motor participation.

Statistical analysis

Analyses were performed using IBM SPSS 25. A multivariate analysis of variance (MANOVA) examined differences in the key variables (fine motor skills, intelligence, sex, maternal education, and age) between children with and without ADHD. To analyze the relation between fine motor skills and intelligence, five hierarchical regressions were computed, one for each dependent variable of intelligence (full-scale IQ, verbal comprehension, perceptual reasoning, working memory, processing speed). The independent variable fine motor skills was mean-centered to address the problem of multicollinearity when introducing an interaction term (Aiken & West, 1991). The control variables sex and maternal education were entered into the first step of the hierarchical regression. Since age-standardized values were examined for fine motor skills and intelligence, age was not again controlled for in the analyses. In the second step, the predictor variables fine motor skills and group (typically developing vs. ADHD) were added. Finally, in the third step, the interaction term of Fine motor skills × Group was included. A significant interaction term was followed up by separate regression analyses for each group. Due to the different sample sizes of typically developing children ($n = 139$) and children with ADHD ($n = 46$), two follow-up sensitivity analyses with same-sized samples were conducted: (a) matched for maternal education, sex, and age and (b) matched for full-scale IQ, sex, and age.

Results

Descriptive statistics of demographic variables, fine motor skills and intelligence of children with and without ADHD are provided in Table 1. The MANOVA showed a significant main effect of group, Wilks multivariate test, $F(1,183) = 12.76$, $p < .001$, $\eta^2 = 0.42$. The two groups differed significantly on every variable of interest. Children with ADHD were predominantly male, their mothers reported lower educational levels, and they showed lower fine motor skills and intelligence scores.

Hierarchical regression analyses for the combined sample are presented in Table 2. Analyses demonstrated significant associations between fine motor skills and full-scale IQ after accounting for effects of sex and maternal education (*ß* = .306; $p < .001$). Furthermore, fine motor skills were specifically related to perceptual reasoning (*ß* = .327; $p < .001$), processing speed (*ß* = .303; $p < .001$), and working memory (*ß* = .185; $p < .01$), whereas fine motor skills and verbal comprehension were not significantly related (*ß* = .121; $p = .117$). Furthermore, results showed significant associations between group (typically developing vs. ADHD) and full-scale IQ (*ß* = .276; $p < .001$), verbal comprehension (*ß* = .170; $p < .05$), perceptual reasoning (*ß* = .196; $p < .01$), and working memory (*ß* = .387; $p < .001$), and a tendency for processing speed (*ß* = .146;

p = .052).[1] Overall, the hierarchical regression analyses for the combined sample demonstrated significant associations between fine motor skills and intelligence above and beyond effects of maternal education.[2]

Moderated hierarchical regressions compared the strength of these associations between the groups. These analyses revealed significant interactions between fine motor skills and full-scale IQ ($ß$ = -.206, p < .01), perceptual reasoning ($ß$ = -.205, p < .05), and verbal comprehension ($ß$ = -.240, p < .01). No significant moderation resulted for processing speed ($ß$ = -.091, p = .274) nor working memory ($ß$ = -.091, p = .250).

Post-hoc hierarchical regression analyses were calculated separately by group for those dependent variables with a significant moderation effect (Table 3). Fine motor skills were more strongly related to full-scale IQ in children with ADHD ($ß$ = .493, p < .001) as compared to typically developing children ($ß$ = .248, p < .01; Figure 1a). The same holds for the relation between fine motor skills and perceptual reasoning (typically developing children: $ß$ = .254, p < .01; children with ADHD: $ß$ = .523, p < .001; Figure 1b). Furthermore, fine motor skills were significantly related to verbal comprehension ($ß$ = .392, p < .01) in children with ADHD, whereas this relation was non-significant for typically developing children ($ß$ = .025, p = .773; Figure 1c).

Discussion

The present study examined the relations between fine motor skills and various aspects of intelligence in typically developing children and explored whether these associations were stronger for children with ADHD. Results indicated significant relations between children's fine motor skills and full-scale IQ, perceptual reasoning, working memory, and processing speed in the combined sample of children with and without ADHD, after accounting for sex, age, and maternal education. This speaks for a general association between cognitive and motor skills, with higher levels of fine motor skills being related to higher intelligence scores. Given that the present study found links between fine motor skills and intelligence above age effects (e.g., Pagani et al., 2010; Suggate & Stoeger, 2014), a maturational hypothesis seems unlikely. Such a hypothesis implies that more advanced and older children demonstrate higher performance on all types of tasks (cf. Cameron et al., 2012). The current findings do also not provide evidence for the socioeconomic hypothesis which states that relations between fine motor skills and intelligence may reflect differences in the socioeconomic background (cf. Cameron et al., 2012). Specifically, it is assumed that achievement gaps are found in children with disadvantages in family, parental, and societal emphasis due to fewer opportunities to enhance their attentional skills and improve fine motor skills as compared to more advantaged children (Grissmer et al., 2010). Given that the present findings hold after accounting for maternal education as well as when matching for maternal education (see footnote 2), the results do not seem to support claims of the socioeconomic hypothesis.

Whereas fluid aspects of intelligence such as perceptual reasoning, processing speed and working memory were related to fine motor skills in the combined sample, there was no significant relation between children's fine motor skills and verbal comprehension, reflecting crystallized aspects of intelligence. Therefore, it seems that aspects of fluid intelligence may be more closely related to fine motor skills as compared to aspects of crystallized intelligence, which is in line with previous conclusions (van der Fels et al., 2015).

Interestingly, the present moderation analyses extend this conclusion with fine motor skills and verbal comprehension not being significantly related in typically developing children. This result contrasts some previous studies demonstrating that fine motor skills were related to language and vocabulary in typically developing children between the ages of 3–6 years (Dellatolas et al., 2003; Pagani et al., 2010). However, the result is in line with the study from Wassenberg et al. (2005), which indicated no significant relation between vocabulary and visuo-motor integration which is a construct related to fine motor skills.

Furthermore, the current findings implied that fine motor skills were related to language in children with ADHD which supports previous findings (e.g., Cameron et al., 2012). Even though explanations for this result remain speculative with the data at hand, significant findings may be explained according to the embodied cognition theories and with the nimble hands nimble minds hypothesis, which supports the idea of learning through fine motor controlled activities (Suggate & Stoeger, 2014). Additionally, some may refer to the higher variance in the intelligence scores of children with ADHD as a greater possibility to detect shared variance between motor and cognitive skills. However, when matching the two groups so that they do not significantly differ in full-scale IQ, the relation between fine motor skills and intelligence as well as the interactions terms remained significant (see footnote 2). This analysis supports the interpretation that the significant interactions in the full sample are not the result of cognitive differences between these two groups. More research is needed to explore the mechanisms underlying these different relations. Nevertheless, the present study provides first evidence that motor-cognition links may be more prominent in school-aged children with ADHD as compared to same-aged typically developing children.

In addition to verbal comprehension, there were also significant interactions for full-scale IQ and perceptual reasoning which indicated stronger relations for children with ADHD as compared to typically developing children. The pattern of findings implies that children with ADHD did not show stronger relations between all indices of intelligence and fine motor skills, suggesting specific patterns and differences between the groups. However, overall, the findings demonstrated stronger relations between fine motor skills and full-scale IQ in children with ADHD as compared to typically developing children which is in line with previous research (Dyck et al., 2006; Houwen et al., 2016). Whereas this may reflect an unusual dependence among neurocognitive processes in children with ADHD, it may also be the case that fine motor performance requires more cognitive control in this clinical sample and is already more automatized in same-aged, typically developing children (cf. Ackerman, 1988). The current study cannot disentangle between these explanations; thus, future research with preferably neuroimaging techniques may be helpful to assess the underlying mechanisms of these differential patterns between children with and without ADHD.

Although there are motor components included in several subtests of the WISC-IV (e.g., Loh et al., 2011), it is unlikely that this is the main influence of this relations. Whereas answering subtests of perceptual reasoning and processing speed requires hand-eye coordination skills, working memory and verbal comprehension do not. Given the significant associations between fine motor skills and working memory as well as verbal comprehension, it seems that fine motor skills and intelligence are connected independently from motor requirements in these cognitive tasks.

The present findings may hold important implications for treating children with ADHD. When diagnosing ADHD according to the criteria of the DSM-IV or ICD-10, the symptoms inattention, hyperactivity, and impulsivity are considered whereas motor abilities are typically not included. Consequently, motor skills are often not acknowledged in ADHD intervention programs (e.g., Fliers et al., 2010). The results of the current study, demonstrating significant relations between fine motor skills and intelligence, advocate the consideration of motor abilities and support multidimensional approaches as for example motor-cognitive interventions. Such interventions focus additionally on children’s motor problems and have been found to increase children’s quality of life (Fliers et al., 2010).

Even though the mechanisms of the relation between fine motor skills and intelligence remain unclear and need further research, the current study extended previous studies and contributed to the understanding of this relation in samples of typical and clinical development. Notably, the usage of a large, homogenous sample of children diagnosed with ADHD enabled to extend previous studies using very heterogenous samples (Houwen et al., 2016; Martin et al., 2010) and allows specific conclusions for the developmental disability of ADHD. Additionally, the large sample of same-aged typically developing children allowed for replicating previous findings and extending this research to an older age range while at the same time serving as a control group to compare results between typical and clinical development. Another strength of the present study refers to the statistical approach which allowed to account for a number of influential variables (age, sex, and maternal education; Aiken & West, 1991). Finally, the present study used standardized measurement instruments of fine motor skills and intelligence which have been proven to be reliable and valid (Henderson et al., 2007; Petermann & Petermann, 2011).

The different sample sizes of children with and without ADHD can be seen as a limitation. However, as the pattern of results was widely similar when using same-sized samples matched for sex, age, and maternal education (see footnote 2), this issue is not considered as problematic. Another possible limitation concerns the significant mean differences and variances of intelligence and fine motor skills between the groups, which largely reflect the symptoms of ADHD and underline the representativity of our sample of children with ADHD. However, since both groups show sufficient variance in our measures, we do not assume that these differences are constraining our correlational approach. Furthermore, our sample of children with ADHD did not allow for separating among different subtypes of ADHD. Such a differentiation may be useful given that previous research showed that children with ADHD in the subtypes “predominantly inattentive” and the combined type had significantly poorer fine motor skills than typically developing children, while children in the subtype “impulsive/hyperactive” did not significantly differ from controls (Egeland et al., 2012; Pitcher et al., 2003). Future research should investigate whether differentiating between these subtypes influences the relation between fine motor skills and intelligence. Additionally, the children with ADHD with medical treatment discontinued their medication prior to the study which could have affected their performance. While this approach enabled to measure children’s baseline performance without the influence of medication, future studies should corroborate these findings examining children with ADHD who continued their medication (Kaiser et al., 2015). Moreover, the correlative, cross-sectional design of the present study does not allow for testing the direction of the association between fine motor skills and intelligence. Future studies may examine relations between fine motor skills and intelligence using a longitudinal approach with cross-lagged model design. Finally, previous research has typically used a M-ABC-2 score below the 16th percentile to identify children with DCD (e.g., Alloway & Temple, 2007). According to this criterion, 15 children with ADHD (32.6%) of the current sample may be considered for a DCD diagnosis. Consequently, the significant relation between fine motor skills and intelligence may not be limited to the clinical sample of children with ADHD and further research is needed to examine this relationship in other clinical samples.

Conclusion

The current study investigated relations between fine motor skills and several aspects of intelligence in typically developing children and children with ADHD aged 7-13 years. Results suggest a close relation between fine motor skills and intelligence in children with and without ADHD. These results add to previous findings suggesting such relations in typically developing children at the age of kindergarten (e.g., Cameron et al., 2012) and proposes that fine motor skills continue to be an indicator for cognitive skills across childhood until early adolescence. Furthermore, the current study highlights stronger associations between fine motor abilities and intelligence in children with ADHD – a developmental disorder characterized by attention deficits and being less perceived for motor difficulties – as compared to typically developing children. The present results lend support for implementing motor-cognitive interventions in treating children with ADHD. Overall, the present findings are in line with an embodied cognition perspective, demonstrating close connections between motor and cognitive skills in typical and ADHD samples.

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Footnotes

1 Based on results from previous research (van der Fels et al., 2015), the present study has focused exclusively on the subcomponent manual dexterity and its relation to children's intelligence. However, to enable comparability, two post-hoc hierarchical regressions with the subcomponents aiming and catching, and balance were calculated. Analyses revealed non-significant relations between children's ball skills and intelligence and its four indices, as well as no significant interactions (all *ß*s < .145; all *p*s > .05). Similarly, associations between balance skills and intelligence were non-significant (except for perceptual reasoning), as well as the interaction terms (*ß*s < .125; *p*s > .05). These results are in line with previous research stating that fine motor skills seem to relate more strongly to cognition as compared to gross motor skills.

2 Two sensitivity analyses revealed that the pattern of results remained widely similar when the total sample of children with ADHD (*n* = 46; Mage = 10.2; 9 girls) was matched with a subsample of typically developing children (it should be noted that these analyses were not adequately powered given the power analyses). In the first analysis, children with ADHD and typically developing children (*n* = 46; Mage = 10.7; 9 girls) were matched for maternal education, sex, and age. The interaction of Fine motor skills × Group (TD vs. ADHD) remained significant for verbal comprehension (*ß* = -.206, *p* = .049). Although, interactions for full scale IQ (*ß* = -.170, *p* = .064) and perceptual reasoning (*ß* = -.166, *p* = .077) shifted to tendencies, the beta values remained widely comparable to results with the full sample. The second analysis tested whether the interactions could be explained by differences in children's cognitive outcome. Subsequently, typically developing children (*n* = 46; Mage = 9.7; 9 girls) were matched for full-scale IQ, sex, and age with children diagnosed with ADHD. Results revealed significant associations between fine motor skills and all five intelligence variables (*ß*s > .226, *p*s < .026). Group (TD vs. ADHD) was no longer significantly related with intelligence (except for working memory) indicating that the matching procedure was successful. Importantly, the interaction of Fine motor skills × Group (TD vs. ADHD) reached significance (*ß*s < -.227 *p*s < .05) for all intelligence variables except for working memory. These follow-up analyses show the robustness of the associations between fine motor skills and intelligence.

Table 1

Descriptive statistics and group differences in the key variables between typically developing children and children diagnosed with ADHD

	Typically developing children (*n = 139)*		Children with ADHD (*n = 46)*		
Variable	*N (%) / M (SD)*	*Range*	*N (%) / M (SD)*	*Range*	*P*
Sex					.002**
Male	76 (54.7%)		37 (80.4%)		
Female	63 (45.3%)		9 (19.6%)		
Maternal education	4.81 (1.33)	2 – 6	3.80 (1.31)	2 – 6	.000***
No school degree	0 (0%)		0 (0%)		
Mandatory school	2 (1.4%)		4 (8.7%)		
Apprenticeship	39 (28.1%)		24 (52.2%)		
High school	10 (7.2%)		3 (6.5%)		
Higher education	21(15.1%)		7 (15.2%)		
University / college	67 (48.2%)		8 (17.4%)		
Age (in years)	10.06 (1.45)	7 – 13	10.64 (1.59)	7 – 13	.023**
Fine motor skills	10.00 (2.66)	2 – 17	7.72 (2.44)	3 – 14	.000***
Full-scale IQ	106.22 (10.52)	84 – 136	93.33 (13.98)	70 – 129	.000***
Perceptual reasoning	34.94 (5.50)	21 – 49	29.74 (6.89)	17 – 42	.000***
Verbal comprehension	32.32 (6.06)	20 – 51	28.57 (6.63)	18 – 44	.000***
Working memory	21.12 (3.83)	11 – 32	16.20 (4.12)	8 – 23	.000***
Processing speed	20.71 (4.41)	10 – 31	17.30 (5.22)	5 – 31	.000***

Note. Data are presented as absolute (and relative) frequencies or means (*SD*). *P*-values are reported from a MANOVA for continuous variables and a X^2 test for categorical variables. $^{**}p < .01$, $^{***}p < .001$.

Table 2

Hierarchical regression analyses with fine motor skills and group (typically developing children and children with ADHD) predicting intelligence indices (N = 185)

Predictors	Intelligence indices: Full-scale IQ	Perceptual reasoning	Verbal comprehension	Working memory	Processing speed
Step 1					
Sex	-.063	-.055	.056	-.138⁺	-.118
Maternal education	.323***	.280***	.275***	.194**	.220**
R^2 of total model	.117***	.088***	.072**	.068**	.074**
Adjusted R^2 of total model	.108***	.078***	.062**	.058**	.064**
Step 2					
Sex	.070	.070	.119	-.021	-.008
Maternal education	.226**	.203**	.220**	.074	.159*
Fine motor skills	.306***	.327***	.121	.185**	.303***
Group (TD vs. ADHD)	.276***	.196**	.170*	.387***	.146⁺
ΔR^2 step 2	.197***	.165***	.050**	.201***	.126***
R^2 of total model	.314***	.253***	.122**	.269***	.200***
Adjusted R^2 of total model	.299***	.237***	.102**	.253***	.182***
Step 3					
Sex	.060	.061	.108	-.025	-.012
Maternal education	.215**	.193**	.208**	.070	.154*
Fine motor skills	.427***	.448***	.262**	.239**	.356***
Group (TD vs. ADHD)	.195**	.155	.076	.351***	.111
Fine motor skills x group (TD vs. ADHS)	-.206**	-.205*	-.240**	-.091	-.091
ΔR^2 step 3	.027**	.027*	.037**	.005	.005
R^2 of total model	.342**	.280*	.159**	.275***	.205***
Adjusted R^2 of total model	.323**	.260*	.136**	.254***	.183***

Note. TD = typically developing children. ADHD = children with attention-deficit hyperactivity disorder. Coefficients are standardized regression coefficients if not otherwise indicated. Step 1: model with control variables predicting intelligence. Step 2: model with fine motor skills and group (TD vs. ADHD) as predictors of intelligence, controlled for variables entered in step 1. Step 3: model with the interaction term fine motor skills x group (TD vs. ADHD) as predictor of intelligence, controlled for variables entered in step 1 and 2. Sex: -1 = female; +1 = male. Group: -1 = ADHD; +1 = TD. $^{+}p < .06$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Table 3

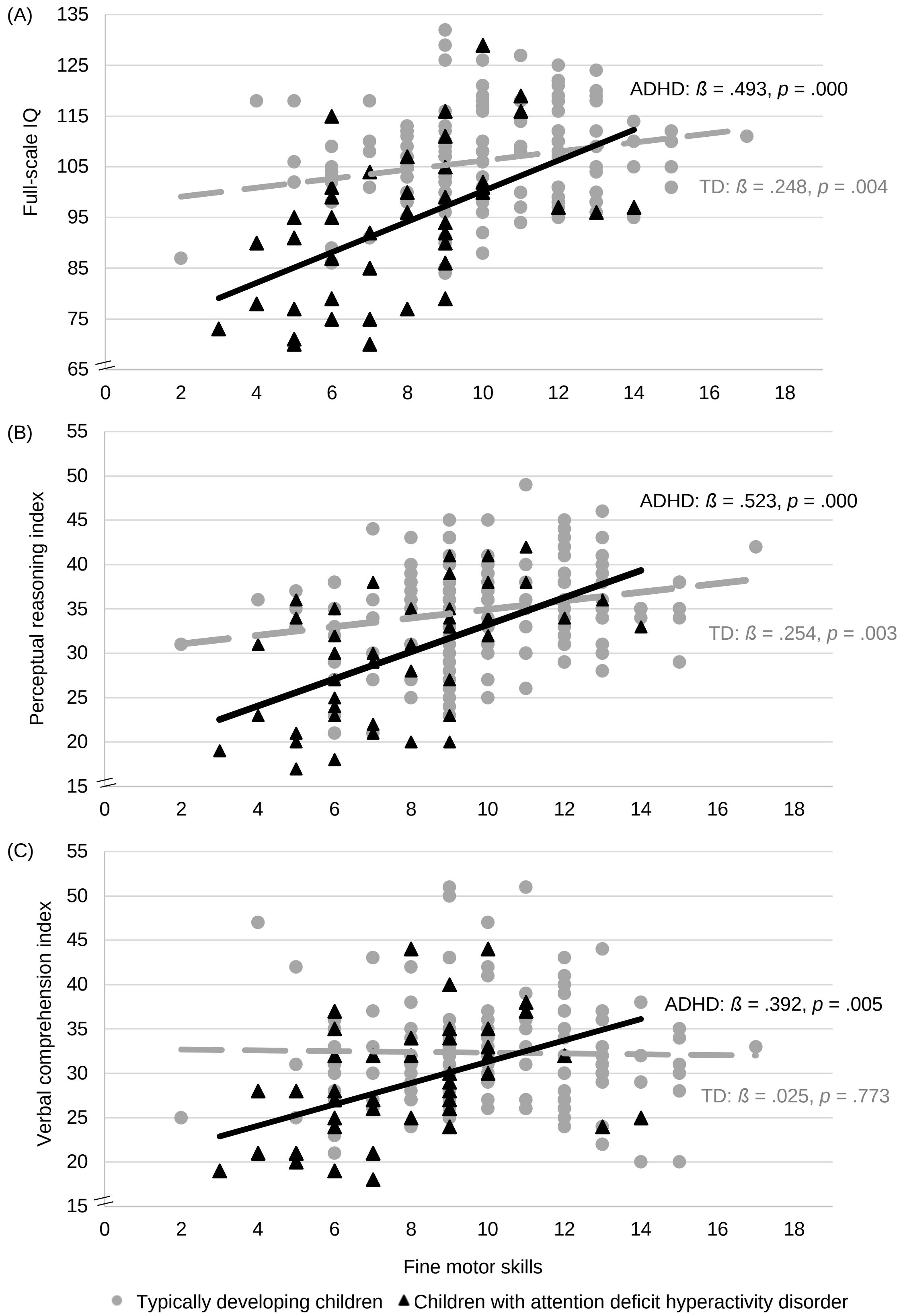
Hierarchical regression analyses with fine motor skills predicting intelligence separated for typically developing children and children with ADHD

	Typically developing children (*n* = 139)			Children with ADHD (*n* = 46)		
Predictor	Full-scale IQ	Perceptual reasoning	Verbal comprehension	Full-scale IQ	Perceptual reasoning	Verbal comprehension
Step 1						
Sex	.026	.005	.167^{+}	-.074	-.035	-.166
Maternal education	.193**	.178**	.171*	.331**	.264^{+}	.310*
R^2 of total model	.036^{+}	.031	.049*	.127^{+}	.075	.149*
Adjusted R^2 of total model	.022^{+}	.017	.035*	.087^{+}	.032	.110*
Step 2						
Sex	.091	.072	.173^{+}	.001	.045	-.106
Maternal education	.202*	.187**	.172*	.293**	.224^{+}	.280*
Fine motor skills	.248**	.254**	.025	.493***	.523***	.392**
ΔR^2 step 2	.057**	.060**	.001	.235***	.264***	.148**
R^2 of total model	.094**	.091**	.049	.362***	.339***	.297**
Adjusted R^2 of total model	.074**	.071**	.028	.316***	.292***	.247**

Note. TD = typically developing children. ADHD = children with attention-deficit hyperactivity disorder. Coefficients are standardized regression coefficients if not otherwise indicated. Step 1: model with the control variables predicting intelligence. Step 2: model with fine motor skills as predictor of intelligence, controlled for variables entered in step 1. Sex: -1 = female; +1 = male. $^{+}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Figure 1

Relations between fine motor skills and intelligence



Note. Relation between fine motor skills and **(a)** full-scale IQ, **(b)** perceptual reasoning and **(c)** verbal comprehension for typically developing children (TD) and children with attention-deficit hyperactivity disorder (ADHD). Standardized regression coefficients (*ß*) and *p* values are presented next to the slopes.

APPENDIX B: STUDY 2

Please note that this is the author's version of a work that was accepted for publication in *Psychological Research.* This paper is not the copy of record and may not exactly replicate the final, authoritative version of the article. The final article is available via its DOI: 10.1007/s00426-022-01749-w.

Aerobic Fitness and Fine Motor Skills are related to Switching and Updating in Typically Developing Children

Stephanie Klupp[*,a], Alexander Grob[a], Wenke Möhring[a,b]

* **Corresponding author:** Stephanie Klupp, University of Basel, Department of Psychology, Missionsstrasse 62, 4055 Basel, Switzerland; Email: stephanie.klupp@unibas.ch

[a] University of Basel, Department of Psychology, Switzerland.

[b] Department of Educational and Health Psychology, University of Education Schwäbisch Gmünd, Schwäbisch Gmünd, Germany.

Author Note

*Correspondence concerning this article should be addressed to Stephanie Klupp, Department of Psychology, University of Basel, Missionsstrasse 62, 4055 Basel, Switzerland. E-mail: stephanie.klupp@unibas.ch

Stephanie Klupp https://orcid.org/0000-0001-7407-5038

Alexander Grob https://orcid.org/0000-0002-0715-4139

Wenke Möhring https://orcid.org/0000-0002-9152-8470

Authorship Contributions

Conceptualization: S. Klupp, A. Grob, W. Möhring. Methodology: S. Klupp, A. Grob, W. Möhring. Investigation: S. Klupp, W. Möhring. Data Curation: S. Klupp, W. Möhring. Validation: W. Möhring. Formal analysis: S. Klupp, W. Möhring. Visualization: S. Klupp. Writing – Original Draft: S. Klupp. Writing – Review & Editing: S. Klupp, A. Grob, W. Möhring.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest and that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Abstract

Background: Movement is essential for everyday life and closely related to cognitive skills. The aim of the current research was to investigate whether different aspects of physical activity, i.e., aerobic fitness and motor skills, contribute above and beyond each other to the variance in children's executive functioning.

Method: Children aged 8-13 years (N = 129, 58 females, M_{age} = 10.7 years, SD_{age} = 1.6 years) participated in the current cross-sectional study. Aerobic fitness was assessed by the Progressive Aerobic Cardiovascular Endurance Run (PACER). Motor skills were assessed using the standardized Movement Assessment Battery for Children 2nd edition (M-ABC-2), including fine motor skills, balance skills, and object control. Components of executive functions (inhibition, switching, updating) were assessed using the following tasks: an animal Stroop task, a local-global task, and a 2n-back task. Hierarchical regressions were conducted to analyze the relative importance of aerobic fitness and motor skills for children's executive functions.

Results: Results indicated that aerobic fitness and fine motor skills were significantly related to switching and updating, whereas relations to inhibition were non-significant. Furthermore, it was found that fine motor skills explained additional variance above aerobic fitness in switching and updating whereas aerobic fitness did not add additional variance above fine motor skills in switching and updating. Balance and object control skills were not related to the three core executive functions.

Significance: Results support the notion that aerobic fitness and fine motor skills are differently related to executive functions and highlight the importance of considering multiple components of constructs in future research.

Keywords: children, motor skills, fitness, fine motor skills, executive function

Introduction

Movement is an essential part of everyday life and is closely related to cognitive, social and emotional development (Libertus & Hauf, 2017; Mancini et al., 2016; Pesce et al., 2016). Besides several beneficial effects on brain functions, movement is also related to physical health (Hillman et al., 2008), as an active lifestyle is a protective factor against obesity, diabetes, and cardiovascular diseases and its importance increases across children's development (Khan & Hillman, 2014). However, according to the World Health Organization (2020), 81% of adolescents do not meet the daily recommendations of at least 60 minutes moderate-to-vigorous-intensive physical activity across the week. This has also been shown in the SOPHYA study: 36% of Swiss children aged 6-16 years did not meet the recommended amount of daily movement (Bringolf-Isler et al., 2016). In addition, approximately 19% of children and adolescents in Switzerland are overweight (Bundesamt für Gesundheit, 2020). These prevalence rates underline the importance of understanding the effects of movement on children's cognitive skills.

Previous research has demonstrated that physical activity is specifically linked to executive functions (Khan & Hillman, 2014). Executive functions are top-down processes of cognitive control which facilitate goal-directed behavior and are associated to other cognitive functions, social behavior and motor development (for a review, see Diamond & Ling, 2019). This construct consists of three related but separable core components: inhibitory control, cognitive flexibility and working memory updating (Diamond, 2013; Diamond & Ling, 2019; Miyake et al., 2000). Firstly, inhibitory control, also called inhibition, includes aspects such as self-control and selective attention, and is the ability to suppress an automated, predominant response (Diamond, 2013; Miyake et al., 2000). Secondly, cognitive flexibility is also known as set shifting or task switching and is the ability to change perspectives or adjust to changing demands (Diamond & Ling, 2019) or switch between a set of rules based on a cue (Miyake et al., 2000). Thirdly, working memory updating (short: updating) is the process which allows to manipulate information held within working memory by evaluating and replacing old, no longer relevant information with newer, more relevant information (Baddeley et al., 1997; Miyake et al., 2000). The present study aims to clarify the relative importance of different aspects of children's physical activity (i.e., aerobic fitness, motor skills) on children's executive functioning. Importantly, the current study will take a holistic approach and will include all components of this multi-facetted construct of executive functions. Such an approach is crucial for creating informed interventions and will increase the understanding of how exactly motor and cognitive development are related.

The idea that motor and cognitive skills are closely related has a long history in psychological theories. For example, Piaget suggested that sensorimotor experiences in the first years of life, such as the integration of sensory inputs with motor actions, contribute to the understanding of the surrounding world (Piaget & Cook, 1952) which thereupon enhances cognitive development. The link between motor skills and children's cognitive development can further be explained by the embodied cognition theory. According to this theory, motor skills facilitate the interactions with objects and other individuals which in turn promote cognitive development (Barsalou, 1999; Leonard, 2016; Loeffler et al., 2016; Pesce et al., 2016). The close link between motor and cognitive skills is also supported by similar developmental trajectories of motor skills and executive functions.

Just like executive functions, selected motor skills such as fine motor skills appear to follow a lengthy developmental path and develop well into adolescence (Diamond, 2000). In addition, motor control and executive functions are accompanied by co-activation of certain brain regions, such as the prefrontal cortex, the cerebellum and the basal ganglia (Diamond, 2000).

Researchers have proposed several mechanisms underlying the relation between motor development and cognition. One set of mechanisms refers to long-term physiological changes in the brain after aerobic exercise. Intervention studies demonstrated beneficial effects on executive functions after chronic interventions (Liu et al., 2020; Verburgh et al., 2014). These chronic physiological changes refer to increased levels of brain-derived neurotrophic factors which facilitate synaptic plasticity. Such neurotrophic factors contribute to the growth of neurons and support learning and memory functions (Phillips, 2017). Further, chronic physical exercise influences the neuronal systems of attention, learning and memory as it increases neuroelectric activity, brain volume and blood flow, allowing for more efficient and flexible cognitive functioning (Ratey & Loehr, 2011). In addition, cognitive engagement during physical activity may depend on the complexity of the movement, with more complex motor tasks involving higher cognitive engagement which may have stronger effects on executive functions (Best, 2010; Ludyga et al., 2020; Pesce, 2012).

Aerobic Fitness and Executive Functions

It is important to define and consider the different aspects of human movement as this will help integrating previous research findings. Although physical activity and physical fitness are aspects of human movement and closely related to one other, they are conceptually distinct. While physical activity is a behavior that is defined as “any bodily movement produced by skeletal muscles that results in energy expenditure” (Caspersen et al., 1985, p. 126, p.129); physical fitness is a physiological attribute that is defined as the ability to perform human movements such as physical activity (Caspersen et al., 1985; Pettee Gabriel et al., 2012). Physical fitness refers to an individual’s capacity of cardiovascular and respiratory systems to utilize oxygen, as well as the ability to carry out lengthy vigorous exercise (Esteban-Cornejo et al., 2019; Ortega et al., 2008), and thus creates a crucial interplay with physical activity. Further, physical fitness consists of various skill- and health-related components such as coordination, balance, muscular endurance and strength, flexibility as well as cardiorespiratory endurance which is often also called aerobic fitness (Caspersen et al., 1985; Pettee Gabriel et al., 2012).

Research investigating associations between children’s aerobic fitness and executive functioning yielded close associations. Studies have rarely assessed all three components of executive functions in a single study design (for an overview, see van Waelvelde et al., 2019), however, a recent review summarized several single studies and reported a positive, cross-sectional association, with greater aerobic fitness being related to children’s increased executive functioning (van Waelvelde et al., 2019). However, when focusing on particular relations between aerobic fitness and the three core executive functions, results are less consistent. For example, Nieto-Lopez et al. (2020) found significant relations between aerobic fitness and inhibition, but no significant relation to switching (updating was not investigated). Pindus et al. (2016) demonstrated neither significant associations between aerobic fitness and inhibition nor working memory (switching was not investigated). Possible explanations for the inconsistency may refer to using different measures and the assumed impurity of executive functions tasks. For example, Zhan et al. (2020) have found significant associations between aerobic fitness and response times for all three executive functions, however, when using accuracy as dependent variable only the relation to updating was significant.

Motor Skills and Executive Functions

Another aspect of movement includes motor skills, which are defined as goal-directed movement patterns including running, throwing and writing (Burton & Rodgerson, 2001). Motor skills vary widely among individual children and will predict children's physical activity. From a theoretical point of view, motor skills are a complex construct that can be separated into several subcomponents. Naturally, such a view influences standardized assessment. In several standardized assessments, general motor ability is separated into fine motor skills, balance skills, object control skills and locomotion (Gandotra et al., 2021; Henderson et al., 2007). Fine motor skills relate to the control of small muscle movements using hand-eye coordination (Clark & Whitall, 1989; Magill, 1996). Balance skills refer to the ability to maintain equilibrium while standing or moving (Caspersen et al., 1985). Object control skills involves the control of objects such as balls with either the hand or the foot, including for example catching, throwing or kicking (Clark & Whitall, 1989; van Capelle et al., 2017). Locomotion is defined as the movement of the body from one point to another by means of walking, running or jumping (Clark & Whitall, 1989; van Capelle et al., 2017).

The relation between motor skills and children's executive functions was historically often examined in children with developmental coordination disorder or attention deficit hyperactivity disorder due to a high comorbidity between these pathologies. A first systematic review on the relation between motor and cognitive skills that focused on typically developing children was published by van der Fels et al. (2015). Regarding executive functions, the authors showed moderate-to-weak correlations with fine motor skills, moderate-to-no correlations with object control, and weak-to-no correlations with locomotion, while correlations with balance skills were not presented (van der Fels et al., 2015). The conclusions drawn from this review revealed an insufficient number of studies examining this relation between subcomponents of motor skills and children's cognition but tentatively suggested that more complex motor skills seemed related to higher-order cognitive functions. Following this review, the number of publications increased demonstrating significant relations between executive functions with fine motor skills (e.g., Oberer et al., 2017; Stockel & Hughes, 2016), as well as gross motor skills (e.g., Stuhr et al., 2020; van der Fels et al., 2019). In addition, a recent meta-analysis examined the relation between motor skills and executive functions more closely. This meta-analysis by Gandotra et al. (2021) confirmed significant and robust effects between in particular fine motor skills and all three executive function components. However, there was no significant relation between object control and executive functions, with low Rosenthal's fail-safe-N values indicating no robust results. In addition, locomotion skills revealed a significant and robust effect with working memory, while inhibition and switching were not significantly related to locomotion and Rosenthal's fail-safe-N revealed the findings must be interpreted with precaution. In extension to the review from van der Fels et al. (2015), significant associations between balance skills and all three executive functions were found, with only inhibition reaching a robust effect (according to Rosenthal's fail-safe-N).

The Present Study

Building on the previous studies above, the aim of the current research was to examine how different aspects of physical activity, namely aerobic fitness and motor skills, relate to all three core subcomponents of executive functions. In extension to previous studies, these associations were not only considered separately but also simultaneously. Thus, the present study investigated whether aerobic fitness and motor skills would contribute above and beyond each other to the variance of children's executive functioning. This approach is innovative because it will increase the in-depth understanding of the specific relationships between the variables of interest. Previous literature is qualified by (a) investigating all three subcomponents of executive functions allowing a comprehensive overview; (b) exploring the relative importance of motor skills and aerobic fitness on children's executive functions; and (c) controlling for important confounding variables.

With respect to the first point, published articles examining these relations have seldomly included all three core executive functions but rather focused on one or two. For example, 19 of the 26 studies in the review about physical fitness from van Waelvelde et al. (2019) examined one executive function, five studies examined two components and only two studies (Aadland et al., 2017; Schmidt et al., 2015) examined all three executive functions. Furthermore, it was reported that in particular switching was underrepresented and examined in only seven of the 26 studies. Furthermore, looking at executive functions individually is important for at least two reasons. On the one hand, theoretical models advocate the separability of the components (Diamond, 2013) and findings may yield crucial information with respect to this point. On the other hand, studies show that the three components reveal differences in their developmental trajectories, such that inhibition for example seems to develop first out of the three (Huizinga et al., 2006). Given that 8- to 13-year-olds were included in the present study, findings may add to our understanding about these different developmental paths.

With respect to the second point, the literature highlights that aerobic fitness and motor skills are both related to executive functions; however, there is also evidence suggesting that they may be differently related. In the review from Haapala (2012), aerobic fitness seemed associated with tasks that require memory encoding, while motor skills seemed closely related to inhibitory control. In addition, many studies examining the relation between motor skills and executive functions did not control for aerobic fitness (e.g., Houwen et al., 2017) and vice versa (e.g., Scudder et al., 2014), although the relation between motor skills and aerobic fitness is well-known (e.g., Lubans et al., 2010).

Regarding the last point, many studies included in the meta-analysis by Gandotra et al. (2021) did not report information regarding participants' socioeconomic status. Furthermore, other confounding variables such as sex, body mass index or intelligence were not consistently accounted for within the studies. Therefore, the current study examined relations among motor skills, aerobic fitness, and executive functions whilst accounting for age, sex, body mass index, intelligence and parental education (as an indicator for socioeconomic status). Building on the body of research outlined above, it is hypothesized that motor skills and aerobic fitness explain significant variance in children's executive functioning (inhibition, switching, and updating). As previous research does not allow explicit expectations, it is further explored whether aerobic fitness and motor skills would contribute above and beyond each other to the variance of children's executive functioning (in each separate component).

Materials and Methods

Participants

One hundred and thirty-nine children aged 8-13 years participated in the current cross-sectional study examining motor and cognitive skills (for demographic details, see Table 1). Children were recruited from 57 local schools and fulfilled the inclusion criteria of no developmental or psychopathological diagnosis (e.g., attention deficit hyperactivity disorder) according to a parental questionnaire. The local ethics committee approved the present study. Prior to participation, parents signed a written informed consent, while children assented verbally.

Measures and Procedure

To examine the relation between different aspects of physical activity (motor skills, aerobic fitness) and executive functions, children were individually assessed in two two-hour sessions in two consecutive weeks at the laboratory of the University of Basel. In the first session, participants' anthropometric data (e.g., height, weight) was measured and they solved a series of executive function tasks. At the end of this session, children performed a Progressive Aerobic Cardiovascular Endurance Run (PACER; Léger et al., 1988). Within this first session, participants also performed several dual tasks that are described elsewhere and are beyond the scope of the present study (Möhring et al., 2020). The second assessment session included standardized batteries such as the Movement Assessment Battery for Children 2nd edition (M-ABC-2; Henderson et al., 2007). To account for children's intellectual functioning, they also solved four subtests (vocabulary, matrix reasoning, letter-number sequencing, and coding) of the Wechsler Intelligence Scale for Children 4th edition (WISC-IV; Petermann & Petermann, 2011). Performance on these subtests was computed to an intelligence score in accordance with recommendations from Waldmann (2008). In addition, parents filled in a questionnaire including demographic and general information about their child and their education, which were included as control variables in the statistical analysis.

Aerobic Fitness Assessment

The PACER measures physical fitness and more specifically aerobic capacity (for a review, see van Waelvelde et al., 2019). It is an established reliable and valid measure in children and adolescents (Carrel et al., 2012; Olds et al., 2006). Due to limited room length, the shortened version was used, consisting of two borders 15 meters apart (Meredith & Welk, 2010). Participants were asked to run back and forth between these borders as long as possible. An audio recording with sound signals indicated when participants should have reached the opposite border. These signals set the pace by starting slowly and increasing progressively. The shuttle run was finished when the participant failed to reach a border before the signal for a second time. The score composed of the number of completed runs, with a greater score indicating a higher level of aerobic capacity.

Motor Skill Assessment

Motor skills in children aged 3;0 to 16;11 years can be measured with the M-ABC-2 on the three motor subcomponents (a) manual dexterity indicating fine motor skills; (b) balance skills and (c) aiming and catching also labelled as object control skills. This standardized motor assessment reports high retest-reliability coefficients between 0.73 and 0.84 and high inter-rater reliability coefficients between .92 and 1.00 (cf. the M-ABC-2 manual; Henderson et al., 2007, p. 139). The tasks differ slightly for the two age bands of 7-10 years and 11-16 years. Most tasks included practice attempts before testing. Furthermore, most tasks included two attempts for each task of which the better score was taken into account.

The subcomponent fine motor skills consists of three subtests: a one-handed posting task, a bimanual assembly task, and a trail-drawing task. The younger age group placed pegs into a board, threaded a lace, and drew a line through a trail. The older age group turned pegs on a board, constructed a triangle with nuts and bolts, and drew a line through a narrower trail. While time of completion was assessed in the first two subtests, the third subtest measured the number of errors.

The subcomponent balance consists of three subtests: a board balance task, a walking balance task and a jumping task. The younger age group completed a one-legged stance on a balance board, a heel-to-toe forwards walk, and one-legged hopping task. The older age group completed a heel-to-toe stance on a balance board, a toe-to-heel-backwards walk and one-legged zigzag hopping task. The first task was measured in seconds; the second task was measured by the number of successful steps; the third task by the number of successful jumps.

The subcomponent object control consists of two subtests: catching a ball and aiming at a target. The younger age group was asked to throw a tennis ball against a wall and catch it with both hands as well as to throw a bean bag onto a target mat on the floor. The older age group was asked to catch the ball with one hand only and throw the ball one-handed at a target on the wall. Both tasks were completed once with the left and once with the right hand and the number of successful completions were measured.

Raw scores of the subtests were converted into age-standardized scores, resulting in scores for the three subcomponents (fine motor skills, balance, object control) as well as the total motor score (M = 10, SD = 3, range = 1-19). The total motor score is often used in clinical samples but also in typically developing samples to indicate motor problems such as developmental coordination disorder (Houwen et al., 2017; Kaiser et al., 2015). The equivalent percentile of the total motor score suggests a significant motor difficulty below the 5th percentile and a risk of motor difficulty below the 16th percentile (Sartori, 2019).

Executive Function Assessment

Participants completed three tasks each tapping one of the executive functions (inhibition, switching, and working memory updating). The order of the executive function tasks was counterbalanced across participants. Children were sitting on a chair with the stimuli being projected on a wall in front of them. The test phase for each executive function task included eight pre-randomized trials with a total of 96 items. Children were asked to say their answers out loud. The number of errors out of the maximum of 96 possible correct answers served as dependent variable.

Adjustment

Generally, tasks measuring executive function components differ widely with respect to the presented material (e.g., visual, auditory stimuli), the required response (e.g., verbal, motor response), and their difficulty. In the current study, comparability across the executive function tasks was increased by using visual material only, recording verbal responses, and equating difficulty across participants and executive function tasks. Such an adjustment controls for differences among individual children's baseline performance (Saxena et al., 2017) and ensures that effects are not found because of inherent differences in difficulty among the executive function tasks. Firstly, children were familiarized with each executive function task though practice trials. Then, participants completed a set of easy items (level 1) with long presentation times and long inter-stimuli-intervals, to identify their baseline performance level. In a subsequent set of level-2 items, presentation times and inter-stimuli-intervals were shortened in order to decrease participants' performance level to approximately 90% as compared to their baseline level-1. If children did not meet this criterion, participants completed another set of level-3 items with even shorter presentation times and inter-stimuli-intervals. Therefore, the dependent variable of the current study relates to the performance level, at which the participants met the criterion of approximately 90% performance. For example, if a participant produced five errors at baseline level-1, the participant would be expected to produce approximately ten errors in the more difficult level-2 and if not achieved, level-3 would be applied (for a more detailed description of the procedure, stimuli sizes and presentation times, see Möhring et al., 2020).

Inhibition

Participants completed a classic Stroop task as a measure of their ability to inhibit a predominant response (Stroop, 1935). An animal Stroop task was used in which the stimuli comprised of a picture of one of four animals used from the Intelligence and Development Scales-2 (Grob & Hagmann-von Arx, 2018). Children were asked to name the correct color of this animal (blue - dolphin, yellow - chick, green - frog, red - ladybug) as quickly and accurately as possible. In accordance to Miyake et al. (2000), the total of 96 items contained 48 neutral items with animals printed in black-white, 12 congruent items displaying animals in the correct color (e.g., a green frog), and 36 incongruent items displaying animals in the incorrect color (e.g., a blue frog).

Switching

Participants completed a local-global task as a measure of their ability to switch between a set of rules (Navon, 1977). Children were presented with a large, global figure that was composed of many smaller, local figures (e.g., a triangle made of many smaller circles). Stimuli consisted of four geometric shapes (circle, cross, triangle, square) which were systematically combined with the exception that the global figure could not be identical to the local figures. This resulted in 12 possible combinations. The cue indicating which figure to name was determined by the color it was presented in. When the figure was presented in blue color, children were asked to say the name of the global figure; when the figure was presented in black, they were asked to say the name of the local figure. While Miyake et al. (2000) instructed adults to name the number of lines of the target figure, the current task was adapted for children by asking them to name the geometric figure instead. Out of the 96 items total, 48 were presented in blue and black color, respectively. Furthermore, half of the trials involved no switch (no change in color), while the other half involved a switch (either from local to global or from global to local).

Updating

Participants completed a 2n-back task as a measure of their ability to update old, no longer relevant information with newer, more relevant information (Dobbs & Rule, 1989). Stimuli consisted of single digits from 1 to 9. Digits were presented in pre-randomized trials with two constraints. Firstly, consecutive numbers did not occur and secondly, the identical digit did not repeat within a proximity of three positions. Children were asked to postpone the naming of each digit by two positions (2n-back; cf. Schaefer et al., 2008).

Statistical Analysis

One participant was excluded due to a diagnosis with attention deficit hyperactivity disorder as reported within the parental questionnaire and therefore not fulfilling an inclusion criterion. Another participant was excluded due to potentially being at risk for a Developmental Coordination Disorder (M-ABC-2 < 16th percentile; Henderson et al., 2007), while no child had to be excluded due to a potential intellectual impairment (WISC-4 IQ < 70; Petermann & Petermann, 2011). Furthermore, eight participants had to be excluded due to missing data in the key variables (M-ABC-2: n = 3; PACER: n = 1; WISC-4: n = 1; parental education: n = 3). Therefore, the final sample consisted of 129 typically developing children (58 females, M_{age} = 10.7 years, SD_{age} = 1.6 years, see Table 1 for demographic information)[1]. Analyses were performed using IBM SPSS 26.

To analyze the relative importance of motor skills and aerobic fitness for children's executive functions, a series of hierarchical regressions was conducted. Regressions were computed separately for each of the three dependent variables of executive functions (inhibition, switching, updating). In the first step, the control variables age, sex, body mass index, intelligence and parental education were entered. In the second step, aerobic fitness was entered, followed by fine motor skills, balance skills and object control skills in the steps three to five respectively. The order of these motor skills was determined by the expected associations according to conclusions from a recent meta-analysis (Gandotra et al., 2021)[2]. Furthermore, variables were entered in separate steps in order to identify the amount of explained variance for each skill. Vice versa, this analysis was repeated in reversed order to also determine the explained variance of aerobic fitness above and beyond the motor skills. In this regression analysis, control variables were again entered in first step, fine motor skills were entered in the second step, balance skills and object control skills in the steps three and four, and lastly, aerobic fitness in the fifth step.

Results

Descriptive statistics of demographic variables, aerobic fitness, motor skills and executive functions of children are provided in Table 1. Hierarchical regression analyses are presented in Tables 2 and 3. Results are accounted for effects of age, sex, body mass index, intelligence and parental education in the first step of the hierarchical regression. Effects of age were significant across all three executive functions (all *p*s < .001; all *ß*s > -.423), revealing that older children showed fewer errors than younger children in inhibition, switching, and working memory updating. Further, a significant sex effect was found for the inhibition task (*p* = .002; *ß* = .264), due to males making more errors; however, no significant sex effects were found in the switching or updating tasks (both *p*s > .125; both *ß*s < .114). In addition, the body mass index revealed a tendency in inhibition and switching (both *p*s < .074; both *ß*s > .154), but no significance in updating (*p* = .380; *ß* = .069), because children with a higher body mass index showed more errors in inhibition and switching. Additionally, intelligence was significantly related to switching and updating (both ps < .030; both ßs > -.177), but not to inhibition (*p* = .784; *ß* = -.023), indicating that children with higher intelligence showed fewer errors in the switching and updating task. Parental education was not significantly related to errors in executive functions (all *p*s > .154; all *ß*s < .115). Overall, the control variables explained a significant portion of the variance for inhibition (21.1%), switching (25.6%), and updating (35.8%; see Step 1 in Tables 2 and 3).

In the first series of hierarchical regressions (Table 2), aerobic fitness was added in the second step and explained a significant part of the variance in the switching task (4.0%, see Figure 1). When entering fine motor skills in the third step of the same regression, another significant part of the variance in switching (3.2%) was explained. Similar results are found for the updating task: Entering aerobic fitness in step 2 explained a significant part of the variance in the updating task (2.6%; see Figure 1), and another significant part of the variance in updating (2.6%) was explained through fine motor skills. Balance and object control skills did not explain any additional variance for switching and updating. The regression analysis with inhibition as dependent variable revealed no significant relations. Therefore, it seems that fine motor skills explain variance in children’s switching and updating skills beyond aerobic fitness.

In the second series of hierarchical regressions (Table 3), in which control variables were entered in the first step, followed by fine motor skills, balance, and object control in steps two to four, and aerobic fitness in the last step of the model, results showed an even clearer picture of the relative contributions. Adding fine motor skills in the second step explained a significant part of the variance in the switching task (5.5%, see Figure 2). Entering aerobic fitness in the last step yielded a non-significant explained variance of 1.8% (*p* = .079) in switching. Similar results are found for the updating task: Adding fine motor skills in the second step explained a significant part of the variance in updating (4.2%; see Figure 2), while adding aerobic fitness in the last step was not found to add any explained variance in updating (0.8%). Again, balance and object control skills did not add any explained variance in switching and updating. Moreover, no significant relations were found between motor variables and inhibition. Results indicate that aerobic fitness does not seem to explain any significant variance beyond fine motor skills.

Discussion

The current study investigated the relations between children's aerobic fitness, motor skills, and executive functions, whilst considering relevant confounding variables such as age, sex, body mass index, intelligence and parental education (e.g., Gandotra et al., 2021). In the hierarchical regression analyses, it was found that aerobic fitness and fine motor skills were significantly related to switching and updating, however, relations to inhibition were non-significant. More concrete, it was found that fine motor skills explained additional variance above aerobic fitness in switching and updating. In contrast, aerobic fitness did not significantly explain any additional variance in children's switching and updating performance when simultaneously accounting for fine motor skills. Interestingly, balance and object control skills were not related to any of the three core executive functions.

Most of the current results are in line with previous research. The significant results between aerobic fitness as well as fine motor skills with switching and updating strengthen the findings of recent reviews and meta-analyses (Gandotra et al., 2021; van der Fels et al., 2015; van Waelvelde et al., 2019). In line with Cabral et al. (2021), a significant association between aerobic fitness and switching as well as a non-significant relation to inhibition was demonstrated. Furthermore, taking a closer look at the definition of motor skills above (Clark & Whitall, 1989), balance skills within the M-ABC-2 assessment do not only include components of balance but also locomotion such as jumping and walking forwards or backwards (referring to dynamic balance). The non-significant associations between balance skills and executive functions found in the current study are thus in accordance with conclusion from van der Fels et al. (2015), while Gandotra et al. (2021) found significant small effects to all three executive functions. However, given that Gandotra and colleagues suggested that the effects of switching and updating were not robust, the current results reinforce this interpretation of caution. Further, Gandotra et al. (2021) found also no significant effects between locomotion and inhibition and switching as well as between object control and all three executive functions which is in line with the present results.

Furthermore, previous research highlighted the importance of including control variables (Gandotra et al., 2021). The present analyses found females to produce fewer errors within the inhibition task compared to males which is supported by previous studies (Mileva-Seitz et al., 2015; Singh et al., 2022). However, a recent meta-analysis summarized findings from 22 studies and indicated no significant sex difference in inhibition, even though four studies showed differences in favor of females and two studies in favor of males (Gaillard et al., 2021). Similarly, the present findings regarding children with higher BMI producing more errors in inhibition and switching is in line with previous research (Lavagnino et al., 2016). The authors of this respective study explained the association as a lack of inhibitory control which may cause impulsive eating leading to obesity.

The main contradictory finding of the current study compared to the majority of previous studies are the non-significant relations to inhibition (for comparable results, see Aadland et al., 2017). From a descriptive perspective, this relation was similarly positive as for the switching and updating results, however, it was not significant. One possible explanation could be the examined age range of children. Studies that did find significant relations (e.g., Stockel & Hughes, 2016) have predominantly assessed children in kindergarten age (≤ 6 years of age; for an overview see, Gandotra et al., 2021). Building on research indicating that inhibition seems to develop at an earlier age as compared to switching and updating, it seems that relationships between motor skills and components of executive functions may change across childhood and adolescence (Best & Miller, 2010; Huizinga et al., 2006; Möhring et al., 2021). Another possible explanation could be the variety of tasks used in previous research. In the majority of studies, children performed a flanker task (e.g., Hillman et al., 2009; Roebers & Kauer, 2009; Scudder et al., 2014) or a Stroop task with numbers or fruits (e.g., Buck et al., 2008; Roebers et al., 2014; Van Der Veer et al., 2020). Other studies included tasks such as the Go/no-go task, Simon task, Cambridge neuropsychological test automated battery, neuropsychological assessment 2nd edition or parental questionnaires (for an overview see, Gandotra et al., 2021). However, there are studies that also used a similar animal Stroop task as in the current study (Wright et al., 2003), and found that children with poor fine motor skills exhibited lower inhibition skills (Stockel & Hughes, 2016). Lastly, another possible explanation could be the perceived difficulty of the present inhibition task. Even though there was considerable variation among children's inhibition performance, children did show fewer errors in inhibition as compared to the other executive function tasks.

Regarding the findings showing that fine motor skills explain variance of children's executive functions above aerobic fitness but not vice versa, there are different possible explanations. Previous research has suggested that aerobic fitness and fine motor skills are correlated (Haapala, 2013)[3], and therefore, they reduce a part of the explained variance from each other. Interestingly, the present results suggest that this reduction is not the same strength in both directions. Tasks measuring fine motor skills often engage cognitive processes, such as for example decision making and sustained attention (Geertsen et al., 2016), whereas the aerobic fitness task is assumed to require less cognitive engagement (De Bruijn et al., 2020). These differences of cognitive demands in different types of movement are for example also found in current research of open vs. closed-skilled sports, specifically in relation to executive functions (Formenti et al., 2021; Ludyga et al., 2022). Therefore, the differences in cognitive engagement inherent in each motor task could be one possible explanation for the different explained variance. Furthermore, a recent study examined the impact of task novelty on the relation between motor tasks and executive functions; indicating that newer tasks were more strongly related to executive functions than repeated known tasks (Maurer & Roebers, 2020). Given that the task measuring fine motor skills included three different measures as opposed to running back and forth between two borders in the aerobic fitness task, this aspect of novelty may have factored into the analyses. In addition, when looking at the repetitions within the two motor tasks, the majority of the tasks measuring fine motor skill were practiced twice before conducting two test trials. In contrast, the aerobic fitness task revealed a range of 10 – 94 runs, thus supporting the argument of higher task novelty within fine motor skills.

Moreover, the current study highlights that typically developing children with poor motor skills showed more errors in switching and updating tasks than children with higher motor skills. This result is particularly important for future interventions. These children with poor motor skills often do not meet the clinical cut-off values of motor difficulties as determined by criteria for a developmental coordination disorder according to the 5th edition of the Diagnostic and Statistical Manual (DSM-V). Other criteria such as from the Developmental Coordination Disorder Questionnaire (DCD-Q) indicate motor problems for scores below the 10th percentile and suspected motor problems between the 10th and 25th percentile, while the M-ABC-2 suggests a significant motor difficulty below the 5th percentile and a risk of motor difficulty below the 16th percentile (Sartori, 2019). However, the present results using a dimensional perspective indicate that even when children do not meet these criteria, they show significantly lower cognitive performance. This may hold not only for typically developing children but also for example for children with attention deficit hyperactivity disorder in which motor problems occur in 30-50% and are usually neither included in the assessment nor the intervention (Fliers et al., 2010; Klupp et al., 2021). Argumentatively, a more dimensional view onto children’s difficulties can be helpful in the future to accommodate and support also typically developing children with motor skills below average.

Strengths, Limitations and Future Research

The current study examined the relation between motor skills and executive functions in a large sample of school-aged children, and thus focused on an age range that has been insufficiently studied until now. The main strength of the current study is the integrated and differentiated approach by including several components of motor skills as well as children’s executive functions. The majority of previous studies has focused on only one or two executive functions, and in particular the switching component has often been neglected up to now (van Waelvelde et al., 2019). Therefore, findings of the current study could be strengthened in future research by taking care to cover several facets of executive functions and motor skills. Furthermore, it can be considered as a strength that aerobic fitness was assessed at the end of the test session and therefore after the executive function tasks. This order of presented tasks makes sure that there were no acute effects of physical fitness on performance in the executive function tasks. Regarding the assessment of motor skills, standardized and established measurements such as the M-ABC-2 and the PACER were conducted. In addition, common measures of executive functions were used such as the Stroop task, the local-global task and the 2n-back task.

There are limitations that warrant mention. Firstly, the animal Stroop task showed less errors as compared to the other executive function tasks which may indicate that the task might have not been challenging enough for the present sample. However, as can be seen in Table 1, there is still considerable variance within the task. Another possibility why inhibition did not reach significance as expected, might emerge from research showing that inhibition develops first out of the three executive functions (Huizinga et al., 2006). This may explain why studies with younger samples found significant relations (Stockel & Hughes, 2016) and why variances in the current study are greater in the other two executive function tasks. Future studies may examine other tasks tapping inhibition in samples of school-aged children, and preferably model each component of the executive functions (i.e., inhibition) as latent variables. Secondly, although the PACER is a standardized and established measure, fitness can also be measured using other assessments such as the maximal oxygen consumption (van Waelvelde et al., 2019). Ideally, future studies should include multiple assessments to form a latent construct. Thirdly, the power analysis revealed that the present study is sufficiently powered. However, as other previous studies (for overviews, see Gandotra et al., 2021; van Waelvelde et al., 2019) have also found lower effect sizes, future studies should examine this associations with larger samples. In addition, the distribution of parental education within the present sample was slightly skewed towards higher-educated parents. Future studies should replicate the present findings using more representative samples. Lastly, the current study used cross-sectional data. This design precludes examining the direction of the effects as well as children’s intra-individual development. Thus, longitudinal research is needed and strongly recommended for future investigations.

Conclusion

The present study revealed that fine motor skills explained additional variance above aerobic fitness in children’s switching and updating skills which could not be confirmed vice versa. This supports the notion that aerobic fitness and fine motor skills are differently related to executive functions (Haapala, 2013). Importantly, relations were only revealed for switching and updating, whereas inhibition showed no significant associations with motor skills nor aerobic fitness. In summary, the current findings emphasize the importance of considering multiple components of constructs such as aerobic fitness, motor skills and executive functions to ensure an overarching, comprehensive insight.

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Footnotes

1 Previous research has found small-to-moderate effect sizes in analyses showing that children's fitness was associated with executive functions (van Waelvelde et al., 2019). A power analysis with G-Power 3.1, based on an effect size of $f^2 = 0.137$ (e.g., from Buck et al., 2008), assuming a power of .80, and a significance level of $p = .05$, revealed a minimum sample size of 124 participants. Thus, it can be concluded that the present study should be sufficiently powered, using a final sample of 129 participants.

2 In additional analyses, the order of the three motor skills (fine motor skills, balance skills, and object control skills) in steps 3-5 were changed and no significant difference to the current results was found.

3 In the current study, children's fine-motor skills and aerobic fitness were significantly correlated, $r = .217$, $p < .05$. Collinearity statistics revealed a diagnostic value of the variance inflation factor (VIF) of 1.12 which indicates no to low collinearity issues.

Table 1

Descriptive statistics of key variables (N = 129)

Variable	*N (%) / M (SD)*	*Range*
Age (in years)	10.73 (1.60)	8 – 13
Sex		
Male	71 (55%)	
Female	58 (45%)	
Body mass index [a]	17.57 (2.34)	14 – 26
Intelligence [b]	114.26 (15.60)	72 – 156
Parental education	6.05 (1.34)	1 – 7
No school degree	2 (1.6%)	
Primary school	0 (0%)	
Mandatory school	1 (0.8%)	
Apprenticeship	22 (17.1%)	
High school	9 (7%)	
Higher education	22 (17.1%)	
University / college	73 (56.6%)	
Aerobic fitness (PACER) [c]	41.34 (16.32)	10 – 94
Fine motor skills (M-ABC-2) [d]	9.19 (2.32)	4 – 15
Balance skills (M-ABC-2) [d]	12.15 (2.41)	5 – 15
Object control skills (M-ABC-2) [d]	10.48 (2.57)	4 – 15
Inhibition errors (animal Stroop)	4.38 (3.45)	0 – 15
Switching errors (local-global)	10.15 (6.90)	0 – 32
Updating errors (2n-back)	10.25 (9.76)	0 – 42

Note. Data are presented as absolute (and relative) frequencies or means (*SD*). [a] Body mass index is calculated by the formula of kilograms x height in meters squared. [b] Intelligence was computed in accordance with recommendations from Waldmann (2008) using the four subtests vocabulary, matrix reasoning, letter-number sequencing, and coding of the Wechsler Intelligence Scale for Children 4th edition (WISC-IV; Petermann & Petermann, 2011). [c] Aerobic fitness is determined by the number of laps in the Progressive Aerobic Cardiovascular Endurance Run (PACER; Meredith & Welk, 2010). [d] Motor skills are measured with the standardized Movement Assessment Battery for Children, 2nd edition (M-ABC-2; *M* = 10, *SD* = 3, range = 1-19; Henderson et al., 2007).

Table 2

Hierarchical regression analyses examining relations between aerobic fitness, motor skills, and executive functions (N = 129). Variables are entered in a way answering the question whether motor skills explain additional variance above aerobic fitness on children's executive functions.

	Inhibition		Switching		Updating	
Model and variable	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	**.211*** **		**.256*** **		**.358*** **	
Age		**-0.423*** **		**-0.519*** **		**-0.554*** **
Sex		**0.264** **		0.041		0.114
Body mass index		**0.156$^+$**		**0.154$^+$**		0.069
Intelligence		-0.023		**-0.177** **		**-0.283** **
Parental education		0.053		0.115		0.038
Step 2	.007		**.040***		**.026***	
Age		**-0.365** **		**-0.380*** **		**-0.442*** **
Sex		**0.273** **		0.064		0.132$^+$
Body mass index		0.121		0.07		0.001
Intelligence		-0.024		**-0.181***		**-0.285*** **
Parental education		0.06		**0.132$^+$**		0.051
Aerobic fitness		-0.101		**-0.244***		**-0.196***
Step 3	.001		**.032***		**.026***	
Age		**-0.370** **		**-0.416*** **		**-0.475*** **
Sex		**0.265** **		0.000		0.075
Body mass index		0.125		0.099		0.027
Intelligence		-0.018		**-0.137$^+$**		**-0.246** **
Parental education		0.058		0.119		0.040
Aerobic fitness		-0.091		**-0.168+**		-0.128
Fine motor skills		-0.027		**-0.203***		**-0.183***
Step 4	.001		.004		.003	
Age		**-0.370** **		**-0.417*** **		**-0.474*** **
Sex		**0.260** **		0.013		0.064
Body mass index		0.119		0.114		0.014
Intelligence		-0.018		**-0.138$^+$**		**-0.244** **
Parental education		0.061		0.111		0.047
Aerobic fitness		-0.087		**-0.181$^+$**		-0.117
Fine motor skills		-0.023		**-0.217***		**-0.171***
Balance skills		-0.025		0.072		-0.061
Step 5	.000		.003		.000	
Age		**-0.366** **		**-0.405*** **		**-0.472*** **
Sex		**0.267** **		0.034		0.067
Body mass index		0.117		0.107		0.013
Intelligence		-0.017		**-0.136$^+$**		**-0.244** **
Parental education		0.059		0.104		0.046
Aerobic fitness		-0.084		**-0.174$^+$**		-0.115
Fine motor skills		-0.018		**-0.202***		**-0.169***
Balance skills		-0.022		0.082		-0.060
Object control skills		-0.021		-0.065		-0.010

Note. Step 1: model with control variables explaining performance in executive function. Step 2: Aerobic fitness was added. Step 3: fine motor skills were added. Step 4: Balance skills were added. Step 5: Object control skills were added. Sex: -1 = female; +1 = male. Significant results +p < .1, *p < .05, **p < .01, ***p < .001 are presented in bold.

Table 3

Hierarchical regression analyses examining relations between motor skills, aerobic fitness, and executive functions (N = 129). Variables are entered in a way answering the question whether aerobic fitness explains additional variance above motor skills on children's executive functions.

	Inhibition		Switching		Updating	
Model and variable	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	**.211*** **		**.256*** **		**.358*** **	
Age		**-0.423*** **		**-0.519*** **		**-0.554*** **
Sex		**0.264** **		0.041		0.114
Body mass index		**0.156⁺**		**0.154⁺**		0.069
Intelligence		-0.023		**-0.177** **		**-0.283** **
Parental education		0.053		0.115		0.038
Step 2	.003		**.055** **		**.042** **	
Age		**-0.421*** **		**-0.510*** **		**-0.546*** **
Sex		**0.249** **		-0.029		0.053
Body mass index		**0.156⁺**		0.157⁺		0.071
Intelligence		-0.012		-0.124		**-0.236** **
Parental education		0.051		0.106		0.030
Fine motor skills		-0.054		**-0.252** **		**-0.220** **
Step 3	.001		.002		.005	
Age		-0.417***		**-0.516*** **		**-0.537*** **
Sex		0.244**		-0.022		0.042
Body mass index		0.146		**0.171***		0.05
Intelligence		-0.011		-0.124		**-0.235** **
Parental education		0.056		0.099		0.040
Fine motor skills		-0.045		**-0.264*** **		**-0.201***
Balance skills		-0.037		0.048		-0.077
Step 4	.001		.005		.000	
Age		**-0.410*** **		**-0.496*** **		**-0.532*** **
Sex		**0.253** **		0.006		0.049
Body mass index		0.142		0.159⁺		0.047
Intelligence		-0.011		-0.123		**-0.235** **
Parental education		0.053		0.091		0.038
Fine motor skills		-0.038		**-0.243*** **		**-0.196***
Balance skills		-0.032		0.062		-0.073
Object control skills		-0.028		-0.080		-0.020
Step 5	.004		**.018⁺**		.008	
Age		**-0.366*** **		**-0.405*** **		**-0.472*** **
Sex		**0.267** **		0.034		0.067
Body mass index		0.117		0.107		0.013
Intelligence		-0.017		-0.136⁺		**-0.244** **
Parental education		0.059		0.104		0.046
Fine motor skills		-0.018		**-0.202***		**-0.169***
Balance skills		-0.022		0.082		-0.060
Object control skills		-0.021		-0.065		-0.010
Aerobic fitness		-0.084		**-0.174⁺**		-0.115

Note. Step 1: model with control variables explaining performance in executive function. Step 2: fine motor skills were added. Step 3: Balance skills were added. Step 4: Object control skills were added. Step 5: Aerobic fitness was added. Sex: -1 = female; +1 = male. Significant results $^{+}p < .1$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$ are presented in bold.

Figure 1

Relations between executive function with aerobic fitness (N = 129)

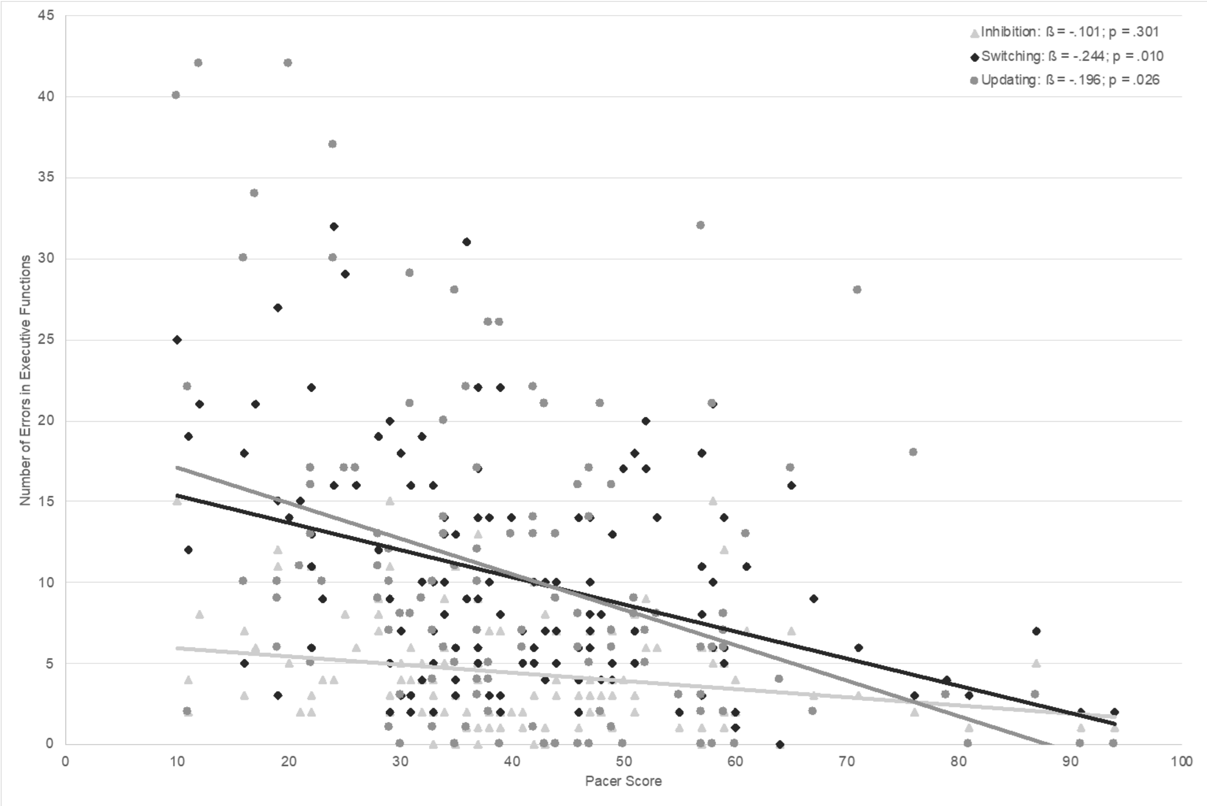
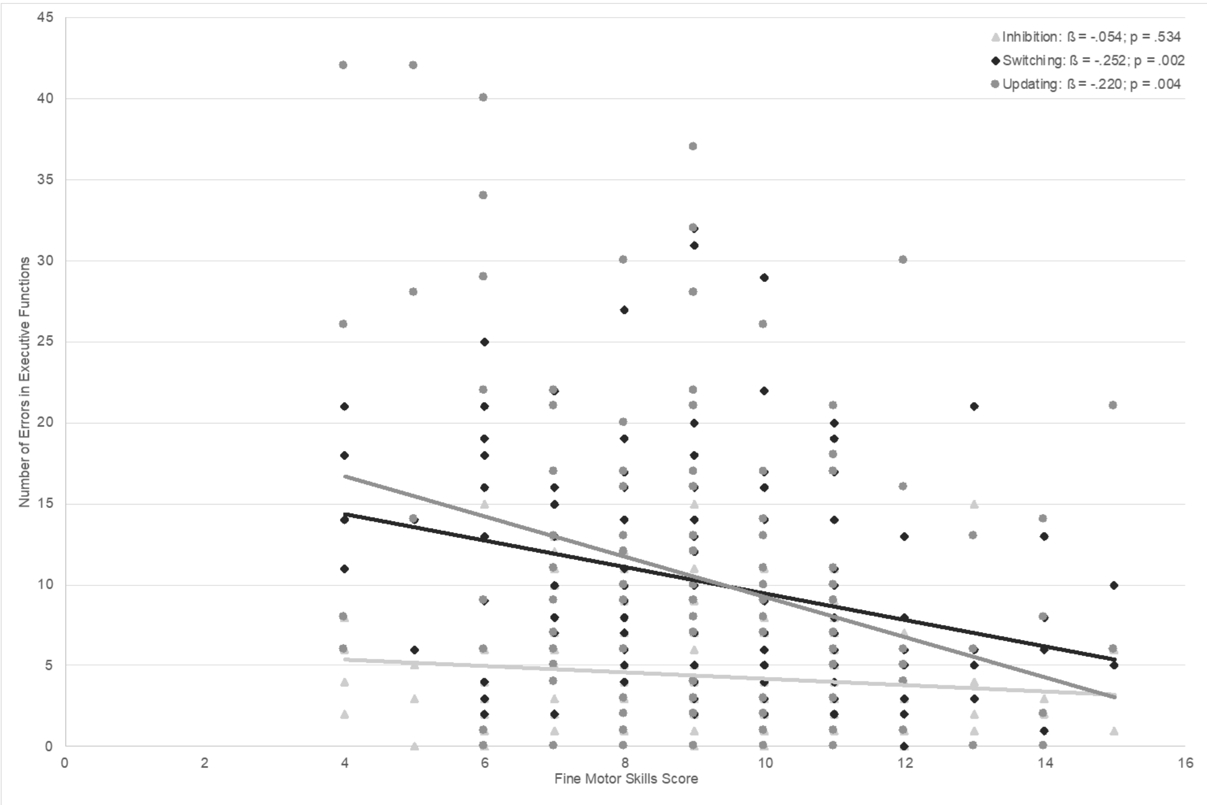


Figure 2

Relations between executive function with fine motor skills (N = 129)



APPENDIX C: STUDY 3

Please note that this is the author’s version of a work that was accepted for publication in *Perceptual and Motor Skills.* This paper is not the copy of record and may not exactly replicate the final, authoritative version of the article. The final article is available via its DOI: 10.1177/00315125221143966.

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Gait variability relates to prosocial, emotional and risk-taking behavior in typically developing children

Stephanie Klupp[*,a], Alexander Grob[a], Wenke Möhring[a,b]

* **Corresponding author:** Stephanie Klupp, University of Basel, Department of Psychology, Missionsstrasse 62, 4055 Basel, Switzerland; Email: stephanie.klupp@unibas.ch

[a] University of Basel, Department of Psychology, Switzerland.

[b] Department of Educational and Health Psychology, University of Education Schwäbisch Gmünd, Schwäbisch Gmünd, Germany.

Author Note

*Correspondence concerning this article should be addressed to Stephanie Klupp, Department of Psychology, University of Basel, Missionsstrasse 62, 4055 Basel, Switzerland. E-mail: stephanie.klupp@unibas.ch

Stephanie Klupp https://orcid.org/0000-0001-7407-5038

Alexander Grob https://orcid.org/0000-0002-0715-4139

Wenke Möhring https://orcid.org/0000-0002-9152-8470

Authorship Contributions

Prof. Dr. Wenke Möhring: Validation, Investigation, Data Curation, Formal analysis, Writing - Review & Editing. **Prof. Dr. Alexander Grob:** Conceptualization, Methodology, Writing - Review & Editing. **Stephanie Klupp M Sc:** Investigation, Data Curation, Formal analysis, Writing - Original Draft, Visualization, Writing - Editing.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest and that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Abstract

Background: Motor skills enable multi-facetted interactions with the environment and allow children to develop social skills and respond appropriately to situational social demands when interacting with peers and adults. Previous research with clinical samples (e.g., children diagnosed with Developmental Coordination Disorder) showed that children's motor skills are closely linked to their psychosocial behavior (e.g., prosocial, hyperactive, inattentive, interpersonal), but studies with typically developing children are rare.

Research question: We sought to fill this research gap by examining relationships between gait variability as an indicator of motor skills and prosocial behavior, problem behavior, and risk-taking behavior in typically developing children.

Methods: Participants were a large cross-section of 7-13-year-olds (N = 221). They were asked to walk normally across an electronic pathway (GAITRite). We assessed their gait variability (i.e., stride time, stride length and stride velocity). Their parents completed the Strengths and Difficulties Questionnaire that assessed their child's prosocial behavior, hyperactivity, emotional symptoms, and any conduct or peer relationship problems. Parents also provided information on an adapted scale of the Tridimensional Personality Questionnaire assessing risk-taking behavior. We used multilevel modeling to account for individual interdependence and to analyze the maximum number of strides for each participant.

Results: Children with greater stride length variability and velocity showed significantly less prosocial behavior, had more emotional symptoms and demonstrated less risk-taking behavior. Stride time variability was not significantly related to any variables.

Significance: These results align with past findings that gait is sensitive to motor skill differences, and they extend past findings of these associations between gait and facets of intra- and interpersonal characteristics from children within clinical disorders to typically developing children.

Keywords: gait, prosocial behavior, emotional symptoms, risk behavior, children

Introduction

Motor behavior has been associated with psychosocial skills and general wellbeing in that the accuracy and coordination of movement is essential to psychological and social development (Mancini et al., 2019; Piek et al., 2006). This relationship might be explained with the embodied cognition theory, according to which motor skills facilitate social interaction (Harbourne & Berger, 2019). Optimal motor development in young children may enable play with peers, which, in turn, supports the development of social skills and interpersonal relationships (Mancini et al., 2019). Accordingly, children with poor motor skills are often victims of social ostracism as well as bullying and show low self-esteem (Missiuna & Campbell, 2014).

Several studies suggest that poor motor skills are a risk factor to optimal development in several domains of psychosocial functioning (Mansoubi et al., 2020). In previous studies, the term “poor motor skills” has been used as an umbrella term, covering a variety of observations that describe clumsy or uncoordinated behavior (Bejerot et al., 2013). Typically, investigators have used three methodological approaches to measure children’s poor motor skills: (a) diagnostic determinations of developmental coordination disorder (DCD; e.g., according to the DSM-V); (b) standardized measures of motor performance (M-ABC-2; Henderson et al., 2007) for identifying motor skills that are below the 16^{th} percentile in relation to the general population and indicate potential DCD; and (c) parent observations as determined through parent-completed questionnaires such as the DCD-Questionnaire which indicates or suspects DCD below a score of 46-57, depending on the age group (Wilson et al., 2009). These methods of operationalizing motor deficits have been applied within clinical samples, based on certain cut-off values. However, a more dimensional view with continuous rather than categorical perspectives or groupings of motor abilities may suggest similar associations for typically developing children.

The Environmental Stress Hypothesis has conceptualized how children’s poor motor skills may contribute to emotional difficulties in which children internalize emotional discomfort such as anxiety and depression (Cairney et al., 2013; Mancini et al., 2016). According to this theoretical framework, poor motor coordination is a primary stressor that increases a risk for experiencing intra- and interpersonal conflicts (e.g., decreased self-esteem or experiences with bullying) that in turn lead to internalizing problems (Blank et al., 2019; Cairney et al., 2013). Past empirical evidence has supported this relationship between poor motor skills and children’s mental health and behavioral problems when these variables have been studied in children with clinical conditions (Bouffard et al., 1996; Cantell et al., 1994; Mancini et al., 2019; Skinner & Piek, 2001). This association has seemed to begin early in life, as shown by a longitudinal study that examined the development of gross motor skills up to the age of four years and later assessed anxiety and depression scores at school age (Piek et al., 2010). The authors found gross motor skill development at early childhood predicted later emotional symptoms. This increased risk of *intra*personal difficulties was also supported by an increased probability of lower prosocial skills, hyperactivity, inattention, and emotional symptoms in children with poorer motor skills than their peers (Lingam et al., 2012). In addition, children with poor motor skills have appeared more nervous and less sociable, and they have experienced more social exclusion from peer play (Engel-Yeger & Hanna Kasis, 2010; Smyth & Anderson, 2000; Zwicker et al., 2012). These *inter*personal difficulties were further supported by research findings that children with poor motor skills spend more time alone, report fewer friends, interact less positively with peers and perceive less social support (Lingam et al., 2012; Mancini et al., 2019; Poulsen et al., 2008). Even though children with poor motor skills are at greater risk of being bullied and victimized (Bejerot et al., 2013; Campbell et al., 2012; Piek et al., 2005), there has been no evidence that they are at significant risk for more externalizing behavior problems such as conduct problems (Lingam et al., 2012), as less is known about the relationship between motor skill difficulties and delinquent behavior such as lying, cheating and stealing. Also, novelty seeking, risk-taking and reward dependence have not yet been examined in relation to children’s poor motor skills.

As a consequence of their negative social experiences, children with poor motor skills have often used avoidance as a coping strategy (Bouffard et al., 1996), and they have been seen to withdraw from situations that may involve motor competence. This avoidance may emerge due to children’s fear of failure and peer criticism, and it may create a vicious circle, such that reduced social interactions yield fewer opportunities to practice motor skills, with accentuated movement problems which result over time (Cairney et al., 2013; Skinner & Piek, 2001), leading to further reductions in social participation and even greater risk of emotional and behavioral problems (Schoemaker & Kalverboer, 1994; Zwicker et al., 2012). Whereas poor motor skills are often seen as a primary stressor for developing emotional and behavioral problems, as suggested by the Environmental Stress Hypothesis, this relationship may be more reciprocal than has been previously assumed (Cairney et al., 2013; McClelland & Cameron, 2019). Research examining the bidirectional nature of these associations and the potential cascading effects has been sparse to date and is needed now.

In the present study, we attempted to build upon prior research by using a novel methodological approach in which we assessed children’s gait as an indicator of their motor ability and related gait functioning to inter- and intra-personal behavior. Gait is a type of locomotion which requires coordination between the central nervous system and lower limb motions (Adolph & Berger, 2006). Infants reach the motor milestone of walking at around the first year of life (World Health Organization, 2006). Afterwards, their gait reaches a stabilized and mature pattern at around seven years of age (Adolph et al., 2003), with some gait characteristics such as gait variability still under development well into adolescence (Danion et al., 2003; Hagmann-von Arx et al., 2016). Considering this lengthy developmental progression, gait variability is a sensitive measure of general motor skill development and it may be used to reflect poor motor ability (Van Emmerik et al., 2005) and study the reciprocal relationship of poor motor ability and psychosocial functioning.

Several investigators have suggested a specific relationship between gait and facets of a child’s intra- and interpersonal characteristics (e.g., Mansoubi et al., 2020; Schneider et al., 2014). When infants learn to walk, their relationships to objects and other people change, which, in turn, allows them to make changes in their initiation of social interactions (Iverson, 2010) to create a context for acquiring psychosocial skills (Karasik et al., 2011). Consequently, when children’s motor abilities are not age-appropriate, they may impact general behavior and psychosocial functioning (Hagmann-von Arx et al., 2016). Further evidence comes from research showing that emotional states can be reflected in the human gait. For example, the work “*Show me how you walk and I tell you how you feel*” demonstrated that negative (i.e., angry) emotional walking was associated with enhanced brain activation (Schneider et al., 2014). Similarly, Atkinson et al. (2012) found an increase in brain activity for happy body movements. Gross et al. (2012) showed that adults increased their walking speed when they felt joy and anger. In studies with clinical samples, investigators have suggested relationships between decreased gait speed and anxiety (Zhao et al., 2019) and depressive symptoms (Lemke et al., 2000; Michalak et al., 2009). Finally, in studies focusing on the relationship between gait and social victimization, several investigators demonstrated that walkers' self-reported experiences in victimization were associated with more vulnerable gait cues (i.e., less synchronous, less fluid, long or short strides) as identified by naïve observers (Blaskovits & Bennell, 2019; Grayson & Stein, 1981).

Despite this focus on gait in adult studies, investigations of the relationship between children's gait and their intra- and/or interpersonal difficulties have been rare. To our knowledge, only one recent study examined this relationship in a sample of 13-year-olds (*N* = 76). This research team found that children with more emotional symptoms and overall behavior difficulties walked faster with shorter steps (Mansoubi et al., 2020). Clearly, more research with children of a broader age range and involving a larger array of intra- and interpersonal characteristics is needed. Our aim in the current research was to study these associations in a large, cross-sectional sample of typically developing 7-13-year-old children. We assessed children's gait variability objectively and reliably with an electronic pathway and measured their intra- and interpersonal characteristics with parental reports. Given that gait variability shows a considerable developmental progression well into adolescence (Danion et al., 2003; Hagmann-von Arx et al., 2016), we focused on this specific indicator of children's gait. We hypothesized that children with higher gait variability would show fewer prosocial skills, more hyperactive behavior, more emotional symptoms and more peer problems. We also explored relations between gait variability and both conduct problems and risk behavior.

Methods

Participants

Our local ethics committee approved the present study, and, prior to any child's participation in this research, parents gave their written informed consent, and child participants assented verbally. We recruited 239 children aged 7-13 years from local schools by handing out invitation letters for children to take home to parents. We focused on typically developing children who fulfilled our inclusion criteria of no gait problems and no developmental disorder, and we excluded participants who were at risk for DCD (*n* = 4). Additionally, missing data (in parental questionnaire: *n* = 6, gait: *n* = 4, and other measures: *n* = 4) reduced our final sample to 221 participants (104 females, 117 males; M_{age} = 10.54 years; see Table 1 for further demographic information).

Measures and Procedure

Prior to assessing participants' normal walking, we gathered their anthropometric data (e.g., height, weight and leg length). They then walked over an electronic carpet system at their own self-selected pace. To account for children's varied intellectual functioning, we gathered data regarding their performance on four subtests (Vocabulary, Matrix Reasoning, Letter-Number Sequencing, and Coding) of the German version of Wechsler Intelligence Scale for Children 4th edition (Petermann & Petermann, 2011; Wechsler, 2004). These were pro-rated to yield an estimated summary intelligence score (Waldmann, 2008) that we could use as a control variable.

Parent Reports

Participants' parents completed several standardized questionnaires, including the Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997) to assess children's prosocial and problem behaviors, and an adapted version of the Tridimensional Personality Questionnaire (TPQ; Brandau & Daghofer, 2010; Cloninger et al., 1991) assessing children's risk-taking behavior.

The SDQ is a reliable and valid screening tool in which parents can identify behavioral problems in children aged 4-16 years (present sample: total α = .71; strength α = .72; difficulties α = .81). The questionnaire can be separated into five subscales with five items each on a 3-point Likert scale (Goodman, 1997). The strength domain is measured by the first subscale: (a) prosocial behavior (e.g., "*considerate of other's feelings*"). The other four subscales measure difficulties: (b) hyperactive and inattentive behavior (e.g., "*restless, overactive*"); (c) emotional symptoms (e.g., "*often seems worried*"); (d) conduct problems (e.g., "*often lies or cheats*"); and (e) peer problems (e.g., "*generally liked by other children*").

Based on Cloninger's three-dimensional model of personality (Cloninger et al., 1991), the TPQ was adapted and validated into a short 15-item parental questionnaire in German (2010). This version permits a reliable assessment of children's risk-taking behavior (present sample: α = .86). Notably, Cloninger's dimension "harm avoidance" was reversed into the dimension "risk-taking" (Brandau et al., 2011). This adapted questionnaire consists of three subscales with five items each on a 4-point Likert scale: (a) novelty seeking (e.g., "*interrupts monotonous activities*"); (b) risk-taking (e.g., "*does things others find risky*"); and (c) reward dependence (e.g., "*easily frustrated*").

Walking assessment

We assessed children's walking ability with the gait assessment system GAITRite (CIR Systems, NJ), an objective, reliable and valid measure of gait (Dusing & Thorpe, 2007). The GAITRite is a 7 meter long carpet in which over 23'000 sensors are embedded. Additional 1.25 meter inactive sections in the beginning and end of the carpet accounted for effects of acceleration and deceleration. In the present study, we included two cross-sectional samples, with one subsample (n = 88) completing 4 walks across the electronic walkway and the other subsample (n = 133) completing 8 walks[1]. The GAITRite recorded different gait parameters: temporal (stride time), spatial (stride length) and spatial-temporal parameters (stride velocity). The analysis focused on participants' stride-to-stride fluctuations (i.e., gait variability), represented by the coefficient of variation (CV; Yogev et al., 2005).

Statistical analyses

We determined and excluded outliers (mean ± 3 *SD*s) within the gait parameters (1.14%). Further, we computed gait variability on three variables (a) stride time, (b) stride length and (c) stride velocity (e.g., CV stride time = stride time standard deviation/ stride time mean x 100). Since participants repeated their normal walking for 4-8 walks, these data showed a differential, nested structure, with subsequent walks being more closely related with respect to gait characteristics as opposed to, for example, the first and last walk. The use of a multilevel modeling (MLMs) approach took this difference and individual interdependence into account and allowed an analysis of the maximum number of strides for each participant. Moreover, MLMs are a form of regression models which determine standardized coefficients and *p*-values but have the advantage of considering potential grouping of the data.

We conducted a two-level structural analysis model to examine the relationships between children's gait and their intra- and interpersonal characteristics. In Level 1, we analyzed gait variability across individual walks (CV stride time; CV stride length; CV stride velocity); and, in Level 2, we included characteristics of the individual child (age, sex, intelligence, and parental report). Sex was coded with '-1' for females and '+1' for males. Previous studies have often included age, height and weight as control variables, but age correlated highly with height (r = .835) and weight (r = .716), as did height with weight (r = .854) and this potential collinearity was confirmed through the diagnostic values in the present data (VIF > 3). Therefore, only age was included in the following analyses to prevent collinearity issues[2]. Missing values were handled with the maximum likelihood estimation approach. Three separate models were conducted for each gait variability. In the null model, age, sex, and intelligence were included as level 2 effects. Subsequently, a full model was computed by adding the dimensions of the SDQ and the TPQ as level 2 effects to the null model. To test the effects of these intra- and interpersonal characteristics, the full model was then compared to the null model. The Statistical Package for the Social Sciences (SPSS, Version 26, IBM Corp.) was used for these MLMs analyses, and statistical significance was set at $p < .05$.

Results

An overview of the children's demographic and anthropometric characteristics and other descriptive statistics can be found in Table 1. The first full model with children's CV stride time did not significantly improve the model fit compared to the null model (χ^2 = 13.23, df = 8, p = .104). Thus, even though some variables reached significance in the full model of CV stride time, those were not interpreted. However, the models with CV stride length (χ^2 = 30.33, df = 8, $p < .001$) and CV stride velocity (χ^2 = 20.52, df = 8, $p < .01$) resulted in a significant improvement of the model fit after adding the variables of the SDQ and TPQ to the null model.

The significant full-null model differences indicated significant relationships between children's gait and their prosocial behavior, problem behavior and risk-taking behavior as elaborated below (see Table 2). Additionally, these two full models showed significant effects of age and sex. Males walked with a significantly longer CV stride length and faster CV stride velocity as compared to females (b = .093 – .134, all ps < .01).

Furthermore, younger children displayed a higher gait variability as compared to older children (b = -.014 – -.015, all ps < .001)[3].

The models with CV stride length and CV stride velocity demonstrated similar patterns. Children's gait variability in normal walking (stride length: b = -.051, p < .01; stride velocity: b = -.057, p < .05) was related to their prosocial behavior. In addition, gait variability (stride length: b = .063, p < .01; stride velocity: b = .071, p < .05) was also significantly related to children's emotional symptoms. More concretely, we found that children whose parents rated them with more prosocial behavior walked with less variable stride length and stride velocity. Furthermore, children with more emotional symptoms walked with higher variability in stride length and velocity. Additionally, the relationship between risk-taking and gait variability was significant for CV stride length (b = -.056, p < .01), while there was a tendency toward a significant relationship between risk-taking and CV stride velocity (b = -.044, p = .073), such that children with lower risk-taking behavior showed a higher gait variability.

Discussion

In the present study, we examined associations between gait variability and facets of intra- and interpersonal behavior in a large, cross-sectional sample of typically developing 7- 13-year-olds. As hypothesized, we found that children with fewer prosocial skills showed higher gait variability in both stride length and stride velocity. This result is in line with previous research focusing on children with DCD, showing that children with this diagnosis more often played alone, or watched other children playing or moving around without being engaged in peer play (Smyth & Anderson, 2000). This isolation and lack of peer interaction carries risks for continued poor social and motor skills (Cairney et al., 2013; Smyth & Anderson, 2000). Secondly, as hypothesized, our findings suggested that children with more reported emotional symptoms (e.g., physical discomfort, nervousness, sadness and anxiety) produced higher gait variability in stride length and velocity. These results are also in line with previous research (Mansoubi et al., 2020) and support the Environmental Stress Hypothesis (Cairney et al., 2013). Thirdly, as opposed to previous research with children diagnosed with DCD, associations between gait variability and the subscales of hyperactivity and peer problems revealed non-significant effects in our sample of typically developing children. However, our findings of non-significant effects regarding conduct problems are in line with one previous study (Lingam et al., 2012), which similarly demonstrated that children with motor weaknesses did not show an increase in conduct problems.

Our exploratory research regarding associations between gait and risk-taking behavior revealed inverse relations between risk-taking and gait variability in stride length and stride velocity. Children who were reported to engage in more risky activities and overestimate their own skills showed more gait regularity with respect to stride length and stride velocity. Conversely, this result implies that children who were reported to be less risk-taking and more cautious showed higher gait variability. A possible explanation could be that children with riskier behavior seek more demanding situations and explore their boundaries. These situations often involve higher physical activity and may train various aspects of children's motor abilities, which may lead, in turn, to less gait variability. In addition to this finding, measures of novelty seeking and reward dependence were not significantly related to gait variability.

Strengths, Limitations and Directions for Further Research

Overall, strengths of this study included a large sample, with multiple gait repetitions that were measured objectively and reliably. Moreover, measurements of all walks were included by the MLMs approach that accounted for the interdependence between walks. The sensitivity of gait variability and the evaluation of all questionnaire scales enabled precise, comprehensive, and transparent reporting. In that respect, a possible limitation was our reliance on parent reports of their children's behavior. Especially, in later childhood, adolescents have been found to report more internalizing and externalizing problems in self reports than were reported by their parents (Seiffge-Krenke & Kollmar, 1998). Since our youngest participants were 7 years old, self-reports were not feasible in this study. Supportively, there has been satisfactory internal consistency between parental- and self-report on the SDQ (Koskelainen et al., 2000). Future studies might include self-reports, interviews and more objective measures of children's behavior. Furthermore, even though we included a wide age range (7-13 years) of participants, future investigators might examine the relationship between children's gait and their intra- and interpersonal characteristics at ages above and below this age range. It seems likely that results may differ across and between age groups, as developing social behavior contributes to the major developmental tasks across the first years of life (Williams & Berthelsen, 2017), and internalizing as well as externalizing problems change across childhood and adolescence (Wong et al., 2021). In addition, future studies should include information of onset age of walking to clarify potential effects on variability. Our cross-sectional research design is a further limitation that prevents causal assumptions between these correlations. An additional longitudinal study with crossed-lagged design testing these relationships would be informative going forward.

Conclusion

In summary, data from this study provide insights into how children's normal walking relates to their psychosocial behavior. We found significant relationships between gait variability and children's prosocial behavior, their emotional symptoms, and their risk-taking behavior. These findings are in line with earlier research in clinical populations demonstrating that intra- and interpersonal behaviors are related to children's body movements (Simpson et al., 1993). However, our findings add dimensionality to this association, since we show that typically developing children whose motor weaknesses are not categorized as clinically significant also show associations with intra- and inter-individual characteristics, leading to the conclusion that typically developing children at the lower end of motor abilities similarly as clinical samples should be entitled for support programs and interventions. Especially, as the current significant associations are found above effects of age, children do not seem to outgrow their gait variability. An important implication of these findings is that an awareness of children's early motor difficulties, perhaps with gait in particular, can be a path toward early identification of and early interventions for children at risk for emotional and interpersonal problems.

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Footnotes

1 A post-hoc sensitivity ANOVA revealed no significant group differences between the two subsamples with respect to our dependent variables (CV stride time p = .906, CV stride length p = .877, CV stride velocity p = .137).

2 Three additional sensitivity analyses revealed that the pattern of results remained the same, when including (a) height and weight, (b) only height, and (c) only weight as additional Level 2 variables.

3 Additional sensitivity analyses including interactions with age revealed non-significant results.

Table 1

Participants' Descriptive Statistics for Key Variables Including the Correlation Matrix for Parent-Completed Questionnaires.

Variable	*M (SD)*	*Range*	1	2	3	4	5	6	7
Sex									
Female (*N* = 104, 47%)									
Male (*N* = 117, 53%)									
Age (in years)	10.53 (1.57)	7 – 13							
Height (in cm)	145.57 (11.45)	119 – 184							
Weight (in kg)	37.60 (9.65)	22 – 70							
Intelligence (WISC-IV)	111.79 (14.42)	72 – 156							
Gait variability									
CV stride time	2.00 (0.50)	0.91 – 3.37							
CV stride length	2.14 (0.67)	0.91 – 4.32							
CV stride velocity	2.65 (0.73)	1.20 – 5.52							
SDQ parental questionnaire									
1. SDQ prosocial score	8.19 (1.83)	2 – 10							
2. SDQ hyperactivity and inattentive	2.43 (2.20)	0 – 10	**-.245**						
3. SDQ emotional symptoms score	1.43 (1.66)	0 – 8	-.128	**.254**					
4. SDQ conduct problems score	1.63 (1.55)	0 – 8	**-.495**	**.523**	**.382**				
5. SDQ peer problems score	1.24 (1.50)	0 – 7	**-.190**	**.204**	**.284**	**.318**			
TPQ parental questionnaire									
6. TPQ novelty seeking	4.31 (2.00)	0 – 12	**-.272**	**.547**	**.318**	**.556**	**.235**		
7. TPQ risk-taking	2.63 (2.13)	0 – 12	**-.284**	**.538**	**.230**	**.564**	**.194**	**.568**	
8. TPQ reward dependence	5.13 (2.89)	0 – 14	**-.354**	**.420**	**.460**	**.612**	**.188**	**.616**	**.495**

Note. *N* = 221. Data are presented as means (standard deviation). WISC-IV = Wechsler Intelligence Scales 4th edition. SDQ = Strengths and Difficulties Questionnaire, maximum range per index: 0 – 10. TPQ = Tridimensional Personality Questionnaire, German adapted short version by Brandau and Daghofer (2010), maximum range per index: 0 – 15. Significant correlations at the 0.01 level (2-tailed) are presented in bold.

Table 2

Variance Contributed by SDQ and TPQ Scales, and Control Variables in Children's Gait Variability: Linear Mixed Models.

	CV stride time[a]				CV stride length				CV stride velocity			
	b	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*	*b*	*SE*	95% CI	*p*
Age	**-.012**	**.001**	**[-.014, -.009]**	**< .001**	**-.014**	**.002**	**[-.017, -.011]**	**< .001**	**-.015**	**.002**	**[-.019, -.011]**	**< .001**
Sex	**.111**	**.027**	**[.058, .164]**	**< .001**	**.093**	**.033**	**[.027, .159]**	**.006**	**.134**	**.041**	**[.054, .215]**	**.001**
Intelligence	-.001	.002	[-.004, .003]	.738	.000	.002	[-.005, .004]	.918	.002	.003	[-.003, .007]	.455
SDQ prosocial	-.016	.016	[-.047, .015]	.321	**-.051**	**.020**	**[-.090, -.013]**	**.009**	**-.057**	**.024**	**[-.104, -.009]**	**.020**
SDQ hyperactive/inattentive	.018	.015	[-.011, .048]	.220	.023	.019	[-.014, .060]	.220	-.009	.023	[-.054, .036]	.694
SDQ emotional symptoms	.030	.018	[-.006, .066]	.108	**.063**	**.022**	**[.019, .107]**	**.005**	**.071**	**.028**	**[.017, .125]**	**.011**
SDQ conduct problems	.005	.025	[-.045, .054]	.850	-.024	.031	[-.085, .037]	.437	.018	.038	[-.057, .093]	.643
SDQ peer problems	**.037**	**.019**	**[.001, .074]**	**.045**	.009	.023	[-.037, .054]	.709	.035	.028	[-.021, .091]	.217
TPQ novelty seeking	-.008	.019	[-.044, .029]	.674	-.015	.023	[-.060, .030]	.516	.008	.028	[-.048, .064]	.779
TPQ risk-taking	-.019	.016	[-.051, .013]	.234	**-.056**	**.020**	**[-.096, -.017]**	**.005**	**-.044**	**.025**	**[-.093, .004]**	**.073[+]**
TPQ reward dependence	-.014	.013	[-.040, .013]	.311	.026	.017	[-.007, .059]	.121	-.019	.020	[-.059, .021]	.352

Note. N = 221. CV = coefficient of variation. CI = confidence interval. SDQ = Strengths and Difficulties Questionnaire. TPQ = Tridimensional Personality Questionnaire, adapted short version by Brandau and Daghofer (2010) in German. Age was entered as linear and continuous variable. Sex: -1 = female; +1 = male. Significant results ($p < .05$) and tendencies ([+] with $p < .1$) are presented in bold. [a]Full-null model comparison not significant.

APPENDIX D: CURRICULUM VITAE

Stephanie Klupp

24.07.1993

stephanie@klupp.com

Education

08/2017 - *	**PhD Developmental and Personality Psychology** University of Basel
08/2015 - 07/2017	**Master of Science in Psychology** **Major in Developmental and Personality Psychology** University of Basel Master's thesis: *The relation between adults' gait and executive functions: Evidence from a cognitive- motor dual- task*
09/2012 - 07/2015	**Bachelor of Science in Psychology** University of Basel Bachelor's thesis: *Wie effektiv sind Selbstmanagement-Programme?*

Professional Activities

06/2022 – *	**Roche Internships for Scientific Exchange (RiSE)** PhD Internship | Early Development | Neuroscience and Rare Diseases Discovery and Translational Area (NRD DTA) | F.Hoffmann-La Roche Ltd.
08/2017 – 07/2022	**Teaching and Research Assistant** Division of Developmental and Personality Psychology | Department of Psychology | University of Basel
01/2021 – 02/2021	**Internship / Wellbeing Study** Novartis Business Assurance & Advisory (NBAA) | Quality, Center of Excellence of Data Analytics & Investigations, Development & Training, Operations & Strategy (QDOS) | Novartis
04/2017 – 01/2018	**Lab Coordinator / Project: Cognitive and Motor Development** Division of Developmental and Personality Psychology | Department of Psychology | University of Basel
01/2017 – 04/2017	**Internship Research Assistant / Project: Cognitive & Motor Development** Division of Developmental and Personality Psychology | Department of Psychology | University of Basel

Teaching

08/2018 – 01/2022	**Masterproject: Cognitive and Motor Development in Children**
	Master Seminar | Department of Psychology | University of Basel
08/2018 – 01/2022	**Supervision of Bachelor Theses**
	Department of Psychology | University of Basel
02/2021 – 01/2022	**Diagnostics**
	Bachelor Seminar | Department of Psychology | University of Basel
08/2019 – 07/2021	**Writing a Bachelor Thesis in Developmental and Personality Psychology**
	Bachelor Seminar | Department of Psychology | University of Basel
08/2020 – 01/2021	**Cognitive Development**
+ 08/2018 – 01/2019	Master Seminar | Department of Psychology | University of Basel
02/2019 – 01/2021	**Supervision of a Master Thesis**
	Department of Psychology | University of Basel
02/2020 – 07/2020	**Perception, Cognition and Action across Lifespan**
	Master Seminar | Department of Psychology | University of Basel
08/2019 – 01/2020	**Selected Topics in the Development of Social Cognition**
	Master Seminar | Department of Psychology | University of Basel
02/2019 – 07/2019	**Methods in Developmental Psychology**
	Master Seminar | Department of Psychology | University of Basel

Publications

Klupp, S., Möhring, W., Lemola, S., & Grob, A. (2021, Mar). Relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder. *Research in Developmental Disabilities*, 110, 103855. https://doi.org/10.1016/j.ridd.2021.103855

Klupp, S., Grob, A., & Möhring, W. (2022, Oct). Aerobic fitness and fine motor skills are related to switching and updating in typically developing children. *Psychological Research*. https://doi.org/10.1007/s00426-022-01749-w

Klupp, S., Grob, A., & Möhring, W. (2022, Nov). Gait variability relates to prosocial, emotional and risk-taking behavior in typically developing children. *Perceptual and Motor Skills.* https://doi.org/ 10.1177/00315125221143966

Meachon, E. J., **Klupp, S.**, & Grob, A. (2022). Gait in children with and without ADHD: A systematic literature review. *Manuscript currently under review.*

Möhring, W., **Klupp, S.**, & Grob, A. (2018, Dec). Effects of dual tasking and methylphenidate on gait in children with attention deficit hyperactivity disorder. *Human Movement Science, 62*, 48-57. https://doi.org/10.1016/j.humov.2018.09.007

Möhring, W., **Klupp, S.**, Segerer, R., Schaefer, S., & Grob, A. (2020, Jun). Effects of Various Executive Functions on Adults' and Children's Walking. *Journal of Experimental Psychology: Human Perception and Performance, 46*(6), 629-642. https://doi.org/10.1037/xhp0000736

Möhring, W., **Klupp, S.**, Zumbrunnen, R., Segerer, R., Schaefer, S., & Grob, A. (2021, Jun). Age-related changes in children's cognitive-motor dual tasking: Evidence from a large cross-sectional sample. *Journal of Experimental Child Psychology, 206*, 105103. https://doi.org/10.1016/j.jecp.2021.105103

Möhring, W., **Klupp, S.**, Ludyga, S., & Grob, A. (2022, May). Executive functions in children engaging in open- and closed-skilled sports. Psychology of Sport and Exercise, 61. https://doi.org/10.1016/j.psychsport.2022.102218

Conference Contributions

Klupp, S., Möhring, W., Sakari. L., Grob, A. (2020, May) *Relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder*. Symposium talk in "Relations between motor and cognitive abilities: Evidence from dual-task studies, atypical development, and intervention studies" at the 52nd annual congress of the German Society of Sport Psychology (ASP), conducted virtual due to Covid-19.

Klupp, S., Möhring, W., & Grob, A., (2019, July). *Fine motor skills and intelligence: Evidence from typically developing children and children with attention-deficit hyperactivity disorder*. Poster presented at the Conference of the International School Psychology Association (ISPA), Basel, Switzerland.

Klupp, S., Möhring, W., & Grob, A., (2019, May). *Fine motor skills and intelligence: Pre-liminary evidence from typically developing children and children with attention-deficit hyperactivity disorder*. Poster presented at the 51st annual congress of the German Society of Sport Psychology (ASP), Halle. Germany.

Klupp, S., Möhring, W., & Grob, A., (2019, September). *Relations between physical fitness and executive functions in typically developing children: Preliminary evidence*. Poster presented at the Gemeinsame Tagung der Fachgruppen Entwicklungspsychologie und Pädagogische Psychologie (PaEpsy), Leipzig, Germany.

Further Qualifications

09/2021	**Agile Project Management Executive** | IUE Hochschule Basel
03/2021	**Scrum Master Professional** | IUE Hochschule Basel
01/2020	**Certificate in Teaching Didactics (Hochschuldidaktik)** | University of Basel

Further Education

07/2021	**Mixed Methods |** Berliner Methodentreffen **|** International Academy Berlin
11/2020	**Project Management – Toolbox for Scientists** | Transferable Skills **|** University of Basel
10/2020	**ZOOM@Novartis** | Graduate Center **|** University of Basel
09/2020	**Introduction to data analysis with R |** Transferable Skills **|** University of Basel
09/2020	**Basic-Life-Support & Automated-External-Defibrillator First Aid |** Reaplus
02/2020	**Increase your Wordpower |** Transferable Skills **|** University of Basel
11/2019	**Publishing Research Articles: Strategies & Steps |** Transferable Skills **|** University of Basel
10/2019	**Skills for Supervising Bachelor & Master Theses |** Transferable Skills | University of Basel
05/2019	**Good Scientific Practice |** Transferable Skills | University of Basel
04/2019	**Writing to be Published – Academic Writing |** Transferable Skills **|** University of Basel
09/2018	**Introduction to Regression Analysis |** Methodenwoche | University of Freiburg
02/2019	**Writing Productivity: Tools and Techniques** | Transferable Skills **|** University of Basel
10/2018	**Efficient scientific writing |** Transferable Skills **|** University of Basel
09/2018	**Introduction to Analysis of Variance** | Methodenwoche **|** University of Freiburg
09/2018	**Data Preparation & Missing Values** | Methodenwoche **|** University of Freiburg
04/2018	**Structural Equation Models with AMOS** | Methodenwoche | University of Freiburg
03/2018	**Articles in Sciences: Structure & Clarity |** Transferable Skills **|** University of Basel

Academic and Language Skills

MS Office	Advanced **|** Writing scientific articles (Word); Formulas, tables and plotting (Excel); Teaching and scientific presentations (Power-Point)
Endnote	Advanced **|** Literature management
SPSS	Advanced **|** Data preparation and analysis
R	Advanced **|** Data preparation and analysis Tables and Graph plotting
German	Mother tongue (C2)
English	Fluent in speaking and writing (incl. scientific articles and presentations; C1)
Portuguese	Intermediate (B1)
French	Intermediate (B1)