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Development of Executive Function in typically-developing preschoolers in relation to motor skill development

presented by
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Abstract

Executive Function (EF) is an umbrella term for higher-order cognitive skills, which build the basis for goal-directed behavior. In general, three separable, yet interrelated components are assumed, Inhibition, Working Memory and Shifting. Because of their predictive power for many positive outcomes, they are regarded as crucial competences for coping with various aspects of everyday life. Recent research has found evidence for an interrelation between EF and motor skills. Since both EF and motor skills develop rapidly during early childhood, this age range is of particular interest for research. The dissertation at hand aimed at providing more evidence for (a) age-related increases regarding two “core” Executive Functions, Inhibition and Working Memory, and (b) their proposed interrelation with fine and gross motor skills, both cross-sectionally and longitudinally.

The present research project was designed as a 3-year-longitudinal study with annual intervals. 170 normally-developing children between 3 and 6 years of age were tested at the first point of data collection. In the following two years, 109 and 60 children respectively participated again. At each interval, EF was assessed via performance-based tasks and parent ratings and motor skills were assessed via a standardized assessment battery.

The analyses of the cross-sectional data collected at the first point of data collection provide further evidence for age-related increases in Inhibition and Working Memory. Furthermore, a Structural Equation Model showed significant interrelations between fine motor skills and both EF components, and substantial, albeit non-significant, correlations between gross motor skills and both domains of EF. The analysis of the longitudinal data stated a significant prediction of Inhibition via gross motor skills one year earlier.

Although to a large part exploratory and hypotheses-generating, the results of the research project provide further evidence for an interrelation between EF and motor skills and give rise to the question, whether motor skills can be used in intervention studies aiming at the promotion of EF. However, due to the modicum of research regarding this topic in preschoolers, the results should be regarded first and foremost preliminary.

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1. Introduction

What discriminates human beings from animals, apart from other human-specific-competences such as verbal language, is the ability to regulate impulses and emotions and to act towards a goal, no matter how far from the present it might be (i.e., writing a dissertation over the course of a couple of years). This ability is often referred to as self-regulation. Self-regulated behavior is crucial for successful adaptation to social life, since every social interaction requires the compliance with normative rules. Many of these rules include the ability to control one's emotions and needs, i.e., controlling one's anger instead of shouting at another person; waiting in line instead of jumping the queue. The same applies for professional and academic life, which often requires the ability to pursue a task or goal over a longer period of time, i.e., an adolescent who decides to study medicine and pursues this goal over a couple of years of studying and gaining experience and finally earns a doctorate. This competence also requires the ability to delay immediate gratifications in favor of a long-term goal: In the example of the medical student, it is conceivable that he dispensed with going to college parties and instead decided to stay at home and learn for some exam. Longitudinal studies have stated the predictive power of early self-regulation and the ability to delay gratifications for many aspects of successful psychosocial functioning: Mischel, Shoda, and Rodriguez (1989) showed that self-regulation at age four served as a significant predictor for social competences, academic performance and stress management more than 10 years later. Besides, there is evidence that self-regulation outperforms even intelligence in its predictive power for academic achievement (Blair & Razza, 2007; Duckworth & Seligman, 2005). These findings illustrate the importance of self-regulation for individual success in life and explain why scientific research has focused intensively on this ability during the past decades.

As the cognitive basis for every self-regulated action, three separate, yet interrelated higher-order skills are widely acknowledged, namely Inhibition, Working Memory/Updating and Shifting/(Cognitive) Flexibility. These skills refer to the abilities to (a) ignore irrelevant stimuli, (b) maintain information in mind over a longer period of time and (c) switch flexibly between tasks. Altogether, they are referred to as “Executive Function” (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000).

The ability to self-regulate and the cognitive skills associated with this ability follow a protracted development across the lifespan (Blair, 2010; Wiebe & Karbach, 2018). Adults generally perform way better in these competences than young children do. Still, there seem to be specific time periods characterized by pronounced increases of the ability to inhibit prepotent behavior and act flexibly under changing circumstances: A critical life period is early childhood (Chevalier & Clark, 2018), which is marked by rapid changes in the brain regions related to Executive Function (Casey, Tottenham, Liston, & Durston, 2005). The associated increases in these abilities can be observed optimally in preschoolers: While temper tantrums and impulsive behavior are typical for two- and three-year-olds, schoolchildren are usually able to control their emotions and to sit still and wait their turn.

Another set of skills, which describe a crucial part of normal functioning, are motor skills. They are among the first skills to develop during human ontogenesis, but, just like Executive Function, show a protracted development (Diamond, 2000; Krombholz, 1985).

It has long been assumed that motor and cognitive skills were separate domains (Diamond, 2000). However, since neurobiological findings have proven simultaneous activation of brain areas involved in self-regulatory as well as motor processes, a close interrelation of these two domains has been assumed (Diamond, 2000). The development of motor skills can furthermore be regarded as a prerequisite for the development of cognitive skills, since the extension of motoric competences enables the child to progressively expand its horizon (Krombholz, 1985; Piaget & Inhelder, 1993).

Only recently, the interrelation between motor skills and Executive Function in children has become a topic of interest in scientific research (van der Fels et al., 2015).

The present thesis focuses on the development of Executive Function in normally-developing preschoolers and its relationship with motor skills.

In the first chapter, the theoretical background concerning the concept of Executive Function is presented and the attempt of a definition is made. For this purpose, a differentiation to the terms self-regulation and Effortful Control is made. Two important models of Executive Function, the “Unity and Diversity” and the “Hot vs. Cool” approach, are presented and the current research state regarding the conceptualization of Executive Function in preschoolers is explained. After that, the assessment of Executive Function across the lifespan is outlined with an emphasis on the assessment in preschoolers. Then, the development of Executive Function during childhood is presented and a short survey of influencing factors is given. This leads over to the second topic of this dissertation, the relationship between motor skills and Executive Function. In this context, a definition of motor skills is given and their development during childhood is presented. Then, the assessment of motor skills in preschoolers is explained. Next, the current state of research regarding the relationship of Executive Function with motor skills is explained. In the last part of the theoretical background, a conclusion is given and the implications for the study at hand are integrated. This leads to a presentation of the research project the present dissertation is based on. The results from this longitudinal research project are subdivided into three consecutive studies with different foci, which are presented then. In the last part, a discussion of the results regarding all three studies is given. Implications for theory and practice are derived and limitations are described. Finally, a prospect for future research is given.

2. Executive Function

For several decades, researchers from different scientific fields such as psychology, sociology and medicine have focused on the human ability to regulate their own behavior and act towards goals (Nigg, 2017), which has led to a large quantity of publications about this topic (Hughes, 2011). Since every discipline has used its own terms to describe the phenomenon of this ability, different terms and definitions have coexisted for the last decades (i.e., self-regulation, self-control, Effortful Control, Executive Function…), and there are no common definitions available, which puts forward a challenge for researchers in this scientific field. Some of these terms are often used synonymously, albeit there are certain differences between the terms and the underlying concepts they describe. In the following chapter, an attempt is made to define the term “Executive Function” on the basis to the most commonly used definitions and to distinguish it from other related terms while referring to its historical origins.

The term “Executive Function” (EF) originally stems from neuropsychological research and was used to summarize cognitive processes that were related to neural activation in prefrontal brain regions (Otero & Barker, 2014). It came up in the second part of the 20th century when patients with deficits in decision-making or planning of future actions were witnessed and their impaired abilities were related to damages in certain brain regions, such as the Prefrontal Cortex (PFC, Zelazo & Müller, 2004). A famous case is the story of Phineas Gage, a railroad foreman who survived an accident in 1848 in which an iron bar destroyed a big part of his frontal brain and who suffered from severe personality changes and impaired self-regulatory skills afterwards. Since then, there has been growing interest on the role of frontal brain regions in the governing or “executive” role in human behavior (Goldstein & Naglieri, 2014).

Other disciplines, i.e., developmental psychology, adapted the concept of EF and investigated its origin and development in clinical as well as healthy populations across the lifespan. When longitudinal studies (i.e., the well-known Dunedin study by Poulton, Moffitt, & Silva, 2015) revealed the important role of self-control for multiple important positive outcomes, this phenomenon increasingly became a major focus of interest. To date, several studies have found evidence for the predictive power of the ability to self-regulate for emotional well-being (Mischel et al., 1989) and academical success (i.e., Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; McClelland, Acock, & Morrison, 2006; McClelland et al., 2007) and have thereby supported the importance of this psychological ability for many domains of everyday life.

For a long time in the history of research concerning EF, it was assumed that this skill would not emerge before late childhood or adolescence (Anderson, 2002; Lurija, 1997) and would reach adult-level performance at about 10-12 years of age (Welsh, Pennington, & Groisser, 1991). Thus, it was concluded that no self-regulated behavior was existent until that age. However, during the last three decades a multitude of studies has proven considerable age-related changes in EF during early childhood (Carlson & Wang, 2007; Huizinga, Dolan, & van der Molen, 2006; Willoughby, Wirth, & Blair, 2012). These findings point to the fact that the ability to plan and execute behavior according to future goals develops significantly during this period, and are underpinned by observational findings about preschoolers' behavior: As can easily be observed, for a three-year-old it is a huge challenge to sit down and wait or to control his or her emotions, whereas a six-year-old is expected to do both over a longer period of time, especially in the school context. Younger children are more easily distracted by suddenly appearing stimuli; they have difficulties in focusing their attention and rely on set rules, instead of flexibly shifting their behavior when external circumstances have changed (Chevalier & Clark, 2018). These observations serve as proof for the rapid development of EF during early and middle childhood and the self-regulation of emotion and behavior it permits. But how can this improvement become possible?

Theories about the development of EF have been greatly influenced by neuropsychologist Alexander Romanowitsch Luria, whose neurodevelopmental model comprises several stages of human development which are associated with the maturation of certain brain regions (Luria, 1980). He postulated that environmental factors (i.e., cultural factors or sensorimotor input) would enhance cognitive abilities and that several brain areas would interact in order to enable normal psychological functioning (in contrast to the idea that single brain regions were responsible for either motor or cognitive processes). Since the PFC is functionally connected with every other brain region, it is sometimes labelled as the "control center" that gets input from all other brain regions and guides behavior towards long-term goals (Miller, 2000). However, it has to be mentioned that "Executive function is a result of complex interactions between many areas of the brain, and thus, the frontal lobes do not equal a central executive system and represent only one functional category within the frontal lobes" (Otero & Barker, 2014, p. 30).

Considering this remark, the fact that many studies have proven the simultaneous activation of prefrontal brain structures during tasks assessing EF (Diamond, 2013) supports the major role of the PFC in the development and execution of EF. Also, the observation that the development of EF parallels the development of frontal brain regions (Otero & Barker, 2014) in the way that improvements in EF coincide with growth spurts in these brain areas (Anderson, 2002) serves as additional proof. Thus, it can be concluded that the maturation of the PFC plays an important role in the development of EF during childhood. Neurobiological findings observed a peak in synaptogenesis as well as synaptic pruning during preschool years (depicted in Figure 1), which provide evidence for the dramatic changes the PFC undergoes in this time. Thus, the apparent increases of EF during preschool years attributed to the protracted maturation of this brain area (Anderson & Spencer-Smith, 2013) state that this age group is of particular interest for developmental research concerning EF. For this reason, the dissertation at hand focuses on the development of EF in preschoolers and investigates motor skills as one potential influencing factor for these skills.

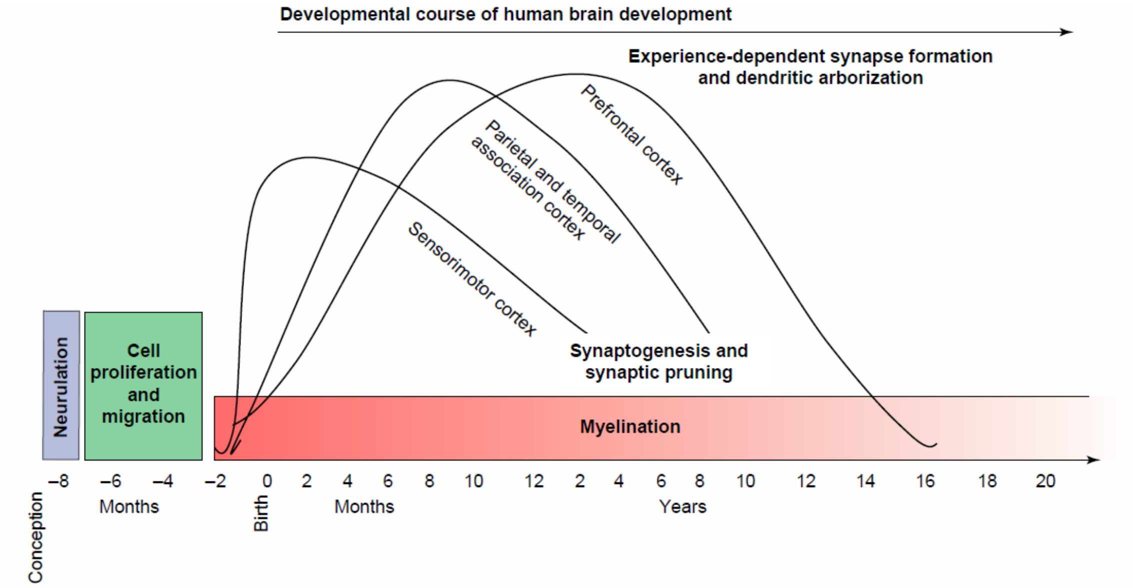

Figure 1. Structural architecture of the developing brain. Graphic retrieved from Casey et al., 2005, p. 105.

2.1 Definition of the term "Executive Function/s" and differentiation from related terms

As mentioned above, when dealing with EF as a scientific construct, it is not easy to find a generally accepted definition. Because of the variety of research fields in which this term is used today, different definitions exist highlighting the various aspects that are summed together under the term "Executive Function". In their up-to-date review, Baggetta and Alexander (2016) explain that within the huge number of studies investigating EF a variety of different definitions (or none at all) are used and that there is an overall lack of a common language. Goldstein, Nagliera, Princiotta, and Otero (2014) list more than 30 separate definitions of EF which have coexisted for the last three decades. The agreement on one common definition can be regarded as a desirable goal, as it would ease mutual understanding between researchers (Baggetta & Alexander, 2016); On the other hand, "premature consensus at this point would likely do more harm than good, as it would stifle innovation and make it more difficult to study all aspects of this complex construct" (Griffin, McCardle, & Freund, 2016, pp. 3–4).

To date, in spite of the variety of contexts in which this term is used, mutual consent seems that EF includes a series of higher-order, top-down regulated cognitive processes that aid in the planning and monitoring of actions (Baggetta & Alexander, 2016) and enable a person to act towards goals (Miyake et al., 2000). Therefore, EF is relevant to almost every domain of everyday life (for a comprehensive overview on this topic, cf. Diamond, 2013). It could be shown that EF is malleable throughout childhood and adolescence (Serpell & Esposito, 2016) and can be promoted through specific interventions (Diamond, 2012).

Typically, a number of several single cognitive processes are subsumed under the term EF, amongst others the ability to inhibit irrelevant stimuli, maintain and update information, plan actions in advance, and flexibly switch between several tasks (Goldstein, Naglieri, Princiotta, & Otero, 2014). In the dissertation at hand, the generic term EF is used, whenever the general cognitive ability needed in order to perform goal-directed behavior is addressed, whereas the single mental processes underlying this construct are referred to as "Executive Functions" (EFs).

A term that is closely related to EF is self-regulation, which is also defined inconsistently. While both terms are sometimes used synonymously

(Barkley, 2012), some distinctions between both concepts can be made: From a comprehensive point of view, self-regulation can be described as the motivationally-driven ability to mentally represent and manage emotional, behavioral and cognitive processes in an adaptive way without taking the bait when temptations are present (Hofmann, Schmeichel, & Baddeley, 2012). According to this perspective, EFs form the cognitive basis for every self-regulated action. Thus, both self-regulation and EF are goal-directed (Chevalier, 2015) and serve as a means to an end (Barkley, 2012).

Another term which is frequently used in this research field is “Effortful Control” (EC), which has been defined as an individual’s “ability to inhibit a dominant response and/or to activate a subdominant response, to plan, and to detect errors” (Rothbart & Bates, 2006, p. 129). EC is thought to be relatively stable over time and contexts (Eisenberg, Smith, & Spinrad, 2010). As a temperamental variable, it differs between individuals and influences behavior in every single moment (Posner & Rothbart, 2000) by actively controlling/regulating attention. Tasks assessing EC include measures for behavioral as well as attentional control (Eisenberg et al., 2010). While some aspects of EC and EF clearly overlap (Cuevas, Rajan, & Bryant, 2018), like the inhibitory component, the concept of EC has its origins in research about temperament, while the concept of EF originally stems from neuroscientific research (as described above). One difference between these two concepts is that EC, due to its stable aspect, is thought to be “bottom-up”-regulated, whereas EFs are “top-down”-regulatory processes (Diamond, 2013). Besides, EC is described as a unitary construct, whereas EF is defined as a multidimensional construct including several cognitive skills (EFs).

According to the current state of research, the heterogeneity in the research of EF represents the ongoing challenge for each scientific researcher to find their own appropriate point of view about the concept of EF. For the dissertation at hand, the proposal made by Gawrilow and Rauch (2017) to differentiate EF from self-regulation was selected: The authors explain that self-regulation can be defined as the ability to adjust thoughts, feelings and behavior in order to achieve one's aim in an optimal way. This ability therefore requires the use of several distinguishable EFs that (a) are helpful in the representation and monitoring of relevant information as well as (b) the inhibition of undesired impulses and (c) the ability to flexibly shift between the means to reach the desired outcome or even the outcome itself (Gawrilow & Rauch, 2017). Regarding this definition it becomes apparent that EF cannot be considered a uniform construct; a closer look at the conceptualization of EF is presented in the following chapter.

2.2 Conceptualization and theoretical models for EF

The lack of a shared understanding of EF has led to different perspectives on underlying theoretical models, yet overall agreement seems to be that "executive function is a multidimensional rather than unidimensional construct" (Baggetta & Alexander, 2016, p. 15). Still, different concepts of EF have emerged during the past decades, mostly divided by disagreement with regard to the number of dimensions that EF comprises. Two famous models of EF, the "Hot vs. Cool"-model and the "Unity and Diversity"-model, were chosen and will be presented in detail in the following chapters (for an overview on other existing models of EF, cf. Goldstein et al., 2014).

2.2.1 “Hot vs. Cool” EFs

This differentiation goes back to findings of patients with damages in the OFC (Bechara, 2004), that “provided strong support for the notion that adaptive decision making and related goal-oriented behavior cannot be explained entirely by “cold” cognitive processes” (Peterson & Welsh, 2014, p. 50). It refers to more emotion-based (“hot”) vs. more cognitive-based (“cold”) aspects of EFs and their underlying neural networks (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009). According to the neuropsychological finding that EFs are related to neural activation in prefrontal brain regions (Casey et al., 2005), an attempt made by Zelazo and Müller (2004) aimed at further differentiating activation in the orbitofrontal cortex (OFC) and the dorsolateral prefrontal cortex (DL-PFC) and their specific impact on impairments in certain aspects of EF: They described that damages in the OFC were usually related to “inappropriate social and emotional behavior” (Zelazo & Müller, 2004, p. 448), for example risky behavior, and defined these as “hot” EFs, whilst damages in the DL-PFC were usually related to impairments in “cool” EFs, that is, for example, planning of future actions without emotional or motivational involvement. This differentiation goes back to findings of patients with damages in the OFC who showed similar behavior in rather unemotional situations compared to healthy controls, but were more likely to show risky behavior in an emotionally or motivationally relevant context (Bechara, 2004).

Although “hot” and “cool” EFs are considered separable processes with specific underlying neural networks (Happaney, Zelazo, & Stuss, 2004), they both work together in order to enable normal psychological functioning in both motivationally and emotionally “hot” or rather “cool” situations (Zelazo &

Carlson, 2012). Supporters of this model argue that human behavior is seldomly independent from motivational or emotional influences and thus consider this a more realistic model of EF (Zelazo & Carlson, 2012).

2.2.2 The "Unity and Diversity"-model of EF

For a long time, there has been disagreement in research about the organization of EF, whether there was one unitary underlying factor (similar to the "g-factor" idea of intelligence, Duncan, 2005) or if there were several, distinguishable factors that should be subsumed under the "umbrella term" EF. Three often postulated factors were Working Memory/Updating, Inhibition and Shifting/Cognitive Flexibility.

Working Memory capacity is needed whenever an individual is presented with new information (Diamond, 2012), and can be witnessed in everyday activities such as reading, talking to others or doing mental arithmetic (Diamond, 2016). Neuroimaging studies showed that prefrontal brain regions, especially the dorsolateral and the parietal part, were activated when participants performed Working Memory tasks, suggesting that these brain regions are crucial for normal Working Memory functioning (Chung, Weyandt, & Swentosky, 2014).

Inhibition means the ability to stop an initial, impulsive response or an ongoing process in favor of a more elaborate response (Barkley, 2001). On a neurobiological base, inhibitory processes are associated with activation in the ventrolateral PFC and the inferior frontal gyrus (Chung et al., 2014). An example for Inhibition is the ability to stop walking when the traffic light has switched from green to red.

Shifting (also called Switching or Cognitive Flexibility) is referred to as the ability to switch attention between two or more relevant tasks (Miyake et al., 2000), or to change perspectives spatially as well as interpersonally (Diamond, 2013). It also involves flexibility in situations where the context or goal has changed, and it describes the opposite of rigidity (Diamond, 2013). The ability to shift between tasks is, e.g., observable in a working context when somebody focuses on writing an e-mail and suddenly another e-mail with a higher priority arrives and the person decides to answer this e-mail first.

An approach by Miyake, Friedman, Emerson, Witzki, and Howerter (2000) aimed at providing evidence on how EFs are organized: By conducting a confirmatory factor analysis on several established EF tasks assessing the three often formulated EFs Working Memory, Inhibition and Shifting in an adult population, their study highlights the unity as well as diversity of EFs by proposing a three-factor-structure of EFs with these three moderately interrelated, but clearly separate domains (Miyake et al., 2000).

Their findings significantly influenced research in the field of EF and, although originally developed for adults, received some support in younger populations: Lehto, Juujärvi, Kooistra, and Pulkkinen (2003) conducted a similar study with children between 8 and 13 years of age, using different tasks for the same three domains. They found similar results, that is a three-factor-structure with interrelated factors, that showed much better model fit than the unsatisfactory one-factor- model. In dependence on Miyake et al. (2000) they named the three factors Inhibition, Working Memory and Shifting.

Other studies with younger populations, ranging from 9-12 years (van der Sluis, de Jong, & van der Leij, 2007) and with a sample of four different age groups (7-, 11-, 15-, and 21-year olds. Huizinga et al., 2006), found evidence for the existence of only two separable factors, Shifting and Updating/Working Memory.

Following the results for a two-factor-structure of EF, a revised version of the “Unity and Diversity”-model was proposed in a more recent article (Miyake & Friedman, 2012), which proved a common EF factor as well as Updating-specific and Shifting-specific abilities (there are no Inhibition-specific abilities anymore, since precedent studies proved that the Common EF factor completely accounted for their variance, once it is added to the model). Figure 2 shows the initial model on the left and the revised model on the right.

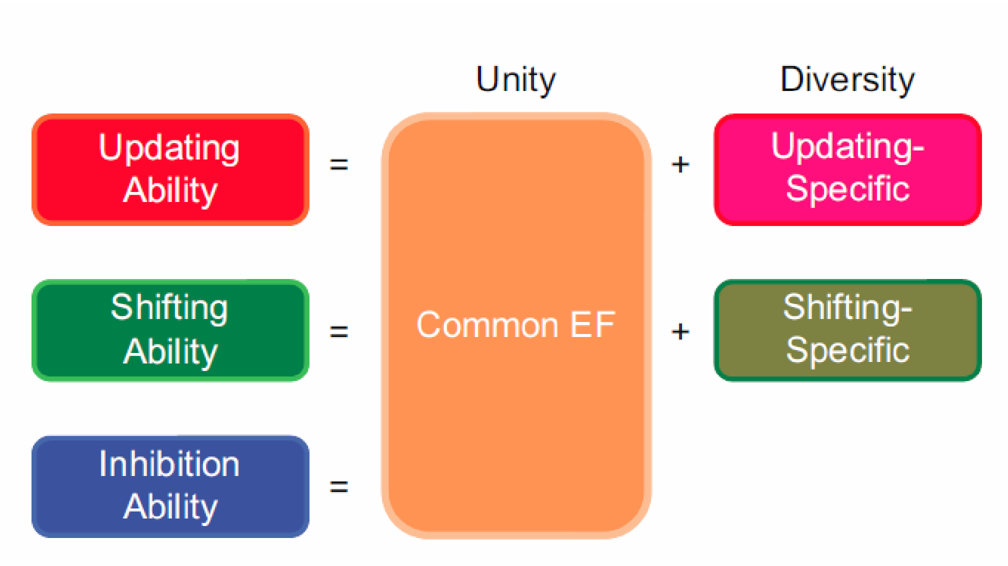

Figure 2. Schematic representation of initial (left) and revised (right) “Unity and Diversity”-model of EF. Graphic retrieved from Miyake & Friedman, 2012, p. 11.

In a nutshell, the theoretical idea of separate, interrelated factors of EF, as opposed to a unitary structure, has significantly influenced research and has gained general consensus (Diamond, 2013). Although the number of separate factors varies between studies and is still under debate, the theoretical conceptualization of the three principal EF factors Inhibition, Working Memory and Shifting is helpful for understanding that EFs are complex mental processes. Furthermore, this perception aids in the differentiation between situations or tasks in which a single one of these processes is especially required in contrast to situations where the interplay of several EFs is necessary.

In the dissertation at hand, EFs concerning the regulation of emotional processes are not in focus. Thus, the differentiation between “hot” and “cool” EFs is not appropriate. The understanding of EF is based on the “Unity and Diversity”-model and assumes that there are separate, yet related factors of EF.

2.2.3 Conceptualization of EF in preschoolers

As mentioned above, the idea of three principal components of EF has reached agreement for adult populations; however, the conceptualization of EF in children is still under debate. Many studies have tried to adopt the “Unity and Diversity”-model to preschool populations and thereby produced heterogeneous results: Some of them successfully replicated the original three-factor-structure (Espy et al., 2004), whereas others found evidence for a unitary EF factor (i.e., (Fuhs & Day, 2011; Wiebe, Espy, & Charak, 2008) or rather a two-factor-model (i.e., Lee, Bull, & Ho, 2013; van der Ven, Kroesbergen, Boom, & Leseman, 2013). These controversial findings about the conceptualization of EF in preschoolers brought up the idea that the factor-structure of EF might underlie age-related changes: In infancy and early childhood, EF might be a unidimensional construct, which during preschool years separates into two principal components, Inhibition and Working Memory, which in turn form the basis for the third and more complex component, Shifting (Diamond, 2013).

Supporting this hypothesis, evidence from developmental cognitive neuroscience suggests that certain kinds of switching are only possible after developmental changes in parts of the prefrontal cortex during ages 3 to 5 years (Bunge & Zelazo, 2016). The summary by Monette, Bigras, and Lafrenière (2015) about findings from multiple studies concerning the factor structure of EF in preschoolers supports this hypothesis: They proposed that the number of factors depends on the children's age (Monette et al., 2015). In three-year-old children, the existence of a unitary EF factor seems rather uncontroversial, as consistent results from studies investigating this age-group have shown (Wiebe et al., 2008; Wiebe et al., 2011; Willoughby et al., 2012). Still, it has to be noted that there was an absence of tasks assessing the Shifting component in these studies, so that a three-factor-model could not be tested. The construction of tasks assessing Shifting in children aged three years and younger seems rather difficult and can be considered a challenge for future studies (a study aiming at developing Shifting-tasks for children under the age of 3 is currently conducted at the laboratory headed by Prof. Dr. Sabina Pauen, Heidelberg).

Among studies investigating the factor structure of EF in four- and five-year-old children, both a single-factor-model (Fuhs & Day, 2011; Wiebe et al., 2008) and a two-factor-model (Lee et al., 2013; van der Ven et al., 2013) have found support. It should be noted, however, that there were methodological limitations in the studies supporting a single-factor-model, i.e., not measuring one of the principal factors of EF (Working Memory was not measured in the study by Fuhs and Day, 2011, and there were no tasks assessing Shifting included in the study by Wiebe et al., 2008), which significantly influenced the results: As Miller, Giesbrecht, Müller, McInerney, and Kerns (2012) could show, the absence of tasks assessing the Shifting component leads to the best fit for a one-factor-model, whereas a two-factor-model can be assumed when all three principal EF components are measured. This finding is supported by Monette et al. (2015), whose study included tasks measuring all three “core” EFs. Their analyses found the best model fit for a model comprising two distinct EF factors in preschoolers, namely Inhibition and Working Memory/Flexibility. According to this point of view, Figure 3 shows a model of EF proposed by Diamond (2013), which attempts to integrate hitherto existing theories about EF and related constructs, some of which have already been described above. Its structure is based on the “Unity and Diversity”-concept, since Inhibition, Working Memory and Cognitive Flexibility (that is Shifting) are thought to be the main components of EF. In contrast to the model postulated by Miyake et al. (2000), this model assumes that Cognitive Flexibility/Shifting emerges from the two other components and develops much later in life. Therefore, this model can be described as a kind of “developmental model for EF”, appropriate for children.

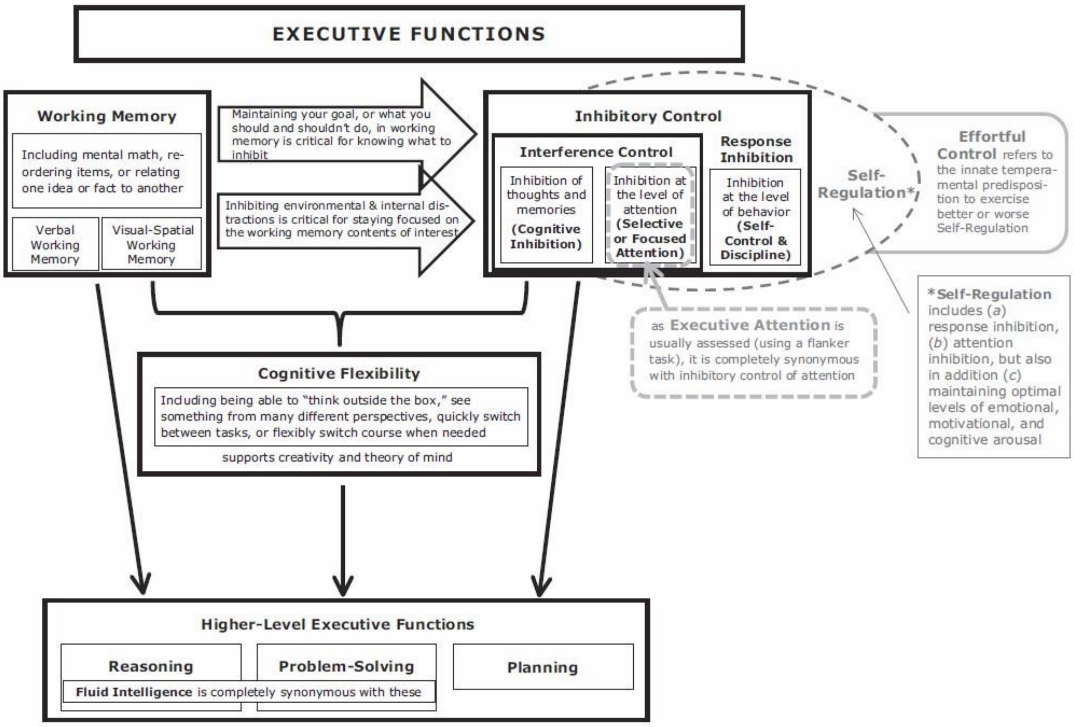

Figure 3. Definition of EFs and related terms and depiction of their interrelation and emergence. Graphic retrieved from Diamond, 2013, p. 152.

Research trying to find proof for the two dissociable constructs of "hot" and "cool" EF in preschoolers has not yet been successful (for a detailed review on this topic, cf. Peterson & Welsh, 2014), although, as mentioned above, EF guides behavior in emotional as well as cognitive contexts.

Taken together, scientists seem to agree that the structure and organization of EF might underlie fundamental changes across the lifespan in the form of a fractionation from a unidimensional towards a multidimensional structure (Cuevas et al., 2018; Monette et al., 2015): The three-factor-structure of EF that can be found in adolescents and adults (Miyake et al., 2000) might not yet be present in infancy, but seems to emerge during early and middle childhood. For the factor-structure of EF in preschoolers, both a one-factor and a two-factor-model have found support. Regarding methodological limitations among studies proposing the one-factor-model and recent evidence supporting the two-factor-model (Carlson, Faja, & Beck, 2016), for the dissertation at hand two distinguishable, yet interrelated components of EF namely Working Memory and Inhibition, are assumed in preschoolers and will be investigated further.

2.3 Assessment of EF across the lifespan

Since the construct of EF has its origin in neuropsychological research (as described above), the original way of assessing impairments in EF was via performance-based tasks which aimed at identifying cognitive deficits caused by traumatic brain injuries (Labudda et al., 2009) or developmental disorders characterized by impairments in EF, i.e., ADHD (Barkley, 2015). These tasks were typically conducted in a clinical, laboratory setting with a medical practitioner or psychologist as an experimenter and the patient as a subject. Therefore, many studies describing impaired EFs in patient with frontal lobe damages are single-case-studies (Bechara, 2004; Bechara, Tranel, Damasio, & Damasio, 1996).

A well-known task which has been used over decades to detect damages in the PFC is the Wisconsin Card Sorting Test (WCST, Nyhus & Barceló, 2009). In the original version of this game (Heaton, 1981), different cards have to be sorted by a certain rule the subject has to find out via trial-and-error and examiner feedback. After several correct trials, the rule is changed without warning. Finding the next rule requires mental set shifting. Of course, Working Memory and Inhibition skills are required as well during the whole game. Thus, the WCST is a combined measure for EFs. Another example is the Stroop task, invented by J. Ridley Stroop in 1935, which serves as a measure for Inhibition: In this task, color-words are depicted in the ink of either the same or a different color and the subject has to read the word aloud. Several studies replicated the finding that reading speed of a color-word is slower, if the word is written in a differently colored font (cf. MacLeod, 1991, for a review on the Stroop-effect).

In accordance with the differing theoretical definitions of EF, the assessment of this ability significantly depends on the underlying theoretical understanding of the construct: Supporters of the “Hot vs. Cool EF”-model usually differentiate tasks embedded in a highly emotional context for the assessment of the “hot”-component from purely cognitive tasks assessing the “cool”-aspects. An example for the assessment of the affective (“hot”) component is the Iowa Gambling task (Bechara et al., 1996), which requires the regulation of affect and motivation: In this task, the subject may choose cards from advantageous vs. disadvantageous decks. Subsequent choosing of disadvantageous cards leads to penalties (i.e., loss of play money), whereas the selection of cards from the advantageous deck leads to rewards. Tasks assessing “cool” EF are typically embedded in an emotion-free context, i.e., the Stroop-task.

From the perspective of the “Unity and Diversity”-model, it was a main target to select tasks which “purely” assess one of the principal components of EF, but this has proven to be difficult, because single EFs are often difficult to assess: Since “any target EF must be embedded within a specific task context (so that the target EF has something to operate on), any score derived from an EF task […] necessarily includes systematic variance attributable to non-EF processes associated with that specific task context […]. Unfortunately, this systematic non-EF variance and measurement error (random noise in the data) are substantial, making it difficult to cleanly measure the EF variance of interest" (Miyake & Friedman, 2012, p. 8). This challenge in the assessment of single EFs is described as the "task-impurity problem" (Miyake & Friedman, 2012). One solution to this problem was the use of latent variable approaches in order to find the underlying shared variance of multiple measures of the same EF component (Miyake & Friedman, 2012). Therefore, the use of several established performance-based measures for each single EF is recommended. According to the presented definitions of these EFs, tasks assessing Inhibition usually comprise a certain rule that conflicts with the prepotent response, whereas tasks assessing Working Memory usually require the subject to remember and update information in mind. In tasks assessing the Shifting component, there is always a change in the rule of the original task included or the subject is asked to switch between tasks.

As described above, tasks developed for the assessment of EFs were originally designed for patients suffering from impairments in these skills, but were later used for the assessment of EF in healthy adults. Furthermore, the awareness that EF is already present in infants and develops rapidly during early childhood (Chevalier & Clark, 2018) has led to a growing interest in the investigation of the development of EF. However, the assessment of EFs in preschoolers "has provided a number of challenges, both theoretical and practical" (Anderson, 2002, p. 69). In the following, several of these challenges are presented:

The assumption that EFs were not present before school-age was significantly influenced by the observation that children failed at mastering the performance-based tasks designed for adults (Wild & Musser, 2014). When simplified versions of these tasks were administered, results showed that even small children indeed disposed of EFs (Carlson, 2005; Diamond, 1990b). However, "in simplifying EF tasks for children there is a real danger of losing the critical EF component" (Hughes, 2011, p. 255).

Besides that, the methodology of data collection led to another problem: Since the concept of EF has emerged from neuropsychological research, a laboratory setting seemed the appropriate way for the assessment of EFs. Thus, according to the traditional ways of assessing EFs via performance-based measures, researchers tried to adapt already existing tasks designed for adults, such as the WCST or the Stroop-Task, to preschoolers' abilities. Since small children do not always show their optimal behavior in such a test session (Toplak, West, & Stanovich, 2013), a snapshot of their performance is subject to fluctuations caused by motivational influences.

Another problem that generated from the use of performance-based measures for the assessment of EF was the observation that some patients suffering from damages in frontal brain regions performed equally well in these tasks compared to healthy controls but struggled with coping the daily routine (Levine et al., 2011). In addition, when research about EF in children and adolescents revealed discrepancies in dependence of the information source (i.e., parents vs. teachers), critic came up on the influence of confounding factors as limitations for the ecological validity and generalizability of the findings (Roth, Isquith, & Gioia, 2014). Thus, apart from the tradition of conducting tasks with subjects in a laboratory, rating scales were developed, which were designed to assess everyday EFs in a naturalistic setting over a longer period of time. One of the first of these rating scales was the Behavior Rating Inventory of Executive Function (BRIEF, Gioia, Isquith, Guy, & Kenworthy, 2000), which was “developed to capture the behavioral manifestations of executive dysfunction across the lifespan” (Roth et al., 2014, p. 302). The BRIEF comprises a collection of items describing problematic behavior assigned to a specific EF skill (i.e., Inhibition), and subjects are asked to rate the amount of problematic behavior. To date, there are four different version of the BRIEF with self- as well as informant reports.

In the assessment of EFs in preschoolers, caregivers’ (parents and kindergarten teachers) perception of the children’s EFs has been considered an additional valuable and important source of information. The Preschool version of the BRIEF (BRIEF-P, German version: Daseking & Petermann, 2013) is appropriate for this way of assessment of preschoolers’ EFs. Studies using this rating scale proved a decrease in problematic EF behavior with increasing age (Huizinga & Smidts, 2011), thereby consolidating the findings from studies with performance-based measures stating increases in EF performance during preschool years.

Another challenge in the assessment of EF in preschoolers, especially in longitudinal studies, lies in the selection or development of tasks which are feasible with three-year-olds as well as six-year-old without producing ceiling effects (Carlson, 2005), which show internal as well as ecological validity and are reliable over time (Carlson et al., 2016). Carlson (2005) provides an overview of a variety of tasks measuring EF(s) in preschoolers and the task difficulty for three-, four- and five-year old children separately. The analyses of the majority of tasks show significant age-related improvements in EF skills during preschool years. This finding is in concordance with numerous other studies, which proved age-related increases in EF skills during preschool years both cross-sectionally and longitudinally (Cadavid Ruiz, Del Río, Egido, & Galindo, 2016; Carlson & Wang, 2007; Davidson, Amso, Anderson, & Diamond, 2006; Hongwanishkul, Happaney, Lee, Wendy S C, & Zelazo, 2005; Zelazo & Carlson, 2012).

Despite the above described challenges, to date a multitude of performance-based tasks exists, which can be administered across the whole preschool period (Willoughby et al., 2012), and during the past decades, numerous studies have proven their feasibility (Bassett, Denham, Wyatt, & Warren-Khot, 2012; Carlson, Davis, & Leach, 2005; Diamond & Taylor, 1996, only to name a few). Examples for these tasks are a simplified version of the Stroop-task, the Day-Night-Stroop task (Gerstadt, Hong, & Diamond, 1994) and other Stroop-like tasks like the “Shape Stroop” (Kochanska, Murray, & Harlan, 2000) or “Grass/Snow Stroop” (Carlson & Moses, 2001), which serve as measures for Inhibition. Working Memory is, e.g., assessed via digit span tasks, in which the order of the pronounced word has to be repeated in either the same or the reversed order (Davis & Pratt, 1995). However, due to the complexity of the construct of EF and the variety of skills that are subsumed under this term, it is not possible to measure EF with one single task (Chevalier & Clark, 2018). Thus, the use of multiple performance-based tasks as well as caregiver ratings is recommendable in order to capture EF from a holistic viewpoint.

Altogether, research about EF with healthy subjects employed performance-based measures from patients suffering from neurological damages in order to describe the development of EFs and its variations in normally-developing children and adults (for an extensive review on the development of EF across the lifespan, cf. Hughes, 2011, and Wiebe & Karbach, 2018). To date, a variety of tasks as well as rating scales for the assessment of EF in different age groups exists and has led to a multitude of studies providing a detailed view on the development of EF and its importance for normal psychological functioning.

2.4 Development of EF during childhood

The development of EF starts in infancy and continues throughout the whole lifespan paralleling the protracted maturation of anterior cortical brain structures (for an overview on this topic, cf. Wiebe & Karbach, 2018). However, there are certain phases that are marked by a more rapid increase in EF performance, i.e., early childhood (Chevalier & Clark, 2018) and adolescence (Crone, Peters, & Steinbeis, 2018). Since the dissertation at hand focuses on the development of EF in preschoolers, the presentation of the development of EF across the whole lifespan is renounced. Instead, an attempt is made to describe the developmental trajectory of EF during childhood, although it has to be mentioned that this is made difficult due to the multitude of research results on this topic (Hughes, 2011) and with regard to the above mentioned heterogeneity in the definition and conceptualization of the construct of EF.

Studies with infants of four months and older have provided evidence for the existence of basal Inhibition and Working Memory skills, which can be regarded as precursors of later EFs (for an overview on the emergence of EF in infancy, cf. Cuevas et al., 2018). Thus, even small children are capable of general forms of goal-directed behavior, although their attention is erratic and stimulus-driven. This "platform of rudimentary attention" (Chevalier & Clark, 2018, p. 30) describes the basis for the development of later EFs.

Toddlers' behavior is characterized by the inability to resist temptations (i.e., to delay eating candy although they are told to do so) and to overcome learned responses. Instead, young children show perseverative behavior (Diamond, 1990a). From infancy to middle childhood, EF undergoes profound changes regarding the conceptualization (as reported above) and the extent to which children at a specific age are able to perform a certain EF task, since performance in these skills increases steadily during the first years of life (Chevalier & Clark, 2018). Thus, it can be concluded that EFs in general show a rapid improvement during preschool years, although there is evidence that the development of single EF skills, i.e., Inhibition and Working Memory, seems to be independent (Huizinga et al., 2006) and to follow different temporal patterns across the lifespan (for an extensive overview, cf. Wiebe & Karbach, 2018).

Best and Miller (2010) provide an overview on children's development concerning inhibitory skills by listing studies using different tasks and describing age-related improvements. Accordingly, children's performance depends on task complexity and improvement of inhibitory skills can be observed until early adolescence. Nevertheless, there seems to be a more rapid improvement in preschool years (Anderson & Reidy, 2012) and a less steady improvement later on (Best, John, R. & Miller, 2010). Findings from parent ratings support the improvement in EF skills by stating a decrease in problematic EF behavior from childhood to adolescence (Huizinga & Smidts, 2011).

An important point that should be taken into consideration is that the selection of tasks significantly influences the results: Since tasks used for the assessment of Inhibition or Working Memory differ in their level of difficulty (Carlson, 2005), age-related increases in one single task might not necessarily equal the observed increase in performance in another task. Thus, when increases in both EF domains are observed, the task-dependency of the findings should always be kept in mind.

A general finding generated from studies investigating the development of Inhibition and Working Memory in preschoolers is that five- and six-year-old children outperform three-year-olds in tasks assessing both EF domains, irrespective of whether data were collected cross-sectionally (i.e., Carlson, 2005; Evers, Walk, Quante, & Hille, 2016) or longitudinally (Willoughby et al., 2012). In order to find out whether the increase of performance within this age range was constant, Willoughby et al. (2012) conducted a 3-year-longitudinal study with children who were three years old at the beginning of the study. They used tasks tapping the Inhibition as well as Working Memory component of EF and found that performance in both skills increased slightly faster between three and four years than between four and five years of age.

Over and above general age-related increases of both EFs, interindividual differences seem to be present, as suggested by a short-term longitudinal study (3-month-interval between both measurement points) with three- and four-year-old children) that stated significant stability of individual differences for two tasks assessing Inhibition (Bassett et al., 2012).

Taken together, the performance in tasks assessing EF increases rapidly during early childhood, which points to the fact that children both ameliorate their abilities to maintain and update information and to inhibit impulsive behavior. Besides, the improvement in these fundamental domains of EF leads to the emergence of more complex EFs, i.e., the ability to shift between two tasks.

2.5 Influencing factors on the development of EFs

Knowing that EF plays a major role in many domains of successful adaption to everyday life, interesting research questions in this matter are: Which factors influence the development of EFs and how can they be used in order to promote EF?

As an answer to the first question, some influencing factors have already been proposed; amongst these are gender and socio-economic status (SES). In many studies, it could be shown that girls outperform boys in EF tasks and are rated higher by caregiver reports (for a review on this topic, cf. Hosseini-Kamkar & Morton, 2014). Furthermore, a higher SES (often measured by parents' years of education or the family's average monthly income) is typically associated with better EFs (Bassett et al., 2012; Cadavid Ruiz et al., 2016; Cameron Ponitz et al., 2008). There is evidence that the quality of the children's home environment, i.e., sensitive parent-child-interactions and consistent positive parenting, serves as a mediating factor on this relationship (Finch & Obradovic, 2018). Apart from static and invariable factors (gender and SES), the quest for mutative factors has proposed several possibilities, and one of these potential influencing factors is physical activity. A positive effect of exercising on cognitive functioning in children has been proposed in several studies (Prakash, Voss, & Kramer, 2013): In one study, the positive effect of aerobic fitness on Inhibition as measured by the Stroop-task was found (Buck, Hillman, & Castelli, 2008). Also, better Working Memory was reported in high-fit as compared to low-fit children (Chaddock et al., 2010). The supposed mechanism of action behind this relation is the increased functional capacity of frontal brain regions as an effect of aerobic exercises (Prakash et al., 2013). According to findings that favor a positive relationship between physical activity and EFs in children, the use of activity games in classrooms or playgroups is recommended (McClelland & Tominey, 2016). Also, several training programs designed for preschoolers aiming at promoting EFs include activity games (Diamond & Lee, 2011; Kubesch & Walk, 2009; Tominey & McClelland, 2011; Walk & Evers, 2013).

Apart from the above mentioned influencing factors the dissertation at hand investigates a potential link between motor skills and EFs. This proposed relationship is the topic of the second part of this thesis. Thus, in the next chapter motor skills are defined and their development is shortly explained. After that, the hitherto existing literature concerning a possible connection between EFs and motor skills is presented.

3. Motor skills in preschoolers and their relation to EF

The development of motor skills is one of the crucial dimensions of human ontogenesis (Bös & Ulmer, 2003) and builds a necessary requirement for a child’s cognitive development. Milestones in motor development, i.e., crawling and walking, enable the child to broaden its mind: Through autonomous locomotion, a child can actively move towards interesting objects and thus expose itself with new stimuli (Lohaus & Vierhaus, 2013), which in turn leads to the development of neuronal connections. From this perspective, motor skills enable a child to progressively explore and thereby comprehend its living environment (Krombholz, 1985). Also, the promotion of motor skills leads to an increasing autonomy of the child. On the other hand, deficits regarding motor skills are often accompanied by a variety of problematic behaviors: Hence, Developmental Coordinative Disorder (DCD), a developmental disorder indicated by a significant delay in motor skills, is often accompanied by Attention-Deficit-Hyperactivity-Disorder (ADHD, Sergeant, Piek, & Oosterlaan, 2006).

During preschool years, a child's changes regarding body proportions and the maturation of the central nervous system significantly influence the development of motor skills (Vogt, 1978). Besides that, EFs show a rapid increase between 3 and 6 years of age, which explains why this phase is interesting for researchers focusing on the relationship between motor skills and EF.

In this chapter, the term "motor skills" is defined and the concept of fine vs. gross motor skills is explained. After that, the assessment of motor skills in preschoolers is outlined. Then, the literature concerning an assumed relationship between motor skills and EF is presented.

3.1 Definition and development of motor skills during early childhood

The term "motor skills" describes all kinds of internal processes that get input from sensory and cognitive systems and are regulated by certain subcortical and cortical brain regions including the cerebellum (Diamond, 2000) and primary motor cortex (Piek, Hands, & Licari, 2012) in order to enable the body to perform certain movements (Burton & Miller, 1998). It also refers to external, observable movements of the body itself (Voelcker-Rehage, 2008). Motor skills can be executed with or without conscious control (Krombholz, 1985). The term is discriminated from motor abilities, which describe the prerequisite for an individual to perform a certain movement (i.e., walking or throwing a ball) and can be differentiated in conditional and coordinative motor abilities (Bös, 1987).

The development of motor skills follows several principles, including the principle of the cephalo-caudal development (meaning that an infant learns to lift its head before it can control the trunk and extremities) and the proximo-distal development (gross motor skills are mastered before fine motor skills) (Vogt, 1978). Furthermore, early childhood is the phase of life in which motor skills develop at the quickest pace compared to all other life stages and motor skills that have been mastered cannot be unlearned (Vogt, 1978).

Regarding motor skills, it can be distinguished between body movements that include large muscular activation (gross motor skills) in contrast to those that use only smaller muscles (fine motor skills) (Krombholz, 1985).

Gross motor skills are defined as all kinds of movement functions that include the movement of the body as a whole, i.e., running, jumping etc. (Bott, 2015). The body needs physical balance, body awareness and muscular tension in order to perform gross motor movements (Pauen & Vonderlin, 2007). Fine motor skills refer to the movement of single parts of the body, i.e., facial movements, albeit the coordination of hand movements might be the fine motor skill which is most often referred to (Bott, 2015). Both fine and gross motor skills begin to develop during the prenatal phase and show a rapid increase during the first years of life (Lohaus & Vierhaus, 2013): Especially the first two years of life are a phase marked by rapid growth in the motoric repertoire and the majority of motor skills is usually mastered by children aged 8-10 years (Ahnert & Schneider, 2007; Piek et al., 2012), although the maximum performance is not observed before late adolescence (Ahnert & Schneider, 2007). The development of both gross and fine motor skills is influenced by biological (maturational), personal and environmental factors (Bös & Ulmer, 2003; Vogt, 1978). Maturational factors can be considered the basis for the emergence of motor abilities. Besides that, children benefit significantly from role models, who guide them in improving their motor skills (Vogt, 1978).

The biggest and most important changes in gross motor skills (also referred to as locomotion or locomotor skills) occur until the second year of life. During this phase, a newborn's innate reflexes gradually change into coordinated body movements (Lohaus & Vierhaus, 2013). In early childhood, the rudimentary movement abilities develop: The child learns to turn the whole body, to crawl, to sit down, and to lift itself and until the 16th month of life, most children learn to walk freely (for a good overview on the development of gross motor skills during early childhood, cf. Pauen & Vonderlin, 2007). The development of these abilities can be witnessed in every normally-developing child, albeit there are significant interindividual differences regarding the time of occurrence (Krombholz, 1985; Lohaus & Vierhaus, 2013; Pauen & Vonderlin, 2007). During preschool years, a rapid increase in motor skills and the development of general fundamental skills can be witnessed (Krombholz, 1985), which is biologically determined due to body growth processes and maturation of the central nervous system (Ahnert & Schneider, 2007; Piek et al., 2012) as well as the maturation of the body organs (Bös & Ulmer, 2003). The change in children's body proportions and the gain in physical strength lead to an improvement of motor skills: Through repeated rehearsal, motion sequences become more fluid and the body coordination is enhanced (Bös & Ulmer, 2003; Vogt, 1978). Also, motor abilities and motor skills are applied in different contexts and the learned motor sequences are combined into complex skills (Bös & Ulmer, 2003), with the effect that additional gross motor skills, i.e., throwing and catching or riding a bike, are added to the child's repertoire. The performance in tasks assessing gross motor skills (i.e., standing on one leg or forward bend) increases steadily between three and six years of age and the course of development does not differ in dependence of gender (Bappert & Bös, 2007, cf. also Vogt, 1978 for a detailed study on the development of a variety of motor skills during preschool years), albeit studies have shown that boys often have more proficient gross motor skills than girls of the same age (Robinson, 2011) and girls outperform boys in tasks tapping fine motor skills (Ahnert & Schneider, 2007).

From birth, fine motor skills (also called manual control) are crucial for the exploration of objects: In the first weeks and months of life, these objects are the child's own body parts (hands and feet), but soon after that the child begins to investigate its environment by holding objects in his or her hands and exploring them extensively. The development of the pincer grip at about 9-13 months enables the child to pick up and investigate even tiny objects (Pauen & Vonderlin, 2007). This skill is the basis for a variety of possibilities for tool use, i.e., the ability to hold a pencil properly and write with it. Although handwriting skills are hardly present before entry into elementary school, handwriting readiness and pre-writing skills develop during preschool years (Piek et al., 2012). Furthermore, fine motor skills enable the child to become more and more autonomous, insofar as the ability to eat and drink independently (between approximately the first and second birthday) and dress oneself, which most three-year-olds are proficient in (Pauen & Vonderlin, 2007), are milestones for independent and autonomous acting.

Taken together, rapid changes in motor skills occur during childhood. Until the sixth year of life, the initially entirely dependent infant develops into an autonomously acting child. Obviously, the most striking improvements take place within the first two years of life. During preschool years, these abilities are further refined and allow the child to develop additional motor competences regarding fine and gross motor skills.

3.2 Assessment of skills in preschoolers

Preschoolers' motor skills can be assessed via behavioral observation by caregivers and health practitioners (pediatricians, preschool teachers, occupational therapists). Furthermore, standardized tests batteries, which include tasks measuring specific fine and gross body movements, are helpful in order to evaluate a child's developmental state. Although there is no "gold standard" tool available in German language, there are several standardized developmental inventories, which include tests for the assessment of motor skills as well as other domains of children's development, i.e., cognitive, social, emotional and verbal development. The "Wiener Entwicklungstest" (Kastner-Koller & Deimann, 2012) and the "Entwicklungstest sechs Monate bis sechs Jahre (ET 6-6)" (Petermann, Stein, & Macha, 2008) fall in that category. Besides these, test batteries for the exclusive assessment of motor skills were designed. One of these is the “Motoriktest für vier- bis sechsjährige Kinder (MOT 4-6)” (Zimmer & Volkamer, 2015), which comprises 17 tasks measuring the subject’s developmental state. Information on reliability and validity as well as norms based on the data of over 2000 children are available. The test can be conducted with preschoolers aged 4-6 years, thereby excluding three-year-olds.

A test battery that covers the whole range of preschool years (3 to 6 years of age) and has been used in various, international studies (Piek et al., 2012) is the Movement-Assessment Battery for Children (German version: M-ABC-2, Petermann, Henderson, Sugden, & Barnett, 2011). It assesses coordinative motor abilities in three different age bands (3 to 6 years, 7 to 10 years and 11 to 16 years) via altogether 8 tasks. These tasks fall into three categories: Manual Dexterity (3 tasks), Aming and Catching (2 tasks) and Balance (3 tasks). Studies investigating the reliability and validity of the test are available. Besides that, the original norms based on data of over 1000 children were extended by data from a German sample. Due to its use in multiple, international studies the M-ABC-2 can be regarded as a useful tool for the assessment of fine and gross motor skills (Slater, Hillier, & Civetta, 2010).

3.3 Relationship between motor skills and EF in preschoolers

For a long time, motor and cognitive skills were considered as separate domains with independent underlying neurological processes and activated brain structures (Diamond, 2000). Nevertheless, the idea that motor and cognitive skills like EF are interrelated can be led back to developmental theorist Jean Piaget, who described how sensorimotor intelligence in infants develops as a prelingual precursor of later cognitive intelligence and how cognitive functions can only arise by reason of anterior sensorimotor experiences (Piaget & Inhelder, 1993). From this point of view, infants acquire knowledge through input provided in the course of advancing motor skills, which explains why developmental improvements in motor skills are often accompanied by enhanced cognitive abilities (Rosenbaum, Carlson, & Gilmore, 2001). With developing motor skills like crawling and walking, a child gets to explore its environment further, and every new experience stimulates cognitive development. Besides, a child's brain functions are not as specialized as an adult's brain functions, since the differentiation of brain areas that can be observed in adult brains has yet to emerge (Piek et al., 2012); therefore, the same brain regions that regulate cognitive functioning (mostly frontal regions) are activated when body movements are executed. Plus, body movements are not yet automated and therefore require higher cognitive control (Krombholz, 1985).

Several explanations can be taken into regarded when trying to explain the connection between motor and cognitive skills (van der Fels et al., 2015): First, with regard to the definition of EF and self-regulation (s. chapter 3.1), the relationship with motor skills seems quite obvious: Motor skills include not only the visible movement of body parts, but also the preceding cognitive processes that enable a movement to be reasonable and goal-directed (Cameron, Cottone, Murrah, & Grissmer, 2016). Self-regulatory processes involving Working Memory capacity are needed in order to monitor body movements; In addition, the inhibition of prepotent impulses is necessary for the correction of imprecise movements (Piek et al., 2004). Therefore, every motor action requires

EFs and, vice versa, every self-regulated action is made visible in overt behavior executed by body movements (Cameron et al., 2016). Second, as described before, early childhood is a time in which both motor skills and EFs show great improvement suggesting that these abilities “follow a similar developmental timetable” (Roebers & Kauer, 2009, p. 175) and might therefore influence each other. Third, neurobiological findings report simultaneous activation of areas both involved in motor and cognitive tasks (Marsh, Gerber, & Peterson, 2008), such as the PFC and cerebellum, the basal ganglia and the striatum (Diamond, 2000). Fourth, evidence from children with deficits in both EFs and motor skills might indicate a common cause (Sergeant et al., 2006): For example, children suffering from ADHD often also show impairments in motor coordination as well as fine motor skills (Pitcher, Piek, & Hay, 2003). Furthermore, in children with ADHD or DCD, Working Memory deficits can often be observed (Alloway, Rajendran, & Archibald, 2009).

Apart from the above-mentioned indirect evidence about the connection between EF and motor skills, data exploring the direct relationship between these two domains provide important information (Roebers & Kauer, 2009): Stöckel and Hughes (2016) found in their cross-section analyses that Inhibition and Working Memory capacity could significantly predict fine motor skills, as measured by the Manual Dexterity scale of the Movement-ABC, in a sample of five- and six-year-olds. Vice versa, Piek et al. (2008) reported that gross motor skills served as a significant predictor for Working Memory. Those controversial results show that the direction of the relationship between EF and motor skills is still unclear; there might be a direct effect from motor skills on EF or vice versa, or rather a bidirectional relationship. However, cross-sectional designs are not appropriate to answer questions about causality; in fact, longitudinal designs are needed in order to provide evidence for the direction of effect between motor skills and EF.

One longitudinal study was performed by Roebers et al. (2014). Their findings support the assumption, that EF serve as an important factor in explaining the association between motor skills and academic achievement.

In their systematic review, van der Fels et al. (2015) summarized findings of 21 articles about the relationship between motor and different aspects of cognitive skills in normally developing children and adolescents between 4 and 16 years of age. They report strong evidence against a correlation between EF and gross motor skills and some evidence for a weak to moderate correlation between EF and fine motor skills. As an explanation for this finding, they assume that the relationship between motor and cognitive skills might depend on the degree of cognitive demand needed for the execution of the motor action; following this idea, they hypothesize that fine motor skills have a higher cognitive demand compared to gross motor skills. The parallel activation of the cerebellum and PFC mentioned above serves as a neuropsychological supporting idea in this context. Furthermore, they found that the relationship of cognitive and motor skills seems to decrease in children older than 13 years, which might be caused by higher fractionation of the brain with age.

Taken together, there is plenty of theoretical as well as empirical evidence that points to an association between cognitive and motor skills. Preschool children are presented with new, challenging tasks on a daily routine and need EF in order to plan, monitor and control their actions and the associated body movements (Roebers & Kauer, 2009). Previous studies with children and adolescents using different tasks in order to assess EFs and motor skills were in the majority designed as cross-section-models and thus allowed only correlational analyses instead of evidence about causality. Current research states that there is no uniform relationship between general motor skills and EF (Cameron et al., 2016). Rather, there seem to be very specific interrelations depending on the aspect of EF and whether gross or fine motor skills are investigated.

3.4 Conclusion and research gap

The theoretical background of the thesis at hand was divided into two main parts. The first part centered around EF with the main focus on the emergence of EF in early childhood. A historical excerpt about the theoretical construct of EF was presented, in which it was illustrated that this concept has its origins in neuropsychology but has spread out into many other research fields. It was reported that EF is an important cognitive ability for coping with challenges in all areas of everyday life, which emerges during infancy and continues to develop throughout the lifespan; thus, it is an interesting topic for developmental psychology. Furthermore, an attempt was made to define this heterogeneous term, stating that EF is a multidimensional construct that includes a series of cognitive skills and serves as the neurocognitive basis for every goal-directed and self-regulated action. The challenges and incongruity regarding the conceptualization of EF were explained. Also, two major theoretical constructs, the “Hot vs. Cool EF” and the “Unity and Diversity”-concept were portrayed and it was explained that, for the dissertation at hand, the idea of two distinct, yet interrelated components, namely Inhibition and

Working Memory, was chosen as the conceptualization of EF in preschoolers. Besides, an outline on the assessment of EFs via performance-based tasks and rating scales was given and it was concluded that a combination of these measures would be appropriate in order to provide a comprehensive overview of the development of EF. Then, the development of EF during childhood was described: Studies reporting age-related increases of EFs from infancy to early childhood were presented. The question of influencing factors for the promotion of EF was raised and led to the second main topic, which focused on motor skills as a possible influencing factor for EF. For a better understanding of this proposed relationship, the definition and development of fine and gross motor skills was outlined: Age-related increases in motor skills during early childhood were described and the assessment of motor skills via standardized test batteries was introduced. Then, the current state of knowledge about the relationship between EF and both fine and gross motor skills was presented.

From the presented literature, it can be concluded that early childhood is marked by significant performance increases in tasks assessing EF (Carlson, 2005; Huizinga et al., 2006), and this change is confirmed by parent reports of EF (Huizinga & Smidts, 2011). However, the question of the conceptualization of EF in preschoolers is still under debate. Also, it is still to be discussed whether performance-based tasks and parent ratings of EF assess the same underlying latent construct (Toplak et al., 2013).

Furthermore, several studies have already pointed to a potential relationship between EF and motor skills in preschoolers (Davis, Pitchford, & Limback, 2011; Livesey, Keen, Rouse, & White, 2006; Roebers et al., 2014), yet the results are heterogeneous. Although a relationship between fine, but not gross motor skills has been proposed (van der Fels et al., 2015), more research is necessary to support these preliminary findings. Furthermore, many researchers have pointed out the necessity of longitudinal studies in order to assess the relationship between EF and motor skills over time, but so far only few have done so (Cameron et al., 2016). While information from studies with children suffering from self-regulatory or motor impairments served as a theoretical foundation for a link between these domains (Gawrilow, Kühnhausen, Schmid, & Stadler, 2014), studies with normative samples are needed in order to prove that these comorbidities do not appear coincidentally or are caused by mediating factors such as a lack of motivation (Roebers & Kauer, 2009).

4. The present research project

The present research project, which forms the basis of the dissertation at hand, was designed as a three-wave-longitudinal study with timely intervals of approximately one year between each point of data collection and the next. The main topic of the research project was the longitudinal relationship between motor skills and EF, although data about several additional variables (i.e., family routines, household chaos and parenting) were collected as well. A variety of performance-based measures for EF appropriate and feasible for children between 3 and 6 years of age were selected from the literature (Anderson & Reidy, 2012) and conducted. Also, parent ratings of EF were assessed. This multi-faceted approach allows the use of structural equation modeling, which circumvents the task-impurity problem mentioned above (Miyake & Friedman, 2012) by using a latent variable approach and thereby extracting a purer measure of Working Memory and Inhibition as separate domains of EF. It should be mentioned here, that no tasks assessing the Shifting component were included in the analyses. One task assessing Shifting had been conducted at the first point of data collection, but since three- and four-year-olds had performed an easier version of this task than five- and six-year-olds, it was excluded from statistical analyses. For the assessment of motor skills, a standardized test battery was chosen. All mentioned instruments were applied repeatedly over the course of the years with the participating children and their parents. The research project was approved by the local ethic committee.

In the interest of legibility, the central issues of the thesis at hand were split and three separate studies were created. Each study consists of a short introduction adapted to the specific research question, the methods and results section, and a short discussion. The three studies will then be followed by an extensive discussion, in which the main results of the studies will be summarized and implications for theory and practice will be presented. Besides, limitations of the research project will be mentioned.

Study 1 focuses on the development of EF in preschoolers, which has already been investigated in earlier studies. In addition to previous studies, the study analyzes age-related changes in two EF components, Inhibition and Working Memory, as assessed via performance-based measures and parent ratings. Thus, the study centers around the conceptualization of the underlying theoretical construct of EF as well as the question of whether these two different ways of assessment are appropriate in order to measure the same latent construct.

Study 2 aimed at presenting more information about the relationship between EF and motor skills in preschoolers. So far, the direct association between the two EF components Working Memory and Inhibition with fine and gross motor skills is still unclear. Thus, the second study focuses on the specific relationship between two principal components of EF, Inhibition and Working Memory, with fine and gross motor skills.

In Study 3, the longitudinal data concerning the relationship between EF and motor skills are analyzed in order to provide evidence for the direction of effect between these two domains. As in Study 2, Inhibition and Working Memory as separate components of EF as well as fine and gross motor skills were differentiated. Hence, a detailed analysis of the causality between these two “core” EFs and two main domains of motor skills is presented.

5. Study 1: Age-related performance increases in preschoolers' EF

5.1 Introduction

EF has been investigated thoroughly in the past decades, since these skills are positively associated with multiple important outcomes such as academic achievement (Blair & Razza, 2007; Brock et al., 2009). Many studies have already demonstrated age-related performance increases of EF in preschoolers (Carlson, 2005; Davidson et al., 2006; Zelazo & Carlson, 2012), stating that there is a rapid development of EF during preschool years, which appears to be associated with maturational and growth processes of the Prefrontal Cortex (Otero & Barker, 2014). Although the theoretical construct of EF in preschoolers is still controversially discussed, there is a broad consensus that EF comprises a multitude of cognitive top-down processes (Goldstein et al., 2014) that aid in the goal-directed planning and execution of behavior (Barkley, 2001). Former research concerning the factor structure of EF in preschoolers found evidence for two interrelated yet distinct factors of EF, which can be labeled "Inhibition" and "Working Memory" (Monette et al., 2015). Inhibition describes the ability to stop an impulsive reaction in favor of a more deliberate one (Barkley, 2001); Working Memory is needed for temporary storage and manipulation of information (Diamond, 2013).

In order to measure these constructs in preschoolers, two different ways of EF assessment are commonly used: Many studies present results collected from performance-based measures of EF, which can be conducted in the laboratory, demonstrate construct validity and little potential for observer bias

(Cameron Ponitz et al., 2008; Carlson, 2005). However, the assessment of preschoolers' EF via performance-based measures is laborious, since young children have limited attention capacity and get tired quickly (Anderson & Reidy, 2012). Therefore, the number of tasks that can be conducted is limited. In addition, critic came up on the exclusive use of performance-based measures of EF in preschoolers as being "too narrow and failing to accurately capture children's "real-world" functioning" (Liebermann, Giesbrecht, & Müller, 2007, p. 512).

The second way of assessing preschoolers' EF is via caregivers' (parents and kindergarten teachers) report, which allows a cross-situational assessment of more global aspects (Isquith, Crawford, Espy, & Gioia, 2005, p. 209) of EF in everyday life (Roth et al., 2014). Both ways of assessment have been used in studies investigating the development of EF in preschoolers and it has been assumed for a long time that they both measure the same underlying construct. However, Toplak, West and Stanovich (2013) recently conducted a meta-analysis investigating the interrelation between performance-based measures and rating scales of EF. They found only small correlations and hence came to the conclusion that there is no convergent validity observable between these two ways of assessment for EF. Thus, they suggest the use of both ways of assessment while carefully acknowledging that different aspects of EF are assessed. However, their analyses included no study with a non-clinical sample of preschoolers (Toplak et al., 2013) which means that the question about the convergence between performance-based measures and parent ratings of EF in preschoolers remains unanswered. Furthermore, alternative ways of statistical analyses to correlational analyses are needed in order to find out whether both ways of assessment actually measure the same underlying construct (i.e., confirmatory factor analysis, CFA).

Former studies proving age-related increases in Inhibition and Working Memory with preschoolers imply that especially between three and four years of age, a major improvement takes place (Bassett et al., 2012; Willoughby et al., 2012). However, they assessed these two EF factors via performance-based-measures (Cadavid Ruiz et al., 2016; Willoughby et al., 2012), but not via parent ratings. Since both caregivers' reports and performance-based measures assess different aspects of children's EF (Toplak et al., 2013), both ways of assessment should be used. Thus, the present study aimed at closing this gap by investigating the development of the two EF domains Inhibition and Working Memory in preschoolers via performance-based tasks as well as parent ratings.

Specifically, the present study aimed at answering the following research questions: (1) Is there an age-related increase in performance of Inhibition and Working Memory in preschoolers, which can be shown via performance-based measures as well as parent rating? A significant increase of performance with age was expected for performance-based measures as well as parent rating scales. (2) Do performance-based measures of Inhibition and Working Memory assess different aspects than parent ratings? Small correlations between performance-based-measures and parent ratings were expected; however, a CFA combining performance-based measures as well as parent ratings is expected to provide evidence for two distinct latent factors (Inhibition and Working Memory).

5.2 Method

5.2.1 Participants

Our sample consisted of 170 children between 3 and 6 years (*M* = 4.79 years, *SD* = 1.02) and their parents who took part in a 3-year longitudinal research project investigating the development of EF in preschoolers and its relationship with motor skills. Data were collected in a middle-sized German University town and families were recruited from local kindergartens and children's play groups.

Data from 15 additional children were excluded from the analyses due to the following reasons: language impairment (*N* = 2); the test session served as a pilot session (*N* = 3); families decided to withdraw from the study after the first test session (*N* = 7); children were not able to concentrate on the tasks, so that the session had to be terminated by the experimenter (*N* = 3).

Table 1 shows the descriptive statistics of our final sample concerning children's gender and age, and the family's migration as well as socioeconomic status. Gender was almost equally distributed (54.1% girls). Participants' socio-economic status was predominantly in the middle-to-upper regions as indicated by maternal education and family income.

Table 1

Descriptive statistics for the sample of Study 1

		%	*N*
Child gender			170
	male	45.9	78
	female	54.1	92
Age groups			170
	three-year-olds	26.5	45
	four-year-olds	31.8	54
	five-year-olds	24.7	42
	six-year-olds	17.1	29
Language(s) spoken at home			170
	only German	68.2	116
	mostly German	15.9	27
	German and another language	13.6	23
	another language than German	2.4	4
Maternal education			165
	certificate of secondary education	2.9	5
	general certificate of secondary education/ polytechnic degree	17.7	30
	qualification for university entrance	75.3	128
Average net family income per month in €			162
	1000 - 2000	3.5	6
	2000 - 3000	7.1	12
	3000 - 4000	24.1	41
	4000 - 5000	16.5	28
	> 5000	44.1	75

5.2.2 Procedure

The study was approved by the local ethic committee. Families were given two individual consecutive appointments for the assessments in our lab, which lasted between 60 and 90 minutes each. At the first session, parents (86% biological mothers) gave written consent for their child‘s participation. The children were then taken to a quiet room next door where the assessment took place by a trained student research assistant. Simultaneously, the parents were interviewed about their socioeconomic status and their child‘s motor and cognitive development by a second student research assistant. The second session took place 25 days later on average (*SD* = 20.6 days). The children’s assessment again took place in a separate room while parents filled out questionnaires concerning their children’s EF and family routines in the waiting room. After each session, the children received small toys and a certificate of participation as rewards for their participation.

Although the present study was part of a larger research project investigating the influences of motor skills and family routines on children’s development of EF, only the tasks that were analyzed within this study will be described at full length below. The tasks were conducted in a fixed order: Session 1: Verbal WM-Task, Session 2: Day-Night-Stroop-Task, Head-to-Toes-Task, Self-Ordered-Pointing-Task, BRIEF-P subscales (filled out by the parents).

5.2.3 Measures

Assessment of EF via performance-based measures

Altogether, four tasks were chosen for the assessment of EF, with two tasks assessing Inhibition and the other two tasks assessing Working Memory. These tasks were selected because they fulfilled the criteria reported in chapter 2.3 (applicable for this age-group, high ecological validity, etc., Evers et al., 2016).

The first was the Head-to-Toes (HTT) task (Cameron Ponitz et al., 2008), which can be described as a motor-stroop-task. Children were instructed to touch their head and their toes, as demonstrated by the experimenter, and then to do the opposite, that is to touch their head when they were told to touch their toes and vice versa. A short training was followed by ten test commands, which were given verbally without feedback from the experimenter. The maximum score was 20 points since children received two points for a correct response, one point for a self-correct and zero points for an incorrect response.

The second task was the Day-Night-Stroop task (Gerstadt et al., 1994). A set of four training cards and 16 testing cards was used, half of them showed a moon and stars, the other half showed a sun (we copied the graphical material used in the original study by Gerstadt et al., 1994, cf. figure 4, in order to facilitate a good replication effect). The procedure resembled the original procedure by Gerstadt, Hong, and Diamond (1994): Children were shown the picture of the moon and instructed to say “day” whenever seeing this card. After that, they were shown the picture of the sun and instructed to say “night” whenever seeing this card. There were two more training trials and the experimenter reassured that the children had understood the task by praising the child for a right answer and correcting them in case of an incorrect answer. After that, 16 test trials without feedback were given. Cards were presented according to a pseudorandom sequence. Children received one point for each correct answer and no points for an incorrect or revised answer. Therefore, up to 16 points could be achieved.

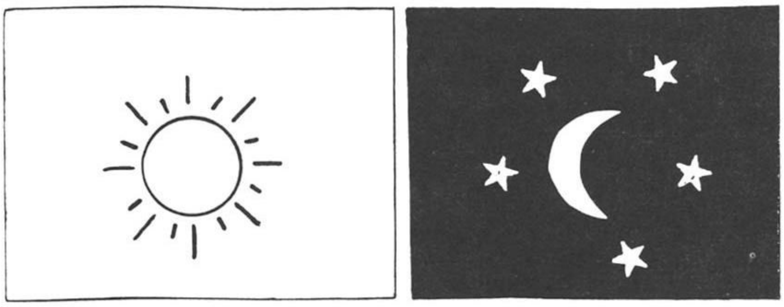

Figure 4. Graphical material used in the Day-Night-Stroop-Task (Gerstadt et al., 1994, p. 135).

The third task was an adapted version of the self-ordered pointing task (Hongwanishkul et al., 2005): Children were shown sets of different pictures of animated characters on laminated sheets of paper, ranging from two to nine pictures in each set. Their task was to pick a picture on each paper, and to remember to always choose a new one (but to never pick the same picture in a set twice). After two demonstration trials with two pictures, the test phase started and children received no feedback anymore nor were reminded of the rules. For each number of pictures there were two different sets, so that whenever children made a mistake in the first set, they were given a second chance. The task was terminated when children failed in both sets of the same number of pictures. The number of points children received in the task equaled the highest number of pictures in the last trial set they had responded correctly to, so that the minimum score was 2 and the maximum score was 9.

A verbal Working Memory task was based on the task “Phonologisches Arbeitsgedächtnis für Nichtwörter” of the “SSV – Sprachscreening für das Vorschulalter” (Grimm, 2003). This task is typically used to assess delay of language development in children between 3 and 6 years of age. In our sample, the task was supposed to assess the phonological part of WM skills.

The children were asked to listen carefully to made-up words (i.e., “Krapselistong”), which were read to them aloud, and then they had to repeat these words. The number of made-up words was 18 and for each word the children repeated accurately, they got one point, so that the maximum score was 18.

Assessment of EF via parent rating

In order to assess Inhibition and Working Memory via parent rating, the Behavior Rating Inventory of Executive Function – Preschool Version® (BRIEF-P, Daseking & Petermann, 2013) was chosen. The BRIEF-P is a standardized rating scale used to assess preschoolers’ EF via parent or kindergarten teacher reports “of everyday functioning in the realworld environment” (Roth et al., 2014, p. 301) and consists of 63 items that can be subdivided into 5 subscales (Inhibit, Shift, Emotional Control, Working Memory and Plan/Organize). The scales show good internal consistency (Cronbach’s alpha varies between α = .75 and α = .89 for parent ratings, Daseking & Petermann, 2013). The German version has been validated (Sherman & Brooks, 2010) and there are age- and gender-adjusted norms available. Children’s behavior is rated over a time frame of the last month on a three-point scale („never“ = 1, “sometimes” = 2, „often“ = 3). For the present study, the two subscales *Inhibit* and *Working Memory* were selected and are therefore presented more detailed:

The *Inhibit* subscale includes 16 items (i.e., item 54: “Has trouble putting the break on his/her actions even after being asked”) and “measures the individual’s ability to stop one’s own behavior at the appropriate time (i.e., the ability to inhibit, resist, or not act on an impulse)” (Roth et al., 2014, p. 303). The internal consistency for this subscale is good (Cronbach’s α = .89).

The subscale *Working Memory* of the BRIEF-P includes 17 items (i.e., item 59: “Has trouble remembering something, even after a brief period of time”) and “captures the capacity to actively hold information in mind for the purpose of completing a task or generating a response” (Roth et al., 2014, p. 303). Again, the internal consistency of this subscale can be considered good (Cronbach’s $\alpha = .88$).

Since higher scores represented inferior skills, the sum scores for all subscales were reversed in order to match the scores of the performance-based measures, in which higher scores represent better skills.

5.3 Results

5.3.1 Preliminary analysis

In the first step of the analyses, data of all performance-based measures as well as the parent ratings of EF were checked for ceiling effects and missings. Ceiling effects were found for the HTT ($M = 14.7$, $SD = 6.2$, $Mdn = 17.5$) and the Day-Night-Stroop-task ($M = 11.8$, $SD = 4.8$, $Mdn = 14$), since Median scores exceeded Mean scores in these tasks.

Missing data were found in the HTT and Verbal WM task, although the amount of missings was small (1% for the HTT and 2% for the Verbal WM task). Missing data were imputed via multiple regression imputation. There were no missing data in the two BRIEF-P subscales since the questionnaires were checked on completeness right after the parents had filled them out. None of the variables were normally distributed, as tested via Kolmogorov-Smirnov test (HTT: $D(170) = .23$, $p < .001$; Day-Night-Stroop task: $D(170) = .23$, $p < .001$; SoP: $D(170) = .14$, $p < .001$; Verbal WM task: $D(170) = .08$, $p < .05$; *Inhibit*:

D(170) = .1, $p < .001$; Working Memory: D(170) = .13, $p < .001$). There was no significant age difference between boys and girls (girls: M_{age} = 4.3 years, SD_{age} = 1.1; boys: M_{age} = 4.3 years, SD_{age} = 1.0 years, t(168) = .11, p = .91).

In the next step of the analysis, Means and Standard Deviations were calculated separately for each age group. As table 2 shows, a steady increase of performance in all performance-based measures dependent from age was evident. For the BRIEF-P subscales, the comparison of means between all age-groups also showed an increase with age for the *Working Memory* subscale. In the *Inhibit* subscale, a similar increase with age was observable, with one exception: Parents rated their five-year-old children on average a little lower compared to all the other age-groups.

Table 2

Means and Standard Deviations for the performance-based measures and BRIEF-P subscales, separated by age-group

Task	three-year-olds	four-year-olds	five-year-olds	six-year-olds
HTT	8.6 (6.9)	15.4 (5.6)	17.9 (2.0)	17.9 (2.8)
Day-Night-Stroop task	8.9 (5.5)	11.8 (5.0)	13.2 (3.5)	14.5 (1.6)
SoP	5.2 (2.1)	6.4 (2.0)	6.6 (2.1)	6.9 (2.2)
Verbal WM task	5.1 (3.6)	9.0 (3.9)	11.6 (2.7)	12.8 (2.9)
Inhibit	39.4 (6.2)	40.3 (4.6)	39.1 (5.4)	41.0 (4.0)
Working Memory	42.9 (5.2)	43.8 (4.9)	45.6 (5.2)	46.8 (3.0)

Note. Standard Deviations are shown in parentheses.

5.3.2 Effect of age

In order to assess the effect of age on performance in the EF tasks, the children of the sample were divided into four groups (three-year-olds: N = 45, four-year-olds: N = 54, five-year-olds: N = 42, and six-year-olds: N = 29) and a

MANOVA was calculated, which proved a statistically significant difference in performance in the EF tasks based on the children's age, F (9.2, 18) = 9.2, p < .001; Wilk's Λ = 0.416, partial η^2 = .25.

Since sample sizes between groups varied and Levene's test proved heteroscedasticity for the HTT (Levene's test, p < .01), Day-Night-Stroop task (Levene's test, p < .01) and Verbal WM task (Levene's test, p < .05), the Games-Howell was chosen for post-hoc-analyses of these tasks (Field, 2015), while Tukey (Janssen & Laatz, 2010) was chosen for the post-hoc-analysis of the SoP (Levene's test, p = .93).

The performance in all EF tasks increased significantly with higher age (HTT: F(3,166) = 32.53, p < .001, partial η^2 = .37; Day-Night-Stroop task: F(3,166) = 11.42, p < .001, partial η^2 = 17; SoP: F(3,166) = 5.35, partial η^2 = .09, p < .01; Verbal WM task: F(3,166) = 41.93, p < .01, partial η^2 = .43).

Figure 5 illustrates age-related differences for all EF tasks separate for each age group.

For the HTT, Games-Howell post-hoc analysis revealed statistically significant differences (p < .05) between all age groups, except for the comparison of five- and six-year-olds, proving that older children showed better performance in the HTT than younger children.

Comparisons of age-groups for the Day-Night-Stroop task showed that compared to three-year-old children, children of all older age-groups performed significantly better (p < .05). Also, six-year-old children had significantly higher scores than three- and four-year-old children respectively (p < .01).

In the SoP, three-year-old children gained significantly lower scores ($p < .05$) than children of all older age-groups. No significant differences were found for the comparisons between the other age-groups.

In the Verbal Working Memory task, there were significant differences between all groups ($p < .01$) except for the comparison of five- and six-year-old children.

Taken together, all of the performance-based measures proved significant age differences between three- and four-year-olds. Besides, two of the tasks (HTT and Verbal WM task) proved a significant increase of performance between four- and five-year-olds. In none of the tasks and rating scales, significant differences between five- and six-year-old children were present.

For the two rating scales *Inhibit* and *Working Memory*, the results of the MANOVA proved a statistically significant age-effect only for the *Working Memory* subscale ($F(3,166) = 4.47$, $p < .01$, partial $\eta^2 = .08$), but not for *Inhibit* ($F(3,166) = 1.14$, $p = .34$, partial $\eta^2 = .02$). Post-hoc-analyses of the *Working Memory* subscale via Games-Howell-test (Levene's test, $p = .01$) revealed that children age 6 received significantly higher ratings than three- and four-year-olds ($p < .01$).

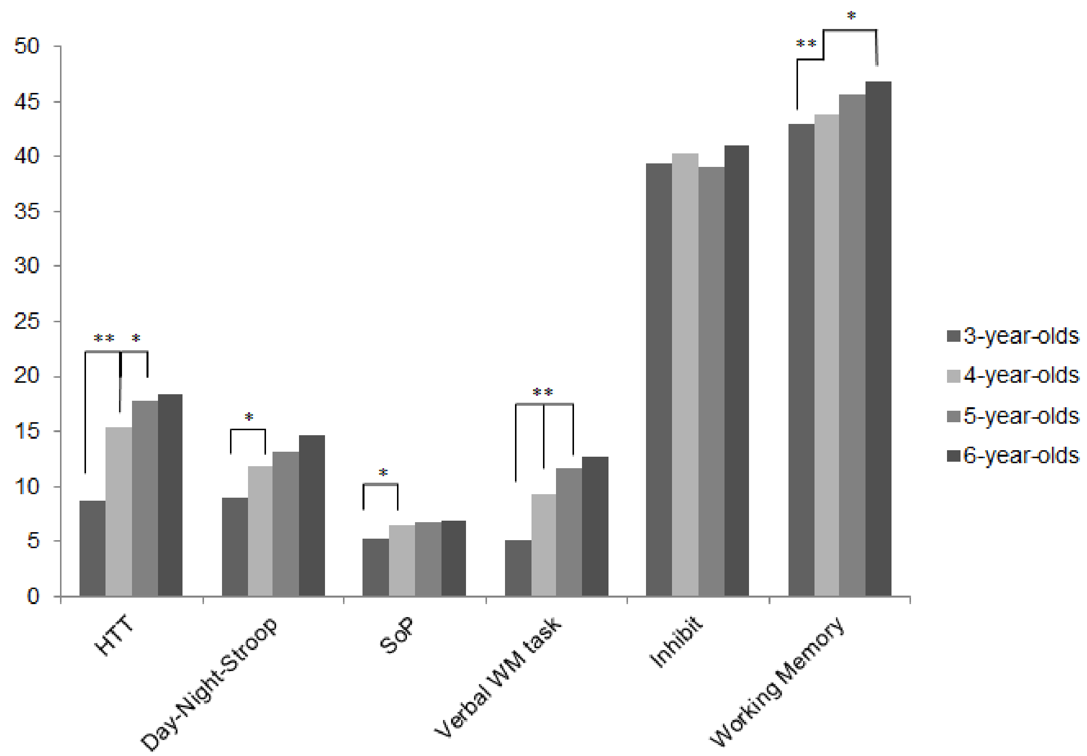

Figure 5. Graphical demonstration of age-related changes in EF. * *p* < .05; ** *p* < .01.

5.3.3 Interrelation of performance-based measures and parent ratings

In order to answer the question whether performance-based measures and parent ratings of the preschooler's Inhibition and Working Memory in our sample were interrelated, Pearson's correlations between all included variables were calculated and are presented in table 3. For the performance-based measures, significant medium-sized correlations were present between the HTT and all other tasks. Besides, the Verbal WM task correlated significantly with all other tasks. For the two BRIEF-P subscales *Inhibit* and *Working Memory*, there was a high significant correlation. Inter-domain-wise, small significant correlations of the *Working Memory* subscale with three of the four performance-based measures were observable. There were no significant correlations between the *Inhibit* subscale and the performance-based measures.

Table 3

Pearson's correlations between performance-based measures and BRIEF-P subscales

	1.	2.	3.	4.	5.	6.
1. HTT	-	.45**	.25**	.51**	.07	.18*
2. Day-Night-Stroop		-	.11	.36**	.07	.07
3. SoP			-	.28**	.15	.27**
4. Verbal WM task				-	.07	.23**
5. Inhibit					-	.59**
6. Working Memory						-

Note. * p < .05; ** p < .01.

Next, the CFA for the EF tasks was computed. It was assumed that the Day-Night-Stroop task, the HTT and the *Inhibit* scale would load on the latent factor "Inhibition" and that the SoP, the Verbal WM task and the *Working Memory* subscale would load on "Working Memory". The latent factors were assumed to be correlated. Also, an additional latent variable ("BRIEF-P") was added to the model as a nuisance factor loading on both BRIEF-P subscales, *Inhibit* and *Working Memory*, to "control" methodological variance caused by the different way of assessment. Figure 6 shows the whole model including the standardized regression weights and correlations between the two latent factors Inhibition and Working Memory. Model fit was assessed using χ^2-test, the Root Mean Square Error of Approximation (RMSEA), the Standardized Root Mean Square Residual (SRMR) and the comparative fit index (CFI). Values indicative of a good fit are a non-significant χ^2 at $p > .05$, a RMSEA < .05, and CFI > .95.

The model fit indices proved excellent model fit (χ^2 (df = 7) = 7.9, p = .34; RMSEA = .03; SRMR = .05; CFI = .99). All factor loadings were highly significant ($p < .01$) except for *Inhibit*, which showed only a small factor loading coefficient on the Inhibition factor.

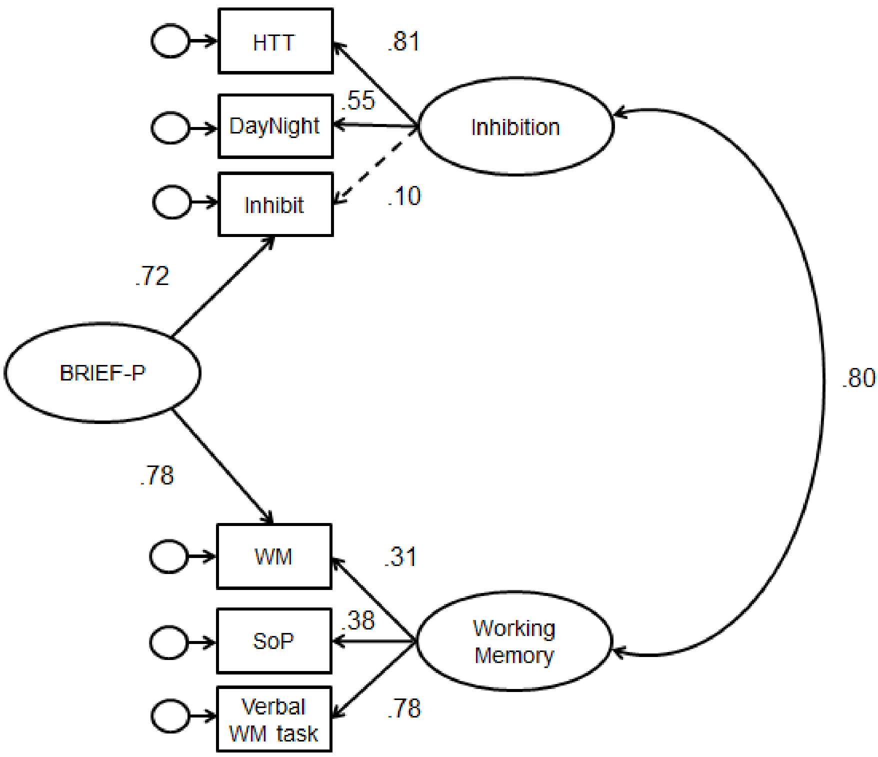

Figure 6. CFA of the two-factor-structure of EF. Standardized regression weights are presented. Dashed lines represent non-significant paths, solid lines represent significant paths (α = .01).

5.4 Discussion

The present study aimed at answering two different research questions: The first research question referred to age-related increases of performance in the two EF domains Inhibition and Working Memory in preschoolers. A general, age-related increase in both EF domains, which had already been demonstrated by a multitude of studies before, was evident in our sample as well: Significant increases of Inhibition and Working Memory were evident in all performance-based tasks and the *Working Memory* subscale, but not in the *Inhibit* subscale. A closer look at the items included in this subscale shows that many of these refer to a certain behavior of the child that can be observed within a social context of peers (i.e., “Needs more surveillance than other children of his age”). For parents with one child (24% of our sample), their child’s behavior in these situations cannot be observed on a daily basis, plus they cannot compare their child’s behavior to other children of the same age. Besides, high within participant variability is often characteristic of preschoolers’ performance in Inhibition (Livesey et al., 2006). For these reasons, it might have been difficult for the parents to witness age-related differences in this EF domain.

Our results indicate a major performance increase between three and four years of age, which has also been described before by (Hongwanishkul et al., 2005; Willoughby et al., 2012). However, a significant difference between three- and four-year-olds could only be found in all of the performance-based tasks, but not in the parent ratings. An explanation for these contradictory finding could be, that there actually is a major increase of Inhibition and Working Memory skills between three and four years of age, but that the parents do not expect this improvement to happen so early, perhaps due to limited knowledge about the emergence of EF in preschoolers. Thus, three- and four-year-olds were rated on an equal level of Inhibition and Working Memory skills by parents, and significant age-differences in Working Memory skills were only present when three-/four- and six-year-olds were compared.

The second research question addressed the question whether performance-based measures of Inhibition and Working Memory in preschoolers measure the same as parent ratings. Corresponding to former results (Toplak et al., 2013), zero-order to low correlations between performance-based measures and the two parent rating scales were found. The above mentioned methodological differences between the two ways of assessment can be taken as explanations for this finding: Performance-based tasks are designed to measure “maximal or optimal performance situations [...] under very structured conditions” (Toplak et al., 2013, p. 140) at one point of time and, at best, “purely” assess the investigated construct. In contrast to that, a child’s behavior, which can be assessed by parent ratings, is never an expression of “pure” Inhibition or Working Memory, there are always other variables included (situational context, level of motivation and attention vs. fatigue, parent-child-interaction and so on). But, as the results of the CFA indicate, both ways of assessment are appropriate to measure the underlying latent constructs Inhibition and Working Memory, as long as methodological differences are considered and “controlled”.

Regarding these methodological challenges, research investigating preschoolers’ EF should acknowledge that both ways of assessment tap different aspects of EF in preschoolers and should not be used interchangeably, but rather as additional sources of information about the construct of EF. Thus, the use of performance-based measures as well as parent ratings of EF in subsequent studies can be recommended and methodological differences between these ways of assessment should be considered and statistically controlled, wherever applicable.

Limitations

One limitation of Study 1 was the self-selected sample, which included only children with a middle-to-high socioeconomic background. For this reason, representability of the sample and generalizability of our findings are limited. Another limitation of Study 1 was the study-design: Data were collected cross-sectionally and therefore only limited conclusions can be drawn on the development of Inhibition and Working Memory over time. Longitudinal collections of data are much more convenient in order to supply information about person-related changes in EF over time.

6. Study 2: Relationship between EF and motor skills in preschoolers

6.1 Introduction

Good EF is a basic prerequisite for coping with challenges in daily life and outperforms even intelligence in its predictive power for several positive outcomes such as academic achievement (Blair & Razza, 2007) and psychological well-being (Poulton et al., 2015). In order to prevent negative effects caused by deficits in EF, it is important to find out which factors positively influence the development of EF, since scientific knowledge about influencing factors for EF can form an approach for the promotion of these skills. In early childhood and pre-school age, a child's brain underlies major structural changes and is extremely malleable (Casey et al., 2005). Thus, interventions are especially effective in early years, and therefore it is necessary to identify potential influencing factors as early as possible.

Since both motor skills and EF show a rapid increase during preschool years, an interrelation between these two domains has been hypothesized (Diamond, 2000). This idea is both supported by results from studies using performance-based tasks (Livesey et al., 2006; Roebers et al., 2014; Stöckel & Hughes, 2016) as well as brain imaging data (Piek et al., 2012), but the results are inconsistent: While some findings provide evidence for a strong relationship between these domains (Gonzalez et al., 2014; Piek, Dawson, Smith, & Gasson, 2008), others found only small correlations (Rigoli, Piek, Kane, & Oosterlaan, 2012; Roebers & Kauer, 2009).

In a recent review (van der Fels et al., 2015), findings from 21 studies with children and adolescents were summarized and the following conclusions were made: (1) There is no evidence for a general relation between these two domains; (2) When fine and gross motor skills are differentiated, there is evidence against an interrelation of EF and gross motor skills. (3) There seems to be a weak to moderate correlation between EF and fine motor skills, but the evidence is insufficient (van der Fels et al., 2015). Since the literature concerning preschoolers is scarce, it is questionable whether these findings also apply for this age group.

In preschoolers, EF can be differentiated into two main domains, Inhibition and Working Memory (Monette et al., 2015). Some studies concerning the interrelation of EF and both fine and gross motor skills in preschoolers measured EF as a uniform construct (i.e., Roebers et al., 2014) or investigated only one of these domains (Livesey et al., 2006). So far, only one study has focused on the separate investigation of these two domains in preschoolers (Stöckel & Hughes, 2016). Findings from this study indicate that both Inhibition and Working Memory are positively correlated with fine motor skills (Stöckel & Hughes, 2016). Yet, in this study gross motor skills were not assessed and each EF domain was measured by only one task. Thus, although some studies have already focused on the specific relationship between Inhibition and/or Working Memory with fine and gross motor skills respectively in preschoolers there is still a lack of research concerning both EF domains as well as fine and gross motor skills. Also, what is still missing is an approach to investigate this relationship on the basis of latent variables.

The present study attempts to close this research gap by examining the interrelation between fine and gross motor skills with the two principal EF components Inhibition and Working Memory in typically developing preschoolers. Over and above correlational analyses, results of a Structural Equation Model (SEM) will be presented.

Although the study is to some extent exploratory, hypotheses were derived from the presented literature and are as follows: (1) On the basis of correlational analyses, no overall relationship between tasks assessing Inhibition and Working Memory with tasks assessing fine and gross motor skills is expected; (2) On the basis of latent variables, (a) regarding gross motor skills, no relationship with preschoolers' Inhibition and Working Memory skills is expected. (b) A relationship between fine motor skills and the two EF domains Inhibition and Working Memory is expected.

6.2 Method

6.2.1 Participants

For the present study, the same sample as in Study 1 was used. Thus, participants and sample characteristics are the same described in Study 1. The final data set consisted of 170 children between 3 and 6 years (*M* = 4.79 years, *SD* = 1.02, 54.1% girls). Most of the children (89.4%) were right-handers according to parents' report.

6.2.2 Procedure

According to Study 1, the tasks were split into two test sessions and were conducted in a fixed order: Session 1: Verbal WM-Task, Movement-ABC tasks; Session 2: Day-Night-Stroop Task, Head-to-Toes-Task (HTT), Self-Ordered-Pointing-Task (SoP), BRIEF-P (filled out by the parents).

6.2.3 Measures

Measures of EF

For the assessment of Inhibition and Working Memory, the same performance-based tasks and parent ratings that were already described in Study 1 were used (c.f. chapter 6.2. for a detailed description of these measures). Altogether, there were four performance-based tasks (HTT, Day-Night Stroop task, SoP and Verbal WM task) as well as two subscales of the BRIEF-P (*Inhibit* and *Working Memory*).

Measures of motor skills

Motor skills were assessed via the Movement Assessment Battery for Children 2 (M-ABC 2, Petermann, Henderson, Sugden, Barnett, 2011). The M-ABC is an inventory assessing coordinative motor skills, i.e., the ability to precisely control and regulate movements (Petermann et al., 2011). It is a standardized battery providing standard values for three different age groups (3-6 years, 7-10 years and 11-16 years). Since our sample consisted of preschoolers, the tests for the youngest age group were selected.

All children in our sample completed the same tasks for the three subscales Manual Dexterity, Ball Handling Skills and Static and Dynamic Balance (= Balance). Table 4 shows a detailed description for each task. All of the tasks were explained and demonstrated by the experimenter to guarantee that the children comprehended the task.

Table 4

Detailed description of the Movement-ABC tasks

Task	Description	DV
Manual Dexterity		
Posting Coins (MD1)	The child is asked to put coins (6 vs. 12 depending on the age) into a box. For each hand, starting with the dominant hand, a training trial followed by a test trial is conducted. If the maximum time is exceeded, a second test trial is conducted.	Time (in seconds)
Threading Beads (MD2)	The child is told to thread beads (6 vs. 12 depending on the age). A training trial is followed by a test trial. If the maximum time is exceeded, a second test trial is conducted.	Time (in seconds)
Drawing Trail (MD3)	The child is told to draw a trail within two black lines. A training trail is followed by a test trial, only the dominant hand is tested. If the child turns the paper more than 45°, the trial is not rated and the child gets a second attempt.	Number of times the child drew above the line
Ball Handling Skills		
Catching a bean bag (BH1)	Both the child and the experimenter stand on a rubber mat 1.8m apart from each other. The child is supposed to catch a bean bag the experimenter throws. Five training trials are followed by 10 test trials.	Number of correct catches (max. 10)
Aiming a bean bag (BH2)	The child, standing on a rubber mat, is supposed to throw a bean bag on a rubber mat located 1.8m away. Five training trials are followed by 10 test trials.	Number of correct tosses (max. 10)
Static and Dynamic Balance		
Balancing on one leg (BL1)	The child is supposed to balance on one leg standing on a rubber mat for as long as possible (max. 30 sec.). Both legs are tested. If the child balances less than 30 sec. in the first trial, it gets a second attempt.	Time (in seconds, max. 30 sec.)
Walking on a balance beam (BL2)	The child is asked to balance on its toes on a 4.5 m long and 2.5 cm wide adhesive tape that was affixed on the floor. A training trial with a maximum of 5 consecutive steps is allowed. If the child makes less than 15 correct steps in the first trial, it gets a second attempt.	Number of consecutive steps (max. 15)
Hopping on mats (BL3)	Five rubber mats are placed on the floor, the child is told to stand on the first mat and make five consecutive hops by hopping on each mat only once. The child gets a second try, if it makes less than five correct consecutive hops in the first trial.	Number of consecutive hops (max. 5)

Note. DV = Dependent Variable.

Figure 7 shows the materials used for the three tasks assessing Manual Dexterity.

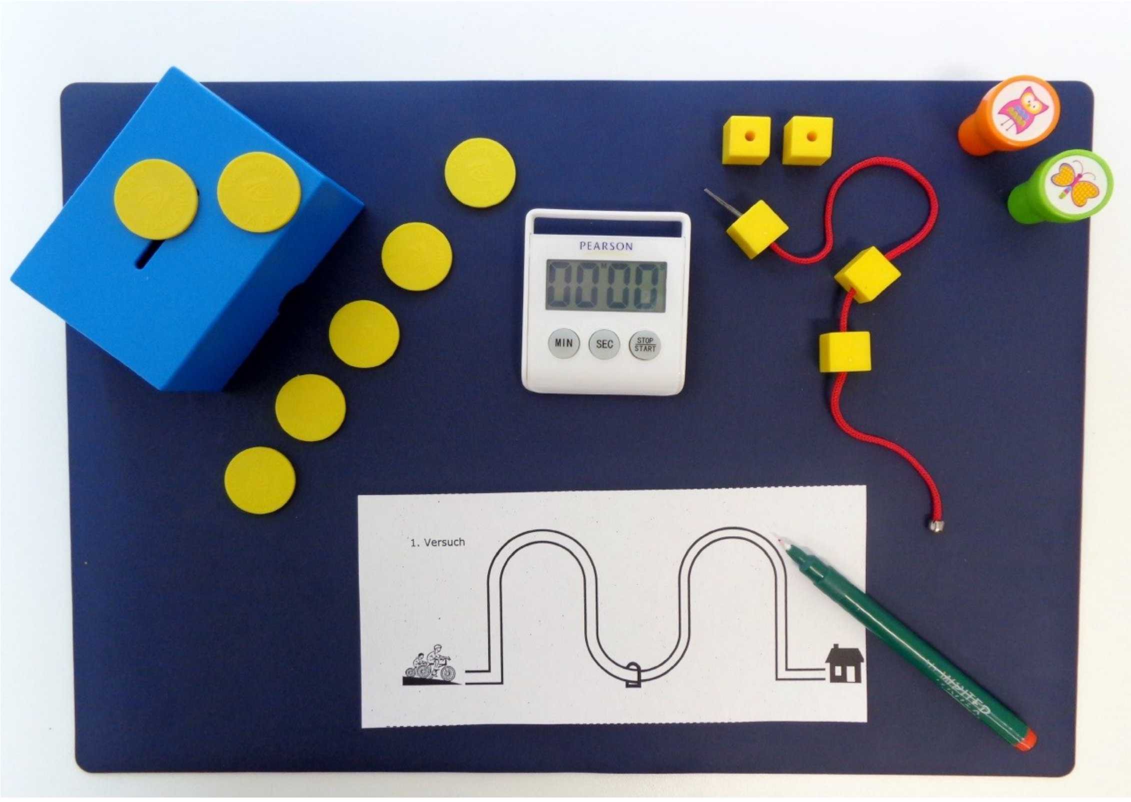

Figure 7. Test materials used for the assessment of the tasks “Posting coins” (top left), “Threading beads” (top right) and “Drawing trail” (below).

Since the raw scores for the two Manual Dexterity tasks “Posting coins” and “Threading beads” were not consistent because the number of coins and beads respectively differed between age groups (three- and four-year-old children received 6 coins or beads respectively whereas five- and six-year-olds received 12), the age-adjusted standard values for each of the eight tasks were taken into the analyses.

In the present study, the subscale Manual Dexterity served as a measure of fine motor skills, whereas Ball Handling Skills and Balance were considered as measures for gross motor skills.

6.3 Results

All analyses were calculated using IBM ® SPSS® Statistics 22 (IBM, 2013) and AMOS Graphics (Arbuckle, 2012).

6.3.1 Preliminary analysis

Table 5 shows the descriptive statistics for all included measures. As visible, the percentage of missing values was very small. Missing data were imputed via multiple regression imputation (the same procedure was already used in Study 1).

Table 5

Descriptive statistics for the tasks assessing motor skills and EF

	M (*SD*)	Min-Max	Missings (%)
Motor skills (M-ABC-2)			
Manual Dexterity	27.7 (6.1)	9-42	0
MD1	10.1 (2.4)	3-15	0
MD2	10.3 (2.8)	1-15	0
MD3	7.2 (3.7)	1-16	0
Ball Handling Skills	18.6 (4.6)	7-33	0
BH1	9.5 (3.3)	3-19	0
BH2	9.1 (2.8)	1-19	0
Static and Dynamic Balance	30.8 (6.0)	13-46	1
BL1	10.1 (2.9)	3-17	0
BL2	9.7 (3.2)	1-17	1
BL3	10.9 (2.5)	3-14	1
EF			
Inhibition			
HTT	14.7 (6.2)	0-20	1
Day-Night-Stroop task	11.8 (4.8)	0-16	0
Inhibit	39.9 (5.2)	22-48	0
Working Memory			
SoP	6.2 (2.2)	2-9	0
Verbal WM task	9.3 (4.4)	0-18	2
Working Memory	44.6 (4.9)	29-51	0

Note. M = Mean, *SD* = Standard Deviation, Min-Max = Minimum – Maximum. For the motor skills tasks, age-adjusted standard values are presented; for the EF tasks, raw scores are presented.

6.3.2 Interrelation between EF and motor skills

In order to investigate interrelations between the tasks assessing EF and motor skills respectively, correlations were calculated and are presented in Table 6. Since Study 1 had already proven age-related differences in preschoolers' EF, partial correlations controlling for age in both EF and motor skills were calculated as well. Within-domain wise, there were small significant correlations between the fine motor skills tasks. The two ball-handling tasks were not significantly correlated. Regarding Balance, BL1 and BL2 were significantly correlated, but neither of these tasks was significantly correlated with BL 3. Note that since age-controlled standard values were calculated for each motor skills task, Pearson's correlations and partial correlations hardly differed for these tasks. Inter-domain-wise, significant correlations between two tasks for Manual Dexterity (MD2 and MD3) and the HTT as well as between MD1 and *Inhibit* were found. Also, Manual Dexterity was significantly correlated with the two Verbal WM task and the *Working Memory* subscale. Ball Handling Skills showed significant correlations with both *Inhibit* and *Working Memory*.

Table 6

Pearson's correlations among all variables are shown above the diagonal, partial correlations controlling for age are shown below the diagonal

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
1. MD1	-	.35**	.16*	.33**	.07	.26**	.16*	.14	.02	.12	.18*	.10	.15	.24**
2. MD2	.35**	-	.14	.18*	.14	.30*	.24**	.12	.18*	.14	.13	.11	.19*	.12
3. MD3	.17*	.17*	-	.05	.07	.21**	.23**	.10	.25**	.03	.11	.08	.06	.09
4. BH1	.33**	.18*	.05	-	.11	.22**	.03	.24**	.05	-.07	.03	.10	.18*	.11
5. BH2	.06	.11	.08	.08	-	.20**	.22**	.08	.09	.09	.10	.21**	.15	.14
6. BL1	.25**	.29**	.23**	.23**	.17*	-	.43**	.11	.19*	.20*	.22**	.20*	.20**	.24**
7. BL2	.16*	.24**	.24**	.03	.22**	.41**	-	.09	.12	.05	.14	.17*	.04	.11
8. BL3	.16*	.12	.11	.23**	.07	.13	.09	-	-.10	-.02	.02	.02	-.03	.18*
9. HTT	-.03	.12	.33**	.03	-.04	.05	.09	-.11	-	.45**	.08	.25**	.51**	.18*
10. Day-Night-Stroop task	.09	.10	.02	-.11	.01	.06	.00	.00	.24**	-	.08	.12	.37**	.08
11. *Inhibit*	.18*	.12	.12	.02	.08	.20**	.13	.01	.03	.04	-	.15	.08	.59**
12. SoP	.09	.08	.10	.11	.19*	.11	.13	.04	.13	-.02	.14	-	.28**	.27**
13. Verbal WM task	.16*	.13	.10	.22**	.01	.02	-.05	-.03	.20*	.07	.04	.12	-	.24**
14. *Working Memory*	.24**	.09	.10	.09	.08	.20*	.09	.15	.04	-.03	.60**	.23**	.09	-

Note. * p < .05; ** p < .01.

In the next step of the analyses, the interrelation between EF and motor skills was investigated on the level of latent variables. As a preparation for the calculation of a SEM, the measurement model for both EF and motor skills were calculated separately via separate CFAs.

For EF, a two-factor-structure with the latent variables Inhibition and Working Memory with three indicator variables for each latent construct (Inhibition: HTT, Day-Night-Stroop task and *Inhibit*; Working Memory: SoP, Verbal WM task and *Working Memory*) had already been established in Study 1 (cf. chapter 6.3).

In order to check whether the three-factor-structure of the Movement-ABC was adequate in our sample, a CFA was computed via AMOS 21 (Arbuckle, 2012). Figure 8 shows the whole model including the standardized regression weights and correlations between the three latent factors. All paths were highly significant ($p < .05$). Model fit was assessed using χ^2-test, the Root Mean Square Error of Approximation (RMSEA), the Standardized Root Mean Square Residual (SRMR) and the comparative fit index (CFI). Values indicative of a good fit are a non-significant χ^2 at $p > .05$, a RMSEA < .05, and CFI > .95. The model fit indices proved acceptable model fit (χ^2 (df = 17) = 26.63, $p = .06$; RMSEA = .06; SRMR = .06; CFI = .92).

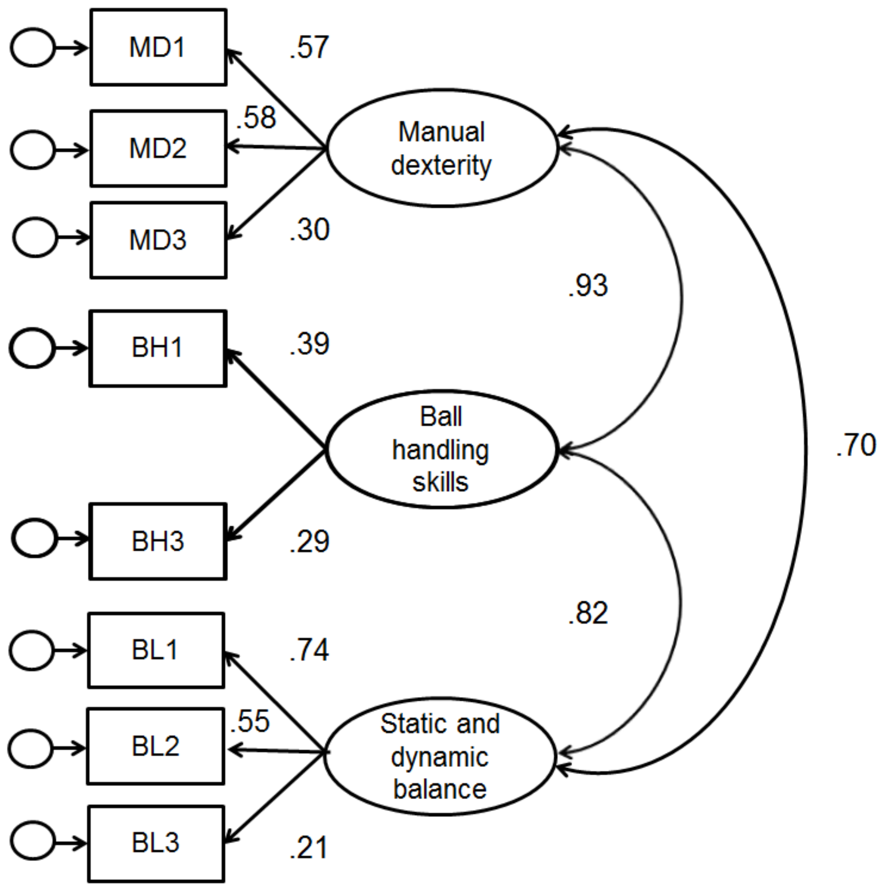

Figure 8. CFA stating the three-factor-structure of the Movement-ABC.

In the next step, both CFAs were combined into a SEM in order to test the hypothesis that there was an interrelation between the two EF domains Inhibition and Working Memory with fine and gross motor skills. Before the SEM could be calculated, data had to be prepared: The use of raw scores was not possible for the variables assessing motor skills (raw scores for the two Manual Dexterity tasks “Posting coins” and “Threading beads” were not consistent because the number of coins and beads respectively differed between age groups) and thus the age-adjusted standard values for each of the eight tasks were taken as indicator variables for the SEM. In order to control for age-effects (cf. Study 1) within the four performance-based measures of Inhibition and Working Memory (HTT, Day Night Stroop task, SoP, Verbal WM task) as well as the BRIEF-P scales *Inhibit* and *Working Memory,* age was controlled via regression analysis and the residuals were saved. Then, for each of the variables, these age-controlled error variables were inserted as indicator variables for Inhibition and Working Memory in the model.

In the hence resultant SEM, interrelations between the two domains of EF and all aspects of motor skills were assumed. The resulting fit of the model with the data was unsatisfactory ($p = .01$; RMSEA = .05; SRMR = .07; CFI = .88), which might have resulted due to a negative covariance between the two latent factors Ball Handling Skills and Inhibition. Therefore, in the next step Ball Handling Skills were excluded from the model. The new model (shown in figure 9) assumed interrelations between Working Memory, Inhibition, Manual Dexterity and Balance. In order to check for multivariate normal distribution of the used variables, Mardia's test (Mardia, 1970) was calculated. A significant result points to non-normally distributed multivariate variables. In this case, the use of Bollen-Stine's bootstrap is recommended (Bühner, 2011). Since the Mardia test was significant ($z = 1.84$, $p < .05$), Bollen-Stine-bootstrap was calculated. The model fit indices proved acceptable fit (χ^2 (df = 47) = 65.72, $p = .04$; Bollen-Stine-bootstrap: $p = .09$; RMSEA = .05; SRMR = .07; CFI = .91). As shown in the model, there were significant inter-domain correlations between Inhibition and Working Memory ($r = .54$, $p < .05$) as well as between Manual Dexterity and Balance ($r = .76$, $p < .01$). Cross-domain-wise, the correlations between the two domains of EF with Manual Dexterity were large and significant ($r = .47$, $p < .05$ for Inhibition and $r = .60$, $p < .05$ for Working Memory). Although the correlations between Balance and Inhibition ($r = .17$, $p =$

.25) or rather Working Memory (r = .26, p =.17) were not significant, they were still relevant in size.

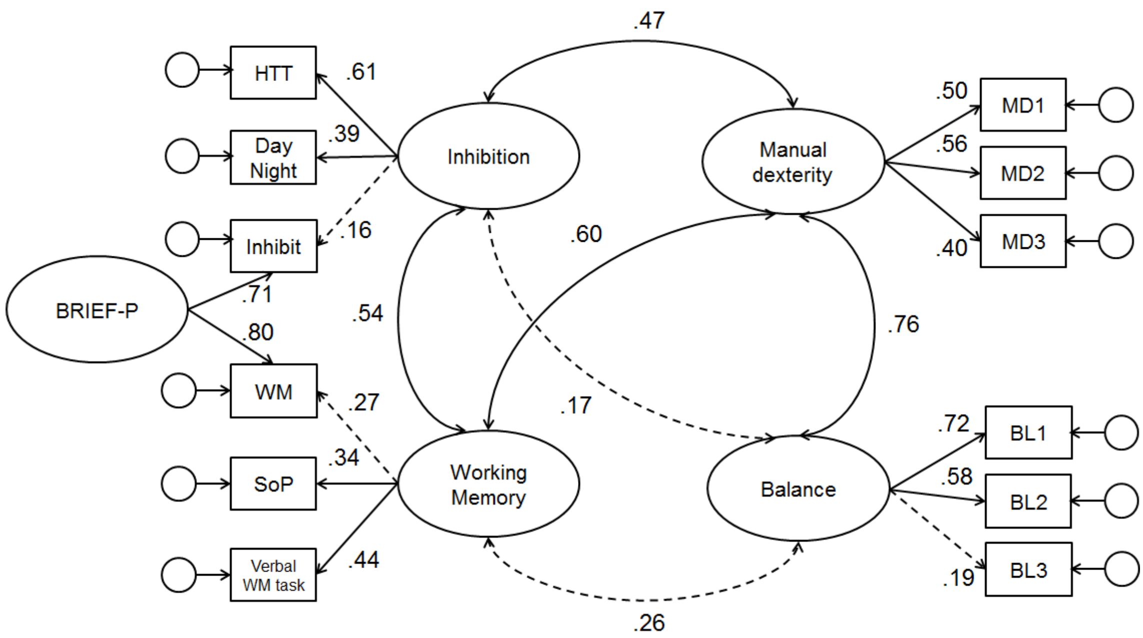

Figure 9. Structural Equation Modeling testing the interrelations between Inhibition, Working Memory, Manual Dexterity and Balance. Standardized regression weights are presented. Dashed lines represent non-significant paths, solid lines represent significant paths (α = .05).

6.4 Discussion

The literature about a possible link between motor skills and EFs in preschoolers is scarce, especially when a differentiated perspective on the conceptualization of EF is taken into consideration. The present study including three- to six-year-olds aimed at closing this research gap by investigating the relation between EF and motor skills. This link was explored on the basis of correlational patterns as well as a latent variable approach. It was hypothesized that no general relationship between tasks assessing the two principal EF Inhibition and Working Memory with tasks assessing fine and gross motor skills would be found. In the following, first the results of the correlational analyses will be discussed. Next, it will be explained why an approach on the basis of latent variables is recommendable, and the results of this approach in the study at hand are summarized and associated with results from former studies. In the last paragraph, implications for research and praxis are suggested.

The correlational pattern indicated the proposed task-dependent results, meaning that some EF tasks showed significant relations with some of the tasks assessing fine and gross motor skills and other did not. As expected, no overall pattern of an interrelation between the EF and motor skills tasks was observable. This finding could explain the heterogeneity of previous studies in this research field: If the level of interrelation between EF and motor skills is to some extent dependent from the selected task, it seems obvious that studies using different measures for EF produce diverse results. Thus, generalizability of results based on correlational analyses exclusively is hardly possible.

For this reason, an approach based on the level of latent variables was chosen. The results of the SEM show that the paths between the two EF domains Inhibition and Working Memory and fine motor skills were significant suggesting bidirectional associations between the included variables. Hence, our results seem to confirm the findings summarized in the review from (van der Fels et al., 2015) stating an interrelation between EF and fine motor skills and add to the hypothesis that these results might also be valid in preschoolers. Although there was no significant relationship between either EF domain with gross motor skills, the correlation coefficients were still relevant in size. Thus, the hypothesis concerning a possible relationship between gross motor skills and EF cannot be refused completely, albeit this relationship was visible to a much lesser extent compared to the interrelation between Inhibition and

Working Memory with fine motor skills. Certainly, there is need for further studies to confirm this hypothesis.

Further studies could include a higher number of measures for EF in order to strengthen the measurement models for each latent variable. Furthermore, other aspects of motor skills over and above fine vs. gross motor skills (that is bilateral body coordination or timed performance in movements) to supply additional information about the relationship of EF with these aspects.

Implications of the findings

Although the design of the present study is not adequate to generate evidence about causality, it could be assumed that the direction of effect might be in the way that fine motor skills (and to a lesser extent also gross motor skills) would influence EF. This hypothesis gives reason to the possibility of improving EF via motor activity. Since EF are key predictors for many positive outcomes such as academic achievement (Blair & Razza, 2007), it is necessary for caregivers to detect EF deficits and to promote EF skills as early as possible. Intervention programs designed to promote children's EF through activity, that is aerobic exercises (Davis et al., 2011) or martial arts (Lakes & Hoyt, 2004), were already found to be successful. Yet, these programs included exercises promoting gross rather than fine motor skills. It might be interesting for future studies to design programs in which tasks that focus on fine motor skills will be included and to compare these to the programs mentioned before.

Limitations

Just like Study 1, the present study is subject to two major limitations: The first is the self-selected sample, which included only children with a middle-to-high socioeconomic background. For this reason, representability of the sample and generalizability of our findings are limited. The second limitation is the cross-sectional study-design, which lowers the possibility to provide information about the direction of the relationship. It would be interesting to analyze data from longitudinal studies in order to answer the question of whether better (fine) motor skills promote EF during preschool years or vice versa. For this reason, a longitudinal study was conducted and the will be presented next.

7. Study 3: Longitudinal analysis of the relationship between EF and motor skills in preschoolers

7.1 Introduction

A proposed relationship between EF and motor skills is still under debate, as discussed in Study 2. There is evidence pointing to a moderate interrelation between motor skills and EF in children and adolescents, which might be higher regarding fine and lower regarding gross motor skills (van der Fels et al., 2015). However, the literature concerning preschoolers is scarce, and most of the studies investigating this potential link included cross-sectional analyses, which have only limited explanatory power with regard to the direction of effect, i.e., whether EF can be predicted by gross motor skills or vice versa. In order to answer this research question, longitudinal study designs are needed. Roebers et al. (2014) studied the relationship of fine motor skills and EF including 169 children. They found significant correlations between fine motor skills and tasks assessing EF one year later, but non-significant paths in a SEM for the prediction of EF via motor skills and vice versa. Although there is evidence for a two-factor-structure of EF in preschoolers (Monette et al., 2015) with Inhibition and Working Memory as two separable components, interestingly Roebers et al. (2014) measured EF as a unitary construct. The relationship between EF and gross motor skills was not investigated in this study. Gonzalez et al. (2014) found that EF, as measured by parent ratings, predicted one aspect of fine motor functioning, hand use, and vice versa. However, their study included only a rather small sample of only 19 preschoolers, and gross motor skills were not assessed.

Thus, a detailed investigation of the relationship between EF with fine and gross motor skills is still missing. The present study aimed at answering the following research questions: (a) Is there a developmental (temporal) relationship between EF and (fine and gross) motor skills? And if so, (b) what is the direction of the relationship: Do early motor skills predict later EF or vice versa?

7.2 Method

7.2.1 Participants

Families of the children, who participated in Study 1, were informed that they took part in a longitudinal study with three consecutive points of data collection at annual intervals. Each time, they were (re)-contacted via telephone calls and invited to participate. Therefore, modes of participant recruiting and testing were the same as in Study 1. For a detailed sample description, cf. Study 1. Since the study was designed for preschoolers aged 3-6 years, children naturally dropped out after their seventh birthday. This was the main reason for dropout (N = 29 children at t2 and N = 30 children at t3). Besides that, many families refused to participate at t2 and t3 stating that participating again would require too much temporal and logistic effort (N = 23 at t2 and N = 12 at t3).

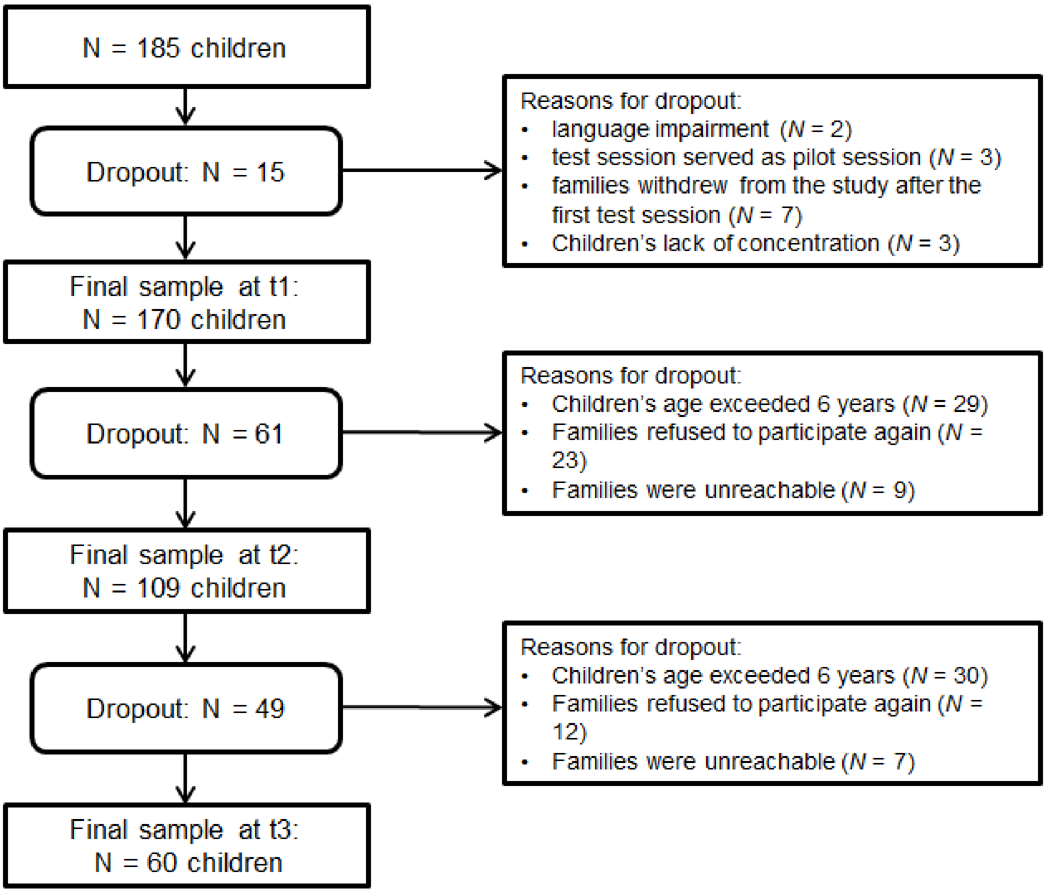

Figure 10. Participant flow chart of the 3-year longitudinal study.

7.2.2 Procedure

The assessments took place over a course of three years. At each point of data collection (t1, t2 and t3) the procedure equaled the one described in Study 1: Families were given individual appointments in our laboratory and the child was tested in a quiet room while the parents waited in the room next door filling out a questionnaire (cf. Study 1 and 2). Due to the high number of performance-based measures and in order to avoid symptoms of fatigue and decrease of motivation of the participating children, the tests were split into two test sessions, which lasted about 45 to 60 minutes each. At each point of data collection, the conducted tasks were presented in a fixed order: t1: Session 1: Verbal WM task, Movement-ABC tasks, Session 2: Day-Night Stroop task, HTT, SoP; t2: Session 1: HTT, Movement-ABC tasks; Session 2: Balance Beam task, Forward and Backward Digit Span, SoP; t3: Session 1: HTT, Movement-ABC tasks; Session 2: Balance Beam, Forward and Backward Digit Span, SoP.

7.2.3 Measures

Assessment of Inhibition and Working Memory

Several performance-based tasks were used for the assessment of Inhibition and Working Memory, which slightly differed between the three points of data collection mostly to prevent training effects. The resulting tasks for each point of data collection are described in the following:

At t1, the four performance-based tasks that were described in detail in study 1 were used, namely HTT and Stroop task (Inhibition) and SoP and Verbal WM task (Working Memory; for a detailed description of these tasks, cf. Study 1). At t2 and t3, the HTT and Stroop task were supplemented by the Balance Beam task as an additional measure for Inhibition. In order to prevent training effects in the Stroop task, the graphical material varied at each point of data collection (sun vs. moon at t1, boy vs. girl at t2 and fish vs. birds at t3).

For the assessment of Working Memory at t2 and t3, the SoP was used again; only the graphical material was extended (12 instead of 9 picture sets). Also, the Backward and Forward Digit Span tasks were conducted.

A detailed description of the additional or alternative tasks used at t2 and t3 follows:

Balance Beam task (BB)

The Balance Beam task, a measure for preschoolers' Inhibition, was conducted according to Bassett et al. (2012): The children were asked to walk on a 4.5 m long tape (the same stripe was used for the BL2 task of the Movement-ABC). In the next trial, they were told to walk “really slowly”, and in the third trial they were told to “walk as slowly as possible”. The dependent variable was the amount of reduction of speed in seconds and was calculated by subtracting the first trial from the mean of second and third trials (Bassett et al., 2012).

Forward digit span (FDS)

This task, which served as a measure for Working Memory, was taken from the German WISC-IV (Petermann & Petermann, 2011). Children were asked to repeat a series of digits (i.e., “2 – 9”) the experimenter read aloud. They gained one point for each correct answer. Each trial consisted of two series of digits and the number of digits increased if at least one of these was repeated correctly. The abort criterion was reached after two incorrect answers with the same number of digits.

Backward digit span (BDS)

This task was also taken from the German WISC-IV (Petermann & Petermann, 2011) and resembled the Forward Digit Span, except that children were now asked to repeat the series of digits in reverse order (i.e., “8 – 2” is “2 – 8”). The scoring system and the abortion criterion were the same.

In table 7, all applied tasks assessing Inhibition, Working Memory and motor skills are presented separately by point of data collection.

Table 7

Tasks assessing EF and motor skills at each point of data collection

	t1	t2	t3
Inhibition	HTT Stroop task	HTT Stroop Task Balance Beam task	HTT Stroop Task Balance Beam task
Working Memory	*SoP (9 sets)* *Verbal WM task*	*SoP (12 sets)* *Forward Digit Span* *Backward Digit Span*	*SoP (12 sets)* *Forward Digit Span* *Backward Digit Span*
Fine motor skills	Manual Dexterity	Manual Dexterity	Manual Dexterity
Gross motor skills	*Static and Dynamic Balance*	*Static and Dynamic Balance*	*Static and Dynamic Balance*

Note. HTT = Head-to-toes Task, SoP = Self-ordered Pointing task.

Assessment of Motor Skills

Two subscales of the Movement-ABC (Petermann et al., 2011) were conducted at each point of data collection (cf. Study 2 for a detailed description). For the following analyses, standard values of the subscale Manual Dexterity (MD), was taken as a measure for fine motor skills and standard values of the subscale Static and Dynamic Balance (BL) were taken as a measure for gross motor skills.

7.3 Results

7.3.1 Preliminary analysis

Missing data were only present at t1 and were imputed via linear regression imputation as in Studies 1 and 2 (1-2% missing data in both studies). Thus, all analyses are based on a complete data set. The descriptive variables for all EF and motor skills task at t1, t2 and t3 are presented in table 8.

Table 8

Descriptive statistics for all motor and EF tasks

	M (*SD*)	Min-Max
t1		
Motor skills (M-ABC-2)		
MD	27.9 (6.3)	9-41
BL	31.1 (5.7)	17-46
EF		
Inhibition		
HTT	14.4 (6.4)	0-20
Stroop task	11.6 (4.9)	0-16
Working Memory		
SoP	6.2 (2.2)	2-9
Verbal WM task	8.7 (4.3)	0-17
t2		
Motor skills (M-ABC-2)		
MD	27.4 (6.9)	11-43
BL	31.7 (5.6)	15-38
EF		
Inhibition		
HTT	16.7 (4.9)	0-20
Stroop task	14.7 (1.8)	8-16
Balance Beam	23.2 (24.9)	-2.1-181.8
Working Memory		
SoP	7.1 (2.9)	2-12
FDS	3.9 (0.9)	2-6
BDS	2.2 (1.2)	0-5
t3		
Motor skills (M-ABC-2)		
MD	26.7 (6.6)	14-40
BL	31.6 (5.5)	12-38
EF		
Inhibition		
HTT	18.2 (3.9)	1-20
Stroop task	14.9 (1.6)	7-16
Balance Beam	30.2 (18.8)	-0.21-83
Working Memory		
SoP	7.9 (2.8)	2-12
FDS	4.1 (1.1)	2-7
BDS	2.5 (0.8)	0-4

Note. M = Mean, *SD* = standard deviation, Min-Max = Minimum – Maximum. MD = Manual Dexterity, BL = Balance, HTT = Head-to-toes Task, SoP = Self-ordered Pointing task, FDS = Forward Digit Span, BDS = Backward Digit Span. For the motor skills tasks, age-adjusted standard values are presented; for the EF tasks, raw scores are presented. The data for t1 and t2 are based on *N* = 109 children and for t3 on *N* = 60 children.

7.3.2 Direction of effect concerning the relation between EF and motor skills

In order to investigate the direction of effect between motor skills and EF on a task-level, correlation coefficients between the motor skills tasks with all EF tasks at each point of data collection were calculated and are presented in table 9. Regarding the correlation of motor skills with later EF, Manual Dexterity (as a measure for fine motor skills) at t1 was significantly positively correlated with most of the EF tasks at t2 and t3. Also, Balance (assessing gross motor skills) at t1 was significantly correlated with three EF tasks one year later, but two years later there were no significant correlations. At t2, Balance was significantly correlated with three EF tasks, but there were no significant correlations between Manual Dexterity at t2 and EF at t3. No overall pattern of relationship was apparent.

In the opposite direction, i.e., when correlations between tasks assessing EF and later fine and gross motor skills were considered, none of the tasks assessing Inhibition and Working Memory at t1 and t2 were significantly correlated with Manual Dexterity one year later. Yet, there were significant correlations between three EF tasks at t2 with gross motor skills at t3.

Table 9

Correlations between EF and motor skills task at each point of data collection

	Motor skills t1		Motor skills t2		Motor skills t3	
	MD	BL	MD	BL	MD	BL
EF t1						
HTT	.24**	.11	.07	.18	.05	.23
Stroop task	.12	.12	.14	.17	.18	.13
Verbal WM task	.18*	.10	.12	.11	.09	.20
SoP	.14	.19*	.10	.16	-.04	-.17
EF t2						
HTT	.25	.30*	.11	.24*	-.21	.29*
Stroop task	.09	-.13	.14	.14	.01	.27*
Balance Beam	.52**	.31*	.25*	.24*	.21	.25
SoP	.28*	.28*	.09	.16	.13	.07
FDS	.27*	.12	.11	.18	.07	.44**
BDS	.40**	.17	.24*	.21*	.05	.20
EF t3						
HTT	.22	-.14	.11	.25	.30*	.05
Stroop task	.27*	.17	.09	.32*	.13	.11
Balance Beam	.62**	.24	.22	.45**	.23	.28*
SoP	.37**	.06	.09	.22	.04	.15
FDS	.14	.14	.11	.14	.11	.14
BDS	.25*	.15	.14	.28*	.25	.10

Note. * $p < .05$, ** $p < 0.01$; at t1, $N = 170$; at t2, $N = 109$; at t3, $N = 60$. MD = Manual Dexterity, BL = Balance, HTT = Head-to-toes Task, SoP = Self-ordered Pointing task, FDS = Forward Digit Span, BDS = Backward Digit Span.

In the next step, the direction of effect between global aspects of Inhibition and Working Memory with fine and gross motor skills was analyzed. Unfortunately, a full cross-lagged-panel design for all latent constructs including the three points of data collection could not be calculated due to the rather low number of cases in relation to the number of observed variables (according to rules-of-thumb, 10 cases per variable (Nunnally, 1967) or rather 5 or 10 observations per estimated parameter (Bentler & Chou, 1987) are advisable). Further attempts of calculating path models were unsuccessful and ended up in poor model fits, perhaps due to statistical reasons (i.e., small sample, varying indicator variables for EF at t1 compared to t2 and t3). Thus, regression analysis was selected as a simpler statistical approach for the calculation of longitudinal influences of motor skills on EFs and vice versa.

As a preparation of the data, global scores for all four constructs (Inhibition, Working Memory, fine and gross motor skills) were computed. Since all tasks differed in scaling, values for each task were converted via z-standardization. For fine motor skills, the z-standardized scores of the subscales *Manual Dexterity* and for gross motor skills, the z-standardized scores of the subscale *Balance* were taken as indicators. For Inhibition, a global measure was calculated by adding the z-standardized scores from the HTT and the Stroop task (Inhibition_t1) or rather from the HTT, Stroop task and Balance Beam task (Inhibition_t2 and Inhibition_t3). For Working Memory at t1, the z-standardized scores from the SoP and the Verbal WM task were added, and for Working Memory at t2 and t3, the z-standardized scores from the SoP, the FDS and the BDS were added. Then, Hierarchical Multiple Regressions were calculated in order to measure the effect of Inhibition and Working Memory on fine and gross motor skills and vice versa. Since the results of Study 1 had already proven age-related differences in Inhibition and Working Memory as assessed via performance-based tasks, age was included as the first predictor in every regression model.

The results of the hierarchical multiple regression analyses are presented in table 10. As expected, age was a significant predictor of both Inhibition and Working Memory in all calculated regression models.

Table 10

Hierarchical Multiple Regression Analysis predicting Inhibition and Working Memory at t2 and t3

	Inhibition_t2		Inhibition_t3		Working Memory_t2		Working Memory_t3	
Predictor	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	.32**		.18**		.10**		.30**	
Age		.57**		.43**		.32**		.54*
Step 2	.03*		.05		.02		.05	
Age		.55**		.43**		.30**		.55**
MD		.18*		.23		.14		.21
Step 3	.03*		.07*		.00		.04	
Age		.53**		.36**		.30**		.49**
MD		.10		.14		.15		.15
BL		.19*		.29**		-.02		.20
Total R^2	.38**		.55**		.12**		.38*	

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

In the regression models including Working Memory, fine and gross motor skills did not significantly predict the dependent variable, neither at t2 nor at t3.

When Inhibition was taken as the dependent variable, fine motor skills served as a significant predictor for Inhibition at t2, but this effect disappeared when gross motor skills were added as a predictor. In both regression models including Inhibition as the dependent variable, gross motor skills served as a significant predictor for Inhibition one year later (for the prediction of Inhibition at t2 by age, MD and BL: $F(3,105) = 21.80$, $p < .000$ and for the prediction of Inhibition at t3 by age, MD and BL: $F(3,56) = 8.12$, $p < .000$).

In order to calculate whether there was a robust effect of Balance at t1 and t2 on Inhibition one year later, Inhibition one year earlier was added to the model. Predictors were age, Inhibition one year before, Manual Dexterity and Balance. A significant regression equation was found for both points of data collection (for the prediction of Inhibition at t2: $F(4,104) = 18.54$, $p < .000$, with an R^2 of .42 and for the prediction of Inhibition at t3: $F(4, 55) = 5.50$, $p < .00$, with an R^2 of .29). The children's predicted Inhibition at t2 was equal to -5.96 + .55 (Balance_t1) + .16 (Manual Dexterity_t1) + .46 (Inhibition_t1) + 1.32 (age_t2). The children's predicted Inhibition at t3 was equal to -5.25 + .76 (Balance_t2) + .13 (Manual Dexterity_t2) + .13 (Inhibition_t2) + .87 (age_t3).

When fine and gross motor skills were predicted by age, Inhibition and Working Memory one year earlier, age did not become a significant predictor in most models, which can be explained by the fact that age-adjusted standard values were taken as scores for fine and gross motor skills. Therefore, age was excluded from the models and the results of the remaining predictors are presented in table 11.

Table 11

Hierarchical Multiple Regression Analysis predicting fine and gross motor skills at t2 and t3

	Manual Dexterity_t2		Manual Dexterity_t3		Balance_t2		Balance_t3	
Predictor	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	.01		.00		.05		.11*	
Inhibition		.10		.05		.23		.33*
Step 2	.02		.01		.00		.04	
Inhibition		.12		-.02		.22		.21
Working Memory		-.14		.12		.04		.22
Total R^2	.03		.01		.05		.14*	

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

When Manual Dexterity was taken into the model as the dependent variable, it could not be predicted by Inhibition or Working Memory, neither at t2 and t3.

Only Balance at t3 was significantly predicted by Inhibition one year earlier, $F(1, 58) = 6.93$, $p = .01$), but this effect remained non-significant when Working Memory was added to the model.

7.4 Discussion

An interrelation between EF and motor skills has been discussed within the last two decades (Diamond, 2000). Although the literature regarding this topic in children is scarce, previous studies provided evidence supporting the idea of a possible link between these two domains in preschool-aged children (Gonzalez et al., 2014; Roebers et al., 2014; van der Fels et al., 2015). However, the majority of these studies collected data cross-sectionally and used correlational analyses in order to corroborate this connection. Consequently, there is a lack of longitudinal studies. Thus, the direction of effect between these two domains is still rather unknown.

The present study aimed at answering the question whether fine or gross motor skills could predict later EF skills or vice versa. Thus, two principal components of EF in preschoolers, Inhibition and Working Memory, as well as fine and gross motor skills were assessed longitudinally over three points of data collection at annual intervals in a sample of preschoolers. The results of the present study suggest that when the relationship between motor skills and EF was analyzed on the basis of correlations, both fine and gross motor skills were significantly related to tasks assessing Inhibition and Working Memory one year later. Thus, the present study supports previous findings by supplying evidence for an association of both constructs. Regarding the direction of effect, regression analyses revealed that preschoolers' gross, but not fine motor skills, robustly predicted later Inhibition skills between the first and second as well as between the second and third point of data collection. In the opposite direction, the two EF components Inhibition and Working Memory were not significantly associated with later motor skills, neither on the basis of correlations nor in the regression analyses. Thus, the present study provides evidence regarding the direction of effect between EF and motor skills in the way that earlier motor skills might serve as a predictor for preschoolers' EF, but not vice versa. Especially the longitudinal relationship between gross motor skills and Inhibition found support in the present study. A possible explanation for this interrelation might be attributed to the tasks chosen for the assessment of Inhibition in our sample. When these are considered in detail, an interrelation with Balance seems rather obvious: Both the HTT and the Balance Beam tasks are measures of Inhibition that require gross motor skills as well. However, significant correlations between tasks assessing EF and motor skills were also found for other measures. So, over and above the amount of motor activity used for the correct execution of an EF task, there seems to be a shared underlying association between Inhibition and gross motor skills.

Due to the modicum of studies, a possible explanation can only be speculative at this particular time and might be found on a neurological basis: When preschoolers exercise their Balance skills, they improve their bodies' ability to correct movements in order to keep it from toppling over. Thereby, they constantly *inhibit* incorrect movements and, unintentionally, improve their inhibition skills. On a neurological level, a simultaneous activation of the cerebellum, which is responsible for the execution of body movements, and the PFC, the “control center” for planning and execution of actions, has been reported (Diamond, 2000). Thus, a body-related training of Inhibition via gross motor activity could underlie a generalization effect in children.

Limitations

For the precise analysis of the direction of effect between EF and motor skills, the analysis on the basis of latent variables would have been desirable. Unfortunately, a full cross-lagged-panel design for all latent constructs over the three points of data collection could not be calculated because of the rather low number of cases in relation to the number of observed variables. Further attempts of calculating path models were unsuccessful and ended up in poor model fits, perhaps due to statistical reasons (i.e., small sample, varying indicator variables for EF at t1, t2 and t3). Therefore, a replication of this study with a larger sample and number of tasks assessing Inhibition and Working Memory as well as motor skills is needed in order to support the findings. Furthermore, the above mentioned potential explanation for the association between motor skills and EF on a neurobiological level are speculative; future studies could include the assessment of neurological data, i.e., via EEG, which could provide evidence for this hypothesis.

The present study is, to the author’s knowledge, the first longitudinal study focusing on the relationship of preschoolers’ fine and gross motor skills with two principal EF components, Inhibition and Working Memory. Although some major methodological limitations, as mentioned above, are present, a first attempt to gain some knowledge in this field of research was made.

8. Discussion

This chapter starts with a summary of each of the three studies presented within the present research project, in which the main findings of the studies are pointed out. Then, limitations regarding the whole research project are discussed. In the last part, implications of the findings from all three studies for theory and practice are deduced and a prospect is given.

The three studies presented in this dissertation are based on data collected in a longitudinal research project with three points of data collection at annual intervals. The aims of the project were to provide further evidence concerning (a) the development of EF and (b) its potential relationship with motor skills, both cross-sectionally and longitudinally, in a sample of preschoolers. In Study 1 and 2, cross-sectional data from the first point of data collection were analyzed. Study 1 investigated the development of EF, whereas Study 2 focused on the analysis of the interrelation between EF and motor skills. In Study 3, data from all three points of data collection were included and the longitudinal interrelation of EF and motor skills was investigated.

8.1 Summary of the main findings from the research project

In Study 1, the development of EF in preschoolers was investigated via two different ways of assessment, i.e., performance-based measures and parent ratings. Age-related increases in EF performance had been proven in previous studies using both ways of assessment (Cadavid Ruiz et al., 2016; Carlson, 2005; Huizinga et al., 2006; Huizinga & Smidts, 2011), yet it had been criticized that different ways of assessment would not measure the same underlying theoretical construct (Toplak et al., 2013). Two “core” EFs, namely

Inhibition and Working Memory, were investigated. It was hypothesized that age-related increases regarding both components as assessed via both ways of assessment would be present. Besides, a two-factor-structure of EF with two separate, yet interrelated factors, Inhibition and Working Memory, was expected, including data from both performance-based measures and parent ratings. The results of the study provided evidence for an age-related increase in both EFs as assessed via performance-based measures; yet, parents reported age-related increases only for Working Memory, but not for Inhibition. The existence of the assumed two-factor-model in the sample examined could be demonstrated. Furthermore, it could be shown that both ways of assessment indeed measure the same underlying latent constructs if methodological differences are considered and included in the CFA.

Study 2 explored the relationship between EF and motor skills. An interrelation between both domains has been proposed (Diamond, 2000) and previous studies investigating this potential relationship pointed to a positive relation between EF and fine motor skills, but not gross motor skills (van der Fels et al., 2015). However, the current state of research regarding preschoolers is scarce. According to the results from Study 1 providing evidence for a two-factor-structure of EF in the sample tested, Inhibition and Working Memory were considered the main components in Study 2 and their interrelation with fine and gross motor skills was investigated. It could be shown that correlational analyses led to unsatisfactory results, since no overall pattern between tasks assessing Inhibition or Working Memory with tasks assessing fine or rather gross motor skills was identifiable. However, the study provided further evidence for an interrelation between motor skills and EF on the basis of latent variables (via calculation of a SEM), albeit the relationship between Inhibition and Working Memory with gross motor skills was to some extent smaller and non-significant compared to medium-sized, significant correlations found between both Inhibition and Working Memory with fine motor skills.

In Study 3, longitudinal data were analyzed in order to answer the question about causality between motor skills and EF. Due to a lack of studies concerning this research question, the study was to a large extent exploratory, and thus, both a potential prediction of EF via motor skills and vice versa was hypothesized. Again, a two-factor-structure of EF was assumed including Inhibition and Working Memory and fine motor skills were differentiated from gross motor skills. Results from correlation analyses pointed towards a relation between motor skills and later EF, but not vice versa. Subsequent regression analyses revealed that EF had no predictive power on later motor skills; nevertheless, Inhibition (but not Working Memory) could be predicted by gross motor skills one year earlier. The results from this study strengthen previous findings regarding an interrelation between motor skills and EF. Moreover, first evidence pointing to gross motor skills as a predictive factor for later Inhibition skills during preschool years is provided.

8.2 Theoretical Implications

There are several theoretical implications that can be derived from the studies presented within this dissertation. In the following, the results from the three studies is embedded into the current state of research in the field of developmental psychology and implications for future studies are presented.

8.2.1 Theoretical Implications regarding EF in preschoolers

The results from Study 1 add to the large body of research stating age-related improvements in EF during preschool years (Cadavid Ruiz et al., 2016; Carlson, 2005; Huizinga et al., 2006; Huizinga & Smidts, 2011). Yet, the optimal way of assessment of the skills subsumed under this theoretical construct is still under discussion. Both performance-based measures and caregiver ratings are useful instruments in order to provide an insight into the development of EF in this age group, and there are advantages and disadvantages concerning each approach: Advantages of performance-based measures of EF are (a) administration in a laboratory, (b) construct validity and (c) little potential for observer bias (Cameron Ponitz et al., 2008; Carlson, 2005). Disadvantageous is that young children have limited attention capacity and get tired quickly (Anderson & Reidy, 2012), so that the amount of tasks that can be conducted is limited. Also, it has been criticized that the exclusive use of performance-based measures for the assessment of preschoolers' EF would neglect “children's “real-world” functioning” (Liebermann et al., 2007, p. 512). In contrast, behavior ratings “provide an ecologically valid indicator of competence in complex, everyday problem-solving situations” (Toplak et al., 2013, p. 133). Nevertheless, they might underlie a potential observer bias. Although both ways of assessment are often used interchangeably, it has been argued that they might assess different aspects of the latent variable EF (Toplak et al., 2013).

According to the finding that both performance-based-measures and parent ratings in our sample indeed measured the same underlying latent variable, when methodological variance was accounted for, it can be concluded that a combination of these ways of assessment might be recommendable, if a holistic perspective on the complex construct of EF is desired. Besides, since EF describes a heterogeneous, multidimensional construct, which cannot be assessed with a single task or questionnaire, it is certainly appropriate to include as many variables as possible. In accordance with Evers et al. (2016) and Toplak et al. (2013), future studies focusing on the development of EF in preschoolers should acknowledge this recommendation and include both ways of assessment. Thus, a number of performance-based tasks feasible for this age group (cf. Carlson, 2005) should be conducted as well as several questionnaires assessing EF in preschoolers should be handed out to parents and other caregivers (i.e., the BRIEF-P, Daseking & Petermann, 2013). Furthermore, methodological differences between these ways of assessment should be considered and statistically controlled, wherever applicable.

8.2.2 Theoretical Implications regarding the interrelation between EF and motor skills in preschoolers

Due to the modicum of research regarding the research question Studies 2 and 3 focused on, both studies were to a large extent exploratory and hypothesis generating. The findings from both Study 2 and 3 provide further evidence for a proposed interrelation between motor skills and EF. The correlational pattern in Study 2, stating no general interrelation between tasks assessing fine and gross motor skills with tasks measuring Inhibition and Working Memory, but rather task-dependent interrelations, conforms to other studies reporting similar results (Stein, Auerswald, & Ebersbach, 2017). The analysis of the data on the level of latent variables revealed that, cross-sectionally, the interrelation between Inhibition and Working Memory with fine motor skills was positively significant and there were small to moderate, albeit non-significant, correlations between gross motor skills and both EF domains. This finding is in concordance with previous studies pointing to a moderate interrelation between fine motor skills and EF in children and adolescents (Stöckel & Hughes, 2016; van der Fels et al., 2015). In order to explain why fine motor skills are more strongly related to EF than gross motor skills, it was hypothesized that especially complex motor skills that require higher cognitive demands, i.e., fine motor skills, are related to EF and that tasks assessing gross motor skills might involve less cognitive involvement (Best, 2010). However, this hypothesis is only speculative and requires further evidence from studies including measures of neuronal activity during motor and cognitive tasks.

In contrast to previous studies, measures assessing both fine and gross motor skills (in contrast to just one of these) were included, providing a more differentiated and comprehensive perspective on the interrelation between motor skills and EF. Besides, the approach on the level of latent variables via a SEM was methodologically advantageous, since a “purer” measure (Miyake & Friedman, 2012) of all included construct was provided and task-related variance was minimized, which might have led to inconsistent findings from previous studies. The results from Study 2, providing further evidence for an interrelation between motor skills and EF, might reflect the proposed simultaneous activation of prefrontal brain areas and the cerebellum and motor cortex (Diamond, 2000) during cognitive tasks that require, e.g. Working Memory capacity (Stoodley & Schmahmann, 2009). There is evidence that, in preschoolers, several cerebellar regions are functionally connected to wide parts of the cerebral cortex, i.a. the PFC (Ramnani, 2006), which interact in order to successfully complete a certain task (Brown & Jernigan, 2012). This is especially the case when a task is difficult or novel and requires a quick response (Diamond, 2000). Unfortunately, this explanation is only speculative for the explanation of the results presented within Study 2, since neuronal measures, i.e., electroencephalography (EEG) or functional magnetic resonance imaging (fMRI), which depict activation in specific brain regions, were not applied.

The findings from Study 3 suggest that, longitudinally, gross motor skills can serve as a predictor for later EF, especially Inhibition. This finding corresponds to Niederer et al. (2011), who reported a significant positive correlation between gross motor skills and Working Memory 9 months later in a sample of preschoolers; however, Inhibition was not assessed in their study; perhaps a positive predictive effect would have been found as well, if a measure for Inhibition had been included. The finding that the development of motor skills is related to increases in EF might trace back to the facts that the underlying brain structures responsible for motor as well as higher-order cognitive skills (i.a. EFs), i.e., the cerebellum and the PFC, follow a protracted developmental course (Tiemeier et al., 2010). Physiological maturation processes seem responsible for this similar prolonged trajectory: “In terms of motor development, both synaptic pruning and myelination are responsible for the improved precision and speed of coordinated movement. In addition, they are important in the development of cognitive skills” (Tierney & Nelson, 2009, p. 12). Thus, the findings of Study 3 could implicate that the maturation of the cerebellum, which is responsible for Balance, precedes the maturation of prefrontal regions responsible for EF during preschool years.

For researchers interested in promoting EF or motor skills respectively in preschoolers, the results of the present research project serve as support for the idea that training of motor skills might have positive influence on both competences (van der Fels et al., 2015). Several studies have already focused on this topic and reported positive effects of programs including acute as well as repeated physical activity, i.e., aerobic exercises, on cognitive functions in children, adolescents and adults (cf. Sibley & Etnier, 2003, and Verburgh, Königs, Scherder, & Oosterlaan, 2014, for meta-analyses on this topic). Besides, there is preliminary evidence for positive effects of exercise in children suffering from ADHD (Berwid & Halperin, 2012). Physiological mechanisms are assumed to explain this direct impact of physical activity on cognitive functions, i.e., increased cerebral blood-flow (Herholz et al., 1987) and release of neurotransmitters (Winter et al., 2007) and a general improvement of cardio-respiratory functioning (Best, 2010). Yet, it is unclear whether this effect is evident in preschoolers as well, since only a few of studies have investigated the effect of intervention programs in preschoolers so far: Palmer, Miller, & Robinson (2013) found that preschoolers performed significantly better in a task assessing sustained attention and showed a non-significant trend towards better performance in an Inhibition task after 30 minutes of physical exercises compared to a sedentary condition.

Apart from interventions including aerobic exercises, coordinative interventions have also proven positive effects on cognitive functions (Budde, Voelcker-Rehage, Pietrabyk-Kendziorra, Ribeiro, & Tidow, 2008). The theoretical assumption behind this finding is that coordinative exercises not only activate the above mentioned physiological processes, but additionally imply a higher cognitive demand and thus induce an improved connection/communication between cortical (i.e., prefrontal) and subcortical (i.e., cerebellar) neuronal structures (Budde et al., 2008; Diamond, 2000). In one study with a sample of preschoolers it could be shown that an acute coordinative intervention led to improved performance in an Inhibition task (Stein et al., 2017). Still, this result has to be treated with caution, because more studies are needed in order to provide further evidence. However, a possible, yet at this time speculative, explanation for the thesis that coordinative exercises could improve EF in preschoolers is the idea that the link between EF and physical fitness might be moderated by motor skills, suggesting that intervention programs are only effective if children’s motor skills are enhanced. Nevertheless, studies including measures for motor skills before and after an intervention based on physical in contrast to coordinative exercises are needed in order to provide evidence for this hypothesis.

A promising study is currently conducted in Denmark (Hestbaek et al., 2017): In this longitudinal study, a program for preschoolers is implemented that comprises a multitude of exercises aiming at the promotion of fine and gross motor skills. Via randomized-controlled trials and a long-term-follow-up, the effectiveness of this program will be analyzed and its effects on social and cognitive skills (i.a. EF) will be tested. Hopefully, the results of this study will shed light on the interrelation between motor skills and EF in preschoolers.

In conclusion, the results from the studies presented within the dissertation at hand correspond to findings, as far as age-related increases of EF during preschool years and an interrelation between EF and motor skills are considered. Regarding the longitudinal interrelation between motor skills and

EF, it can be supposed that the results refer to maturational processes of functionally interrelated brain regions in childhood. The assumption that EF in preschoolers can be promoted via training programs including physical activity or coordinative exercises is to a large extent speculative and should be treated with caution.

8.3 Practical Implications

Although the direct training effect of EF via interventions including physical activity has yet to be proven, motor activity provides an approach that can be used in order to promote EF in children: In a playful way, games that include several rules or the abrupt stopping of a movement can stimulate Working Memory, Inhibition and Shifting skills (Kubesch & Walk, 2009). One example of a traditional playground game is the “Freeze Game”, in which children dance when music plays, but have to stop and freeze once the music is turned off. In an extended version, additional rules can be implemented, i.e., that the children are instructed to dance slowly to fast music and vice versa (Tominey & McClelland, 2011). There are already several manuals available (McClelland & Tominey, 2016; Roth, & Zimmer, 2017; Walk & Evers, 2013), which provide instructions for a multitude of active games including increasing demands on EFs and motor activity, which can easily be applied in the kindergarten context. The three “core” EFs, Inhibition, Working Memory and Shifting, can be trained on different levels and in a group situation, which includes additional demands on children’s EF. This playful, child-appropriate way of training EF seems to be a promising approach for joyful learning and promotion of EF.

8.4 Limitations of the research project

The present research project was subject to several limitations: The first is the self-selected sample, which included only children with a middle-to-high socioeconomic background. SES is considered an influencing factor for the development of EF (Bassett et al., 2012) and there is evidence that a higher SES is associated with better EF (Cadavid Ruiz et al., 2016). Hence, it can be hypothesized that in a sample with children at socioeconomic risk the level of EF in general might have been lower and there might not have been significant age-related increases. For this reason, representability of the sample and generalizability of the presented findings are limited. In order to provide evidence for the generalizability of the above presented results, it would be necessary to replicate the research project with a more heterogeneous sample.

The second limitation refers to the way of assessment of EF: It was pointed out before that the assessment of EFs in everyday life adds to the holistic perspective on the development of EF in preschoolers. In the present research project, parent ratings were taken as a measure of assessing children's EF. However, all children in our sample visited a kindergarten, and thus spent the majority of their time on weekdays apart from their parents. Another source of information concerning the assessment of children's EF are kindergarten teachers. Assessing their perspective can be considered advantageous since kindergarten teachers spend a lot of time with the children and observe their behavior in situations when they interact with other peers. In this context, different behavioral expectations are placed on the children compared to family context (Suchodoletz et al., 2014) and it can be expected that children show different levels of EF in varying situations. For this reason, there is little convergence between these two sources of information about preschoolers' EF (Suchodoletz et al., 2014). Thus, the kindergarten teachers' perspective may serve as an additional, valuable insight and future studies should include parent as well as kindergarten teacher ratings of children's EF, if possible, to create an accurate perspective of preschoolers' EF.

The third limitation concerns the conceptualization of EF: According to the current state of research, there is no general agreement regarding the factor-structure of EF in preschoolers. The three factors proven to exist in adults, Inhibition, Working Memory and Shifting, might be present in early childhood as well (Espy et al., 2004). Still, the theoretical model of EF that was assumed within the dissertation at hand is a two-factor model with Inhibition and Working Memory as separate domains of EF, since this conceptualization has gained evidence through several studies (Lee et al., 2013; Monette et al., 2015; van der Ven et al., 2013). The authors supporting this hypothesis follow the idea of a stepwise fractionation of EF from a unidimensional construct in infancy into the adult three-factor-structure (Cuevas et al., 2018; Monette et al., 2015). It has been hypothesized that Inhibition and Working Memory can be differentiated in preschoolers and that Shifting emerges during early and middle childhood (Monette et al., 2015). However, since this discussion has yet to be resolved, premature conclusions should be avoided. Thus, the absence of Shifting tasks in the analyses of the presented studies can be considered a limitation. Hence, it could not be tested whether a three-factor-structure would have resulted in a better model fit in our sample compared to the tested two-factor model (albeit it was not the aim of the present dissertation to investigate the factor-structure of EF in preschoolers in detail). Besides, no conclusions can be drawn about the relationship between Shifting as a component of EF with fine and gross motor skills. Thus, the above mentioned results of the studies within this dissertation have to be regarded considering this limitation. Future studies could include Shifting tasks in order to provide information about a potential interrelation between this aspect of EF with motor skills.

A fourth limitation applies to the concept of motor skills used within the research project: A common differentiation between fine and gross motor skills was used, i.e., movements involving larger body parts and greater muscular activity were differentiated from movements concerning fine motor precision. However, other aspects of motor skills like bilateral body coordination, object control or timed performance in movements were not investigated. These aspects of motor skills are, just like fine motor skills, considered to require a higher level of cognitive control (Best, 2010) and might thus also be related to EF (van der Fels et al., 2015). Yet, the empirical basis is still weak and future studies including measures for these facets of motor skills are needed.

Furthermore, originally the data of the research project were intended to be analyzed in a cross-lagged panel design including all three points of data collection. Unfortunately, only 60 complete data sets could be included in this model due to sample dropouts at the second and third point of data collection. Several attempts were made in order to calculate the whole statistical model but failed due to error warnings concerning negative covariance patterns. A possible reason could be that the model was too complex for the data, perhaps due to a lack of statistical power caused by the small sample or the distribution of the data (Stevens, 2009); nevertheless, these explanations are only speculative.

In summary, the findings presented within this dissertation provided further (or rather first) information about the proposed relationship between EF and motor skills. Since the studies were subject to several, above mentioned limitations, a replication of the longitudinal research project with a larger and more heterogeneous sample of preschoolers might be advisable. Again, a combination of performance-based measures and caregiver ratings of EF could be assessed; in consideration of the limitations of the present research project, a future study should assess parents' as well as kindergarten teachers' perspective of the children's EF. Besides, it would be recommendable to include measures assessing Shifting. Also, other aspects of motor skills, i.e., bilateral body coordination, could be investigated. Over and above the methods used within the present research project, additional measurement methods assessing neurological activation, i.e., EEG or fMRI could be used in order to shed light on the hypothesis that the interrelation between EF and motor skills might be traced back to simultaneous activation of interconnected brain regions.

8.5 Future prospect

In the future, the investigation of the development of EF across the lifespan and its influencing factors will surely captivate many more researchers. However, they will have to deal with several challenges: The lack of a universally accepted definition (and even a common name) regarding the theoretical construct of what is often referred to as "Executive Function" is surely one of these. Perhaps one day researchers from different scientific fields will agree on one shared definition, but until then hopefully Griffin et al. (2016) will be right in their assumption that the heterogeneous understanding of the construct will result in many new and exciting insights about this complex and multidimensional human ability.

Since poor EF is a risk factor for an adverse development regarding many aspects of everyday life, the focus on the promotion of the underlying skills will likely continue. At present, there is need for further studies to provide evidence for the hypothesis that intervention programs aiming at the promotion of motor skills will reliably lead to improvements in EF. However, motor skills per se play an important role for general infantile development, since they form the basis for age appropriate movement behavior, physical fitness and, accordingly, healthy development (Roth & Zimmer, 2017). For these reasons, it seems without doubt recommendable to incorporate the promotion of motor skills in a holistic education of children.

9. References

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10. List of figures

11. List of tables

12. Erklärung gemäß § 8 Abs. (1) c) und d) der Promotionsordnung der Fakultät für Verhaltens- und Empirische Kulturwissenschaften

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

FAKULTÄT FÜR VERHALTENS- UND EMPIRISCHE KULTURWISSENSCHAFTEN

Promotionsausschuss der Fakultät für Verhaltens- und Empirische Kulturwissenschaften der Ruprecht-Karls-Universität Heidelberg
Doctoral Committee of the Faculty of Behavioural and Cultural Studies, of Heidelberg University

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