

# Early Childhood Executive Function, Literacy, and Mathematics

Direction of Effects and Domain-Specificity  
Across the Transition to School

by

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‘I encourage all of us, whatever our beliefs, to question the basic narratives of our world, to connect past developments with present concerns, and not to be afraid of controversial issues.’

Yuval Noah Harari, 2011

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Stavanger, March 2020

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## Summary

Across the lifespan, early childhood is a time of tremendous and rapid learning. The executive functions (ability to inhibit responses, update working memory, and flexibly shift attention) and early academic skills (literacy and mathematics) that children acquire before school entry are strong, if not the strongest, predictors of their later academic achievement and educational outcomes. The central role of early childhood academic and executive skills for children's prospects makes it vital to understand how these skills relate, especially during the transition from early childhood education to formal schooling. Research on early skill development may provide valuable information on where difficulties may arise and where to put in resources.

Despite an increasing body of literature showing that good executive function in children is positively related to academic skills, previous research has limitations that restrict our understanding of the specific nature of these associations. Specifically, little is known about the direction of effects and possible domain-specific relations. That is, is the relation between executive function and early literacy and mathematics unidirectional or mutually interdependent with certain academic skills also predicting executive function? And, do certain components of executive function differently predict early literacy and mathematics? Early literacy and mathematics are often studied in isolation, despite clear knowledge that these two areas are highly related. How executive function relates to these skills when taking into account their interrelations is less known. Moreover, contextual factors, such as the child's educational environment, may affect the interrelations between executive function and academic skills. The majority of studies have investigated associations in school-readiness early childhood education contexts. Few studies have investigated how these skills relate in children in a play-based early childhood education context, such as Norway.

The main aim of this dissertation was to get a better understanding of the interrelations between executive function (including self-regulation, attentional-, and behavioral control), early literacy, and mathematics when children (ages 5-7) make the transition from early childhood education (kindergarten) to formal education (first grade).

The dissertation includes three studies. *Study I* provides the basis for *Study II* with a psychometric evaluation of the early mathematics assessment used in that study. *Study II* investigates the direction of effects between self-regulation and early literacy and mathematics. *Study III* assesses the pathways from two aspects of executive function (attentional and behavioral control) to early literacy and mathematics. Below follows a brief description of each study.

### *Study I*

In *Study I*, the psychometric properties of an early mathematics assessment (ABMT; Ani Banani Math Test) for kindergarten children were investigated in three samples ( $N = 243$ ,  $N = 691$ , and  $N = 1282$ ). It was expected that the ABMT showed a consistent factor structure across different samples, that items functioned similarly across age, sex, and socioeconomic status, and that it was more strongly related to other math assessments than to measures of executive function or literacy. The results showed that a one-factor structure was the most representative and reliable structure for the ABMT and that it functioned similarly across age and socioeconomic status. Two items showed signs of differential item functioning in favor of boys and one in favor of girls. Furthermore, the analyses provided evidence that the ABMT has concurrent, predictive, and discriminant validity. This indicates that although scores on the ABMT are related to executive function and literacy, it is most strongly an indicator of children's early mathematics.

### *Study II*

Using cross-lagged panel models, in *Study II* the direction of relations between self-regulation and mathematics, expressive vocabulary, and phonological awareness were investigated in children ( $N = 243$ ) making the transition from a play-based kindergarten context to formal schooling in first grade. Bidirectional relations were expected between self-regulation and mathematics and between self-regulation and expressive vocabulary. Self-regulation was expected to predict phonological awareness, but not the reverse. These expectations were partly confirmed; bidirectionality was found for mathematics, but not for expressive vocabulary. While expressive vocabulary did predict self-regulation, self-regulation was not a robust predictor of phonological awareness. These results are in line with the notion that there is a particularly robust bidirectional connection between self-regulation and mathematics and that language is important for the acquisition of self-regulation.

### *Study III*

Because early literacy and mathematics may require different cognitive and behavioral abilities, specific aspects of executive function may be differentially related to these academic skills. Using structural equation modeling, in *Study III* ( $N = 90$ ), it was investigated how two components of executive function (attentional and behavioral control) predicted phonological awareness and early number sense in kindergarten and word reading and mathematics in first grade. Attentional control was expected to be a specific predictor for word reading, while both components were expected to predict mathematics. Results indicated that attentional control predicted word reading and that this relation went via phonological awareness. Behavioral control did not predict word reading but did so indirectly through phonological awareness. Attentional control did not predict mathematics in first grade. Behavioral control, on the contrary, showed a direct and robust relation to later mathematics. These

differential domain-specific relations suggest that the development of early literacy and mathematics may differentially rely on attentional and behavioral control processes.

## List of Studies

### *Study I*

ten Braak, D., Størksen, I. (2019). *Psychometric Properties of the Ani Banani Math Test*. Manuscript submitted for publication.

### *Study II*

ten Braak, D., Størksen, I., Idsoe, T., & McClelland, M. (2019). Bidirectionality in self-regulation and academic skills in play-based early childhood education. *Journal of Applied Developmental Psychology*, 65, 101064. doi: <https://doi.org/10.1016/j.appdev.2019.101064>

### *Study III*

ten Braak, D., Kleemans, T., Størksen, I., Verhoeven, L., & Segers, E. (2018). Domain-specific effects of attentional and behavioral control in early literacy and numeracy development. *Learning and Individual Differences*, 68, 61-71. doi: <https://doi.org/10.1016/j.lindif.2018.10.001>

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# **1 Introduction**

One of the objectives of educational science in general, and educational psychology in specific, is to gain knowledge on human learning. Across the lifespan, early childhood is a time of tremendous and rapid learning. The early executive function (EF), literacy, and math skills that children acquire before school entry are strong, if not the strongest, predictors of their later academic achievement and educational outcomes (Ahmed, Tang, Waters, & Davis-Kean, 2019; Bull, Espy, & Wiebe, 2008; Duncan et al., 2007; Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Robson, Allen, & Howard, 2020; Romano, Babchishin, Pagani, & Kohen, 2010). The role of children's EF in the development of academic skills has received increased attention in educational research in recent years (Jacob & Parkinson, 2015; Pandey et al., 2018). Children's ability to use EF and regulate attention and behavior is regarded as an essential factor for a successful transition to formal schooling (Blair & Raver, 2015; Rimm-Kaufman, Pianta, & Cox, 2000) and a significant predictor not only of later academic achievement, but also of long-term health, wealth, and social outcomes (Moffitt et al., 2011; Robson et al., 2020). EF predicts concurrent and longitudinal academic achievement also when controlling for socio-demographic factors, such as maternal education, child IQ, and initial achievement scores (e.g., Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Duncan et al., 2007; Malanchini, Engelhardt, Grotzinger, Harden, & Tucker-Drob, 2019). The central role of early childhood EF and academic skills for children's future life and prospects makes it vital to understand how these skills relate, especially during the transition from early childhood education and care (ECEC) to formal schooling. Research on early skill development may provide valuable information on where difficulties may arise and where to put in resources in early childhood education.

Despite a growing body of cross-sectional and longitudinal research indicating significant positive associations between EF and early literacy

and mathematics (Robson et al., 2020), several issues remain unclear. First, most researchers agree that EF, including self-regulation, forms a foundation for learning early in life and facilitates the acquisition of academic skills (Blair & Raver, 2015; Diamond, 2013; McClelland & Cameron, 2019; McClelland, John Geldhof, Cameron, & Wanless, 2015). However, the reverse might also be true. EF, early literacy, and mathematics develop rapidly during early childhood. Little is known about the causal direction of the association between EF and early literacy and mathematics and whether the nature of this relation is uni- or bidirectional. Second, EF includes the ability to control both one's behavioral and attentional tendencies (Diamond, 2013). Given that early literacy and mathematics may vary in complexity as well as cognitive and behavioral requirements, attentional and behavioral aspects may be differentially related to these academic outcomes across time. Third, traditionally, separate fields have been considered with the study of early literacy and mathematics, and the two skills are often studied in isolation despite clear knowledge that they are related (Krajewski & Schneider, 2009; Purpura, Hume, Sims, & Lonigan, 2011; Simmons & Singleton, 2008). How EF is related to each domain when taking the interrelations between the skills into account remains less clear. Finally, the majority of studies have investigated associations in preschool and kindergarten children in school-readiness ECEC contexts. Less is known about how these skills relate when children make the transition from a play-based ECEC context to formal schooling.

The central objective of this dissertation was to investigate, at a relatively fine-grained level, how EF (including self-regulation, attentional-, and behavioral control), early literacy, and mathematics are related across the transition from ECEC (kindergarten) to formal education (first grade) by focusing on the direction and domain-specificity of associations.

## **2 Theoretical and empirical framework**

Before outlining the specific objectives of the studies in this dissertation, this section presents theories and research relevant to the aim of this dissertation, including definitional issues, relevant theoretical frameworks, the ECEC contexts, development of the constructs, and issues considering the measurement of EF and academic skills.

### **2.1 Definitional issues**

#### **2.1.1 Defining executive function**

Definitional issues have afflicted research on EF, including self-regulation, across the years (McClelland & Cameron, 2012; Nigg, 2017; Rademacher & Koglin, 2019; Zhou, Chen, & Main, 2012). Differences in definitions, terminology, core components, and measurement of EF and self-regulation often reflect the separate fields (e.g., cognitive and personality perspectives, respectively) in which the constructs have been studied (Hofmann, Schmeichel, & Baddeley, 2012; Malanchini et al., 2019; Zhou et al., 2012) and make a universally accepted definition elusive. These issues are certainly not absent in the present work. The purpose of this section is to provide an overview of the terminology that is used across the studies.

In this dissertation, EF is defined as a multidimensional construct involving a set of subcomponents and processes that enable control over one's automatic or prepotent attentional and behavioral tendencies and allow purposeful and goal-directed behavior (Best & Miller, 2010; Blair, 2016; Diamond, 2013; McClelland & Cameron, 2012; Rademacher & Koglin, 2019; Zhou et al., 2012). Despite definitional issues, there seems to be consensus that the main components of EF include the ability to maintain and update information in working memory, to inhibit automatic or prepotent responses, and to flexibly shift attention (Best &

Miller, 2010; Diamond, 2013; Miyake & Friedman, 2012; Miyake et al., 2000). In short, these processes are referred to as working memory, inhibitory control, and shifting.

Whether EF is unitary, i.e., distinct sub-functions or sub-components cannot be dissociated, or represents a multifaceted nature, is subject of debate (for an overview see for example Lee, Bull, & Ho, 2013). The studies in this dissertation are guided by research supporting that EF components are related but may be dissociable in children age 5-7 (Huizinga, Dolan, & van der Molen, 2006; Lee et al., 2013; Lee et al., 2012; Miller, Giesbrecht, Muller, McInerney, & Kerns, 2012; Van der Ven, Kroesbergen, Boom, & Leseman, 2012) and may differently predict academic outcomes (McClelland et al., 2014; Purpura, Schmitt, & Ganley, 2017; Segers, Damhuis, van de Sande, & Verhoeven, 2016; Van de Sande, Segers, & Verhoeven, 2013).

A conceptual model of EF, as used in this dissertation, is shown in Figure 1. As can be seen, the three EF components of working memory, inhibition, and shifting are included in the broader self-regulation construct that is used in *Study II*. Consistent with the majority of research within the cognitive psychology tradition (Malanchini et al., 2019; Rademacher & Koglin, 2019) self-regulation is studied in line with EF. That is, self-regulation is defined as the integration and behavioral manifestation of EF (Cameron Ponitz, Rimm-Kaufman, Brock, & Nathanson, 2009; McClelland et al., 2014; McClelland & Cameron, 2012).

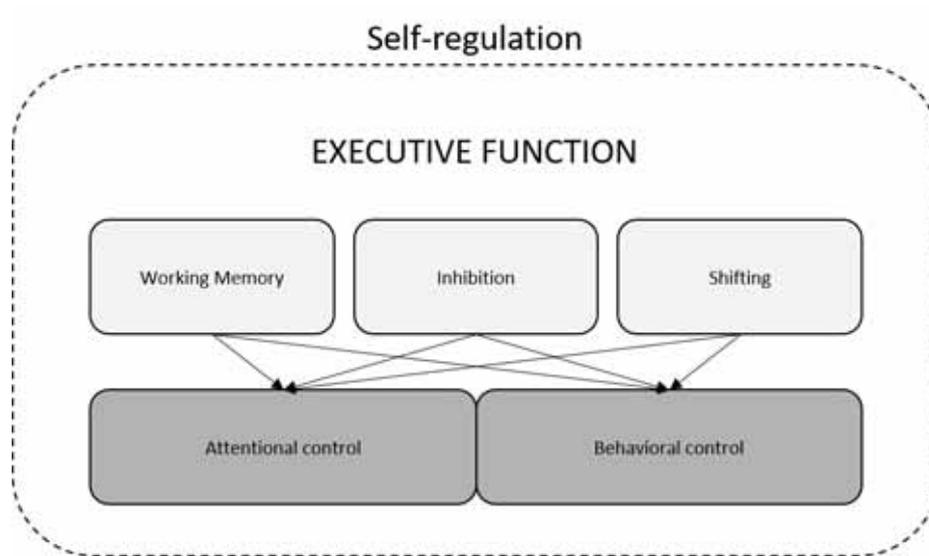


Figure 1 Conceptual model of executive function in this dissertation.

In *Study III* the more specific constructs of attentional and behavioral control are used. Attentional control is defined as the ability to inhibit interference from distractors and keep focus on the target (Diamond, 2013; Friedman & Miyake, 2004) regardless of fatigue (Cartwright, 2012). Behavioral control as the ability to inhibit inappropriate automatic behavior and motoric or vocal responses (Cartwright, 2012; Diamond, 2013; McClelland et al., 2014; Van de Sande et al., 2013). These two constructs are both considered to, besides inhibition, include working memory and shifting aspects of EF, but are distinguished by their difference in inhibition of either attention or behavior. Self-regulation as used in *Study II* is therefore a slightly broader construct than behavioral control in *Study III*. Working memory as used in *Study I* is defined as the temporary storage and manipulation of information in mind (Baddeley, 1992).

Throughout this dissertation, although the term EF was chosen as the umbrella term, both the terms self-regulation and EF are used interchangeably. The difference being that self-regulation is measured as

a broader construct encompassing multiple EFs, while EF may be separated in different components. Most often, the term reflects the way other researchers have referred to the construct in their study. Sometimes the term ‘self-regulatory skills’ is used for EF or EF components (e.g., inhibition, working memory, shifting) for reasons of consistency and readability.

It is also important to note that, in this dissertation, the conceptualization of EF is limited to attentional and behavioral aspects as measured by direct assessments. Teacher or parent questionnaires about children’s behavior in class or at home, or self-regulation as a form of compliance (Kochanska, Coy, & Murray, 2001) are not an explicit part of the concept of EF in this dissertation.

### *2.1.2 Defining academic skills*

When studying the association between EF and academic skills in early childhood, the term academic skills is often used to cover the two main domains of children’s academic achievement: literacy (including reading and writing) and mathematics (e.g., Cadima, Gamelas, McClelland, & Peixoto, 2015; Gestsdottir et al., 2014; McClelland et al., 2014). During early childhood (ages 3 to 8), the terms early (or emergent) literacy (Neuman & Dickinson, 2011; Whitehurst & Lonigan, 1998) and early mathematics (or numeracy) (Jordan, Kaplan, Locuniak, & Ramineni, 2007; Purpura, Baroody, & Lonigan, 2013; Purpura & Lonigan, 2013) are often used to indicate the precursors of these skills that start to develop already before formal reading, writing, and mathematics instruction starts in elementary school. The next sections provide an overview of the definitions and terminology of early literacy and mathematics used in the present work.

### **2.1.2.1 Early literacy**

Early literacy includes oral language skills (e.g., semantic knowledge; receptive and expressive vocabulary, syntactic knowledge; word order and grammar) as well as code-related skills (e.g., print conventions, grapheme-phoneme correspondence, and phonological processing abilities) (Storch & Whitehurst, 2002; Wagner & Torgesen, 1987). Early literacy skills are often defined as the skills, knowledge, and attitudes that are developmental precursors to reading and writing. Yet, the acquisition of literacy is considered a developmental continuum with no clear demarcation between pre-reading and reading skills (Whitehurst & Lonigan, 1998).

In this dissertation, measures of both oral language (expressive vocabulary; *Study I* and *II*), as well as code-related skills (phonological awareness; *Study I, II* and *III*, and word reading; *Study III*) are used as indicators of early literacy. Phonological awareness refers to the ability to perceive and manipulate the sounds of spoken words. This means that children, on top of the more unconscious process of discriminating speech sounds, become aware of and are able to manipulate constituent phonemes, syllables, and rimes in words (Wagner & Torgesen, 1987). Expressive vocabulary refers to the words that a child can produce (Burger & Chong, 2011) and includes semantic knowledge as well as phonological representations (Levelt, Roelofs, & Meyer, 1999; Wise, Sevcik, Morris, Lovett, & Wolf, 2007). Word reading is a decoding skill that refers to an understanding on the word level rather than understanding the comprehension of the meaning of a word. Decoding may be defined as efficient word recognition: “the ability to rapidly derive a representation from printed input that allows access to the appropriate entry in the mental lexicon, and thus, the retrieval of semantic information on the word level” (Hoover & Gough, 1990, p. 130). Both phonological awareness and alphabetic knowledge are important for word decoding (Hjetland et al., 2019; Konstam & Neuhaus, 2011).

### **2.1.2.2 Early mathematics**

Early mathematics consists of a broad range of skills and concepts, including aspects of numeracy (or number sense), such as logical operations, numeral representations, and numeral estimations (Jordan et al., 2007; Van de Rijt, Van Luit, & Pennings, 1999; Van Luit & Van de Rijt, 2009) and aspects of problem-solving and geometry (Clements & Sarama, 2011; Magne, 2003). Early mathematics, and numeracy in specific, includes both informal numeracy skills as well as numerical knowledge and formal numeracy knowledge (Purpura et al., 2013). Informal numeracy skills are traditionally considered those skills that develop prior to and outside of formal schooling, often through day-to-day situations and play. These include numbering (e.g., counting, subitizing, cardinality), relations (e.g., ordinality, relative size, set comparison), and simple arithmetic operations (e.g., addition/subtraction with and without objects, and making number combinations). Written mathematical symbols or algorithms are not considered part of informal skills (Baroody, Gannon, Berent, & Ginsburg, 1984 in Purpura & Lonigan, 2013). Numerical knowledge includes knowledge of the Arabic numeral system, learning numeral names, and being able to differentiate them from letters and other signs. Formal numeracy knowledge consists of the mathematical concepts and skills that children learn through formal instruction, such as making basic combinations (e.g., addition and subtraction) (Purpura & Napoli, 2015).

In this dissertation, measures of both informal and formal aspects of early mathematics are used. In *Study I* and *II*, the term early mathematics reflects informal aspects of children's early numeracy, problem-solving, and geometry skills. Math achievement in first and fifth grade in this study are the formal math skills as measured by standardized tests in school (Norwegian Directorate for Education and Training). In *Study III*, the term number sense reflects children's informal knowledge of logical operations, numeral representations, and numeral estimations (Van Luit & Van de Rijt, 2009) and is interchangeable with the term early

numeracy. Aspects of number sense are; comparison, classification, correspondence, seriation, counting (synchronous, shortened and resultative), applied knowledge of the number system, and estimation. The early math skills in first grade that were used in *study III* reflect the more formal skills that are taught in early elementary school. This includes more complex ways of applying knowledge of the number system (e.g., basic arithmetic skills, elementary fraction, and elementary geometry).

## **2.2 Theoretical framework**

Educational science is understood as an interdisciplinary field with theoretical contributions from scientific research across several academic disciplines such as philosophy, history, psychology, and sociology, and more specific fields such as child development, cognitive neuroscience, and collaborations between these fields. The development of EF, but also language, literacy, and mathematics, are often studied within a neuro-cognitive development framework (e.g., Goswami, 2008), independent of the educational context. Knowledge derived from these studies forms the basis for studies in the field of education. For example, neurobiological and neurocognitive frameworks have been used to model links among the development of EF and academic competence in kindergarten and school settings (Blair, 2002; Blair & Raver, 2015). The work in this dissertation is grounded in developmental systems perspectives (Ford & Lerner, 1992) and socio-cultural development theory (Vygotsky, 1934/1986) that provide a framework for the integration of biological, behavioral, and environmental aspects of development.

### **2.2.1 Developmental systems theory**

Central to developmental systems perspectives such as relational developmental systems theory (RDS; Overton, 2015), dynamic systems theories (Thelen & Smith, 2006), and developmental psychobiological

perspectives (Blair & Raver, 2015) is that the course of development depends on the bidirectional and multilevel interactions among multiple factors at each level of development (Griffiths & Hochman, 2015). The notion of probabilistic epigenesis is the idea that dynamic and continuous bidirectional coactions between several levels of influence (e.g., biology, behavior, and environment) actively and continuously shape individual development rather than a stable and essentially independent contribution of each of these aspects. Self-regulation is often studied within a RDS perspective as it can inform our understanding of the development of EF and self-regulation (McClelland et al., 2015) and how it relates to other developing skills (McClelland & Cameron, 2019). According to this framework, all development represents a bidirectional and dynamic process of person–context relationships and these are mutually regulating. Development of increasingly complex skills at each stage builds on the results of development at an earlier stage. Thus, skills do not develop in isolation and development in one skill (e.g., self-regulation development) may set the stage for further development in another skill (e.g., literacy and mathematics), and vice versa.

One of the core concepts of this framework is *relative plasticity*: the capacity for change (McClelland et al., 2015). This means that individual (child characteristics at a certain stage) and contextual factors (e.g., the child’s environment at a certain stage) may affect the development of EF and academic skills. EF does not develop automatically: children have the potential to develop it in interaction with their environment. The developmental window for plasticity seems especially prominent during early childhood when children show a developmental spurt and rapid growth in neural connections associated with EF (Diamond, 2002).

Another concept that is central in RDS and relevant to the work in this dissertation is the concept of *experiential canalization*: the shape of development is formed by the coaction of biology and experience, which influences behavior over time. The frequent practice of behavior and skills over time leads to automation of skills (that *can* be automated) and

frees cognitive resources to deal with more complex aspects of a task (McClelland & Cameron, 2019; McClelland et al., 2015). For example, the automation of early academic skills such as phonological awareness and letter knowledge may allow the child to attend to the meaning of words and comprehension of text rather than use EF resources on structural features (Cartwright, 2012).

This overarching theoretical framework provides the basis for investigating the bidirectional and domain-specific associations between EF and early mathematics and literacy in *Study II* and *III*.

### **2.2.2 Socio-cultural development theory**

Vygotsky's socio-cultural development theory provides another perspective for the role of language and context in the development of self-regulation and is central to the framework used in *Study II*.

According to Vygotsky (Vygotsky, 1934/1986), language plays an important role in the development of self-regulation (Diaz, Neal, & Amaya-Williams, 1992). Children internalize external rules and structures by increasing use of inner speech that aids them with regulating their thoughts and behavior, solve problems, and reach their goals. Support for this theory is investigated in *Study II*.

Moreover, the development of cognition cannot be separated from culture (Vygotsky, 1934/1986). Accordingly, the development of self-regulation occurs within the child's social and cultural context and thus is contextually specific (Diaz et al., 1992; Trommsdorff, 2009). One aspect of a culture that is most relevant from an educational science perspective is the educational context in which the child is embedded. Educational contexts and traditions vary between countries (Organisation for Economic Co-operation and Development; OECD, 2006) and results from countries with certain educational contexts may therefore not be directly generalizable to a different educational context. In *Study II*, the importance of conducting research on the interrelations

between self-regulation and academic skills in different types of educational contexts is therefore emphasized.

### **2.3 Early childhood education context**

This dissertation makes use of data from Norway (*Study I and II*) and the Netherlands (*Study III*). Below follows a short description of the similarities and differences of two dominant educational traditions that inform the practices in ECEC across countries; the play-based and school-readiness approach. OECD refers to these approaches as a “social pedagogy” and “pre-primary” tradition respectively (OECD, 2006). However, in this dissertation the terms school-readiness approach and play-based approach are used, respectively, to reflect the characteristics, focus, and type of the activities in the two traditions.

#### **2.3.1 School-readiness approach**

The pre-primary school readiness tradition is common in English speaking countries, e.g. United States, United Kingdom, Australia, and Canada, and a few non-English speaking countries such as France and the Netherlands (OECD, 2006). This approach is characterized by an early introduction of the contents and methods of formal education into ECEC. Structured methods are used to promote knowledge and skills that are useful for school (e.g., early literacy and mathematics). There are clear standards about what children should be able to do and know before they transition to formal schooling.

In the Netherlands (*Study III*), children start school at the age of four. They spend the first two years in what would be known as ‘preschool’ and ‘kindergarten’ in the United States. In kindergarten, early academic skills are promoted through playful but structured learning activities with the clear goal of promoting early academic skills, such as literacy and mathematics. Children are expected to obtain a certain level of early literacy skills, such as phonological awareness and letter knowledge, and

early math skills, such as counting up to 10 and solving simple arithmetic problems using their fingers (SLO; Stichting Leerplan Ontwikkeling, 2018). There are no regulations for teacher-child ratio, but groups contain about 23 children on average (Ministerie van Onderwijs Cultuur en Wetenschap, 2020) and teacher-child ratio in 2014 (year of data-collection in *Study III*) was 1:19 (Rijksoverheid, 2019). After kindergarten, children make the transition to formal education.

### *2.3.2 Play-based approach*

The play-based social pedagogy approach characterizes most Nordic (including Norway) and Central European countries (OECD, 2006). Although this approach does acknowledge the importance of early literacy and mathematics for children's development, this pedagogy is characterized by a respect for natural learning strategies, such as learning through free play, interaction, and everyday exploration. Varying somewhat in format and role from country to country, in general, the ECEC system has a more holistic approach to learning.

Because the majority of research on the associations between EF and academic skills has been conducted in school-readiness contexts, Norway (*Study I* and *II*) provides a special case on the far end of the play-based scale as it is characterized by a high percentage of play-based activities - often outside in both summer (70% of the time) and winter (31% of the time) (Moser & Martinsen, 2010), few situations with direct instructional activities, children that choose their own activities, and planned activities being skipped for free-play (Lekhal et al., 2013). Children enter school at the age of six. Before this age, almost all children (attendance 97%: Statistics Norway, 2018) attend public or private ECEC regulated by the 'Framework Plan for the Content and Tasks of Kindergartens' (Framework Plan)(Ministry of Education and Research, 2017). This Framework Plan functions as an orientating guide rather than a curriculum or instrument of normalization criteria. It does not contain any goals or benchmarks for academic or cognitive

development. Regulations prescribe a teacher-child ratio of 1:18 and a staff-child ratio of 1:6 for the 3-5-year-olds meaning that one teacher works together with two assistants on a group of maximum 18.

## **2.4 Development**

Early childhood is characterized by a growth spurt and accompanied increase in neural connections in the prefrontal and frontal cortex - brain regions associated with EF (Diamond, 2002) - that parallels the development of early academic skills (Cartwright, 2012). Knowledge about the developmental trajectories and their interrelations may inform our understanding of how EF and certain academic skills are related across time.

### **2.4.1 EF development**

The development of EF across early childhood manifests itself through the ability to perform increasingly complex tasks. Different periods of growth are expressed by the development of different aspects of EF (for a detailed overview of EF development see, e.g., Best & Miller, 2010; Garon, Bryson, & Smith, 2008). A general attention system begins developing early in life and is considered a foundation for the development of other EF components (Garon et al., 2008). The development of attention allows young children to orient to stimuli, resist distractions, and exert increasing control over incoming information. The length and frequency of the attention span increase with age (Heim & Keil, 2012). Complex working memory abilities (e.g., updating) develop from 15 months and up (Garon et al., 2008). The development of working memory is thought to be continuously refined into adolescence (Best & Miller, 2010; Lee et al., 2013). Across early childhood children gradually become able to inhibit impulses for longer periods of time and use increasingly complex strategies (e.g., use mental representations) to guide their behavior and solve complex inhibition-related tasks (Garon et al., 2008). The ability to shift attention between different mental states,

rules, or tasks is believed to build upon the development of the general attention system and the other EF components (Garon et al., 2008). Older children and adolescents exhibit further development in more complex tasks and reach adult-like levels by mid-adolescence (Best & Miller, 2010).

#### ***2.4.2 Early literacy and mathematics development***

By the age of five children usually comprehend and speak a language fluently (Goswami, 2008). However, learning to read and write requires the further development of early literacy skills, such as phonological awareness, letter knowledge, and decoding. Phonological awareness is a consistent predictor of later reading achievement (e.g., Lonigan et al., 2009; Storch & Whitehurst, 2002; Walgermo, Foldnes, Uppstad, & Solheim, 2018). Together with the acquisition of letter knowledge, phonological awareness sets the stage for word decoding (Hjetland, Brinchmann, Scherer, & Melby-Lervåg, 2017; Hjetland et al., 2019; Lervag, Braten, & Hulme, 2009; Segers et al., 2016). Decoding in turn is an important predictor for later reading comprehension (Hjetland et al., 2017; Hjetland et al., 2019).

The development of mathematical abilities starts early in life with young children having certain competencies in number already from birth (Sarama & Clements, 2009). The acquisition of the count sequence provides the basis for development of the cardinal and ordinal understanding of the symbolic number system (Goswami, 2008). Growth in mathematics can be considered a cumulative learning process in that mathematical skills develop hierarchically. Children are continually faced with more complex mathematical problems, even though initial skills such as counting become automatized (Clements, Sarama, & Germeroth, 2016; Sarama & Clements, 2009).

### **2.4.3 Co-development**

Co-development refers to a process where skills develop alongside and skill gains in one area track with skill development in another (McClelland & Cameron, 2019). Studying the associations among developmental processes is complex because neither set of skills is static. The development of EF and the ability to perform increasingly complex tasks may allow children to acquire increasingly complex academic skills. As literacy and math skills may vary in complexity this has implications for how EF, or specific components of EF, predict these skills at certain points of development. For example, more basic EFs, such as simple response inhibition, are likely to be broadly related to several aspects of early literacy and mathematics, while complex EFs, such as working memory and shifting, likely contribute to more complex and abstract measures of academic achievement (Purpura, Schmitt, et al., 2017). Attentional and behavioral aspects of EF may also differently predict aspects of early literacy, such as phonological awareness and word decoding (Segers et al., 2016; Van de Sande et al., 2013).

Moreover, from an early age on the two domains of early literacy and mathematics are related (Kleemans, Segers, & Verhoeven, 2011) and predictive of each other across time (Duncan et al., 2007; Krajewski & Schneider, 2009; Purpura et al., 2011; Simmons, Singleton, & Horne, 2008). Especially phonological awareness is thought to play a role in the development of early mathematics (Simmons et al., 2008; Simmons & Singleton, 2008). The exact nature of the interrelations between early literacy and mathematics is nevertheless far from clear because factors such as EF have an impact on the development of both skills. For example, Kleemans et al. (2011) found that phonological awareness and grammatical ability mediated the effect of working memory on early numeracy.

## **2.5 Measuring EF and academic skills in early childhood**

The rapid growth of children's cognitive and academic skills during early childhood makes it challenging to find measures that effectively assess the constructs of interest across time. Together with the plethora of conceptual and definitional issues that have characterized the fields that study EF (and self-regulation) this has resulted in a large variety of measures that have been used to measure children's EF and self-regulation (McClelland & Cameron, 2012; Toplak, West, & Stanovich, 2013).

This dissertation relies on several direct measures - also referred to as performance-based assessments (Toplak et al., 2013) - rather than indirect measures, such as questionnaire-based ratings from caregivers or teachers. In direct assessments, the context and interpretation of the task are highly constrained and the child is instructed to maximize performance. Direct measures are therefore considered to assess the efficiency of EF processes and reflect children's optimal (rather than typical) performance in highly structured environments (Toplak et al., 2013).

Academic skills were also assessed through performance-based assessments. The Netherlands (*Study III*) has an ECEC tradition wherein the assessment of children's early academic skills is common and tests suitable for research are widely available (e.g., Utrecht Early Numeracy Test; Van Luit & Van de Rijt, 2009; Screening Instrument for Emerging Literacy; Vloedgraven, Keuning, & Verhoeven, 2009). In Norway, on the contrary, testing of children's academic skills in ECEC is not common and may even be considered controversial. Consequently, few instruments that are suitable for research have been developed. The Ani Banani Math test (Størksen & Mosvold, 2013) was specially designed for research in the Norwegian kindergarten 'Skoleklar' project and is

used in *Study II*. *Study I* was therefore aimed at investigating the psychometric properties of this task.

### **2.5.1 *The Ani Banani Math Test***

Many of the existing mathematical assessments (e.g., Research-Based Early Maths Assessment (REMA); Clements, Sarama, & Liu, 2008; Utrecht Early Numeracy Test; Van Luit & Van de Rijt, 2009; Woodcock-Johnson Tests of Achievement; Woodcock, McGrew, & Mather, 2001) that are suitable for children age 5-7, are developed for the school readiness tradition (as described in paragraph 2.3.1). Considering that a child's development is embedded in the context and type of learning experiences they encounter, mathematical instruments that are constructed for use in the school readiness tradition may be less suitable for use in samples from play-based traditions, such as Norway. In addition, these tasks require considerable time to administer. When assessing knowledge and skills among children it is important to select short and feasible tests to avoid fatigue and poor concentration. Especially since Norwegian kindergartners are not used to being in test situations.

Few, if any, math measures that are suitable for research in ECEC have been validated in Norway. Assessments that do exist are primarily meant for practitioners and are less suited for research purposes. For example, the MIO ("Matematikken, Individet og Omgivelsene [The Mathematics, the Individual, and the Environment]") (Davidsen, Løge, Lunde, Reikerås, & Dalvang, 2008a, 2008b; Reikerås, Løge, & Knivsberg, 2012) is an observational assessment tool where children's math development is observed and reported by the teachers during play and everyday situations across several occasions. It aims to assess skills expected to be present among 5-year-old children and would therefore not be able to show variability in the scores of children performing at the high end of the scale.

The Ani Banani Math Test (ABMT) is a short (ca. 10 min) task that was developed for research purposes (Størksen & Mosvold, 2013) in 5-year-olds (last year of ECEC in Norway). The ABMT is designed for tablet computer use, which has several advantages over traditional paper-and-pencil assessments. Computers seem to provide affordances for mathematical play (Lange & Meaney, 2013) that make them suitable for developing mathematical thinking (Sarama & Clements, 2009). As play is an important aspect of early childhood mathematics education (Sarama & Clements, 2009), especially in the play-based Norwegian tradition, tablets provide unique opportunities to integrate play into a mathematical assessment. Moreover, unlike a traditional computer, the touch screen interface of tablets takes advantage of a more direct mediation through finger moves and gestures allowing children to produce and transform objects directly instead of through a keyboard or a mouse (Sinclair & SedaghatJou, 2013). Further, previous research has shown that the use of technology enhances motivation among children in educational settings (Couse & Chen, 2010; Haugland, 1999; Haugland & Wright, 1997). A practical advantage is that the tablet automatically encodes children's scores and sends the encrypted data to a server which makes data collection and administration time efficient.

Both Norway's Framework Plan (Ministry of Education and Research, 2017) and the Norwegian competence center for mathematics (Matematikksenteret, 2010) emphasize the importance of applying a practical and playful approach when promoting children's early mathematical development in kindergarten. This means that, in Norwegian ECEC, mathematical features, such as shapes, sizes, and numbers, are explored in natural and playful settings, rather than through instructional activities. Items in the ABMT include a figure - a little monkey called Ani Banani - and his imagined everyday activities. Children are asked to help Ani Banani with tasks such as counting toys, finding the largest milkshake, giving him a certain number of bananas, and so on. As such, the ABMT reflects the informal and playful learning

of mathematic skills in Norwegian ECEC. The ABMT aims to tap children's informal math skills, such as recognizing and stating quantities, selecting a given number of objects, and relative size comparisons. The task was developed (Størksen & Mosvold, 2013) to include three areas - numeracy, problem-solving, and geometry (Magne, 2003). These areas are also covered in the Norwegian Framework Plan (Ministry of Education and Research, 2011, 2017).

### **2.5.1.1 Psychometric theory of measurement validity**

In general, validity refers to the degree to which empirical evidence and theoretical rationales support the adequacy and appropriateness of the interpretations and actions based on test scores (Messick, 1989). Put more simply, validity refers to the extent to which a measure in fact measures the concept it is intended to measure.

Six aspects of construct validity can be distinguished: content, substantive, structural, generalizability, external, and consequential aspects (Messick, 1995). The latter four aspects are given a specific focus in *Study I*.

The content aspect includes the evaluation of the boundaries of the construct and the degree to which the items or tasks are representative of the construct domain. It is traditionally evaluated by expert professional judgment.

The substantive aspect moves beyond this judgment by adding empirical evidence (i.e., from correlation patterns among part scores, from "think aloud" protocols, or eye movement records) that the ostensibly sampled construct is actually engaged.

The structural aspect is concerned with the structure of a task (i.e., interrelations between aspects of a task or subtasks) which should represent what is known about the internal structure of the construct domain (Messick, 1989). In the case of ABMT, this would mean that the

ABMT may contain three interrelated components: numeracy, problem-solving, and geometry (Magne, 2003).

Evidence of generalizability depends on the degree of correlation of the task with other tasks that are considered indicators of the same construct but is also affected by generalizability across time or occasions. As such, these latter sources of measurement error underlie traditional reliability concerns. The ABMT was expected to correlate with other math assessments and with itself across time. The generalizability aspect may have overlaps with the external aspect.

The external aspect concerns the extent to which the strength of the correlations with other measures aligns with what would be expected from theory of the construct being assessed. Both convergent and discriminant validity are basic aspects of construct validity (Messick, 1995). For this purpose, the criterion-related and discriminant validity of the ABMT were assessed. Criterion-related validity includes both concurrent and predictive validity and is evident when the ABMT instrument is sufficiently strong related to and predictive of other early math instruments used for the same purpose. Evidence for discriminant validity includes the ABMT being more strongly correlated with other math instruments than with instruments with which it is expected to correlate (e.g., early literacy and EF).

Finally, consequential aspects include a consideration of the intended and unintended consequences of score interpretation and use. Most importantly, sources of invalidity, such as construct underrepresentation or construct-irrelevant variance should not bias the results. Especially if the measure is too broad it may be prone to construct-irrelevant difficulty or easiness. This means that aspects of the task that are not included in the focal construct may make the task more or less difficult for certain individuals or groups. One of the consequences of test invalidity of the ABMT is that certain children may score higher or lower on the ABMT not because of differences in their underlying math skills, but because of

other non-math aspects that are part of an item. For example, a boy with the same ‘true’ math ability as a girl should have the same probability of scoring correctly on an item. However, if that item contains features that are, for example, more appealing or otherwise more motivating for boys compared to girls, that item is likely biased. Similarly, items may include non-math aspects that older children or children from high socioeconomic background are, for example, more familiar with compared to younger children or children with a low socioeconomic background.

The overall aim of *Study I* was to evaluate the validity of the scores on the ABMT as a measure of children’s early mathematics.

## **2.6 Associations between EF and academic skills**

### **2.6.1 The direction of associations**

EF (in *Study II* referred to as self-regulation) is regarded as foundational (Blair & Raver, 2015; Cameron et al., 2012; McClelland & Cameron, 2019; McClelland & Cameron, 2012; McClelland et al., 2015) for a successful development of academic skills. Foundational skills are less visible cognitive processes that are often not explicit targets of instruction but are considered fundamental for learning in one or more content areas (McClelland & Cameron, 2019).

Two pathways through which EF may contribute to early literacy and math development can be distinguished. First, the ability to regulate attention and behavior allows children to benefit from learning opportunities that facilitate the development of early academic skills (Blair & Diamond, 2008; Blair & Raver, 2015; McClelland et al., 2014). EF and self-regulation allow children to ignore irrelevant impulses and peer distractions, listen to and remember instructions, and switch attention from one activity to another in classroom situations. Second, EF may also be directly involved in academic skills (Blair, Knipe, &

Gamson, 2008; Blair & Raver, 2015; Bull & Lee, 2014; Cartwright, 2012). For example, inhibition may help children to ignore certain aspects of a mathematical problem (e.g., irrelevant contextual information from a word problem), good working memory may assist children in storing and retrieving information (e.g., partial results) during the problem-solving process, and shifting may aid the process of, for example, switching between different strategies to solve a problem (Bull & Lee, 2014). Similarly, inhibition may help children with ignoring interfering stimuli when reading (e.g., other words or features on a page), shifting may aid children to flexibly switch between the meaning of a word and its structural features, and working memory may enable children to manage and coordinate elements of a sentence for effective comprehension (Cartwright, 2012).

Though it seems intuitive to assume that EF plays a causal role in the development of early literacy and mathematics, EF may not only set the stage for development in academic skills, but certain academic skills may also contribute to the development of EF, which in turn may spur further academic development, and so on.

The development and mastering of academic skills during early childhood constitutes a challenging and complex developmental task. The repeated use of working memory, inhibition, and shifting during the course of this development suggest that children who practice academic skills may, at the same time, train EF (Clements et al., 2016). Children with good academic skills may seek out or be challenged with more advanced and complex academic activities and more often engage in academics compared to children with lower proficiency. Hence, children's acquisition of high academic achievement and subsequent increase in complexity and frequency of academic activities may lead to more practice of EF skills compared to what is the case for children who do not, or inefficiently practice academic skills (Blair & Raver, 2015; Clements et al., 2016).

Moreover, as outlined in paragraph 2.2.2, Vygotsky (Vygotsky, 1934/1986) reasoned that the internalization of children's caregiver regulatory speech allows them to talk to themselves and monitor and modify their thoughts and behavior. Private speech is considered a domain-general system for verbal self-regulation (Lidstone, Meins, & Fernyhough, 2011). As language develops during early childhood the child gains access to an increasingly growing number of internalized symbols and representations. A child's vocabulary is representative of their symbolic repertoires and children who have larger vocabularies thus have more mental tools to regulate their behavior (Vallotton & Ayoub, 2011). Hence, children's EF may not only predict aspects of language, their language abilities (e.g., vocabulary) may also predict EF.

#### **2.6.1.1 Prior research on bidirectionality**

Awareness about possible bidirectional or reciprocal processes in development and the importance of investigating the direction of causal relations between EF or self-regulation and academic skills has been rising in recent years (Clements et al., 2016; McClelland & Cameron, 2019).

The most consistent evidence for bidirectionality has been found for mathematics and EF. A relatively high number of studies found that EF or self-regulation predicted math as well as vice versa in preschool and kindergarten children (Fuhs, Nesbitt, Farran, & Dong, 2014; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017; Welsh, Nix, Blair, Bierman, & Nelson, 2010), although sometimes the relation became unidirectional with only self-regulation predicting mathematics at later time points (Fuhs et al., 2014; Schmitt et al., 2017) suggesting co-development among EF and mathematics early on, with patterns becoming more specific over time (McClelland & Cameron, 2019).

Results from studies investigating the direction of relations between self-regulation and language have been mixed with some recent studies

showing evidence for bidirectional relations (Cadima et al., 2018; Slot & Von Suchodoletz, 2018) or a combination of uni- and bidirectional relations depending on the time and type of assessment (Bohlmann, Maier, & Palacios, 2015; Fuhs et al., 2014). Consistent across all of these studies, including a study by Fuhs and Day (2011), seems, however, that results included a significant pathway from language to EF or self-regulation across at least one of the time spans. An exception was a study by Weiland, Barata, and Yoshikawa (2014) who found that EF predicted language, but not the reverse. Also, Gooch, Thompson, Nash, Snowling, and Hulme (2016) did not find any evidence for reciprocity between EF and language in children 4 to 6 years. However, their sample included children with a wide range of language abilities including children at risk of dyslexia and or other concerns regarding their language development and may therefore not be representative of the typically developing population. Recently, Meixner, Warner, Lensing, Schiefele, and Elsner (2018) did find a significant path from EF to reading comprehension in first-graders and bidirectional relations between EF and reading comprehension for second and third graders. Taken together, these results suggest a relatively consistent pathway from language to self-regulation and EF, which is in line with Vygotsky's socio-cultural development theory and the role of language in the development of self-regulation, as well as indications of a self-regulation to language pathway.

Finally, studies that have investigated the direction of associations between self-regulation and early literacy skills show a consistent pattern of a unidirectional pathway from self-regulation to early literacy, and not the reverse. However, the strength of this pathway is often weak (beta's often below .20) and not consistently present across time (Fuhs et al., 2014; McKinnon & Blair, 2018; Schmitt et al., 2017; Welsh et al., 2010).

One limitation of prior work on this topic is that, with a few recent exceptions (Hernández et al., 2018; McKinnon & Blair, 2018), none of these studies have looked at the direction of relations between self-

regulation and academic skills when children make the transition between kindergarten and first grade. The transition to first grade is accompanied by a change in educational context from informal to education that is more formal (e.g., sitting still behind a desk for longer periods of time, listening to the teacher, raising a hand before asking a question, focusing on and complete a given task, more instruction and less free play overall) as well as an increase in focus on academic skills. This transition may put a high demand on children's self-regulation in addition to the heightened demand on self-regulatory skills that can be expected because of the increase in a focus on learning academic skills. This may especially be the case in the Norwegian early childhood education context because the transition from a play-based kindergarten to formal schooling may require extra self-regulation in order to cope with the shift from free play to instructional activities.

Moreover, most studies have estimated separate models for early literacy and mathematics. Combined models may provide valuable information on whether the effects are robust when controlling for one another. Schmitt et al. (2017) did include both literacy and mathematics in one model, but this study did not include the transition to first grade. Recently, McKinnon and Blair (2018) published a study where they included early reading skills (letter-word identification) and mathematics in one model and found bidirectional relations for mathematics across the transition to first grade, but only a weak ( $\beta = .09$ ) unidirectional relation from EF to early reading skills.

The aim of *Study II* was to get a better understanding of the direction of associations between self-regulation and early literacy and math skills when children transition from a play-based kindergarten to formal education in first grade. More specifically, is this relationship best represented as *bidirectional* (reciprocal associations between variables), *unidirectional* (self-regulation predicts academic skill or vice versa), or is the association likely better explained by other variables not present in the model (no coupling in any direction)?

### **2.6.2 Domain-specificity of associations**

EF is often considered a domain-general cognitive skill that contributes to the development of both early literacy and mathematics (Best, Miller, & Naglieri, 2011). However, although significant associations are certainly found between EF and early literacy skills (e.g., Best et al., 2011; Blair & Razza, 2007; Gestsdottir et al., 2014; McClelland et al., 2007; Van de Sande et al., 2013), EF often shows stronger and more robust associations with mathematics compared to literacy (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Blair & Razza, 2007; Blair, Ursache, Greenberg, & Vernon-Feagans, 2015; McClelland et al., 2014; Schmitt et al., 2017). This suggests that there are some specific characteristics with mathematics that are different from literacy and that draw more heavily or differently on children's EF's.

One of the key concepts that may be relevant for the differential relation between EF and early literacy and mathematics is the idea that cognitive resources decrease as skills automatize (McClelland & Cameron, 2019). According to this automaticity account, the discrepancy between the strength with which EF predicts literacy and mathematics may arise because the acquisition of early literacy skills is, to a larger degree, about acquiring crystallized knowledge, automatizing skills, and obtaining fluency (Blair, Protzko, & Ursache, 2011; Blair & Razza, 2007). Thus, at the point when new information has been crystalized and children have gained a certain degree of automaticity, the demand on EF diminishes. Mathematics, on the contrast, despite depending on some automation and crystallized knowledge (e.g., subitizing, memorizing times tables, procedural knowledge) steadily increases in complexity (Blair et al., 2008; Blair et al., 2011; Clements et al., 2016). Reasoning and problem solving are an inherent part of mathematics and EF is particularly important when encountering novel and conflicting information or when prior responses and strategies need to be overridden (Blair et al., 2011). Thus, EF may be especially important when early literacy skills are in the process of being acquired. Once acquired and automated, early

literacy skills, such as phonological awareness, may be more essential to further reading development compared to EF. This suggests that early skills may mediate the pathway between EF and later reading skills. Due to its increase in complexity, mathematics may place ongoing demands on EF, even when some early numeracy skills become automated.

Another possible mechanism that may explain any differential relationships between EF and certain academic skills is that early literacy and mathematics may draw upon different cognitive and behavioral abilities within the broader construct of EF. EF encompasses both attentional and behavioral inhibitory processes (Diamond, 2013). However, EF or self-regulation (Becker, Miao, Duncan, & McClelland, 2014; Cadima et al., 2015; Hubert, Guimard, Florin, & Tracy, 2015) is often measured by tasks that require inhibition of a behavioral (action/motor) response (e.g., inhibiting pressing a response key, touching a body part, standing still, not reaching at a previously rewarded location, inhibiting naming what you see rather than the opposite) and do not include an active component of attentional control (e.g., distractor stimuli). This is also the case in *Study II*. Early literacy and mathematics may vary in their relative demand on the ability to control attention versus behavior and associations may have been missed in previous research.

### **2.6.2.1 Prior research on domain-specificity**

*Study III* primarily builds on previous research that found differential effects of attentional and behavioral aspects of EF on early literacy skills in kindergarten and first grade (Segers et al., 2016; Van de Sande et al., 2013). Both studies found that attentional and behavioral control predicted phonological awareness in kindergarten. On the contrary, word reading in first grade was only predicted by attentional control, in part through phonological awareness. Behavioral control only indirectly predicted later word reading via phonological awareness. A recent longitudinal study from kindergarten to 2<sup>nd</sup> grade (Van de Sande, Segers,

& Verhoeven, 2017) also showed that both the control of attention and behavior (action) enabled the development of phonological awareness, which in turn set the stage for later decoding and reading comprehension. However, the contributions of attention and behavior control were, again, different: direct and mediation effects of attentional control to reading skills were found, while for action control only indirect effects were found.

Results from these studies suggest that the control of both attention and behavior in kindergarten function as a prerequisite for the development of early literacy skills such as phonological awareness, but that more formal reading development may be, to a larger degree, a cognitive process involving attentional control rather than the ability to inhibit motoric actions and behavior. The finding that phonological awareness mediated the effect between attentional control and later decoding suggests that when early skills are successfully acquired the demand on attentional control in reading diminishes. The studies hereby highlight the importance of considering the distinction between the two types of control, studying them simultaneously in order to assess their unique associations, and investigating indirect effects.

A limitation of these studies is that they assessed attentional and behavioral control with only one task. This limits the ability to reduce the probability that task-specific characteristics are driving the effects (e.g., language or visuospatial processing) (Miyake et al., 2000). Furthermore, it remains unknown whether attentional and behavioral control uniquely and differently predict early mathematics compared to early literacy. An indication of possible differential effects is provided by a study in American and Chinese preschoolers (Lan, Legare, Cameron Ponitz, Li, & Morrison, 2011) which showed that inhibition (measure of self-regulation) significantly predicted counting, but not reading. Attentional control predicted most academic tasks (reading, counting, and calculation), but was the most robust predictor for reading. A limitation of this study is that separate models were estimated for the

academic outcomes and interrelations between literacy and mathematics were not taken into account.

The aim of *Study III* was to investigate whether attentional and behavioral components of EF, as measured with five EF tasks, not only predicted different aspects of early literacy (e.g., phonological awareness and word reading) differently but also showed unique relations with early mathematics (e.g., number sense and mathematics). Moreover, in order to get a more nuanced picture of the developmental pathways from EF to literacy and mathematics, cross-domain associations were taken into account by including both domains in one model. In addition, considering that the association between EF and early literacy skills may attenuate when basic skills such as phonological awareness are automated, indirect effects via phonological awareness and number sense in kindergarten were assessed.

### 3 Research questions

*Study I* provides the basis for *Study II* with a psychometric evaluation of the early mathematics assessment used in that study. *Study II* investigates the direction of effects between self-regulation and early literacy and mathematics. *Study III* assesses the pathways from two aspects of executive function (attentional and behavioral control) to early literacy and mathematics. The research questions in each study were as follows:

#### Study I

RQ 1.1 What is the factor structure of the ABMT? It was tested whether a one, two, or three-factor model best fitted the data.

RQ 1.2 Do the items of the ABMT function similarly across age, sex, and socioeconomic status?

RQ 1.3 Does the ABMT show concurrent, predictive, and discriminant validity?

#### Study II

RQ 2.1 Does kindergarten self-regulation predict first-grade mathematics, expressive vocabulary, and phonological awareness, controlling for prior skills?

RQ 2.2 Do kindergarten mathematics, expressive vocabulary, and phonological awareness predict first-grade self-regulation, controlling for prior skills?

#### Study III

RQ 3.1 To what extent do attentional and behavioral control predict early literacy (i.e., phonological awareness in kindergarten and word reading in first grade) and early numeracy skills (i.e., number sense in kindergarten and mathematics in first grade)?

## 4 Methods

In this section, a general description of the samples, procedures, ethical considerations, measures, and statistical methods are presented.

### 4.1 Samples and Procedures

This dissertation is based on longitudinal datasets from three Norwegian projects (Skoleklar, Agderprosjektet, and Lekbasert Læring) and one Dutch sample. For *Study I* the three former datasets were used, For *Study II* the Skoleklar dataset was used, and in *Study III* the Dutch dataset.

The main characteristics of these datasets are presented below. For detailed information on the samples see Table 1.

In the Skoleklar project (Sample 1) children were assessed in spring of the last year (2012) of ECEC (referred to as ‘kindergarten’) (T1), in spring of first grade (2013) (T2), and again in fall fifth grade (2016). Data was collected from 19 Norwegian ECECs from one municipality on the west coast of Norway. The sample ( $N_{T1} = 243$ ,  $M_{T1}$  age = 5.78,  $SD_{T1} = .29$ ,  $range_{T1} = 5.29 - 6.30$ ) consisted of 119 boys and 124 girls. Children were assessed individually by trained research assistants in spring of kindergarten and first grade. In first and fifth (*Study I* only) grade, data were obtained from National assessments (The Norwegian Directorate for Education and Training) carried out by the schools.

In the Agderprosjekt (Sample 2) children were assessed individually in fall (2016) (T1) and spring (2017) (T2) of kindergarten by trained research assistants. The used dataset includes data from 71 Norwegian ECECs and 691 children in total. At T1 data from 664 children was available ( $M_{T1}$  age = 5.16,  $SD_{T1} = .26$ ,  $range_{T1} = 4.67 - 5.67$ ). This sample consisted of 332 boys and an equal number of girls.

In the Lekbasert L ering project (Sample 3), a total of 1282 children from 96 Norwegian ECECs were assessed individually in fall (2017) (T1) and spring (2018) (T2) of kindergarten by trained research assistants. Data from 1199 children was available at T1 ( $M_{T1}$  age = 5.14,  $SD_{T1}$  = .28,  $range_{T1}$  = 4.67 - 5.67). This sample consisted of 606 boys and 593 girls.

The latter two projects were intervention studies. To avoid possible sample-specific effects, only the control group's post-test data was used from these intervention studies. All samples were from both rural and urban areas of southern Norway.

For the Dutch dataset (Sample 4), data ( $N_{T1}$  = 90,  $M_{T1}$  age = 5.96,  $SD_{T1}$  = .43,  $range_{T1}$  = 5.25 - 6.83) was collected in spring of kindergarten (T1) (2014) in three schools in urban areas in the south of the Netherlands. The sample consisted of 48 boys and 42 girls. Data was collected by the first author and a trained research assistant. In first grade, data from standardized teacher-administered tasks that are part of the obligatory pupil monitoring system for schools in the Netherlands was used.

Table 1 Overview and Descriptives of the Datasets used in the Studies

	<i>Study</i>	<i>N</i>	Male/female	Mean age (SD)	Age range
Sample 1 – Norway ('Skoleklar')					
Spring kindergarten	<i>I &amp; II</i>	241&243	124/119	5.78 (.29)	5.29 - 6.30
Spring first grade	<i>I &amp; II</i>	239&239	122/117	6.78 (.29) <sup>b</sup>	6.29 - 7.30 <sup>b</sup>
Fall fifth grade	<i>I</i>	160	74/86	10.29 (.29) <sup>b</sup>	9.79 – 10.78 <sup>b</sup>
Sample 2 – Norway ('Agderprosjekt')					
Fall kindergarten	<i>I</i>	664	332/332	5.16 (.26)	4.67 - 5.67
Spring kindergarten	<i>I</i>	292 <sup>a</sup>	141/151	5.99 (.27)	5.50 - 6.42
Sample 3 – Norway ('Lekbasert Læring')					
Fall kindergarten	<i>I</i>	1199	606/593	5.14 (.28)	4.67 - 5.67
Spring kindergarten	<i>I</i>	519 <sup>a</sup>	259/260	5.93 (.28)	5.42 - 6.42
Sample 4 - The Netherlands					
Spring kindergarten	<i>III</i>	90	48/42	5.96 (.43)	5.25 - 6.83
Spring first grade	<i>III</i>	80	39/41	7.00 (.42) <sup>b</sup>	6.25 - 7.83 <sup>b</sup>

Note: For sample 1, 2, and 3 in *Study I*, *N* is the sample with data on the ABMT at that time point. <sup>a</sup> Only control group, <sup>b</sup> Approximation; no data on exact date of testing available, but window was approximately 1 month.

## **4.2 Ethical considerations**

All data in this dissertation came from children under the age of 18. Therefore, informed consent was collected from all parents prior to testing. Parents were informed about the study and its objectives so that they could make an informed decision on whether or not they agreed with their child taking part in data collection. The samples were treated in accordance with the prevailing institutional guidelines as well as with APA ethical standards. In addition, all Norwegian projects had been reported to and approved by the Norwegian Social Science Data Service. All data was de-identified and stored in a secure place.

All tests in this dissertation are considered age-appropriate and child friendly. If a child did not want to take part in, or finish, a task, the child was gently and positively encouraged to continue. This strategy was used to ensure that all children had the chance to overcome initial skepticism. If the child continued to deny participation this was respected. Test time was limited to a maximum of 45 minutes to reduce fatigue effects.

## **4.3 Measures**

### **4.3.1 Executive functions**

In this dissertation, six measures of EF were used. *Study I* and *II* relied on a single task as an indicator for self-regulation (*Study I* and *II*) and working memory (*Study I*), while multiple tasks were used as indicators for attentional and behavioral control in *Study III*. Below follows a description of each of these measures.

The Head-Toes-Knees-Shoulders task (HTKS; McClelland et al., 2014) was used as a direct measure of children's behavioral self-regulation in *Study I* and as one of the indicators of the factor named 'behavioral control' in *Study II*. The scores on the HTKS have been found reliable ( $\alpha$

=.94) and valid, tap aspects of working memory, inhibitory control, and cognitive flexibility (McClelland et al., 2014), and load on one EF factor together with these cognitive processes (Schmitt et al., 2017). The task significantly predicts children's academic outcomes in diverse international samples (McClelland et al., 2007; McClelland et al., 2014; Von Suchodoletz et al., 2013; Wanless, McClelland, Acock, et al., 2011) including Norwegian children (Størksen, Ellingsen, Wanless, & McClelland, 2015), and children in early elementary school (Day, Connor, & McClelland, 2015; Gestsdottir et al., 2014). In previous research, scores on the HTKS have also correlated ( $r = .46$ ) with teacher ratings of behavioral self-regulation (McClelland et al., 2007). In the task children are initially habituated to two different rules ("touch your head/toes) and later needed to inhibit this automatized response and replace it with the opposite (e.g., "touch your head" meant "touch your toes"). The total task consisted of up to three blocks of 10 items each with four additional practice items per block. The test continued to the subsequent block only if the number of points in the previous block totaled to four or more. The first block contained the items "head" and "toes". In the second block "shoulders" and "knees" were added. In the last block the rules were changed.

The Forward/Backward Digit Span subtest from the WISC-IV (Wechsler, 2003) was used as a measure of working memory in *Study I*. Children had to repeat a sequence of digits. First in the same order and then in reversed order.

The Hearts & Flowers task (Davidson, Amso, Anderson, & Diamond, 2006) was used as an indicator for behavioral control in *Study III*. Children had to press, as fast as possible, a button on the same (for hearts) or opposite (for flowers) site of stimulus presentation. Thus, the child must inhibit the automatic tendency to press on the same side of the stimulus. The total test consisted of a congruent, incongruent, and mixed block with stimuli presented on either the left or right side of the screen. In block 1, the congruent block, children had to press on the same side

as the heart, while in block 2, the incongruent block, they had to learn a new rule and press on the opposite side of a flower. Finally, in block 3, the mixed block, children had to switch between both hearts and flowers which were presented randomly, and children were instructed to respond accordingly. Cronbach's  $\alpha$  between the three blocks was considered to be sufficient ( $\alpha=0.74$ ).

A computerized version of the Day/Night task (Berlin & Bohlin, 2002; Gerstadt, Hong, & Diamond, 1994; Livesey, Keen, Rouse, & White, 2006) was used as an indicator of behavioral control in *Study III*. This task can be considered a child version of the Stroop task (Stroop, 1935). Although the Stroop task is also classified as an attention task (Commodari, 2017), in line with previous studies (Friedman & Miyake, 2004; and see Garon et al., 2008) the Day/Night was considered as a measure of behavioral control. Children had to say the opposite word of what was depicted in the image (e.g., say 'night' when a picture of daytime is shown) and hence must inhibit the automatic tendency to name the picture depicted on the screen. Stimuli were day/night, boy/girl, big/little, and up/down. In the first block opposite stimuli were presented four times each, preceded by instructions specific to the pair of stimuli. In the second block, all stimuli were presented four times each in random order and children had to respond accordingly, without any further instructions. Cronbach's  $\alpha$  between the two blocks was considered to be sufficient ( $\alpha=0.71$ ).

The Flanker Fish task (*Study III*) was used as an indicator of attentional control (e.g., Diamond, Barnett, Thomas, & Munro, 2007; Rueda, Posner, Rothbart, & Davis-Stober, 2004; Zaitchik, Iqbal, & Carey, 2014). Children had to respond to certain stimuli on a computer screen while ignoring other stimuli. The task consisted of three blocks in which children were instructed to feed 'hungry' fish. Children had to press the button corresponding to the direction the hungry fish were swimming. The fish were presented either alone, or with four flanker fish swimming in either the opposite or the same direction as the middle fish. In the first

block, the fish were blue, and the hungry fish were located in the middle. Children had to ignore the flanker fish. In the second block, the fish were pink, and the hungry fish were the flankers. In the third block, children had to switch between focusing on the middle or flanker fish as both blue and pink fish alternated and children had to respond according to the previous learned rules of block one and two. Cronbach's  $\alpha$  between the three blocks was considered to be sufficient ( $\alpha=0.71$ ).

A Continuous Performance task (*Study III*) (e.g., Connors, 2001) was used as a measure of the ability to sustain attention to relevant stimuli over a longer period of time. In this task 200 black figures of 10 different animals were shown on a computer screen and children were instructed to press a button, as quickly as possible after seeing each animal, unless it was a lion. Each animal was shown 20 times in random order. The task was initially expected to be an indicator of attentional control but did not load significantly on this factor. It did load on the behavioral control factor and was therefore included in the latter. See *Study III* for more details.

### 4.3.2 Academic skills

#### 4.3.2.1 Early literacy

A measure of vocabulary, as assessed by the Norwegian Vocabulary Task,  $\alpha = .84$  (NVT; Størksen, Ellingsen, Tvedt, & Idsøe, 2013) was used in *Study I* and *II*. Children were presented with 45 different pictures on a tablet screen and had to tell the name of the object depicted. In the Agder- and Lekbasert Læring projects (*Study I*) a shorter version of this task was used (20 items),  $\alpha = .83$  (Lundetrae, Solheim, Schwippert, & Uppstad, 2017).

A blending task (Norwegian Directorate for Education and Training) was used as a measure of phonological awareness in *Study I* and *II*. The measure consisted of 12 items. The target word was auditory presented

in its individual phonemes by the experimenter and children had to indicate the corresponding alternative from four presented images on a tablet screen. Items increased in difficulty and the task was automatically discontinued after three subsequent errors. For example, ‘Here you see a picture of /rips/, /rist/, /ris/, and /is/. Listen carefully and touch the picture that goes with /R/ /I/ /S/’ (presented phoneme-by-phoneme, one per second). Reliability for this task is acceptable,  $\alpha = .75$  (Solheim, Brønnick, & Walgermo, 2013).

In *Study III*, phonological awareness was measured using the Screening Instrument for Emerging Literacy (Vloedgraven et al., 2009) and comprised four tasks: Blending, segmentation, deletion, and letter knowledge. The latter three were assessed via the computer, whereas letter knowledge was assessed on paper. For blending, segmentation, and deletion (15 items each), three different pictures were shown on the screen, followed by a target word that was auditory presented by the computer. For blending, the target word was presented in its individual phonemes and children had to indicate the corresponding alternative from the three presented images on the screen (e.g., “point to the picture for /b/ /u/ /s/”). For segmentation, children had to indicate the alternative that began with the same phoneme as the one in the auditory presented target word (e.g., “point to the picture that begins with the same sound as /c/ /a/ /t/”). In the deletion task, children were presented with a target word (orally) from which they had to omit a phoneme such that it became another word. They had to indicate which of three alternatives corresponded with the new word (e.g., “point to the picture that sounds like ‘clock’ if you take away the /c/”). Finally, during letter knowledge, children were asked to read aloud 34 different letters presented on paper. Internal consistency for this task is high ( $\alpha > .90$ ; Vloedgraven & Verhoeven, 2007).

The Three-Minutes-Reading-Test (Krom, Jongen, Verhelst, Kamphuis, & Kleintjes, 2010; Verhoeven, 1995) was used to assess children’s word reading skills in first grade (*Study III*). This task consists of three cards

with 150 high-frequency content words, presented in columns of 30 words. Children had to read aloud as many words as possible on each card within a time limit of one minute. On each card, all correctly pronounced words were counted and the sum of the scores for the three cards was used. Internal consistency for this task is excellent ( $\alpha = .96$ ; Krom et al., 2010).

#### 4.3.2.2 Early mathematics

The Ani Banani Math Test (ABMT; Størksen & Mosvold, 2013) (*Study I and II*) is a short digital early math assessment on a tablet application. The items included: counting of objects, creating groups, counting (forward and backward), counting to fifty, completion of a puzzle, recognizing geometric shapes, copying geometrical figures, simple arithmetic reasoning, comparing qualitative and quantitative aspects of objects, and problem-solving. The items were embedded in playful contexts, which include a figure - a little monkey called Ani Banani - and his imagined everyday activities, such as counting toys, eating a certain number of bananas, and making a puzzle. To engage the child in the task, items would typically include sentences such as ‘can you help Ani Banani...’ or ‘can you give Ani Banani...’. See Appendix 1 for the individual items. In general, the ABMT was developed to encompass a broad and holistic understanding of early mathematical development (Størksen & Mosvold, 2013). The task takes about 10 minutes to complete. Reliability in kindergarten was  $\alpha = .73$  and  $\alpha = .68$  in first grade.

The Preschool Early Numeracy Scale (PENS; Purpura, Reid, Eiland, & Baroody, 2015), was used in *Study I* to examine the concurrent validity of the ABMT. The PENS is a brief early numeracy measure developed in the United States. It includes 24 items regarding one-to-one counting, cardinality, counting subsets, subitizing, number comparison, set comparison, number order, numeral identification, set-to-numerals, story

problems, number combinations, and verbal counting. The task has been validated and shows excellent reliability  $\alpha = .90$  (Purpura et al., 2015)

Mathematics in first and fifth grade were assessed with the national school assessments (Norwegian Directorate for Education and Training). These tasks were used to assess the concurrent and predictive validity of the ABMT in *Study I*.

In *Study III* early numeracy skills were assessed with the Number Sense Task (also referred to as the Utrecht Early Numeracy Test), version A (Van Luit & Van de Rijt, 2009), a standardized Dutch test suitable for children between 4 and 9 years of age. The task consists of 45 items divided over nine different blocks that assess skills that are indicative of early numeracy (Desoete & Gregoire, 2006; Van Luit & Van de Rijt, 2009). The first four blocks are dedicated to Piagetian concepts: In the comparison block, the child had to compare the qualitative and quantitative aspects of several items (e.g., “On these pictures you see some men. Which of these men is the biggest?”). In the classification block, children had to group several items depending on specific criteria (e.g., “On which of these pictures do you not see a group of five?”). In the correspondence block, children had to compare absolute quantities in a one-to-one relation (e.g., “On this picture you see three busses. Which of these pictures has the same number of dots as the three busses you see here?”). In the seriation block, children had to order items on the basis of specific criteria (e.g., “On which picture do you see the apples arranged from big to small?”). The focus in the other blocks of this task is on counting skills: In the counting block, children had to count both forward and backward, and use their knowledge of ordinal and cardinal aspects of the number system (e.g., “Count to twenty.”). In the synchronous and shortened counting block, children had to count sequentially and then by intervals, using the structure of dice (e.g., “Here you see six groups of two dice. In which group you see ten dots?”). In the resultative counting block, children had to count structured, unstructured and covered quantities without using their fingers or hands

(e.g., “How many pawns are there on the table?”). In the applied knowledge of the number system block, children had to apply knowledge of the number system in simple problems (e.g., “I have twelve cakes and I eat seven of them. How many cakes are left? Point to the picture that depicts the right answer.”). Finally, in the estimation block, children had to indicate the location of a number on a number line (e.g., “Here you see a number line. On which place on this number line would you place the number nineteen?”). Items involved 2D images, graphic numbers, and 3D pawns. Some items requested children to draw lines between associated images or indicate the position of a number on a number line. The instructor read out aloud the instructions and the child worked independently on every item. Correct items were scored as one and sum scores were calculated for each block. The task has excellent reliability ( $\alpha = .93$ ; Van Luit & Van de Rijt, 2009).

In *Study III*, mathematics in first grade were assessed using *CITO Rekenen-Wiskunde, 2012* (Janssen, Hop, Wouda, & Hollenberg, 2015), a standardized teacher-administered task that is part of the obligatory pupil monitoring system for schools in the Netherlands. This task consists of 52 items in the domains of basic arithmetic skills, elementary fraction, and elementary geometry. The task takes about 2 x 40 minutes to administer and includes both contextual problems (e.g., “4 children share 8 cookies together. Every child gets the same amount. How many cookies does each child receive?”), as well as non-contextual problems (e.g.,  $6 - 2 - 2 = ?$ ). Number of correct answers were counted. This task has excellent reliability ( $\alpha = .92$ ; Janssen et al., 2015).

### 4.3.3 Covariates

To rule out potential alternative explanations, several covariates were included in the analyses. Socioeconomic status (SES), age, sex, and minority status have been found to predict individual differences in both EF (Størksen et al., 2015; Wanless, McClelland, Tominey, & Acock,

2011) and academic skills (Wanless, McClelland, Acock, et al., 2011) and were therefore controlled for in the models in *Study II*. Because of the relatively small sample size and complexity of the model in *Study III*, only socioeconomic status was included as a covariate in this study. Inclusion of all covariates led to similar results but problems with model identification resulted in untrustworthy estimates. Socioeconomic status is considered a stronger background characteristic control variable compared to age and sex when assessing associations between EF and academic achievement (Jacob & Parkinson, 2015) and was therefore chosen. Covariates were obtained through questionnaires filled out by the children's caregivers.

#### **4.4 Analytical strategy**

This dissertation relies on structural equation modeling (SEM) for most of its analyses. Analyses within the SEM framework (e.g., exploratory and confirmatory factor analyses, structural path models) were conducted with Mplus version 8 (Muthén & Muthén, 1998-2010).

SEM is a technique that allows for the modeling of complex relations among variables (Jøreskog, 1993) and was therefore considered to be an appropriate approach to answer the research questions in this dissertation. Another feature that distinguishes SEM from other more standard statistical techniques (e.g., multiple regression, analysis of variance) is that it allows for factor analysis and the estimation of latent variables derived from these analyses (Brown, 2015; Kline, 2011). *Study I* and *III* use this technique to investigate whether certain assumptions about observed variables were true.

Before providing a more detailed description of each of the analyses that were conducted in this work, a general description of the principals and assumptions of SEM, including issues considered with sample size, missing data, estimation methods, and goodness-of-fit indices, are described in the next sections.

#### 4.4.1.1 Sample size and missing data issues

It is known that SEM requires large samples. Several factors affect sample size requirements. For example, the required sample for complex models with more parameters is larger than for simple models with fewer parameters (Kline, 2011). Sample sizes in all studies in this dissertation were > 240, except for the sample in *Study III*, which had 90 subjects.

Missing data on the variable level was generally low. In *Study I*, missing ranged from 0.8% to 6.5 % for all ABMT data except for T2 in Sample 3 (Lekbasert Læring) where missing was 12.6%. In *Study II*, missing ranged from 0.8% to 4.1% percent and in *Study III* from 0 to 2.2%. Missing data across time on the participant level (due to attrition) was also relatively low across the studies. In *Study I*, attrition in Sample 1 (Skoleklar) was 0.8%, in sample 2 (Agderprosjekt) 6.4%, and in Sample 3 (Lekbasert Læring) 12.6%. In *Study II*, data from 1.2% children were missing at the second time of testing. Finally, in *Study III*, data from 11.1% children were missing at the second time point.

Several missing data mechanisms can be at play according to missing data theory. When missing is completely at random (MCAR) the probability of missingness does not depend on the observed or missing values. When missing at random (MAR), the probability of missingness partly depends on the observed values, but not on the missing values. This means that missing is actually systematic but can become random after controlling for the observed values that missing depends on. It also means that missing can be accounted for by other auxiliary variables in order to yield unbiased estimates. When missing is not at random (MNAR), the probability of missingness depends on the missing values themselves. This means that the variable suffers from selection bias and the mechanism is non-ignorable. Whether missingness is MCAR, MAR or MNAR cannot be definitely determined. The likelihood that data is MCAR in actual datasets, especially in the social sciences, is small and data was not assumed to be MCAR in the present studies either, but

considering that missingness and attrition were low and variables that may predict missing included in the models, MAR was assumed. Several missing data techniques are available to deal with missing data, such as the classical listwise and pairwise deletion or single imputation techniques. These techniques are not recommended because they lead to low or inaccurate power and, additionally, biased estimates under MAR and MNAR. The full-information maximum likelihood method (FIML) was used as it is the recommended method to deal with missing data in SEM because it provides unbiased estimates under MCAR and MAR and retains accurate power under MNAR (see Kline, 2011). Compared to classical techniques, this method not only retains accurate power but likely yields less biased estimates when the missing data pattern is MNAR as well (Peters & Enders, 2002 in Kline, 2011). The FIML method is explained in more detail in the next section.

#### **4.4.1.2 Estimation**

In contrast to single-equation methods that analyze one equation at a time, full-information maximum likelihood estimates all free model parameters at once. In addition, parameter estimates and their standard errors are calculated directly from the available data without deletion or imputation of missing values. Some of the variables in the studies showed signs of non-normal distributions (e.g., skewness and kurtosis). When non-normally distributed variables are analyzed with the default maximum likelihood (ML), standard errors tend to be too low (resulting in inflated Type I error rates) and model test statistics too high (resulting in inflated true model rejection). Therefore, a robust maximum likelihood (MLR) estimator was used across the studies. This method provides standard errors and corrected model test statistics that are robust to non-normality, the effect of outliers, missing data, and model misspecification (Yuan & Bentler, 2000; Yuan & Zhong, 2013). In *Study I*, robust weighted least squares estimators (WLSMV) were used to deal with the categorical nature of the data. In addition, to deal with the non-normal nature that distributions of indirect effects tend to have, the

bootstrapping process procedure (Preacher & Hayes, 2004) was used to assess the 95% bias-corrected confidence intervals of the standard errors in *Study III*.

#### 4.4.1.3 Goodness-of-fit indices

Across the studies, both absolute model test statistics, approximate fit indexes, and comparative fit indices were relied upon to decide whether the model had an acceptable fit with the data. The chi-square test is an absolute accept-support test where the null hypothesis represents the belief that the model is correct. Thus, the model is supported when the null hypothesis is not rejected. That is, in the case of absence of statistical significance (e.g.,  $p \geq .05$ ) the model is supported. This has consequences for small samples with low power as there is less chance of detecting a false model. This means that the likelihood that the model will be retained increases with smaller sample sizes. With large sample sizes, differences could be flagged even though they are trivial. As such, the chi-square significance test gives preliminary evidence against or in support of a model, but additional information from other fit indexes must also be considered (Kline, 2011). Another absolute fit index, the standardized root mean square residual (SRMR), reflects the average discrepancy between the observed correlations (input matrix) and the model predicted correlations. SRMR values closer to zero indicate better model fit. SRMR values  $\leq .08$  are considered reasonably good fit (Hu & Bentler, 1999). In contrast to absolute fit indices, approximate fit indices are not significance tests, but rather intended as continuous measures of how good or bad the model fits the data. The root mean square error of approximation (RMSEA) is sometimes grouped under the category of absolute fit indices but differs from chi-square in that it assesses the extent to which a model fits reasonably well (rather than exactly) in the population and by rewarding parsimony (models with more degrees of freedom). A value of zero indicates the best result, values of  $\leq .08$  are considered adequate (Browne & Cudeck, 1993) and  $\leq .06$  as a reasonably good fit (Hu & Bentler, 1999). Comparative fit indices such as the

comparative fit index (CFI) and Tucker-Lewis index (TLI) evaluate fit in relation to a more restricted baseline model where all covariances among all input indicators are fixed to zero. Similar to the RMSEA, the TLI gives a penalty for complex models with freely estimated parameters that do not significantly improve model fit. Values close to one ( $\geq .95$ ) indicate good model fit (Hu & Bentler, 1999) and values in the range of .90 and .95 are considered to be acceptable (Bentler, 1990).

#### 4.4.1.4 Factor analysis

In *Study I*, confirmatory factor analyses (CFA) were used to investigate the factor structure of the ABMT. That is, it was investigated whether the items in the ABMT task were best represented by one, two, or three explanatory early math factors. One advantage of CFA over exploratory factor analysis is the possibility to include error theory. That is, additional indicator covariation resulting from common assessment methods (in the case of the ABMT; similar or similarly worded test items) can be modeled through specifying a correlation between the errors. In *Study I*, correlated errors (residual covariances) were included between items that were similar in wording and/or content. However, this was only done when conceptually meaningful and the modification index indicated a substantial area of strain when not freely estimated (modification index  $> 10.0$ ) (Muthén & Muthén, 1998-2010). The number of residual covariances was kept as low as possible and similar across samples for consistency. Items that caused problems with univariate and bivariate distributions containing empty cells (e.g., items with extreme % of correct) were omitted from the analyses. The ABMT has items with only two response categories (correct/wrong). CFA with binary outcomes is equivalent to a two-parameter ogive item response theory (IRT) model (Brown, 2015). Item thresholds and factor loadings in CFA with categorical outcomes are analogous to item difficulty parameters and discrimination parameters in IRT, respectively. See Brown (2015) for an extensive discussion of the differences and similarities between CFA with binary outcomes and IRT.

In *Study III*, CFA with continuous items was used to confirm findings from exploratory factor analyses, also used in previous studies (e.g., Van de Sande et al., 2013) and assure that the tasks in this study actually measure two different constructs. Tasks that loaded significantly on both factors were omitted from further analyses. Through CFA it was possible to test the fit of a model wherein one of the indicators (continuous performance test) was forced on the factor it theoretically was expected to belong to (attentional control). Moreover, it could be assessed whether an alternative one-factor model was a better fit to the data compared to a two-factor model. To reduce complexity of the model, factor scores were saved for further analyses. Factor scores serve as proxies for latent variables and are assumed to have less bias than coarse factor scores (average or sum across items) (Grice, 2001). Factor determinacies were .922 and .866 for behavioral and attentional control, respectively.

#### **4.4.1.5 CFA with covariates**

Another advantage of CFA is that it can be extended by regressing the latent variable and indicators onto covariates so that measurement invariance across the dimensions of the covariate can be tested. This approach is also referred to as multiple indicators multiple indicator causes (MIMIC) modeling and was used in *Study I* to test the items of the ABMT for signs of differential item functioning. The advantages of MIMIC modeling over other invariance testing methods (e.g., multiple-groups CFA) are for example that it usually has smaller sample size requirements because a single input matrix is used rather than separate matrices for each group (Brown, 2015). Furthermore, another advantage, also over IRT, is that both categorical (with multiple groups) and continuous covariates can be used. This allowed the assessment of differential item functioning across sex (categorical), age, and socioeconomic status (both continuous) in *Study I*.

#### **4.4.1.6 Test of the difference between two dependent correlations with one variable in common**

In *Study I*, concurrent and predictive convergent validity was determined by calculating the correlation between the ABMT and other mathematical assessments (school math assessments and PENS). Correlations  $> .50$  were regarded as indications of good convergent validity. Discriminant validity was determined by comparing correlations to show that the correlations between the ABMT and other math assessments were significantly higher than between the ABMT and related constructs. For this purpose an interactive calculator (Lee & Preacher, 2013) that yields the result of a test of the equality of two correlation coefficients that share one variable in common, and are obtained from the same sample, was used. The result is a z-score which was compared in a 1-tailed fashion.

#### **4.4.1.7 Path models**

In *Study II*, autoregressive cross-lagged path models were estimated to investigate the direction of associations between self-regulation and mathematics, expressive vocabulary, and phonological awareness. Autoregressive models are derived from the idea that previous outcomes are the best predictor of present outcomes. If the autoregressive effect is weak, this indicates individual differences in change over time, if it is strong this indicates that a significant portion of individual differences remained stable over time. The cross-lagged effects indicate whether there is some instability that is not explained by the autoregressive effect but predicted by another temporally preceding variable. Residuals at the same time-point are allowed to be correlated to take into account shared occasion-specific effects. To ensure that the hypothesized model was the best fitting model compared to other possible models, four versions of the models were compared: A full cross-lagged bidirectional path model, two uni-directional models (one where the path from the academic skill to self-regulation was constrained to zero and one vice versa), and finally

a model where the cross-lagged pairs were constrained to be zero to reflect the possibility that the association between the variables was actually fully explained by a third factor not included in the model. Because a robust estimator was used, the significances of differences in model fit across models in *Study II* were investigated using the Satorra-Bentler scaled chi-square difference statistic. In addition, a combined path model wherein all variables were regressed on each other was estimated to reflect the within- and across-domain associations between the academic skills (e.g., Kleemans et al., 2011; Purpura et al., 2011). This model provides information on the unique contribution of each skill over-and-above the other. Age, sex, maternal education, and immigrant status were controlled for in the models.

In *Study III*, a path model was estimated to investigate the direct and indirect pathways from attentional and behavioral control to word reading and mathematics while taking into account the interrelations between the variables. All pathways from attentional and behavioral control to early literacy and early numeracy skills in kindergarten and first grade were estimated. Socioeconomic status (parental education) was included as a control variable.

## 5 Results

### 5.1 *Main findings Study I*

Confirmatory factor analyses indicated that both a one, two, and three-factor model had an adequate fit with the data. However, the factors of the two and three-factor solutions showed poor discriminant validity (highly correlated factors) and a one-factor structure was therefore regarded as the most representative and reliable structure for the ABMT. MIMIC analyses showed that this solution functioned similarly across age and SES. However, two items were found to show signs of differential item functioning in favor of boys and one item in favor of girls. Correlations larger than  $r = .50$  with concurrent and longitudinal math outcomes provided evidence that the ABMT has concurrent and predictive validity. Significantly higher concurrent correlations between the ABMT and other math assessments compared to all other tasks (reading assessments, HTKS, digit span, vocabulary, phonological awareness) indicates sufficient discriminant validity.

### 5.2 *Main findings Study II*

Cross-lagged path analyses indicated a bidirectional relation between self-regulation and mathematics: Self-regulation significantly predicted mathematics ( $\beta = .21$ ) and vice versa ( $\beta = .29$ ) when controlling for prior skills. These effects were robust and remained significant when controlling for expressive vocabulary and phonological awareness. Expressive vocabulary did predict self-regulation ( $\beta = .24$ ) but self-regulation was not a significant predictor of expressive vocabulary when controlling for prior vocabulary skills ( $\beta = .04$ ). The pathway from expressive vocabulary to self-regulation was robust and remained significant when controlling for mathematics and phonological awareness. The cross-lagged path analyses also indicated that although self-regulation showed a weak albeit significant pathway to phonological

awareness ( $\beta = .13$ ), a model without coupling fitted the data equally well and the effect was not robust when controlling for expressive vocabulary and mathematics.

### **5.3 Main findings Study III**

Results from structural equation path modeling indicated that both attentional and behavioral control significantly predicted phonological awareness and number sense in kindergarten. Results from the initial correlational analysis showed that attentional control had a significant association ( $r = .39$ ) with first-grade word reading while the correlation with behavioral control was weak and not significant ( $r = .17$ ). However, results from the path model indicated that the association between attentional control and word reading was mediated by phonological awareness. Moreover, an indirect pathway from behavioral control to word reading was found through phonological awareness. Although attentional control was significantly associated with mathematics in first grade ( $r = .37$ ), this association was not significantly different from zero ( $\beta = .05$ ) when controlling for behavioral control in the final path model. Behavioral control, to the contrary, showed a direct and robust pathway to first-grade mathematics ( $\beta = .41$ ) even when controlling for attentional control, number sense, and phonological awareness in kindergarten.

## 6 Discussion

The central role of both early childhood EF and academic skills for children's transition to formal schooling (Blair & Raver, 2015; Rimm-Kaufman et al., 2000), academic achievement (Duncan et al., 2007), and future life and prospects (McClelland, Acock, Piccinin, Rhea, & Stallings, 2013; Moffitt et al., 2011; Robson et al., 2020) makes it vital to understand the interrelations between these skills in early childhood. Difficulties that arise later in life may be traced back to early childhood (Robson et al., 2020) and research on early development may, therefore, provide valuable information on where and when to put in resources in early childhood education. The results from the current studies provide insight into some of the fine-grained associations between EF and academic skills when children make the transition from kindergarten to first grade.

### 6.1 Interpretation of main results

The main results from *Study I* are discussed in paragraph 6.1.1. To provide a comprehensive and coherent overview of how EF and each academic skill are related across the studies, the results from *Study II* and *III* are discussed according to the overarching topics of early literacy and mathematics (paragraph 6.1.2 and 6.1.3, respectively).

#### 6.1.1 Validity of the Ani Banani Math Test

The results of *Study I* provide initial evidence that the ABMT measures early mathematical skills and is related to, but can still be differentiated from, early literacy and EF. For example, even though the ABMT showed a relatively strong association with working memory and vocabulary in kindergarten ( $r = .545$  and  $r = .483$ , respectively), the association with the established Preschool Early Numeracy Skills Screener (PENS; Purpura et al., 2015) was significantly stronger ( $r$

=.648) providing indications of adequate external validity (Messick, 1995).

Nevertheless, the relative strong concurrent associations with working memory and self-regulation (ranging from  $r = .454$  to  $r = .597$ ) do indicate that early mathematics as measured with the ABMT also contains a strong cognitive component associated with EF. Similarly, together with previous literature showing significant associations between early mathematics and literacy (Purpura & Ganley, 2014; Purpura et al., 2011; Purpura et al., 2015), the moderate correlations with early literacy and vocabulary measures (ranging from  $r = .366$  to  $r = .483$ ) make it clear that the ABMT also has a strong language and literacy-based component. For example, in order to answer the following items: ‘can you give Ani Banani *twice as many* apples’, or ‘select the monkey with the *most* marbles’, children need to understand the meaning of what essentially are language terms. Considering that early mathematics is a relatively strong predictor for later literacy and reading achievement (e.g., Allan et al., 2014; Duncan et al., 2007), mathematics assessments may act as a proxy for early language and EF. Indeed, children’s mathematical language has been shown to mediate the relation between early mathematics and literacy (Purpura, Logan, Hassinger-Das, & Napoli, 2017). This highlights the importance of controlling for EF and literacy when predicting later achievement from early mathematics as a means of assuring that the association is not mainly driven by these components (as has been done in *Study II*).

Nevertheless, the moderate to high factor loadings indicate that children’s math skills explained a significant proportion of the variance in the level of underlying math skills needed to score correct on an item of the ABMT.

The strong correlation ( $r = .601$ ) between the ABMT scores in kindergarten and a mathematics achievement test five years later

indicates high predictive validity and suggests that the ABMT is an adequate predictor of later elementary school math achievement.

One aspect of the ABMT that should be considered is that when aiming to make mean comparisons between girls and boys in future research, the possibility that items may be biased towards either of these groups should be taken into account. The results from *Study I* showed that this was the case for two items which showed a bias towards boys, and one item that showed a bias towards girls. Drawing conclusions about differences in mean scores between girls and boys without assessing whether the items show bias may result in ostensible differences that are not due to differences in children's math skills, but to other aspects that have little to do with mathematics.

Taken together, the data in *Study I* provide initial indications that the ABMT has sufficient concurrent, predictive, and discriminant validity. The ABMT may be considered a brief, easy to administer, and psychometrically adequate research measure that reflects the play-based approach and the playful way through which children learn mathematics in early childhood.

### 6.1.2 *EF and Early Mathematics*

Across the studies in this dissertation and in line with findings (Allan et al., 2014; Blair & Razza, 2007; Willoughby, Blair, Wirth, Greenberg, & Family Life Project, 2012) and theorizing (Clements et al., 2016) from others, EF showed the strongest and most robust associations with early mathematics. The bidirectional relation between self-regulation and mathematics found in *Study II* is in line with results from previous research (performed in school-readiness ECEC contexts) in younger preschool children (Fuhs et al., 2014; Hernández et al., 2018; McKinnon & Blair, 2018; Schmitt et al., 2017; Welsh et al., 2010). Although a few of these studies have found that this association became unidirectional, (EF predicted mathematics) as children got older and entered

kindergarten (Fuhs et al., 2014; Schmitt et al., 2017), a recent study (McKinnon & Blair, 2018) also found bidirectional relations in children making the transition between kindergarten and first grade. Similarly, (Van der Ven et al., 2012) found dynamic associations between growth in EF (updating) and mathematics in older children (7-8 years old), suggesting that age is not a consistent factor predicting the strength and direction of effects. The results from *Study II* also indicated that this association was robust and held even when other academic skills that are known to be related to both mathematics and self-regulation (phonological awareness and vocabulary) were controlled for.

The results from *Study III* add to this finding by showing that the effect from kindergarten behavioral control to first grade mathematics was direct and held even when controlling for mediating effects of early number sense and phonological awareness in kindergarten. This suggests that children's ability to control behavioral impulses is a consistent direct predictor for later math achievement. One explanation for this particular strong association of behavioral control with early mathematics (compared to literacy) may be that early mathematics learning activities may involve relatively more behavioral (e.g., motor) activity compared to reading activities. For example, when children use counting manipulatives or building blocks, and measure and compare different sized objects or spaces, they need to move and maneuver their bodies and learning materials which likely requires some degree of control over (visuo-) motor responses. Indeed, studies show that children's motor skills are related to early mathematics (Becker et al., 2014; McClelland & Cameron, 2019; Reikeras, Moser, & Tonnessen, 2017) as well as to behavioral control (Becker et al., 2014). However, although early math activities may be more physically active, reading activities may certainly not be absent of motor action (e.g., writing letters, turning a page, and guided reading) and associations with motor skills (including visuospatial integration) have been found (Cameron et al., 2015; Cameron et al., 2012; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010).

An effect from attentional control to mathematics was expected in *Study III*. However, although this effect was present to kindergarten number sense, the estimate from attentional control to mathematics in first grade attenuated to non-significance in the final model. This suggests that the association between self-regulation and mathematics is driven by the control of behavior over and above the effect of being able to resist distraction of attention. One explanation for a lack of an attention effect may be that mathematics instruction in first grade is not that attentional demanding yet. It may be that this association would become stronger in higher grades when mathematics becomes more complex and involves more arithmetic and mental calculation. The exact mechanisms through which attentional and behavioral control exert differential effects on early mathematics and literacy remains a topic for future research.

### 6.1.3 *EF and Early Literacy*

Regarding early literacy, results are less conclusive. First, *Study II* showed that self-regulation and expressive vocabulary were significantly correlated across the transition from kindergarten to first grade ( $r = .32$ ). However, the cross-lagged path analyses indicated that expressive vocabulary predicted self-regulation, but not the reverse. This effect was robust as it held when other academic skills (phonological awareness and mathematics) were controlled for. The finding that children's language skills predicted self-regulation is in line with findings from previous studies in younger children (Bohlmann et al., 2015; Cadima et al., 2018; Fuhs & Day, 2011; Fuhs et al., 2014; Petersen, Bates, & Staples, 2015; Slot & Von Suchodoletz, 2018). Although, some of these studies also found bidirectional effects (Bohlmann et al., 2015; Cadima et al., 2018; Fuhs et al., 2014; Slot & Von Suchodoletz, 2018) or unidirectional effects in the opposite direction at certain time points (Bohlmann et al., 2015; Fuhs et al., 2014; Weiland et al., 2014). Because of the transition from a play-based ECEC context in kindergarten to formal education in first grade in Norway, self-regulation was expected to predict expressive

vocabulary in *Study II*. There may be several reasons for why this association was not found in the present study. First, expressive vocabulary showed high stability ( $\beta = .78$ ) meaning that little variance was left to be explained by self-regulation. Other studies had different or additional measures as indicators of children's early language skills, such as receptive vocabulary (Weiland et al., 2014), addition of grammar skills (Slot & Von Suchodoletz, 2018) or oral comprehension (Fuhs et al., 2014). Bohlmann et al. (2015) did find evidence for a pathway between self-regulation and expressive vocabulary, however, their sample was younger (50 months at T1), included dual language learners, and (possibly as a consequence of this) vocabulary was less stable across time ( $\beta = .70$  -  $\beta = .60$ ). Second, other differences in educational context across countries may cause variation in results. For example, a stronger focus on instructional language activities at a younger age in countries with a school-readiness approach may place a higher demand on children's self-regulatory skills yielding stronger associations compared to countries where children mainly learn through free-play situations, such as Norway.

Nevertheless, the fact that expressive vocabulary significantly predicted self-regulation in *Study II* is in line with Vygotsky's theory on the role of language for self-regulation development (Diaz et al., 1992; Vygotsky, 1934/1986) and suggests that Norwegian children's language skills in kindergarten may aid successful acquisition of self-regulation in first grade.

Results from *Study II* showed that the association between self-regulation and phonological awareness was not supported by the data and turned non-significant when other academic skills (vocabulary and mathematics) were controlled for. Conversely, in *Study III* both attentional and behavioral control significantly predicted phonological awareness, with moderate strength ( $\beta = .31$  and  $\beta = .39$ , respectively).

There may be several explanations for this differential finding. First, in *Study III*, self-control and early academic skills were assessed at concurrent time points, likely rendering stronger predictive power. Second, and relatedly, phonological awareness skills at a previous time point were not controlled for in *Study III*. If we compare the concurrent bivariate correlations between the studies it can be seen that they are all of moderate strength with a correlation of  $r = .38$  between self-regulation and phonological awareness in *Study II* and a slightly stronger correlation of  $r = .48$  and  $r = .54$  for attentional and behavioral control respectively in *Study III*. Third, the distinctive factor scores for attentional and behavioral aspects in *Study III* can be seen as free of measurement error (although not free of estimation error) (Skrondal & Laake, 2001), while in *Study II* the measure of self-regulation contains the raw score and thus includes measurement error which may have attenuated the path estimates. If a latent variable approach had been used in *Study II*, the estimates might have been stronger. Finally, the measure of phonological awareness in *Study II* did show some ceiling effects that may have resulted in a reduction of variation at the higher end of the scale and, in turn, attenuated the estimates (more on this in section 6.2.2 and 6.2.3).

Also, literacy skills are known to develop faster in a language with a more transparent orthography, such as Norwegian and Dutch, compared to languages with complex grapheme-phoneme relations, such as English (Aro & Wimmer, 2003; Goswami, 2008; Seymour et al., 2003). Although the Norwegian and Dutch language are both considered to be semi-transparent languages, Norwegian is a slightly more transparent language (Seymour et al., 2003). For Norwegian children it may be easier, and thus require less self-regulation, to become aware of phonemes because letters more consistently map onto one and the same phoneme (Goswami, 2008). Consequently, variation in orthographic depth of languages may also be a cause of variation in relations between self-regulation and phonological awareness.

In *Study III*, and in line with previous studies (Segers et al., 2016; Van de Sande et al., 2013; Van de Sande et al., 2017), attentional control was a specifically strong correlate of later word reading skills in first grade ( $r = .39$ ) compared to behavioral control ( $r = .17$ ). The fact that attentional control showed this initial distinct association with word reading may be because word reading requires children to focus on the target word, identify letters that form relevant orthographic units, and actively suppress visual attention being drawn to other letters and words (Valdois, Roulin, & Bosse, 2019). Also, in line with previous studies (Van de Sande et al., 2013; Van de Sande et al., 2017), the effect from attentional control to word decoding skills attenuated when phonological awareness was entered in the final model. This suggests that it is the phonological part of word decoding that demands attentional control.

Although behavioral control did not show a significant association with word reading ( $r = .17$ ), the variable predicted word reading indirectly through its effect on the acquisition of phonological awareness. This highlights the importance of investigating indirect effects as the absence of longitudinal predictions does not imply that self-regulation does not contribute to the development of a skill through other pathways.

Somewhat surprisingly, in the final path model, behavioral control showed a significant negative prediction to word reading ( $\beta = -.28$ ) indicating a statistical suppression effect (MacKinnon, Krull, & Lockwood, 2000) from phonological awareness. This effect is in line with other studies. For example, in Van de Sande et al. (2013), a non-significant association of .06 between behavioral control and word reading turned to a negative prediction of  $\beta = -.10$  when controlling for the mediating effect of phonological awareness. The negative prediction implies that children with equal phonological awareness, but better behavioral control, have a lower predicted score on the word reading task. The word reading task is a speeded efficiency task that requires children to name words as accurate and fast as possible within three minutes (Three-Minutes-Reading-Test (Krom et al., 2010; Verhoeven,

1995). It may be that children with good behavioral control use their inhibitory skills inefficiently and disadvantageous in a speeded task. That is, maybe they are being too careful. Children with lower behavioral inhibition (but still equal phonological awareness skills) on the contrary may be more inclined to ‘rush’ through the task resulting in a higher score. However, strong positive relations between inhibition and processing speed have been found (van der Sluis, de Jong, & van der Leij, 2007) suggesting that children should benefit from inhibitory control in a speeded task. Moreover, timed measures of EF have positively predicted both untimed and timed measures of reading (Altemeier, Abbott, & Berninger, 2008). Thus, this explanation clearly remains speculative and warrants further study. The effect of processing speed is further elaborated on in paragraph 6.2.3.

Taken together, and when taking into consideration the mixed results from previous research, the associations between EF, including self-regulation, and early literacy skills seem relatively unstable during early childhood. The strength and direction of associations likely depend on several aspects, such as timing of assessment and inclusion of prior skills in the model, type and complexity of literacy assessment, as well as which component of EF is assessed (e.g., attentional or behavioral), and the educational early childhood context of the sample (school-readiness vs play-based). Nevertheless, the pattern that does seem to emerge is that associations between EF and literacy attenuate when early skills are controlled for. This suggests that the effect of EF on the development of literacy is gradual, meaning that the majority of influence of self-regulation on later reading development lays in kindergarten. That is, EF plays an important role when basic literacy skills are in the process of being learned in kindergarten, but when early skills become automated the predictive value of EF diminishes. However, EF may become important again for more complex skills that develop later on, such as reading comprehension (Connor et al., 2016).

## **6.2 Methodological considerations**

Several limitations of each study are mentioned in the individual papers. Below are provided some general methodological limitations considered with the studies' design, reliability, and validity.

### **6.2.1 Study Design**

First, as is common in regression analyses, there is a potential for bias due to omitted variables (Kline, 2011). That is, predictors that covary with measured predictors, and are a determinant of the dependent variable but that are not included in the statistical models. The way omitted variables may bias estimates is that the model attributes the effect of the missing variables to the estimated effects of the included predictors and thereby over-estimates (upward bias) or under-estimates (downward) the effect of one or more other predictors. Some of the modest percentages of explained variance in the outcome variables (e.g., 27% and 29% for phonological awareness and self-regulation in *Study II*, respectively) indicate that indeed other variables are likely to be critical as well. Although efforts have been made to include variables that are known to correlate with both the predictors as well as the outcomes (e.g., age, sex, and socioeconomic status), other variables that have not been measured in the present data samples and that are absent in the models may still have biased the results.

For example, recently, scholars have started to advocate for the inclusion of other non-EF or so-called foundational cognitive abilities (e.g., speed of processing, fine motor skills) as part of EF measurement (e.g., McClelland & Cameron, 2019; Willoughby, Blair, Kuhn, & Magnus, 2018). Not only may other non-EF cognitive skills possibly be related with both EF and academic outcomes, EF and non-EF sources of variation are often conflated within EF tasks and this task impurity may bias the associations with other criterions. Recently, Willoughby et al. (2018) showed that simple reaction time was significantly related to

performance on a battery of EF tasks and proposed including reaction time measures to address problems of measurement impurity in EF tasks. Similarly, van der Sluis et al. (2007) found that non-EF sources (rapid naming speed) explained a considerable amount of variance in reading and arithmetic and attenuated the association between EF and these measures of academic achievement. Thus, not accounting for sources of task impurity may obscure the exact nature of the associations between EF and academic outcomes.

Second, it is known that SEM requires large samples and especially *Study III* has a relatively small sample size. Small sample size not only limits statistical power, but may also result in less trustworthy estimates, bias in standard errors and associated significant tests, and goodness-of-fit statistics (Kline, 2011). Although efforts were made to reduce the complexity of the model (e.g., by saving factor scores) and several estimation procedures were used to determine the standard errors (e.g., MLR, bootstrapping), other approaches to address the potential for bias could have strengthened the interpretation of results (e.g., Monte Carlo simulations). Moreover, although the bootstrapping procedure may minimize bias in significance testing and is recommended when assessing indirect effects, this method is also known to produce biased estimates in small samples (Kline, 2011). Thus, results should be interpreted taking this limitation into account. Nevertheless, the fact that results were similar across estimation procedures and in line with results from similar studies in other samples (Segers et al., 2016; Van de Sande et al., 2013; Van de Sande et al., 2017) does provide some confidence that present results are not just sample specific.

Third, only two time points were available in the datasets of *Study II* and *III*. This limits the possibility to assess dynamic relations over time, model growth, and separate within-person from between-person variation (Berry & Willoughby, 2017; Curran, Howard, Bainter, Lane, & McGinley, 2014; Willoughby, Wylie, & Little, 2019).

### 6.2.2 Reliability

Score reliability refers to the degree to which scores in a particular sample are precise (Kline, 2011). Internally consistent measures are specifically important when directly observed scores are used in the analyses (as is the case for all academic skills and the self-regulation measure in *Study II*). A measure with poor internal reliability may reduce statistical power and may attenuate the observed correlation between two variables. Most measures used in this dissertation have been selected for the projects because prior research has indicated that they show sufficient reliability for use in research (e.g., see paragraph 4.3). However, as Kline (2011) states, it is an ‘apparently widespread but false belief that it is tests that are reliable or unreliable, not scores in a particular sample...The truth is that reliability and validity are attributes of scores in particular samples...’. (p. 90).

Internal consistency reliability is most commonly estimated with Cronbach’s coefficient alpha ( $\alpha$ ). However, the use of alpha as either a reliability or internal consistency index has been criticized in the psychometric literature (e.g., Brown, 2015; Raykov, Dimitrov, & Asparouhov, 2010); despite its widespread use it is known that  $\alpha$  will under- or overestimate scale reliability when the measure contains correlated measurement errors. If a scale does not contain correlated measurement errors,  $\alpha$  will still be an underestimation of true scale reliability when indicators do not have equal factor loadings on a given factor (tau equivalence does not hold). Thus, these limitations must be kept in mind when interpreting alpha.

Another limitation concerns the factor scores that were used in *Study II*. Although these refined factor scores are favored over unweighted composites because they have less bias than the latter when used as predictors (Grice, 2001), they do not have the same properties as true latent factors. This means that correlations with other variables may have been different if true factors had been used.

Finally, another limitation concerns the reliability of the test scores for the phonological awareness and self-regulation task at T2 in *Study II*. The scores on these tasks showed some indications of skewed distributions which may have limited the scores on the higher end of the scales and a subsequent reduction in variability. A restriction of range limits internal consistency reliability and may increase the chance of Type II errors as it may attenuate correlations between variables.

### 6.2.3 Validity

In *Study I*, special efforts were made to assess the structural, external, generalizability, and consequential aspects of validity (Messick, 1995). However, although the ABMT was designed by two experts in the field of child psychology and mathematics education (Størksen & Mosvold, 2013), content validity, which is established by expert opinion (Kline, 2011; Messick, 1995), was not explicitly assessed in *Study I*. Moreover, the strong correlations between the different factors of the ABMT suggest substantive validity. However, other empirical evidence such as “think aloud” protocols may have provided insight in whether the items of the ABMT indeed evoke cognition about the mathematical aspects of the task or whether aspects of language or context are driving the outcome on an item.

Also, the ABMT was designed to assess children’s math skills in ‘real-life’ situations (e.g., put the table for a birthday party, give bananas to a hungry monkey, help a monkey make a puzzle). As such, the ABMT may be assumed to have high ecological (external) validity in that it reflects real-world situations that are common in children’s every-day life (Wegener & Blankenship, 2007). However, although a rich illustrated story context may motivate children to solve a mathematical problem, it may also act as a distractor, heightening demands on attentional control (Heim & Keil, 2012).

In *Study II* only single measures of self-regulation and academic skills were available and thus no latent variable approach could be used to eliminate some of the task-impurity issues and correct for measurement error. The HTKS is a validated and internationally recognized measure of self-regulation that has been extensively used in prior research (McClelland et al., 2007; Størksen et al., 2015; von Suchodoletz & Gunzenhauser, 2013; Wanless, McClelland, Acock, et al., 2011). Nevertheless, there may be task-specific aspects of the HTKS that are not considered to be part of the construct of self-regulation. For example, the HTKS has a social component in that children need to interact with an experimenter more so as in fully computerized tasks. The task may also tap gross motor skills as the children need to move their arms up and down their whole body when pointing to the different body parts. Similarly, language skills may be important in order to be able to understand the instructions that increase in complexity as the task progresses. The same limitations apply to the academic measures. It is therefore important to keep in mind that issues of task-impurity and measurement error may affect the validity of the task scores and associations with other variables.

Another validity issue is the use of direct versus indirect measures of self-regulation in this dissertation. Direct measures of self-regulation have the advantage of limiting bias due to, for example, subjective interpretations of reporters as may be the case in indirect measures such as teacher- or parent-reported assessments of self-regulation. However, the highly constrained context and interpretation of the task represents children's optimal rather than typical performance (Toplak et al., 2013) and the specific situation (e.g., on a computer, in a separate room) may not represent children's real-life classroom or home situation. For example, in the HTKS children actually have to do the opposite of what the tester (an adult) tells them to do – something that does not reflect many real-life situations. Computerized tasks where children must push a button upon seeing a stimulus on a screen, do not reflect real-life

situations either. Direct performance-based and indirect rater assessments of self-regulation or EF are often weakly correlated and considered to assess different constructs (Toplak et al., 2013). This also means that associations with academic skills might have been different if teacher reports had been used. Research has found teacher ratings to be the strongest predictors of literacy, and direct assessments of mathematics (Schmitt, Pratt, & McClelland, 2014). Recent results of a follow-up study of *Study II* (Lenes, Størksen, ten Braak, Idsoe, & McClelland, under review) also indicated that teacher-reported self-regulation predicted fifth grade reading comprehension, but not mathematics when controlling for directly measured self-regulation. This suggests that teachers report something additional over and above directly measured self-regulation that is predictive of later reading comprehension, but not of mathematics. Thus, this difference should be kept in mind when making inferences about the results of the studies in this dissertation.

Moreover, ceiling effects may not only have impaired reliability of task scores in some of the measures in *Study II* (e.g., especially phonological awareness), but they may also pose limitations on validity. Ceiling effects particularly pose a threat to validity as the degree to which the sample still represents the population intended to measure decreases. This is because only individual differences between children not scoring the maximum score are captured which limits the possibility to generalize to children at the high end of the ability spectrum.

In *Study III*, multiple EF tasks were included and factor analysis was used to limit issues with task-impurity. However, although factor analysis is considered one way to deal with issues of task-impurity, the problem does not subside as long as non-EF processes contribute to performance across all tasks. EF tasks are often weakly correlated and much of the observed variance is attributed to residual error terms. It remains uncertain what the resulting estimate actually entails (Willoughby et al., 2018). The attentional control factor comprised of

three indicators of the flanker fish task which may have other aspects in common besides EF. For example, the task has a visual processing aspect in that children have to select the correct fish among distractor fish that are visually presented. In addition, the flanker fish task is a speeded task where children have a limited response time. Both these non-EF aspects may relate to the word reading task used in *Study III* (Three-Minutes-Reading-Test (Krom et al., 2010; Verhoeven, 1995)). Reading fluency relies on both visual attention (Valdois et al., 2019) and (naming) speed (Catts, Gillispie, Leonard, Kail, & Miller, 2002; Meiri, Levinson, & Horowitz-Kraus, 2019; Shaul & Nevo, 2015). The three-minute reading task is an efficiency task where words are visually presented and children must read aloud the words correctly, but also as fast as possible. Fluent and automatized reading skills are likely to result in high scores on this task and processing speed may, therefore, play a larger role compared to the math task which is a non-speeded accuracy task. Speed of processing has been shown to be especially related to fluency measures as opposed to non-fluency measures (Meiri et al., 2019). However, timed measures of EF have positively predicted both untimed and timed measures of reading (Altemeier et al., 2008). The absence of non-EF control variables, such as processing speed or visual processing indicators, in the studies in this dissertation implies that, despite high factor loadings and correlations with variables of interest, we may still not be certain whether it is EF alone, a combination of EF and other non-EF processes, or even non-EF processes only, that predicted the outcomes. As such, this poses a threat to internal validity. However, the fact that the association between attentional control and word reading was fully mediated by the non-speeded, auditory phonological awareness accuracy task provides some indications that visual aspects or speed of processing are not solely driving the effect.

### **6.3 Contributions and Implications**

The results of the studies in this dissertation reflect some of the core concepts of the developmental systems framework that underlines the bidirectional and complex interactions between developing skills during early childhood (McClelland et al., 2015).

Moreover, research on the association between EF and academic development in early childhood education in Norway is scarce and few assessments suitable for research have been developed. *Study I* contributes to the empirical literature by investigating the psychometric properties of one of the first Norwegian measures of early mathematics that is suitable for research in ECEC. One study has assessed associations between self-regulation and academic skills in the transition between kindergarten and first grade in Norway (Backer-Grøndahl, Naerde, & Idsoe, 2018). However, this study used a composite measure of academic competence and therefore could not disentangle differential effects on early literacy and mathematics. Moreover, the direction of effects was not assessed. *Study II* is therefore the first study to look at how self-regulation and each academic skill are related in the play-based educational context of Norway and clearly shows differential domain-specific effects for early literacy and mathematics.

*Study II* and *III* contribute to the empirical body of research by integrating EF, early literacy, and mathematics. This allowed for the modeling of the complex interrelations between the skills during early childhood and provides information on the unique effects of each skill over and above the other. *Study III* expanded the current literature by showing that associations between EF and certain academic skills (in this case word reading) may be missed if mainly behavioral aspects of EF are assessed. The results also highlight that even if longitudinal associations between EF and academic outcomes are not found, EF may still exert an indirect effect through the effect on early skill development in kindergarten.

Together with the existing body of research, the present dissertation can inform researchers and practitioners with knowledge of how children's EF and academic skill development may be promoted in early childhood education. In specific, *Study II* may provide support for further research on interventions that promote language development in early childhood education as a means of stimulating the development of EF. As Vygotsky's theory posits, children learn to regulate their behavior through the internalization of caregiver's regulatory speech and the use of inner talk may help children to guide their behavior. As such, language provides a medium to break up the direct stimulus-response chain (Diaz et al., 1992) and gives children the possibility to stop and think before they act (McClelland & Tominey, 2016). Similarly, results from *Study II* provide support for further research on whether a focus on promoting children's math skills in early childhood education may aid children in developing EF. Some studies have found initial evidence for positive effects of math interventions on EF (see Clements et al., 2016; Weiland & Yoshikawa, 2013). However, results are not conclusive yet and more research is needed to determine which type of intervention (e.g., a focus on math only, a combination of math and EF, or a combination with literacy) works and for whom (e.g., for all children, those with low or high baseline math or EF, or low or high socioeconomic status). For example, a recent study (Ribner, 2020) found that children with high EF benefit more from math instruction compared to those with lower levels.

Results from *Study II* and *III* also suggest that interventions aimed at promoting EF may be beneficial for the development of mathematics. Several intervention studies have shown effects, also on children's mathematics (and literacy) (Blair & Raver, 2014; Diamond & Lee, 2011; McClelland et al., 2019; Schmitt, McClelland, Tominey, & Acock, 2015; Tominey & McClelland, 2011). However, a meta-analysis (Jacob & Parkinson, 2015) demonstrated that there is little evidence that interventions targeting EF alone improve children's academic achievement. On the contrary, a recent meta-analysis (Pandey et al.,

2018) reported consistent improvement in self-regulation and improvement on academic achievement after self-regulation-based interventions in children and adolescents. Thus, whether, and under which conditions, EF interventions are effective remains a topic for further research. Jacob and Parkinson (2015) argue that in order to get a better idea of which type of interventions may be effective, researchers must control for other aspects of EF when predicting academic achievement in correlational studies. In line with this, several studies have found that the association between inhibition and mathematics attenuates when working memory is included as an explanatory variable (Bull & Lee, 2014). Considering that different aspects of EF may have common components, without controlling for the other it is difficult to pinpoint which aspect of EF should be given the greatest emphasis in an intervention. *Study III* contributes to a certain degree to this call by providing initial indications that difficulties with learning to decode in first grade may originate in children being easily distracted and having trouble to focus. Raising awareness about attentional aspects of EF in practitioners may be beneficial, while a focus on promoting behavioral control may yield larger effects for children's mathematics.

#### **6.4 Conclusions and Suggestions for Future Research**

The main aim of this dissertation was to get a better understanding of some of the specific interrelations between EF and early literacy and mathematics when children make the transition from ECEC to formal education in first grade. For this purpose interrelations between EF and academic skills were investigated at a relatively fine-grained level by examining the direction and domain-specificity of associations.

Two main results may be emphasized. First of all, across the studies, the association between EF and mathematics was particularly robust. That is, self-regulation showed a robust bidirectional relation with mathematics that seemed to be especially driven by the control of

behavior. Second, the results for literacy were mixed. No evidence for bidirectionality was found. However, expressive vocabulary was a robust predictor of self-regulation and attentional control seemed to be a specific predictor of early reading through its effect on phonological awareness. Taken together, these results reflect domain-specificity of associations between EF, certain components of EF, and early literacy and mathematics.

In light of these results and taking into account the limitations of the present studies, several suggestions for future research can be made. First, to get a complete overview of the dynamic interrelations between EF and academic skills across early childhood, longitudinal studies including multiple measures of EF and several time points are warranted. Second, the mechanisms that may explain the differential relationship between EF and literacy versus mathematics remain largely unknown. For example, an automaticity account (Blair & Raver, 2015; Clements et al., 2016) suggests that EF is especially important in the process of skill acquisition while its predictive value attenuates when a skill becomes automated. This would predict that the association will be strongest for children at the lower end of the ability scale and the difference should be especially prominent for literacy outcomes such as phonological awareness, letter knowledge, and early word reading, which are expected to become fluent and get automated across early childhood. Third, several studies have put into question the causal nature of the association between EF and academic achievement (e.g., Jacob & Parkinson, 2015; Willoughby, Kupersmidt, & Voegler-Lee, 2012). Identifying whether specific components or an overarching EF construct account for the association between EF and academic skills (Nguyen, Duncan, & Bailey, 2019), controlling for other EFs such as working memory (Bull & Lee, 2014), and controlling for non-EF cognitive skills, such as processing speed (Willoughby et al., 2018) and motor skills (McClelland & Cameron, 2019), may be necessary to pinpoint the exact components

## *Discussion*

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through which EF may exert an influence on later academic achievement and provide essential directions for future intervention studies

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## **8 Study I**

ten Braak, D., Størksen, I. (2019). *Psychometric Properties of the Ani Banani Math Test*. Manuscript submitted for publication.



Psychometric Properties of the Ani Banani Math Test

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## Abstract

This study assessed the psychometric properties and validity of a digital early math assessment, the Ani Banani Math Test (ABMT) in three samples ( $N = 243$ ,  $N = 691$ ,  $N = 1282$ ) in kindergarten and first grade (age range 4.67 - 7.30). Confirmatory factor analyses showed a consistent one-factor structure with moderate to high factor loadings and a normal distribution of items varying in difficulty. Differential item functioning with regard to sex, age, and socio-economic status was tested with MIMIC models. All items functioned similar across the covariates with the exception of two items which showed a bias towards boys and one item towards girls. A test of correlated correlations showed that the correlations with other math assessments were strong and significantly higher than with language, literacy, self-regulation, and working memory constructs, indicating both convergent and discriminant validity. The task showed a strong positive correlation with mathematics achievement in fifth grade, indicating high predictive validity.

*Keywords:* early childhood, mathematics, assessment, play, digital

### Psychometric Properties and Validity of the Ani Banani Math Test

During early childhood, children obtain a range of concepts based on their informal experiences and already within the first years of life, they acquire the ability to think mathematically (Sarama & Clements, 2009). These early mathematical skills are a strong predictor of later mathematics (e.g., Duncan et al., 2007). Psychological research on the development of this informal knowledge has amassed, however, most of the mathematical assessments (e.g., Woodcock-Johnson Tests of Achievement (Woodcock, McGrew, & Mather, 2001), REMA (Clements, Sarama, & Liu, 2008) have been developed in the United States which has a kindergarten tradition that focuses strongly on preparing children for school (OECD, 2006). Considering that a child's development depends on the experiences it encounters and is embedded in the context and type of these learning experiences, mathematical instruments that are constructed for use in the school readiness tradition may be less valid for use in samples from other traditions. In Norway, and most other non-English speaking European countries, early childhood education and care (ECEC) is characterized by a social pedagogical play-based approach which has a strong focus on learning through informal experiences encountered during free play and daily activities (OECD, 2006). Norwegian ECEC is regulated by the 'Framework Plan for the Content and Tasks of Kindergartens' (Framework Plan; Ministry of Education and Research, 2017). This plan has a holistic approach to learning and little emphasis on reaching specific academic goals for the transition to first grade. Consequently, few, if any, early math assessments suitable for research have been developed in Norway. In the present study we assess the psychometric properties of a digital early math assessment, the Ani Banani Math Test (ABMT; Størksen & Mosvold, 2013), which reflects the way many children in Norway and other European countries learn mathematics; through free play and daily activities. The following research questions were investigated:

(RQ1) What is the factor structure of the ABMT? We tested whether a one, two, or three-factor model best fitted the data. Although the task was developed to include aspects of three mathematical areas (problem-solving, geometry, and numeracy), we expected that the overlap in content across the items might not yield clearly defined factors.

(RQ2) Do the items of the ABMT function similarly across age, sex, and socio-economic status (SES)? This question was evaluated in an exploratory fashion.

(RQ3) Does the ABMT show concurrent, predictive and discriminant validity? We expected the ABMT to relate more strongly to other mathematical assessments compared to related constructs (e.g., measures of literacy, language, self-regulation, and working memory).

## Method

### Participants and Procedure

Three convenience samples were utilized in this study ( $N = 243$ ,  $N = 691$ ,  $N = 1282$ ). See Table 1 for more details. All samples were collected in both rural and urban areas of southern Norway. Sample 2 and 3 were part of an intervention study and therefore only the data from the control group was used at posttest. Children were assessed individually by a trained research assistant in fall and/or spring of the academic year. Assessments were all conducted on a tablet. All studies were reported to and approved by the Norwegian Social Science Data Service.

### Measures

**Ani banani math test.** The 18 items in the ABMT are administered on a tablet and embedded in playful contexts, which include a figure - a little monkey called Ani Banani - and his imagined everyday activities, such as counting toys, eating a certain number of bananas, making a puzzle. To engage the child in the task, items would typically include sentences such as 'can you help Ani Banani...' or 'can you give Ani Banani...'. Test items were constructed to

include elements of problem-solving, geometry, and numeracy (Magne, 2003). In general, the ABMT was developed to encompass a broad and holistic understanding of early mathematical development (Størksen & Mosvold, 2013). The task takes about 10 minutes to complete. See table 3 for an overview of the items.

**Preschool early numeracy scale.** This task (PENS; Purpura, Reid, Eiland, & Baroody, 2015),  $\alpha = .90$ , is a brief early numeracy measure developed in the United States. It includes 24 items regarding one-to-one counting, cardinality, counting subsets, subitizing, number comparison, set comparison, number order, numeral identification, set-to-numerals, story problems, number combinations, and verbal counting.

**National school math and reading assessments.** In first and fifth grade, mathematics and reading achievement were assessed with the national school assessments (NDET; Norwegian Directorate for Education and Training).

**Vocabulary.** Vocabulary was assessed by the Norwegian Vocabulary Task,  $\alpha = .84$  (NVT; Størksen, Ellingsen, Tvedt, & Idsøe, 2013). Children were presented with 45 different pictures on a tablet screen and had to tell the name of the object depicted.

**Phonological awareness.** Blending task (NDET) with twelve items. The target word was auditory presented in its individual phonemes by the experimenter and children had to indicate the corresponding alternative from four presented images on a tablet screen. Reliability for this task is  $\alpha = .75$  (Solheim, Brønnick, & Walgermo, 2013).

**Self-regulation.** The Head-Toes-Knees-Shoulders task,  $\alpha = .94$  (HTKS; McClelland et al., 2014) was used as a direct measure of behavioral self-regulation. In this task children were initially habituated to two different rules (“touch your head/toes) and later needed to inhibit this automatized response and replace it with the opposite (e.g., “touch your head” meant “touch your toes”) and a different rule (e.g., “touch your head” meant “touch your knees”).

**Working memory.** The Forward/Backward Digit Span subtest from the WISC-IV (Wechsler, 2003) was used as a measure of working memory. Children had to repeat a sequence of digits. First in the same order and then in reversed order.

**Covariates.** Parents filled out their highest obtained education and their children's sex, and age on a questionnaire. Maternal education was used as a proxy for SES.

### **Analytical Strategy**

Confirmatory factor analyses (CFA) were used to investigate the factor structure (RQ1) and were conducted with MPLUS software (Muthén & Muthén, 1998-2010). Robust weighted least squares estimators (WLSMV) were used to deal with the categorical nature of the data. Overall model fit was evaluated using the following criteria: RMSEA  $\leq .08$  (adequate)  $\leq .06$  (good), CFI and TLI  $\geq .90$  (adequate)  $\geq .95$  (good), (Brown, 2015; Hu & Bentler, 1999). Items 1 and 18 were considered fillers (99 % of children scored correctly) and omitted from all analyses as they caused problems with univariate and bivariate distributions containing empty cells. Residual covariances were included between items that were similar in wording and/or content and indicated areas of strain when not freely estimated (modification index  $> 10.0$ ). The number of residual covariances was kept as low as possible (e.g., added until satisfying model fit) and kept similar across samples for consistency. See Table 3.

To investigate whether the items function similar across age, sex, and SES (RQ2) the three samples were merged and multiple indicator multiple indicator causes (MIMIC) models were estimated to assess differential item functioning (DIF). DIF was assessed in an exploratory manner by regressing the latent ABMT variable on the covariate of interest and fixing all direct effects on the indicators to zero and then inspecting modification indices for any salient areas of strain (Brown, 2015).

Concurrent convergent validity (RQ3) was determined by calculating the correlation between the ABMT and other mathematical assessments (school math assessments and PENS) at the same time point, whilst predictive validity was assessed by estimating the correlation between the ABMT and these assessments at a later time point. Discriminant validity was determined by comparing correlated correlations to show that the correlations between the ABMT and other math assessments were significantly higher than between the ABMT and related constructs. Only Sample 1 and 3 were used for these analyses as Sample 2 did not contain any other math assessments.

## Results

### (1) What is the factor structure of the ABMT?

First, a 1-factor model was estimated with the spring kindergarten data because the ABMT was originally designed for this age group. This model showed a good fit with the data. Next, a 3-factor model with a numeracy (items: 3 – 5, 7 – 10, 17), geometry (items: 11 – 13, 15 – 16), and problem solving (items: 2, 6, 14) factor structure was estimated. A 2-factor model without a separate problem-solving factor was also tested (items 2, 6, and 14 added to numeracy). Although these models showed an adequate fit, the correlation between factors was often very high ( $> .8$ ), indicating poor discriminant validity between the latent dimensions. The 1-factor structure was therefore chosen over the other models for reasons of parsimony. This model also showed a good fit in fall of kindergarten (Sample 2 and 3). In first grade (Sample 1), item 4 appeared too easy ( $> 99\%$  correct) and contributed to poor model fit due to distributions containing empty cells. The 1-factor model also showed a good model fit in the combined sample. See Table 2. In Table 3 the item parameters from spring kindergarten in the combined sample are presented from least to most difficult.

**(2) Do the items of the ABMT function similarly across age, sex and SES?**

Mimic models indicated that age ( $\beta = 0.241, p < .001$ ) and SES ( $\beta = 0.237, p < .001$ ) positively predicted the latent ABMT factor. None of the items showed DIF for these two covariates. Sex did not predict the latent ABMT factor ( $\beta = 0.056, p = 0.134$ ). However, DIF was found for item 3 and 17 indicating a bias towards boys, and towards girls for item 11.

**(3) Does the ABMT show concurrent, predictive and discriminant validity?**

Zero-order correlations between the math measures and other related constructs are presented in Table 4. The correlations between the ABMT and other math measures at the same time point were all  $> .50$  indicating convergent concurrent validity. The ABMT also showed correlations  $> .50$  with math measures at a later time point indicating convergent predictive validity. A test of correlated correlations (Lee & Preacher, 2013) showed that the concurrent correlations between the ABMT and the other math assessments were all significantly higher than the correlations between the ABMT and all other constructs indicating both convergent and discriminant validity. See Table 5.

**Discussion**

This study assessed the psychometric properties and validity of a playful and holistic digital early math assessment, the Ani Banani Math Test (ABMT; Størksen & Mosvold, 2013). CFA's showed a consistent pattern: although models with two or three factors showed an acceptable fit with the data, the correlations between the factors were very high making it difficult to discriminate between the dimensions. The one factor model was therefore chosen as the most reliable and representative for the ABMT. The items showed moderate to high factor loadings indicating that children's math skills explain a significant proportion of the variance in

the level of underlying math skills needed to score correct on an item. The ABMT also showed a normal distribution of items varying in difficulty.

MIMIC models showed no DIF for age or SES. However, DIF was found in favor of boys for item 3 (counting to 50) and 17 (counting backward) meaning that, despite equal underlying math skills, boys are more likely to answer correctly on these items. The results also showed that girls were more likely to answer correctly on item 11 (puzzle). Both item 3 and 17 involve counting out loud to the experimenter. It may be that boys have been more involved in games like hide and seek where they need to count out loud and backwards. Girls may have been playing more with puzzles, which may have familiarized them with such challenges. When planning to compare ABMT means between the sexes, it is therefore advisable to rule out any DIF on these items beforehand and omit if necessary.

The analyses provide evidence that the ABMT has concurrent, predictive, and discriminant validity. The ABMT showed consistent high correlations with other math tasks at concurrent time points across all samples. Moreover, these correlations were significantly higher compared to correlations with other language and literacy constructs, such as reading, vocabulary, and phonological awareness, and compared to measures of self-regulation and working memory. This indicates that the ABMT measures a distinct mathematical component that is related to but can still be differentiated from early language and literacy skills and other cognitive domains. It also showed high predictive validity with a strong correlation between the ABMT in kindergarten and a mathematics achievement test five years later.

Taken together, the ABMT appears to be a reliable and valid research measure of early mathematics that reflects the holistic social pedagogical play-based approach that characterizes many countries in Europe and the playful way through which children learn mathematics in early childhood.

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Table 1

*Descriptives of the Three Data Samples*

	N valid	N missing	Percentage missing	Male/ female	Mean age (SD)	Age range
<b>Sample 1</b>						
Spring kindergarten	241	2	0.82%	122/119	5.78 (.29)	5.29 - 6.30
Spring first grade	239	4	1.65%	122/117	6.78 (.29)	6.29 – 7.30
<b>Sample 2</b>						
Fall kindergarten	664	27	3.91%	332/332	5.16 (.26)	4.67 – 5.67
Spring kindergarten	292 <sup>a</sup>	20	6.41%	141/151	5.99 (.27)	5.50 – 6.42
<b>Sample 3</b>						
Fall kindergarten	1199	83	6.5%	606/593	5.14 (.28)	4.67 – 5.67
Spring kindergarten	519 <sup>a</sup>	75	12.6%	259/260	5.93 (.28)	5.42 – 6.42

*Note.* <sup>a</sup> Data from sample 2 and 3 in spring kindergarten only contains half of the sample at fall

because data from the intervention group was excluded.

Table 2

*Fit Indices for Confirmatory Factor Models*

	RMSEA	CFI	TLI	$\chi^2$ (df)	p	r between factors
<b>Sample 1</b>						
Spring Kindergarten						
1-factor model	.034	.958	.950	129.152 (101)	.0309	-
2-factor model	.033	.961	.953	126.679 (100)	.0370	.848(NUM-GEO)
3-factor model	.034	.959	.949	125.861 (98)	.0304	1.263 (NUM-PS) <sup>b</sup> .985 (GEO-PS) .858 (NUM-GEO)
Spring first grade						
1-factor model <sup>a</sup>	.019	.980	.976	94.545 (87)	.2721	
<b>Sample 2</b>						
Fall kindergarten						
1-factor model	.025	.975	.971	141.263 (101)	.0051	-
Spring kindergarten						
1-factor model	.032	.972	.967	131.313 (101)	.0230	
2-factor model	.024	.984	.981	116.932 (100)	.1186	.704 (NUM-GEO)
3-factor model	.025	.984	.980	115.845 (98)	.1054	.899 (NUM-PS) .622 (GEO-PS) .708 (NUM-GEO)
<b>Sample 3</b>						
Fall kindergarten						
1-factor model	.034	.963	.957	243.591 (101)	<.001	-
Spring kindergarten						
1-factor model	.033	.974	.969	156.545 (101)	.0003	
2-factor model	.030	.978	.974	145.980 (100)	.0019	.841 (NUM-GEO)
3-factor model	.030	.978	.973	143.839 (98)	.0018	.850 (NUM-PS) .771 (GEO-PS) .831 (NUM-GEO)
<b>Combined sample</b>						
Spring kindergarten						
1-factor model	.033	.970	.965	219.858 (101)	0.000	-

*Note.* <sup>a</sup> In first grade item 4 was omitted because it was too easy and led to poor model fit. <sup>b</sup> The

latent variable covariance matrix (psi) was not positive definite for this model due to a correlation greater than one between two latent factors and results for this model should not be interpreted.

NUM = numeracy, GEO = geometry, PS = problem solving.

Table 3

*Psychometric Information from the 1-Factor Model in Spring Kindergarten in the Combined**Sample*

no.	Item detail	% correct	Loadings	Thresholds
1	Select biggest milkshake (filler)	99.1	N/A	N/A
18	Divide equal number of apples (filler)	98.5	N/A	N/A
4	Give 5 banana's	89.3	0.707	-1.240
9	Put 5 plates on the table	84.9	0.627	-1.032
12 <sup>a</sup>	Find triangle	83.2	0.453	-0.960
13 <sup>a</sup>	Find triangle again	81.0	0.424	-0.879
8	How many bricks	64.4	0.441	-0.368
7	How many cars	60.8	0.314	-0.275
14	Select monkey with most marbles	58.4	0.443	-0.211
15 <sup>b</sup>	Copy a pattern	57.3	0.622	-0.185
5	Give 17 banana's	45.4	0.645	0.115
10	Put more plates so there's place for 7	38.7	0.617	0.286
16 <sup>b</sup>	Copy a pattern	37.5	0.556	0.320
11	Complete a puzzle	35.1	0.451	0.383
3 <sup>c</sup>	Count to 50	27.8	0.741	0.589
2	Select next smallest milkshake	22.4	0.449	0.758
17 <sup>c</sup>	Count backwards from 15	14.6	0.664	1.052
6	Give twice as many apples	11.4	0.502	1.204

*Note.* <sup>abc</sup> freely estimated correlations between error terms.

Table 4

*Zero-Order Correlations between the ABMT and Related Constructs in Sample 1 and 3*

	T2														T3			T2
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	PENS			
1. ABMT T1	-																	
2. HTKS T1	.477	-																
3. Digit span T1	.597	.516	-															
4. Vocabulary T1	.456	.328	.468	-														
5. Phonological awareness T1	.400	.381	.407	.408	-													
6. National math test T2	.587	.403	.434	.259	.211	-												
7. National reading test T2	.484	.399	.435	.335	.293	.666	-											
8. ABMT T2	.669	.480	.575	.395	.405	.685	.532	-		.545	.483						.648	
9. HTKS T2	.436	.380	.392	.316	.195	.547	.418	.454	-									
10. Digit span T2	.500	.368	.647	.414	.353	.421	.437	.488	.357	-	.395							
11. Vocabulary T2	.424	.306	.445	.816	.347	.224	.337	.394	.298	.417	-							
12. Phonological awareness T2	.344	.305	.364	.397	.397	.326	.649	.366	.311	.368	.350	-						
13. National math test T3	.601	.305	.542	.366	.263	.661	.479	.621	.467	.532	.345	.291	-					
14. National reading test T3	.511	.337	.550	.479	.338	.516	.492	.521	.389	.479	.424	.314	.694	-				

*Note.* Correlations for sample 1 are below the diagonal. Correlations for sample 3 above the diagonal. T1 = spring kindergarten in

sample 1 and fall kindergarten in sample 3, T2 = first grade in sample 1 and spring kindergarten in sample 3, T3 = fifth grade.

Table 5

*Results from the Test of Correlated Correlations between the ABMT and the National Math Assessment and the PENS versus other Constructs*

Sample 1	National math assessment versus:	z-score
First grade	National reading assessment	3.912
	HTKS	4.982
	Digit span	3.877
	Vocabulary	4.845
	Phonological awareness	5.576
Sample 3	PENS versus:	
Spring kindergarten	Digit span	3.332
	Vocabulary	4.964

*Note.* All differences significant at  $p < .001$

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## **9 Study II**

ten Braak, D., Størksen, I., Idsoe, T., & McClelland, M. (2019). Bidirectionality in self-regulation and academic skills in play-based early childhood education. *Journal of Applied Developmental Psychology*, 65, 101064. doi: <https://doi.org/10.1016/j.appdev.2019.101064>





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## Bidirectionality in self-regulation and academic skills in play-based early childhood education

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### ABSTRACT

Support for the idea that self-regulation and early academic skills co-develop in young children is accumulating. The majority of this research, however, is conducted in countries with a school readiness approach to early childhood education. We investigated bidirectional relations between self-regulation and mathematics, expressive vocabulary, and phonological awareness in children ( $N = 243$ , ages 6–7) making the transition from a play-based kindergarten context to a formal educational context in first grade in Norway. Cross-lagged panel models showed that there were bidirectional relations between self-regulation and mathematics, but not between self-regulation and expressive vocabulary or phonological awareness. Expressive vocabulary significantly predicted self-regulation, and self-regulation significantly predicted phonological awareness, although the latter association attenuated when controlling for vocabulary. Given these interrelations, intentionally targeting a combination of these skills in a playful manner may support children's transition from a play-based kindergarten context to a more formal learning environment in first grade.

### Introduction

During early childhood, children experience a rapid development of cognitive skills that underlie self-regulation (Best & Miller, 2010; Garon, Bryson, & Smith, 2008). They learn to shift attention, manipulate elements in memory, and inhibit automatic responses. Self-regulation can be defined as the integration and behavioral manifestation of these skills in adaptive real-world behaviors (Cameron Ponitz, McClelland, Matthews, & Morrison, 2009; McClelland et al., 2014; McClelland & Cameron, 2012). During this same period, early academic skills, such as mathematics (Sarama & Clements, 2009), language, and literacy emerge (Cartwright, 2012). Children's self-regulation and early academic skills in kindergarten are important for a successful transition to formal schooling and further academic achievement (Duncan et al., 2007; McClelland, Acock, Piccinin, Rhea, & Stallings, 2013; McClelland et al., 2014). Several studies show that self-regulation is associated with early academic skills such as mathematics (Becker, Miao, Duncan, & McClelland, 2014; Cadima, Gamelas, McClelland, & Peixoto, 2015;

McClelland et al., 2014; von Suchodoletz & Gunzenhauser, 2013), vocabulary (Becker et al., 2014; McClelland et al., 2007; McClelland et al., 2014), and phonological awareness (Gestsdotir et al., 2014; Van de Sande, Segers, & Verhoeven, 2013). The present study examined the direction of associations between self-regulation and these early academic skills in Norwegian children who make the transition from a play-based kindergarten<sup>1</sup> context (ages 5–6 years) to a formal educational context.

#### Theoretical foundation

This study is guided by theoretical models reflecting the assertion that skills develop through dynamic interrelations and interactions with the environment (Fischer & Bidell, 2006; McClelland, John Geldhof, Cameron, & Wanless, 2015), and thus may be bidirectionally related and culturally specific (Trommsdorff, 2009). According to relational developmental systems theories (e.g., dynamic skill theory and developmental psychobiological systems theory), skills do not develop in

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<sup>1</sup> In Norway, children attend Early Childhood Education and Care (ECEC) centers from the age of one to six years old. Although Norwegian children do not attend kindergarten as it is known in the United States, for simplicity we use the name kindergarten as this study includes only the eldest children from the ECECs. Kindergarten attendance is high at 97% (Statistics Norway, 2018).

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isolation and all development represents a bidirectional and dynamic process between the development of increasingly complex skills over time and across contexts (Blair & Raver, 2015; McClelland et al., 2015).

For example, although self-regulation can be regarded as foundational for the development of academic skills, both develop rapidly during early childhood (Best & Miller, 2010; Cartwright, 2012; Garon et al., 2008). This simultaneous development suggests that the developmental processes may be overlapping and bidirectional (Fuhs, Nesbitt, Farran, & Dong, 2014; McClelland & Cameron, 2019; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). Bidirectionality may occur because development in one skill (e.g., language development) sets the stage for further development in another skill (e.g., self-regulation). For example, the growing ability to use language to regulate behavior may also promote gains in self-regulation that allow children to attend to learning situations that further promote language.

A child's context may also shape these interrelations. Cross-cultural studies indicate that although universal patterns are present, culture-specific differences in functioning of self-regulation may emerge (Gestsdottir et al., 2014; Wanless et al., 2011). The educational system is one aspect of a child's context that may influence the experiences and processes through which academic skills and self-regulation are promoted. Many studies include samples from the United States (U.S.), which has a different early childhood education (ECE) system compared to Norway and most other non-English speaking Nordic and Central European countries (e.g., a school readiness versus play-based system, respectively (OECD, 2006)). These educational systems may vary in the ways through which self-regulation and academic skills are promoted. For example, a play-based ECE context may promote children's self-regulation gradually through social interaction with peers and physical activity in free-play situations and hereby set the stage for development of academic skills in school. A school readiness ECE context may introduce academic skill instruction early on hereby familiarizing children with formal learning situations and prepare children for a smooth transition to school.

Developmental systems theories thus provide a relevant basis for investigating associations between self-regulation and academic skills within a bidirectional framework and in samples from other educational contexts, such as Norway.

#### *Self-regulation and academic skill development*

Self-regulation includes the ability to modulate behavior through the integration of attentional or cognitive flexibility, working memory, and inhibitory control (McClelland et al., 2014; McClelland & Cameron, 2012). These cognitive components are often referred to as executive functions (EF) (Miyake et al., 2000). Children's self-regulatory skills are regarded as an important indicator of school readiness and predictors of later academic achievement (Blair & Raver, 2015; Duncan et al., 2007; McClelland et al., 2007; McClelland et al., 2013; McClelland et al., 2014).

Self-regulation allows children to benefit from learning opportunities that facilitate the development of early academic skills (Blair & Raver, 2015; McClelland et al., 2014). This can be seen when children ignore irrelevant impulses and peer distractions, listen to and remember instructions, and switch attention from one activity to another in classroom situations (e.g. Blair & Diamond, 2008; Blair & Raver, 2015; McClelland et al., 2014). Moreover, self-regulatory skills are also directly needed when engaging in academic activities. For example, children may need to ignore certain aspects of a mathematical problem while updating others (Blair, Knipe, & Gamson, 2008; Blair & Raver, 2015) or shift attention from the meaning of a word to its structural features (Altmeier, Abbott, & Berninger, 2008; Walcott, Scheemaker, & Bielski, 2010).

In turn, advances made in academic skills may influence the development of self-regulation. One mechanism through which academic skills may enhance self-regulation is that children who develop rapidly

in academic knowledge may be more likely to engage in more advanced and complex academic activities, thereby practicing higher order information processing and self-regulatory skills (Blair & Raver, 2015; Clements, Sarama, & Germeroth, 2016). Neuroscientific studies indicate that the prefrontal cortex, a brain region strongly associated with EF, plays a significant role in attention and working memory aspects of both mathematics and reading (Ashkenazi, Black, Abrams, Hoef, & Menon, 2013). Engaging in academic skill learning might, therefore, enhance neural connections in the prefrontal cortex associated with EF and thereby contribute to better self-regulation. During early childhood, children have to learn a tremendous amount of new skills, and exactly this learning of new skills, rather than exercising already learned skills, may enhance EF (Clements et al., 2016).

#### *Associations between self-regulation and mathematics*

The likelihood of learning new and higher order processing skills may especially be prominent in children showing high proficiency in mathematics. When children engage in mathematics they need to keep parts of an equation in memory while updating others, inhibit a prepotent tendency that interferes with the correct solution, and shift attention between different aspects of a mathematical problem (Blair et al., 2008; Blair & Razza, 2007; Clements et al., 2016). Growth in mathematics can be considered a cumulative learning process in that mathematical skills develop hierarchically. Children are continually faced with more complex mathematical problems, even though initial skills such as counting become automatized (Clements et al., 2016; Sarama & Clements, 2009). The development of mathematics and exposure to increasingly complex problems thus continuously engages executive processes that may promote self-regulation.

Empirically, relatively robust and stable relations between self-regulatory skills and mathematics over time have been found (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Blair & Razza, 2007; McClelland et al., 2014) as well as significant effects of self-regulation interventions on math skills (Schmitt, McClelland, Tominey, & Acock, 2015; Tominey & McClelland, 2011). A few studies have investigated the direction of effects and results point to a consistent pattern of bidirectional relations between self-regulation and mathematics across preschool and kindergarten (Fuhs et al., 2014; Schmitt et al., 2017; Welsh, Nix, Blair, Bierman, & Nelson, 2010) and kindergarten and first grade (Hernández et al., 2018; McKinnon & Blair, 2018). Taken together, the cognitive characteristics and demands of mathematics suggest reciprocal associations with self-regulation across early childhood.

#### *Associations between self-regulation and vocabulary*

Self-regulatory skills are considered to play a critical role in the development of language. For example, to understand the meaning of a sentence, children need to remember what happened first and relate this to what happened later (Diamond, 2013), flexibly switch between ways of using information, suppress irrelevant cues, and inhibit the tendency to perseverate when distracted (Mazuka, Jincho, & Oishi, 2009). Indeed, several studies indicate that self-regulation predicts early language skills such as vocabulary (e.g., McClelland et al., 2007; McClelland et al., 2014).

However, this developmental pathway may also be bidirectional. According to Vygotsky (Diaz, Neal, & Amaya-Williams, 1992; Vygotsky, 1934/1986), language plays an important role in the development of self-regulation. Children internalize external rules and structures by increasing use of inner speech that aids them with regulating their thoughts and behavior. This supports the notion that there may be a developmental pathway between verbal skills that support inner speech and self-regulation. Results from previous studies, however, are mixed: Some studies find bidirectional associations (Cadima et al., 2018; Slot & Von Suchodoletz, 2018), while other studies not (Fuhs & Day, 2011; Weiland, Barata, & Yoshikawa, 2014) or only during a specific time

period (Bohmann, Maier, & Palacios, 2015; Fuhs et al., 2014; Meixner, Warner, Lensing, Schiefele, & Elsner, 2018). Moreover, none of these studies covered the transition from kindergarten to school.

#### *Associations between self-regulation and phonological awareness*

Self-regulatory skills play an important role in the development of early literacy and reading (Cartwright, 2012). For example, in the acquisition of phonological awareness children need to learn to switch attention from the semantic meaning of a word to its individual sound components, become aware of the actual existence of phonemes and syllables in words, attend to relevant sounds, and ignore irrelevant phonological information. This allows children to subsequently process, manipulate, and deliberately act upon this information (Goswami, 2001; 2008).

The acquisition of phonological awareness may require children to actively use several aspects of EF and thereby practice self-regulation. However, phonological awareness may become automatized more quickly compared to for example mathematics, which continues to increase in complexity and make ongoing demands on reasoning ability (Blair, Protzko, & Ursache, 2011). This automaticity theory is also reflected in the shift from activation in brain areas associated with slow and effortful processing of phonological information to greater activity in brain areas associated with rapid and automatic skilled reading as readers get older (Schlaggar & McCandliss, 2007). Studies investigating bidirectional relations between early literacy and self-regulatory skills have found that the latter predicted early literacy at some point in time but not consistently, and not vice versa (Fuhs et al., 2014; McKinnon & Blair, 2018; Schmitt et al., 2017; Welsh et al., 2010).

#### *Early childhood education contexts*

With a few recent exceptions (Cadima et al., 2018; Meixner et al., 2018; Slot & Von Suchodoletz, 2018), all of the bidirectional studies described above have been conducted in countries with a school readiness approach to ECE, such as in the U.S.. This tradition has a strong focus on preparing children for school and promoting the early academic and self-regulatory skills important for this transition (e.g., Bierman et al., 2008; Blair & Raver, 2015; OECD, 2006). Instruction in literacy and mathematics may start at an early age (3–4), and this focus on academic instruction may put strong demands on children's self-regulation. However, it may also familiarize children with instructional demands similar to school settings, such as sitting still for long periods at a time, paying attention to instructions from the teacher, and focus on a task while resisting distraction from peers. Experience with such situations may make the transition to first grade less demanding in terms of self-regulation.

In most non-English speaking Nordic and Central European countries, with the exception of France, ECE is characterized by a social pedagogical play-based tradition (OECD, 2006), which embeds children in a notably different educational context. In play-based ECE, there is little structured curricula and free play is regarded as one of the most important sources of learning. For example, in Norway, during the summer 70%, and during winter 31%, of children's total time in kindergarten is dedicated to outdoor play together with children of different ages (Moser & Martinsen, 2010). This context may promote self-regulation through complex social interactions combined with physical activity in challenging environments. Curricular guidelines do not specify what children should learn, rather, they place trust in young children as agents of their own learning (OECD, 2006). Children usually get to choose their own activities and it is not unusual to skip planned activities in favor of free play (Lekhal et al., 2013). Formal instructional activities to promote academic skills, such as mathematics and phonological awareness, are usually not introduced before first grade (around age 6).

Although early childhood interventions focused on early literacy and social emotional skills (Bierman, Domitrovich, et al., 2008; Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008) as well as free play (Elias & Berk, 2002) have been found to promote self-regulatory skills, academic skills are often promoted by a more structured environment (Pyle, 2018). However, it is unknown whether the different processes through which academic and self-regulation skills are acquired may lead to different developmental trajectories. Nonetheless, the amount of time children spend in formal learning situations may be lower in play-based ECE. As a consequence, children may make the transition from kindergarten to first grade with little experience with formal learning situations, which may put extra demands on children's self-regulation as they need to adapt to the new context in first grade. This may be the case in Norwegian ECE contexts which implement a strong play-based approach.

The divergent educational practices and type of learning activities between the school readiness and play-based approaches may result in different experiences that children encounter in kindergarten and first grade. Results from studies conducted in countries with a school readiness approach to early childcare may therefore not be directly generalizable to children growing up in countries with a play-based context, such as Norway.

#### *Present study*

The present study investigates the developmental pathways between self-regulation and mathematics, expressive vocabulary, and phonological awareness, in children making the transition from a play-based kindergarten context to formal education in first grade in Norway. More specifically, we investigated 1) whether kindergarten self-regulation predicted first-grade mathematics, expressive vocabulary, and phonological awareness, controlling for prior skills, and 2) whether kindergarten mathematics, expressive vocabulary, and phonological awareness predicted first-grade self-regulation, controlling for prior skills.

Because Norwegian children undergo a relatively large transition from a play-based learning context to a formal learning environment in first grade, we expected that attending to the learning instructions in first grade would require strong self-regulation, and thus we expected self-regulation to predict all academic outcomes. Furthermore, in line with relational developmental systems theories (e.g., McClelland et al., 2015), ideas about the strong involvement of self-regulation in mathematics (e.g., Blair et al., 2008; Clements et al., 2016), and the importance of language for the development of self-regulation (Diaz et al., 1992; Vygotsky, 1934/1986), we expected mathematics and expressive vocabulary to predict self-regulation. Finally, self-regulation was expected to predict phonological awareness, but not the reverse (e.g., Fuhs et al., 2014; Schmitt et al., 2017; Welsh et al., 2010).

#### **Method**

##### *Participants and procedure*

A total of 287 children from 19 Norwegian kindergartens from one municipality on the west coast of Norway were approached to participate in this study. Of those, 84.7% (243 children: 119 girls and 124 boys) were given consent from parents to participate. The mean age of the children in kindergarten was 5.8 years, ranging from 5.3 to 6.3 ( $SD = 0.29$ ). From this sample, 31 children (12.8%) had at least one parent who was born outside of Norway, including five children (2.1%) from whom both parents were born in the EU/EEA (but outside of Scandinavia), USA, Canada, Australia or New Zealand, and eight children (3.3%) from whom both parents came from either Asia, Africa, Latin-America, Oceania (except Australia and New Zealand), or from another country in Europe outside the EU/EEA. These latter 13 children

were regarded as having an immigrant status in the present study. All children spoke Norwegian and were assessed in Norwegian. Of the mothers, 48.3% reported having three years of college/university education or more. The data used for this study was part of a larger research project called *Skoleklar*. The project was reported to and approved by the Norwegian Social Science Data Service (NSD).

Children's self-regulation and academic skills were measured twice, during spring in kindergarten and approximately one year later in first grade. Trained research assistants with an education in child development tested each child individually in a private room. Testing was part of a larger test battery containing six tests on a tablet. Total administration time of the battery was approximately 45 min per child. The research assistant provided instructions and feedback on practice trials, after which children worked independently, without receiving feedback, on the remainder of the tasks.

### Measures

#### Self-regulation

The Head-Toes-Knees-Shoulders task (HTKS; McClelland et al., 2014) was used as a direct measure of behavioral self-regulation. Research has demonstrated that the HTKS is a reliable ( $\alpha = 0.94$ ) and valid measure of self-regulation, taps aspects of working memory, inhibitory control, and cognitive flexibility (McClelland et al., 2014), and loads on one EF factor together with these cognitive processes (Schmitt et al., 2017). Research has also shown that it significantly predicts children's academic outcomes in diverse and international samples (McClelland et al., 2007, 2014; von Suchodoletz & Gunzenhauser, 2013; Wanless et al., 2011), including Norwegian children (Størksen, Ellingsen, Wanless, & McClelland, 2015), and children in early elementary school (Day, Connor, & McClelland, 2015; Gestsdottir et al., 2014). In previous research, scores on the HTKS have also correlated ( $r = 0.46$ ) with teacher ratings of behavioral self-regulation (McClelland et al., 2007).

Children were initially habituated to two different rules ("touch your head/toes) and later needed to inhibit this automatized response and replace it with the opposite (e.g., "touch your head" meant "touch your toes"). The total task consisted of up to three blocks of 10 items each with four additional practice items per block. The test continued to the subsequent block only if the number of points in the previous block totaled to four or more. The first block contained the items "head" and "toes". In the second block "shoulders" and "knees" were added. In the last block the rules were changed. Responses were scored with two points when correct, one point when the child made an incorrect movement but ended up with the correct response, and zero points for incorrect responses. The sum of both practice and test items was used to create more variability in the lower end (e.g., Fuhs et al., 2014), giving a maximum score of 84.

#### Mathematics

The Ani Banani Math Test (ABMT; Størksen & Mosvold, 2013), a short digital math assessment on a tablet application that included 18 items aimed to cover three areas of mathematics - numeracy, geometry, and problem-solving, was used to measure early mathematics. The items included: counting of objects, creating groups, counting back- and forward, counting to fifty, completion of a puzzle, recognizing geometric shapes, copying geometrical figures, simple arithmetic reasoning, comparing qualitative and quantitative aspects of objects, and problem-solving. Children were asked to help a little monkey, such as, 'Ani Banani is a little bit hungry today, can you give him five bananas?' The task correlated  $r = 0.74$  with another validated early numeracy task, the Number Sense Task (Van Luit & Van de Rijt, 2009) in kindergarten and  $r = 0.69$  with an existing teacher administered math assessment in first grade (Utdanningsdirektoratet, 2017). Reliability in kindergarten was  $\alpha = 0.73$  and  $\alpha = 0.68$  in first grade.

#### Expressive vocabulary

Expressive vocabulary was assessed by the Norwegian Vocabulary Task (NVT; Størksen, Ellingsen, Tvedt, & Idsøe, 2013). In this task, children were presented with 45 different pictures on a tablet screen. Children had to tell the experimenter the name of the object that was depicted on the screen. Reliability was  $\alpha = 0.84$  in kindergarten and  $\alpha = 0.82$  in first grade.

#### Phonological awareness

This early literacy ability test was taken from the official literacy screening battery from The Norwegian Directorate for Education and Training. The measure consisted of 12 blending items. The target word was auditory presented in its individual phonemes by the experimenter and children had to indicate the corresponding alternative from four presented images on a tablet screen. Items increased in difficulty and the task was automatically discontinued after three subsequent errors. For example, 'Here you see a picture of /rips/, /rist/, /ris/, and /is/. Listen carefully and touch the picture that goes with /R/ /I/ /S/' (presented phoneme-by-phoneme, one per second). Reliability (Cronbach's alpha) for this task is  $\alpha = 0.75$  (Solheim, Brønning, & Walgermo, 2013).

#### Demographics

Parents completed a demographic questionnaire where they filled out information such as their highest obtained educational level, their country of birth, and their children's age and sex. Education level was reported as follows: 1 = junior high school, 2 = senior high school, 3 = 1–2 years of college/university, 4 = 3 years of college/university, 5 > 3 years of college/university. Immigrant status was coded as follows: 1 = both parents born outside of Norway, 0 = at least one parent born in Norway.

#### Analytic strategy

Rates of missing data were generally low (0.8%–4.1%). Little's MCAR test (Little, 1988) was not significant ( $p = .55$ ), suggesting that data were missing completely at random. Full information maximum likelihood with robust methods was used to deal with any missing data and deviations from normality. Age, sex, maternal education, and immigrant status were controlled for in the models as they may relate to children's self-regulation and academic outcomes (McClelland et al., 2014; Størksen et al., 2015).

In line with previous studies (e.g., Bohlmann et al., 2015; Fuhs et al., 2014; Meixner et al., 2018) we estimated a series of autoregressive cross-lagged path models in Mplus (Muthén & Muthén, 1998–2010) to investigate how self-regulation predicts mathematics, expressive vocabulary, and phonological awareness, and vice versa. Cross-lagged path models allowed us to determine how children's relative standing on self-regulation predicted their relative standing on the academic skill and vice versa. Auto-regressive and cross-lagged effects were each estimated controlling for the stability in the other (Kline, 2011) and high stability indicated that children who scored higher than the sample mean in kindergarten also tended to score higher than the sample mean in first grade, independent of whether the sample mean increased, decreased or remained the same.

To ensure that the hypothesized model was the best fitting model compared to other possible models, four versions of the models were compared. The scaling correction factor for MLR was used for chi-square difference testing (Muthén & Muthén, 2005). In model one, the full cross-lagged path model was estimated. In model two, the path from the academic skill to self-regulation was constrained to be zero. In model three, the path from self-regulation to the academic skill was constrained to be zero. In model four, both cross-lagged paths were constrained to be zero to reflect the possibility that the association between the variables was actually fully explained by a third factor not included in the model. To evaluate whether the strength of associations

was significantly different in one direction or the other, unstandardized regression coefficients for the cross-lagged paths were statistically compared by applying equality constraints and comparing this model to the freely estimated model.

Finally, to account for interrelations between all academic and self-regulatory skills, we estimated a combined path model wherein all variables were regressed on each other. Although this model is more conservative, it reflects the within and across domain associations between the academic skills (e.g., Kleemans, Segers, & Verhoeven, 2011; Purpura, Hume, Sims, & Lonigan, 2011) also postulated in relational developmental systems theories, and provides information on the unique contribution of each skill over-and-above the other. To evaluate the fit of the models the following fit indices and criteria were used:  $p$ -value  $\chi^2 > 0.05$ , CFI and TLI  $\geq 0.95$ , RMSEA  $\leq 0.06$  and SRMR  $\leq 0.08$  (Hu & Bentler, 1999).

**Results**

*Descriptive statistics*

Table 1 shows the means, standard deviations, ranges, skew and kurtosis of the assessed variables in kindergarten and first grade. Table 2 shows the bivariate correlations. All variables of interest

**Table 1**  
Descriptive Statistics.

	Min	Max	M	SD	Skewness	Kurtosis
HTKS T1	0	83	52.22	20.14	-0.92	0.25
HTKS T2	1	84	68.48	11.96	-2.18	8.37
Ani Banani Math Task T1	2	18	10.62	3.13	-0.32	-0.19
Ani Banani Math Task T2	5	18	14.52	2.57	-1.01	1.18
Norwegian Vocabulary Task T1	10	39	26.35	5.69	-0.42	-0.16
Norwegian Vocabulary Task T2	14	42	30.72	4.96	-0.63	0.44
Norwegian Blending Task T1	0	12	3.66	3.38	0.59	-0.91
Norwegian Blending Task T2	1	12	10.21	1.91	-1.75	3.98
Maternal Education <sup>a</sup>	1	5	3.28	1.30	0.09	-1.54
Age T1	5.29	6.30	5.79	0.29	0.06	-1.16

Note. T1 = kindergarten; T2 = 1st grade; HTKS = Head-Toes-Knees-Shoulders task.

<sup>a</sup> 1 = junior high school, 2 = senior high school, 3 = 1–2 years of college/university, 4 = 3 years of college/university, 5 > 3 years of college/university.

**Table 2**  
Bivariate Pairwise Correlations between Variables.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. Self-regulation <sup>a</sup> T1	-											
2. Mathematics <sup>b</sup> T1	0.481***	-										
3. Expressive vocabulary <sup>c</sup> T1	0.353***	0.457***	-									
4. Phonological awareness <sup>d</sup> T1	0.382**	0.401**	0.408**	-								
5. Self-regulation <sup>a</sup> T2	0.403***	0.446**	0.322**	0.220**	-							
6. Mathematics <sup>b</sup> T2	0.480***	0.669***	0.395**	0.409**	0.470**	-						
7. Expressive vocabulary <sup>c</sup> T2	0.323**	0.425**	0.818**	0.346**	0.301**	0.393**	-					
8. Phonological awareness <sup>d</sup> T2	0.307**	0.348**	0.402**	0.396**	0.319**	0.368**	0.353**	-				
9. Maternal Education <sup>e</sup>	0.125	0.293**	0.275**	0.200*	0.219**	0.322**	0.311**	0.168*	-			
10. Age	0.140*	0.179**	0.138*	0.204**	0.074	0.120	0.123*	0.070	0.043	-		
11. Immigrant status	-0.085	-0.064	-0.407**	-0.094	0.044	-0.054	-0.397**	-0.143*	-0.150**	-0.015	-	
12. Sex (girl = 1, boy = 2)	-0.251***	-0.165**	-0.119	-0.279**	-0.098	-0.156*	-0.106	-0.273**	-0.069	-0.035	0.087	-

Note. T1 = kindergarten; T2 = first grade.

<sup>a</sup> Head-Toes-Knees-Shoulders task.

<sup>b</sup> Ani Banani Math Task.

<sup>c</sup> Norwegian Vocabulary Task.

<sup>d</sup> Norwegian Blending Task.

<sup>e</sup> 1 = junior high school, 2 = senior high school, 3 = 1–2 years of college/university, 4 = 3 years of college/university, 5 > 3 years of college/university.

\*  $p < .05$ .

\*\*  $p < .01$ .

\*\*\*  $p < .001$ .

showed moderate to strong positive correlations over time. Self-regulation was positively correlated with all academic skills at both time points.

*Associations between self-regulation and mathematics*

To investigate whether there was evidence for the expected bidirectional relation between self-regulation and mathematics, four models were estimated. Model fit indices for these models are presented in Table 3. The bidirectional model for self-regulation and mathematics showed the best fit with the data. Alternative models had significantly worse model fit, indicating that a bidirectional model best represented the associations between self-regulation and mathematics. As can be seen in Fig. 1a, kindergarten self-regulation positively predicted first-grade math scores and kindergarten math scores positively predicted self-regulation in first grade when controlling for initial scores in kindergarten, age, sex, maternal education, and immigrant status. Constraining these pathways to be equal resulted in a significantly worse fit ( $\Delta\chi^2(1) = 19.26, p < .001$ ), indicating that mathematics was a significantly stronger predictor for self-regulation than vice versa. The auto-regressive pathways for self-regulation and mathematics were both positive and significant.

*Associations between self-regulation and expressive vocabulary*

Next, to investigate whether there was evidence for bidirectional relations between self-regulation and expressive vocabulary, four new models were estimated. Table 3 shows that the bidirectional model for self-regulation and expressive vocabulary had a good fit with the data. However, constraining the pathway between self-regulation and expressive vocabulary to zero (model 3) did not result in a significant drop in model fit, indicating that this association did not contribute significantly to explain the relationship between the two variables and a unidirectional model represents the data equally well. As can be seen in Fig. 1b, expressive vocabulary in kindergarten significantly and positively predicted first grade self-regulation, but self-regulation did not significantly predict expressive vocabulary ( $p = .340$ ) when controlling for expressive vocabulary in kindergarten, age, sex, maternal education, and immigrant status. The difference between the strength of the pathways was significant ( $\Delta\chi^2(1) = 11.00, p = .001$ ), indicating that expressive vocabulary was a stronger predictor for self-regulation than self-regulation was for expressive vocabulary. The auto-regressive

**Table 3**  
Model Fit Results and Chi-square Differences between Bidirectional and Alternative Models.

Model	$\chi^2$ (df)	<i>p</i>	RMSEA	CFI/TLI	SRMR	$\Delta\chi^2$ ( $\Delta$ df)	<i>p</i>
<b>Mathematics</b>							
1: Bidirectional (Self-regulation < - > Mathematics)	0.487 (4)	0.975	0.000	1.000/1.051	0.007		
2: Unidirectional (Self-regulation - > Mathematics)	18.569 (5)	0.002	0.106	0.956/0.841	0.050	20.117 (1)	< 0.001
3: Unidirectional (Mathematics - > Self-regulation)	15.215 (5)	0.010	0.092	0.967/0.880	0.036	14.337 (1)	< 0.001
4: No coupling	36.164 (6)	< 0.001	0.145	0.902/0.706	0.073	36.314 (2)	< 0.001
<b>Expressive vocabulary</b>							
1: Bidirectional (Self-regulation < - > Expr. vocabulary)	6.767 (8)	0.562	0.000	1.000/1.009	0.041		
2: Unidirectional (Self-regulation - > Expr. vocabulary)	17.375 (9)	0.043	0.063	0.977/0.945	0.060	11.471 (1)	0.001
3: Unidirectional (Expr. vocabulary - > Self-regulation)	7.663 (9)	0.568	0.000	1.000/1.009	0.042	0.891 (1)	0.345
4: No coupling	18.383 (10)	0.049	0.060	0.977/0.950	0.062	11.93 (2)	0.003
<b>Phonological awareness</b>							
1: Bidirectional (Self-regulation < - > Phon. Awareness)	5.412 (8)	0.713	0.000	1.000/1.038	0.038		
2: Unidirectional (Self-regulation - > Phon. Awareness)	5.730 (9)	0.767	0.000	1.000/1.042	0.038	0.114 (1)	0.736
3: Unidirectional (Phon. awareness - > Self-regulation)	9.032 (9)	0.434	0.004	1.000/1.000	0.046	3.974 (1)	0.046
4: No coupling	9.559 (10)	0.480	0.000	1.000 /1.005	0.047	4.724 (2)	0.094

Note. Chi-square differences are calculated between bidirectional (models 1) and alternative models.

pathways for self-regulation and expressive vocabulary were both positive and significant.

#### Associations between self-regulation and phonological awareness

Next, to investigate the direction of associations between self-regulation and phonological awareness four models were estimated. As can be seen in Table 3, the bidirectional model showed a good fit with the data. However, a unidirectional model (model 2) and a model without any coupling (model 4) fit the data equally well, indicating that the pathway from phonological awareness to self-regulation did not contribute significantly to explain the relationship between the two variables and that the association might also be explained by some other variable. In the bidirectional model, self-regulation in kindergarten was a significant predictor of phonological awareness in first grade, but not vice versa ( $p = .684$ ) when controlling for initial phonological awareness scores in kindergarten, age, sex, maternal education, and immigrant status. The auto-regressive pathways for self-regulation and phonological awareness were both positive and significant, see Fig. 1c.

#### Combined path model

Finally, we estimated a model in which all variables were included and regressed on each other (see Fig. 2). The fit of this model was good ( $\chi^2$  (15) = 6.543,  $p = .969$ , CFI = 1.000, TLI = 1.042, RMSEA = 0.000, SRMR = 0.021). This model showed that bidirectional relations between self-regulation and mathematics remained after controlling for the other academic skills. Vocabulary predicted self-regulation, but the association between self-regulation and phonological awareness became nonsignificant ( $p = .547$ ).

Regarding the control variables, maternal education had a significant positive effect on kindergarten mathematics ( $\beta = 0.283$ ,  $p < .001$ ), vocabulary ( $\beta = 0.222$ ,  $p < .001$ ), and phonological awareness ( $\beta = 0.187$ ,  $p = .002$ ), and on first grade self-regulation ( $\beta = 0.117$ ,  $p = .014$ ), mathematics ( $\beta = 0.117$ ,  $p = .024$ ), and vocabulary ( $\beta = 0.084$ ,  $p = .041$ ). Age had a significant positive effect on kindergarten mathematics ( $\beta = 0.164$ ,  $p = .009$ ), vocabulary ( $\beta = 0.124$ ,  $p = .026$ ), and phonological awareness ( $\beta = 0.174$ ,  $p = .003$ ). Immigrant status had a significant negative effect on kindergarten vocabulary ( $\beta = -0.363$ ,  $p < .001$ ) and a significant positive effect on self-regulation in first grade ( $\beta = 0.161$ ,  $p = .012$ ). Being a boy had a significant negative effect on kindergarten self-regulation ( $\beta = -0.222$ ,  $p < .001$ ), mathematics ( $\beta = -0.109$ ,  $p = .048$ ), and phonological awareness ( $\beta = -0.241$ ,  $p < .001$ ), and on first grade phonological awareness ( $\beta = -0.172$ ,  $p = .001$ ).

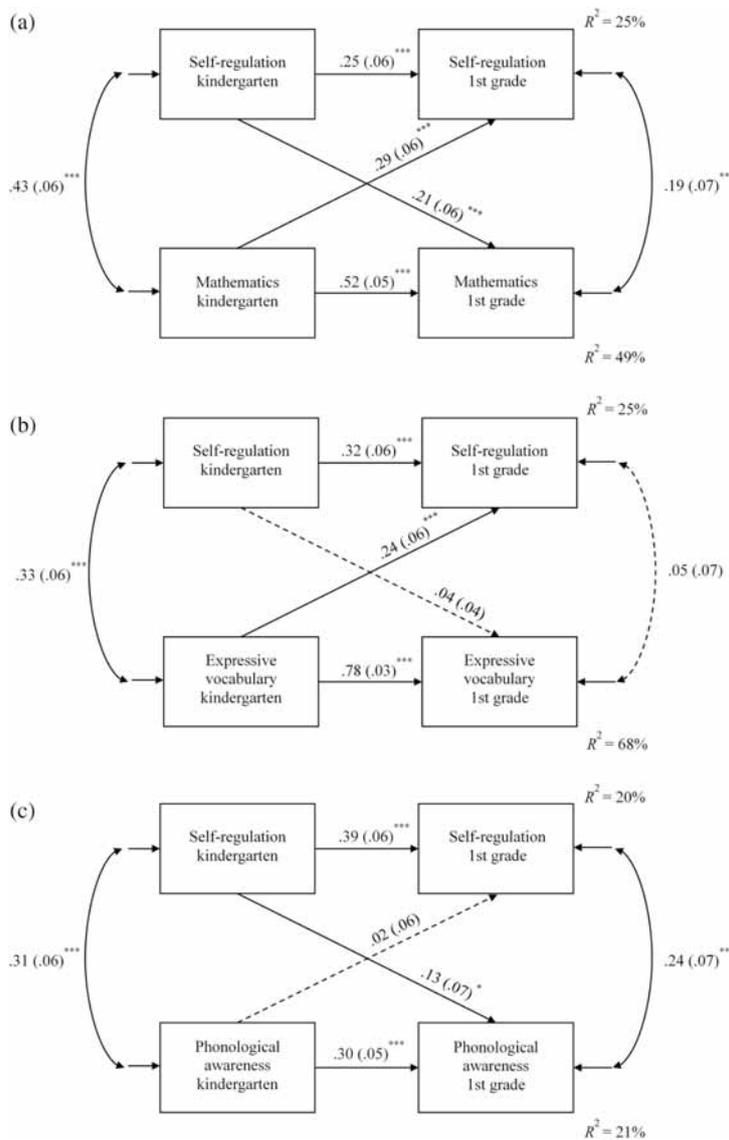
#### Discussion

Acknowledging the dynamic nature and context dependency of early skill development, the aim of the present study was to assess bidirectional relations between self-regulation and mathematics, expressive vocabulary, and phonological awareness in children making the transition from a play-based ECE context to formal schooling. The majority of previous studies have been conducted in the U.S., where ECE is characterized by a school readiness approach that introduces instruction in literacy and mathematics at an early age to prepare children for the transition to school. Children in play-based ECE's are more likely to make this transition less familiar with formal learning environments. Considering that the transition involves a change from a little structured free play environment to a formal learning environment, where children have to regulate their behavior according to the demands of the teacher and activities in the classroom, we expected a strong demand on self-regulatory skills and for self-regulation to predict all academic outcomes. Furthermore, based on theory and previous studies, we expected bidirectionality for mathematics (e.g., Blair et al., 2008; Clements et al., 2016) and expressive vocabulary (Diaz et al., 1992; Vygotsky, 1934/1986), and a unidirectional association from self-regulation to phonological awareness (e.g., Fuhs et al., 2014; Schmitt et al., 2017; Welsh et al., 2010).

As expected, results suggest evidence of bidirectional associations between self-regulation and mathematics. Regarding expressive vocabulary, our expectations were partly confirmed. Controlling for prior levels, expressive vocabulary predicted self-regulation, however, self-regulation did not predict expressive vocabulary. Finally, when controlling for all other academic skills, no evidence of a relation between self-regulation and phonological awareness was found. Taken together, the results did not show the expected strong demand on self-regulation, except for mathematics. It may be that the Norwegian play-based kindergarten context provides children with more time and activities related to vocabulary and phonological awareness (e.g., story book reading, role play, songs and rhymes) compared to mathematics. This is supported by research showing that Norwegian kindergarten staff spend more time and focus on children's language and literacy compared to other skills like mathematics (Østrem et al., 2009). This could make children more familiar with these language and literacy aspects and links between language and literacy and self-regulation more difficult to detect or less strong overall.

#### Associations between self-regulation and mathematics

The results showing strong bidirectional relations between self-regulation and mathematics are consistent with bidirectionality found

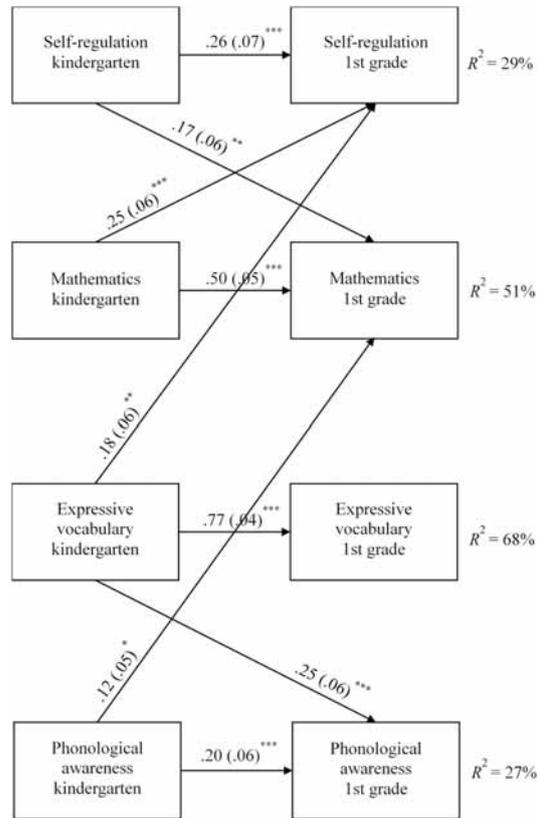


**Figure 1.** Cross-lagged path analysis of self-regulation and (a) mathematics, (b) expressive vocabulary, and (c) phonological awareness. Control variables are not shown in favor of clarity. Standardized parameters are reported. Standard errors in parentheses. Dashed lines indicate nonsignificant pathways. \* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ .

in preschool (Fuhs et al., 2014; Welsh et al., 2010), kindergarten (Schmitt et al., 2017), and first grade children in U.S. school readiness contexts (Hernández et al., 2018; McKinnon & Blair, 2018) and provide support for the idea that proficiency in mathematics may promote the development of self-regulation, and vice versa (e.g., Blair et al., 2008; Clements et al., 2016).

In spite of a play-based approach, the relations between self-regulation and mathematics look relatively similar in Norway compared to U.S. school readiness contexts. One reason for this could be that self-

regulation and math skills are predicted less by school context and more by proximal factors such as parenting including autonomy-support and sensitivity (Distefano, Galinsky, McClelland, Zelazo, & Carlson, 2018; Fay-Stammach, Hawes & Meredith, 2014). Future research should examine the influence of parenting on children's self-regulation and math skills in a Norwegian context. Overall, this study adds cross-cultural evidence to the growing body of literature showing relatively robust bidirectional associations between self-regulatory skills and mathematics.



**Figure 2.** Combined cross-lagged path analysis of self-regulation and mathematics, expressive vocabulary, and phonological awareness. Control variables, correlations, non-significant pathways, and correlations between variable residuals are not shown in favor of clarity. Standardized parameters are reported. Standard errors in parentheses.

\* $p < .05$ , \*\* $p < .01$ , \*\*\* $p < .001$ .

#### Associations between self-regulation and expressive vocabulary

The present study found that children's expressive vocabulary predicted later self-regulation and provides support that language plays a role in the development of self-regulation (Vygotsky, 1934/1986). These results are in line with findings in younger preschool children in school readiness contexts (e.g., Bohlmann et al., 2015; Fuhs & Day, 2011) and suggest that children with better expressive language skills tend to show a stronger relative increase in self-regulation.

Furthermore, based on the expectations that the transition from a play-based context to a formal learning environment would require strong self-regulation in order to attend to the language activities in first grade, it was expected that self-regulation would also predict expressive vocabulary. Although some studies with younger children in the U.S. (Bohlmann et al., 2015; Fuhs et al., 2014; Weiland et al., 2014) and in other European countries (Cadima et al., 2018; Slot & Von Suchodoletz, 2018) have found that self-regulatory skills predict aspects of language when tested bidirectional, the cross-lagged models in the present study did not show this. This difference may be due to contextual factors of the school readiness approach such as a high demand on self-regulatory skills when children need to attend to instructional

activities aimed at improving their language already at a young age. The play-based context of Norway may have provided children with other pathways for developing their vocabulary rather than through self-regulatory demanding instructional language activities. For example, the ability to interact with peers through (sociodramatic-) play is an important predictor of language development (Harris, Golinkoff, & Hirsh-Pasek, 2011). Also, children in settings in which free choice activities predominated have been shown to have significantly better language performance (Montie, Xiang, & Schweinhart, 2006), suggesting that children may indeed develop their language through other activities than formal learning situations.

However, the different age ranges and variation in aspects of language that are assessed across studies and contexts makes it difficult to directly compare results. For example, while expressive vocabulary did predict self-regulation in the present study, receptive vocabulary did not predict later executive function in pre-kindergarten in a study from the U.S. (Weiland et al., 2014). One explanation may be that expressive vocabulary better reflects the capacity to use inner speech than receptive vocabulary. In addition, expressive abilities in children may help to elicit better quality or higher quantity of socialization experiences that scaffold self-regulatory skills at both home and school. Nevertheless, receptive vocabulary did predict self-regulation in a recent study (Cadima et al., 2018) and self-regulation has been shown predictive of both expressive and receptive vocabulary (Bohlmann & Downer, 2016). Taken together, more comprehensive research is needed to disentangle the reasons for the mixed results across samples.

#### Associations between self-regulation and phonological awareness

In line with some previous early literacy studies in younger children in school readiness contexts (e.g., Welsh et al., 2010), the initial cross-lagged panel model showed that children's self-regulation was a weak, but significant, predictor of phonological awareness and not the reverse. However, the fact that a model without coupling between the two variables did not show a significant poorer fit indicates that the association is not particularly robust. Other factors not included in the model may actually fully explain the association. Indeed, when controlling for all academic skills, the association became nonsignificant, indicating that self-regulation did not predict phonological awareness over-and-above the effect of expressive vocabulary. Welsh et al. (2010) also controlled for language skills and did find that EF predicted emergent literacy skills. However, their sample included younger low-income children for whom self-regulatory skills may be of extra importance in order to follow instructions and pick up on the learning opportunities they may not receive at home.

Another explanation for the lack of a significant association in the present sample may be that the Norwegian language has a shallower depth of orthography compared to the English language (Seymour et al., 2003). This means that correspondence between the spelling of a word and its pronunciation is more consistent in the Norwegian language. This may place a limited demand on self-regulatory skills as there are fewer instances when children need to inhibit other possible sounds that letters can represent (e.g., in the English language "c" can be /k/ in "cat" or /s/ as in "center"). Moreover, relations between self-regulation and more complex measures, such as reading comprehension, rather than automatized or knowledge-based crystallized abilities, may emerge later in elementary school (Blair, Ursache, Greenberg, & Vernon-Feagans, 2015).

Together with the inconsistent results from previous studies in the U.S. the present study suggests that the association between self-regulation and early language and literacy may be more sensitive to the context, developmental timing, and type of assessment, while relations between self-regulation and mathematics seem more robust or may be explained by other factors such as parenting.

### Limitations and future directions

This study has several limitations. First, in line with recent studies (e.g., McKinnon & Blair, 2018; Meixner et al., 2018; Slot & Von Suchodoletz, 2018) we used cross-lagged panel models to analyze the data. Recent research suggests that cross-lagged panel models can produce biased estimates as they do not account for time-invariant stability (Hamaker, Kuiper, & Grasman, 2015) and cannot dissociate between within and between-person effects (Berry & Willoughby, 2017; Curran, Howard, Bainter, Lane, & McGinley, 2014). In the present study, only two time points were assessed. This limits the possibility of investigating individual growth trajectories or applying other analytical approaches that aim to model trait-like stability. However, a strength of cross-lagged path models, compared to for example simple regression models, is that they allow us to determine how children's relative standing on self-regulation predicts their relative standing on the academic skill and vice versa while accounting for previous levels. The likelihood that effects observed across time are merely the result of correlations between self-regulation and academic skills in kindergarten is thus reduced. Moreover, our models showed a good fit with the data and previous work shows little evidence of trait-like stability in similar longitudinal relations between EF and academic skills (Schmitt et al., 2017). Nevertheless, results should be interpreted keeping this limitation in mind and future studies should aim to include additional time points.

Second, the present data did not allow for estimation of latent constructs that would account for measurement error. For this reason, and to deal with the impurity issue of cognitive tasks (Miyake et al., 2000; Van der Ven, Kroesbergen, Boom, & Leseman, 2012), future research should include multiple tasks of self-regulation and academic skills, so that a latent variable approach can be used.

Third, the phonological awareness measure showed some evidence of ceiling effects, indicating that this measure did not capture all variability at the higher end, which may have attenuated some of our estimates. However, McKinnon and Blair (2018) found similar standardized coefficients ( $\beta = 0.08$ ) for EF predicting early literacy skills from kindergarten to first grade, when controlling for prior levels, as the current study ( $\beta = 0.13$ ). Results are also in line with previous studies on bidirectional relations between self-regulation and literacy skills (Fuhs et al., 2014; Schmitt et al., 2017; Welsh et al., 2010). Similarly, children's scores on the HTKS in first grade were high (mean of 68 out of 84 points), which suggest that the measure may not have fully captured the range of individual variability. However, only 1.26% of the children actually scored at ceiling level and previous studies have shown reliability and validity of the HTKS with elementary students (e.g., Day et al., 2015; Gestsdottir et al., 2014).

Explained variance for phonological awareness and self-regulation was modest at 27% and 29% respectively, even when children's age, sex, socioeconomic background, immigrant status, and academic skills were included as predictors. Other factors not included in this study, such as alphabet knowledge for phonological awareness (Senechal, LeFevre, Smith-Chant, & Colton, 2001) and parenting practices (e.g., maternal warmth) for self-regulation (Colman, Hardy, Albert, Raffaelli, & Crockett, 2006), are likely to be critical for growth in these domains as well. It is also important to note that the measure of self-regulation in this study is not based on observations of classroom behavior. Although the HTKS is correlated with teacher-reported classroom regulation (McClelland et al., 2007), results might be different if teacher reports had been used.

Finally, in line with previous studies among young children (e.g., Bohlmann et al., 2015; Fuhs & Day, 2011), vocabulary showed high stability from kindergarten to first grade. This may have affected the ability of self-regulation to predict additional variance. Other studies have also shown that the effect of self-regulation on vocabulary attenuates when controlling for vocabulary at a previous time point (e.g., McClelland et al., 2007).

### Conclusions and practical implications

One aim of research on academic skill development in young children is to determine where possible difficulties in the process of acquiring academic skills originate (Blair et al., 2011). For example, are deficits in mathematics or reading due to earlier domain-specific problems, are they related to problems with self-regulatory skills, such as focusing attention, inhibiting automatic responses, or manipulating information in working memory, or a combination of both?

The present study indicates that self-regulation, in addition to earlier acquired skills, is important for the successful acquisition of mathematics and, to a certain degree, for the acquisition of phonological awareness. When children make the transition from a play-based context to formal schooling they experience an increase in situations where they need to pay attention to the teacher, focus on the task, and resist distraction from peers, in order to benefit from the activities that promote early academic skills. Promoting self-regulation in kindergarten may thus be a promising strategy in helping children with the acquisition of early math and literacy skills in first grade. At the same time, the results of the present study suggest that children's expressive vocabulary may be an important prerequisite for a successful development of self-regulation. Practice may therefore benefit from including a focus on the development of children's language skills prior to and during self-regulation interventions. Similarly, an increased focus on mathematics in kindergarten may benefit the development of self-regulation. By improving our understanding of these reciprocal associations, kindergarten practices can be adjusted so that the necessary skills are supported and the transition to first grade becomes smoother for all children.

A growing body of research from kindergarten samples with a school readiness approach has focused on whether and how children's self-regulatory skills can be successfully improved in such educational settings (Blair & Diamond, 2008; Schmitt et al., 2015; Tominey & McClelland, 2011) and a meta-analysis of self-regulation interventions demonstrated positive effects (Pandey et al., 2018). In addition, a few experimental studies have shown significant, albeit small, positive effects of math interventions (see Clements et al., 2016), although effects may fade over time (Watts, Duncan, Clements, & Sarama, 2018).

One challenge with a play-based educational practice is that there is limited time set aside for the implementation of intentional activities as children are expected to develop through free play and at their own pace. Given the bidirectional relations between early self-regulation and math and the foundational role of expressive vocabulary for self-regulation, comprehensive approaches (e.g., Størksen et al., 2018) targeting multiple skills by supporting each child's self-regulation, language, and mathematics in a meaningful and playful manner (Hirsh-Pasek, Michnick Golinkoff, Berk, & Singer, 2009) may be promising.

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## **10 Study III**

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## Domain-specific effects of attentional and behavioral control in early literacy and numeracy development<sup>☆</sup>



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## ABSTRACT

In a longitudinal study, we investigated the direct and indirect contributions of two aspects of executive functioning - attentional and behavioral control - to the development of early literacy and numeracy in kindergarten and first grade. Ninety children (mean age = 6.0 years at Time 1) were assessed on multiple direct measures of executive functioning, as well as phonological awareness and number sense in kindergarten, and word reading and mathematics in first grade. Structural equation models showed that both attentional and behavioral control predicted phonological awareness and number sense. Attentional control had an indirect (via phonological awareness) effect on word reading only, while behavioral control had a direct effect on mathematics and an indirect effect (via phonological awareness) on word reading. Since attentional and behavioral control differentially relate to the emergence of literacy and numeracy, it is concluded that executive functioning has domain-specific effects on children's development.

## 1. Introduction

Literacy and numeracy are key components in early childhood education (Duncan et al., 2007). The development of these skills follows distinct but related pathways (Simmons & Singleton, 2008) from phonological awareness to reading (Storch & Whitehurst, 2002) and from number sense to mathematics (Hornung, Schiltz, Brunner, & Martin, 2014). A successful acquisition of these early academic skills is associated with the development of children's executive functioning (EF) and an increase in the ability to control thoughts and actions (Blair & Raver, 2015; Diamond, 2013). Despite consensus on the importance of children's EF, especially for the transition from kindergarten to formal schooling (e.g., Blair & Raver, 2015; Fitzpatrick, McKinnon, Blair, & Willoughby, 2014), relatively little is known about domain-specific effects of EF. Moreover, EF encompasses both attentional and behavioral control processes (Diamond, 2013), and children's ability to direct their attention and behavior to learning activities in the classroom is regarded as foundational for early academic development (McClelland & Cameron, 2012). However, early literacy and numeracy skills in kindergarten and first grade may vary in their relative demand on the ability to control attention versus behavior. In the current study we therefore investigate the domain-specific effects of attentional and behavioral control on children's phonological awareness and number

sense in kindergarten, and word reading and mathematics in first grade. We define attentional control as the ability to inhibit interference from distractors and keep focus on the target (Diamond, 2013; Friedman & Miyake, 2004) regardless of fatigue (Cartwright, 2012), and behavioral control as the ability to inhibit inappropriate automatic behavior and motoric or vocal responses (Cartwright, 2012; Diamond, 2013; McClelland et al., 2014; Van de Sande, Segers, & Verhoeven, 2013).

## 1.1. Development of early literacy and numeracy

Beginning in infancy, early experience with language, such as caregivers speech directed to the child, builds the foundation for the development of later literacy (Fernald & Weisleder, 2011). In kindergarten literacy is further promoted through playful activities, focusing on the acquisition of phonological awareness, in order to prepare children for learning to read in first grade (e.g., Verhoeven, Leeuwe, Irausquin, & Segers, 2016). Phonological awareness refers to the ability to perceive and manipulate the sounds of spoken words. This means that children, on top of the more unconscious process of discriminating speech sounds, become aware of and are able to manipulate constituent phonemes, syllables, and rhymes in words (Wagner & Torgesen, 1987). In first grade, when children transition to a more formal learning environment, children need this ability to learn to read. That is, decoding

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requires children to be phonologically aware of the speech sounds that correspond with letters. Phonological awareness has been found to be a critical longitudinal predictor of individual differences in children's word decoding skills and thus provides the basis for learning to read during early elementary school (e.g. Dally, 2006; Lervag, Braten, & Hulme, 2009; Schaars, Segers, & Verhoeven, 2017; Storch & Whitehurst, 2002).

The development of mathematical abilities starts early in life with young children having certain competencies in number already from birth (Sarama & Clements, 2009). There are major differences in how number sense, also referred to as early numeracy (e.g. Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Purpura, Hume, Sims, & Lonigan, 2011), is defined in the literature (Berch, 2005). However, a consensus seems to emerge towards the fact that it entails a broad range of skills, including logical operations, numeral representations, and numeral estimations (Van Luit & Van de Rijt, 2009). Logical operations refer to the more classical Piagetian skills, such as comparison, classification, correspondence, and seriation (Van de Rijt, Van Luit, & Pennings, 1999). Numeral representations refer to such skills as counting and applying knowledge of the number system, and numeral estimations rely on understanding of numerical magnitudes and the ability to make number line estimations (Laski & Siegler, 2007). Previous research has indicated that number sense is the most reliable predictor of later mathematical achievement (e.g. Aunio & Niemivirta, 2010; Desoete & Gregoire, 2006; Gersten, Jordan, & Flojo, 2005; Hornung et al., 2014; Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Purpura & Lonigan, 2013), even after controlling for domain-general skills such as intelligence, working memory, and demographic factors (Geary, Hoard, Nugent, & Bailey, 2013). Although some aspects of number sense overlap conceptually with formal mathematical achievement skills (e.g., number sense includes aspects needed for mathematics such as comparing quantities and applying knowledge of the number system), formal mathematics can be considered to include higher order skills that involve more complex ways of applying knowledge of the number system (e.g., performing arithmetical operations). These skills include arithmetic skills (e.g. addition, subtraction, multiplication, and fraction) and elementary geometry, solving mathematical word problems, and the application of these skills in everyday situations (Janssen, Hop, Wouda, & Hollenberg, 2015; Ruijsseenaars, van Luit, & van Lieshout, 2004); skills that are typically not formally taught before elementary school.

Although there are clear developmental trajectories for early literacy and numeracy, these do not develop independent of one another. Several studies have indicated that the acquisition of phonological awareness is related to the development of early numeracy (e.g. Kleemans, Segers, & Verhoeven, 2011; Krajewski & Schneider, 2009; Purpura et al., 2011; Simmons & Singleton, 2008) as certain aspects of mathematics (e.g., number fact recall) involve the manipulation of verbal codes (Simmons & Singleton, 2008) which are stored in a phonological format and used for retrieval of number facts from long term memory (De Smedt & Boets, 2010). It is therefore important to incorporate this link when studying aspects critical for the development of number sense and early mathematics.

### 1.2. Domain-specific effects of EF in early literacy and numeracy

The complexity of EF and separate fields in which EF has been studied makes a universally accepted definition elusive. There seems, however, general agreement that EF encompasses those cognitive processes that underlie the adaptive, goal-directed control of thoughts, behaviors, and emotions (e.g., Best & Miller, 2010; Blair, 2016; Diamond, 2013; McClelland & Cameron, 2012). EF is generally regarded to be important for the development of early academic skills and a successful transition to formal schooling (Blair & Raver, 2015). Due to the variation in complexity of specific early literacy and numeracy

skills, the development of these skills likely places different demands on specific components of EF (Purpura, Schmitt, & Ganley, 2017). Whether EF is unitary, i.e., distinct sub-functions or sub-components cannot be dissociated, or that EF represents a multifaceted nature, is still subject of debate (e.g., Garon, Bryson, & Smith, 2008; Lee, Bull, & Ho, 2013; Miyake et al., 2000). The present study is guided by evidence that EF components are related but may be dissociable (Huizinga, Dolan, & van der Molen, 2006; Miyake et al., 2000) and differently predict academic outcomes (McClelland et al., 2014; Purpura et al., 2017).

Although attentional and behavioral control can be conceptualized as two distinct but related aspects of the inhibitory component of EF (Diamond, 2013; Friedman & Miyake, 2004) we chose to use the broader term EF rather than inhibition as comprising these two components because attentional and behavioral control likely show both psychometrical and neuro-anatomical overlap with each other as well as with other components of EF, such as working memory and shifting (Carlson, 2005; Diamond, 2013; Espy & Bull, 2005; Friedman & Miyake, 2004; Garon et al., 2008; Lee et al., 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Important to note is that in the literature attentional control also is referred to as sustained-selective and executive attention (Steele, Karmiloff-Smith, Cornish, & Scerif, 2012), interference control (Friedman & Miyake, 2004), or cognitive inhibition (Diamond, 2013). Behavioral control is also referred to as response inhibition (Diamond, 2013), action control (Segers, Damhuis, van de Sande, & Verhoeven, 2016), or behavioral self-regulation (Cameron Ponitz, McClelland, Matthews, & Morrison, 2009; McClelland et al., 2007).

In general, the contribution of EF to the development of early literacy and early numeracy may differ (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Purpura et al., 2017). While in some studies it has been found that EF's are highly important for the emergence of early literacy skills (Best, Miller, & Naglieri, 2011; Blair & Razza, 2007; Cameron et al., 2012; Van de Sande et al., 2013; Welsh, Nix, Blair, Bierman, & Nelson, 2010) other studies did not find evidence for such relations (Blair, Ursache, Greenberg, & Vernon-Feagans, 2015; Cameron Ponitz et al., 2009). More robust and stable relations have been found between EF and mathematical skills (Allan et al., 2014; Blair & Razza, 2007; Dulaney, Vasilyeva, & O'Dwyer, 2015; Geary, 2011; McClelland et al., 2014). A theoretical explanation for these differential findings is that EF is important for the acquisition of early literacy skills, such as phonological awareness, but that the demand on EF diminishes as these early skills become more automated over time (Blair, Knipe, & Gamson, 2008; Blair & Raver, 2015). In contrast, the development of mathematics is thought to rely on complex reasoning and problem solving processes that continuously tap into elements of EF. For example, keeping parts of an equation in memory while updating others, inhibiting a prepotent tendency that interferes with the correct solution, and shifting attention between different aspects of a mathematical problem (Blair et al., 2008; Blair, Protzko, & Ursache, 2011; Blair & Razza, 2007; Clements, Sarama, & Germeroth, 2016). Moreover, EF (often conceptualized as self-regulation) is frequently measured at the behavioral level (e.g., Becker, Miao, Duncan, & McClelland, 2014; Cadima, Gamelas, McClelland, & Peixoto, 2015; Hubert, Guimard, Florin, & Tracy, 2015), yet the development of early literacy and numeracy may vary in their demand on attentional and behavioral control processes.

### 1.3. Role of attentional and behavioral control in early literacy

Regarding early literacy, children need to pay attention and filter out individual phonemes, monitor and shift attention between cognitive representations, and switch attention from the meaning of a word to its structural features (Altemeier, Abbott, & Berninger, 2008; Walcott, Scheemaker, & Bielski, 2010). Previous studies have shown that attentional control predicts phonological awareness in kindergarten (Dice & Schwanenflugel, 2012; Walcott et al., 2010) and early reading skills

in first grade (Dally, 2006; Walcott et al., 2010). Moreover, visual attention has been shown to contribute to reading performance even after controlling for IQ, verbal fluency, vocabulary, and single letter identification skills (Bosse, Tainturier, & Valdois, 2007). Children in first grade are still easily distracted from interfering stimuli (Commodari, 2016) and phoneme awareness and problems with visual attention are thought to be underlying cognitive deficits in dyslexia (Bosse et al., 2007). Recently, Commodari (2017) also found several aspects of attention associated with reading accuracy in first grade. Behavioral control is thought to help children benefit from early literacy and reading instructions and has also been found to relate to early literacy skills in kindergarten (e.g., Becker et al., 2014; Gestsdottir et al., 2014; McClelland, Acock, & Morrison, 2006; McClelland et al., 2014) and first grade (Gestsdottir et al., 2014). However, these studies assessed either elements of attentional control or of behavioral control and were therefore not able to compare the relative contribution of each aspect.

Recent studies including measures of both attentional and behavioral control show differential effects for these aspects of EF on different early literacy skills over time. Van de Sande et al. (2013) showed that both attentional and behavioral control predicted phonological awareness in kindergarten, whereas only attentional control predicted word reading in first grade, partly via phonological awareness. Behavioral control only indirectly predicted later word reading via phonological awareness. In a similar vein, Segers et al. (2016) showed that both attentional and behavioral control predicted phonological awareness in kindergarten, but that only attentional control additionally predicted first grade word reading after controlling for non-verbal intelligence and verbal short term memory. These results indicate that both attentional and behavioral control are important for the initial acquisition of phonological awareness in kindergarten, but that domain specificity emerges when children learn to decode in first grade. Learning to decode seems, to a larger degree, a cognitive process involving attentional control, rather than the ability to inhibit motoric actions and behavior.

#### 1.4. Role of attentional and behavioral control in early numeracy

Regarding early numeracy, children need to shift their attention from one aspect of a mathematical problem to another (Commodari & Di Blasi, 2014), sustain attention on relevant aspects over time (Dulaney et al., 2015), and ignore conflicting stimulus dimensions (Friedman & Miyake, 2004; Merkley, Thompson, & Scerif, 2016). Dulaney et al. (2015) found that attentional control predicted mathematics achievement in kindergartners when controlling for verbal intelligence. Hassinger-Das, Jordan, Glutting, Irwin, and Dyson (2014) showed that both attention problems and EF were unique predictors of mathematics outcomes in first grade. Behavioral control is thought to help children benefit from early numeracy activities, inhibit the tendency to use incorrect or unessential strategies and act on dominant number representations (Blair et al., 2008; Bull & Lee, 2014). In general, behavioral control has been found to be a relative robust predictor of early numeracy and math skills in kindergarten (Becker et al., 2014; Cadima et al., 2015; Hubert et al., 2015; McClelland et al., 2014) and first grade (von Suchodoletz & Gunzenhauser, 2013). For example, Cadima et al. (2015) found that behavioral control was associated with mathematics after controlling for child verbal intelligence, age, gender and family sociodemographic risk. McClelland et al. (2014) found that, between prekindergarten and kindergarten, children who showed the most growth in behavioral control also demonstrated the most growth in mathematics. However, again, these studies did not assess both aspects of EF at the same time and the unique contributions of attentional control and behavioral control on mathematical development remain therefore unknown.

#### 1.5. The present study

To sum up, converging evidence shows that EF plays an important role in the development of early academic skills in children making the transition from kindergarten to first grade. However, it is still unclear to what extent attentional and behavioral control are differentially related to the developmental pathways of early literacy and early numeracy. Therefore, in the present study, direct and indirect effects were investigated following a longitudinal design from kindergarten to first grade. The present study contributes to existing research in two ways. First, the role of attentional and behavioral control in early literacy and numeracy was investigated in both academic skills in one design. This allowed us to take into account the differential developmental pathways for early literacy and numeracy as well as the cross-domain relations between the two. Second, although previous studies (Segers et al., 2016; Van de Sande et al., 2013) have made the distinction between attentional and behavioral control, in these studies only one task was used to assess attentional control and behavioral control respectively. In the present study, multiple tasks of EF were used to reduce the problems with task impurity - the probability that task specific characteristics related to the criterion variable, such as verbal or mathematical content, are driving the effects (Miyake et al., 2000).

Our research question was thus to what extent attentional and behavioral control predict early literacy (i.e., phonological awareness in kindergarten and word reading in first grade) and early numeracy skills (i.e., number sense in kindergarten and mathematics in first grade). In line with previous research (Segers et al., 2016; Van de Sande et al., 2013), we expected that attentional and behavioral control would both predict phonological awareness in kindergarten, but that only attentional control would directly predict word reading in first grade. This latter relationship was expected to be partly indirect, via phonological awareness. Furthermore, considering the previously found robust relations between EF and mathematics (Allan et al., 2014; Blair & Razza, 2007; Dulaney et al., 2015; Geary, 2011), we expected both attentional and behavioral control to directly predict number sense in kindergarten and mathematics in first grade.

## 2. Methods

### 2.1. Participants

Ninety children (48 boys and 42 girls) were recruited from three public schools in three different cities in the south of the Netherlands. The sample was treated in accordance with the prevailing institutional guidelines as well as with APA ethical standards. Schools gave active consent to participation in the study. Next, parents or caregivers were informed about the purpose of the study, the duration of the tests, the procedures, and their right to decline participation, through a letter. They were given the possibility to object to participation of their child and withdraw from the research at any time. Both teachers and parents were informed about whom to contact for questions about the study. Objection rate was < 10%. Parents or caregivers filled out information about their socioeconomic status (SES) using a short questionnaire. In line with Kleemans, Peeters, Segers, and Verhoeven (2012), SES was based on a Dutch scale of Denessen, Driessena, and Slegers (2005), and was measured on a 4-point scale ranging from 1 to 4. A “1” indicated that no postsecondary education was completed; a “2” indicated that the parent completed intermediate postsecondary education; a “3” indicated that the parent completed higher education, and a “4” indicated that the parent completed university. Of the mothers that responded to the question (90%), 33% completed higher education or university and of the fathers that responded (88%), 29%. A mean score of maternal and paternal education levels was calculated for each child. On average, the children’s parents at each school completed at least intermediate postsecondary education. Parents of four children indicated that they spoke another language at home in addition to the Dutch language.

Data was collected in the last year of kindergarten (age:  $M = 72$  months,  $SD = 5$ ) and at the end of first grade, approximately 14 months later ( $N = 80$ ).

In the Netherlands, children start school at the age of four where they attend kindergarten for two years. In kindergarten, children are involved in playful learning activities that promote early academic skills such as phonological awareness and number sense. After that, they make the transition to formal education. At the end of kindergarten, children are expected to be able to count (up to 10) and solve simple arithmetic problems (e.g., one apple plus one apple makes two apples) using their fingers. With respect to early literacy skills, children are expected to have phonological awareness (i.e., rhyming, blending) and knowledge of some letters of the alphabet (Van der Stap, 2009) by the time they leave kindergarten. In first grade, they typically learn all graphemes and how to correctly and easily decrypt written words (Krom, Jongen, Verhelst, Kamphuis, & Kleintjes, 2010). They acquire basic mathematical knowledge, such as the use of mathematical language, computing operations, and strategies for solving computing and measurement problems (Janssen et al., 2015).

## 2.2. Measures

### 2.2.1. Executive functioning

**2.2.1.1. Head Toes Knees Shoulders task.** This task (HTKS; Cameron Ponitz et al., 2008) is considered a behavioral regulation or inhibition task as children need to inhibit the automatic response to touch the named body part and replace this response by touching another part of the body. In block one, children were told to touch their head when the instructor said 'touch your toes' and touch their toes when the instructor said 'touch your head'. In block two these instructions were extended with the opposite actions to shoulders and knees. In block three the rules were changed and children had to shift from one set of rules to another; head was coupled with knees and shoulders with toes. Every block had 10 items with scores of 0 (incorrect), 1 (self-correct), or 2 (correct) for each item. The sum of the scores of each block was used for further analysis. Internal consistency for this test is high ( $\alpha = 0.94$ ; McClelland et al., 2014).

**2.2.1.2. Hearts & Flowers task.** In this task (Davidson, Amso, Anderson, & Diamond, 2006) children had to press, as fast as possible, a button on the same (for hearts) or opposite (for flowers) site of stimulus presentation. Thus, the child must inhibit the automatic tendency to press on the same side of the stimulus. The total test consisted of a congruent, incongruent, and mixed block with stimuli presented on either the left or right side of the screen. In block 1, the congruent block, children had to press on the same side as the heart, while in block 2, the incongruent block, they had to learn a new rule and press on the opposite side of a flower. Finally, in block 3, the mixed block, children had to switch between both hearts and flowers which were presented randomly and children were instructed to respond accordingly. Stimulus presentation time was 1500 ms. The first two blocks each had 12 items, the third block 32 items. Responses were scored as correct or incorrect and proportion of correct responses was calculated for each block. Cronbach's  $\alpha$  between the three blocks was considered to be sufficient ( $\alpha = 0.74$ ).

**2.2.1.3. Day/Night task.** A computerized version of the *Day/Night task* (Livesey, Keen, Rouse, & White, 2006), a child version of the Stroop task (Stroop, 1935), was used. Although the Stroop task is also classified as an attention task (Commodari, 2017), in line with previous studies (Friedman & Miyake, 2004; and see Garon et al., 2008) we consider the Day/Night as a measure of behavioral control, because children had to say the opposite word of what was depicted in the image (e.g., say 'night' when a picture of daytime is shown) and hence must inhibit the automatic tendency to name the picture depicted on the screen. It comprised two blocks of 16 items each. Stimuli were: day/night, boy/

girl, big/little, and up/down. In the first block opposite stimuli were presented four times each, preceded by instructions specific to the pair of stimuli. In the second block, all stimuli were presented four times each in random order and children had to respond accordingly, without any further instructions. Responses were scored as correct or incorrect. A sum score for each block was calculated. Cronbach's  $\alpha$  between the two blocks was considered to be sufficient ( $\alpha = 0.71$ ).

**2.2.1.4. Flanker Fish task.** In this attention task (e.g., Diamond, Barnett, Thomas, & Munro, 2007; Rueda, Posner, Rothbart, & Davis-Stober, 2004; Zaitchik, Iqbal, & Carey, 2014) children had to respond to certain stimuli on a computer screen while ignoring other stimuli. The task consisted of three blocks in which children were instructed to feed 'hungry' fish. Children had to press the button corresponding to the direction the hungry fish were swimming in. The fish were presented either alone, or with four flanker fish swimming in either the opposite or the same direction as the middle fish. In the first block, the fish were blue and the hungry fish were located in the middle. Children had to ignore the flanker fish. In the second block, the fish were pink and the hungry fish were the flankers. In the third block, children had to switch between focusing on the middle or flanker fish as both blue and pink fish alternated and children had to respond according to the previous learned rules of block one and two. Stimulus presentation time was 2000 ms. The first two blocks had 16 items each, the third block had 44 items. Responses were scored as correct or incorrect and the proportion of correct responses was calculated for each block. Cronbach's  $\alpha$  between the three blocks was considered to be sufficient ( $\alpha = 0.71$ ).

**2.2.1.5. Continuous Performance task.** Finally, a *Continuous Performance task* was used as a measure of the ability to sustain attention to relevant stimuli over a longer period of time. In this task 200 black figures of 10 different animals were shown on a computer screen and children were instructed to press a button, as quickly as possible after seeing each animal, unless it was a lion. Each animal was shown 20 times in random order. Presentation time and inter stimulus interval was 1500 ms. The test lasted approximately 5 min. Responses were scored as hit, miss, false alarm, or correct rejection. D-prime ( $d' = Z(\text{hit rate}) - Z(\text{false alarm rate})$ ) values were computed as a measure of overall sensitivity.

### 2.2.2. Early literacy

**2.2.2.1. Phonological awareness kindergarten.** Phonological awareness was measured using the *Screening Instrument for Emerging Literacy* (Vloedgraven, Keuning, & Verhoeven, 2009) and consisted of four tasks: *blending*, *segmentation*, *deletion* and *letter knowledge*. The latter three were assessed via the computer, whereas letter knowledge was assessed on paper. For *blending*, *segmentation*, and *deletion* (15 items each), three different pictures were shown on the screen, followed by a target word that was auditory presented by the computer. For *blending*, the target word was presented in its individual phonemes and children had to indicate the corresponding alternative from the three presented images on the screen (e.g., "point to the picture for /b/ /u/ /s/"). During *segmentation*, children had to indicate the alternative that began with the same phoneme as the one in the auditory presented target word (e.g., "point to the picture that begins with the same sound as /c/ /a/ /t/"). During *deletion*, children heard a target word from which they had to omit a phoneme such that it became another word. They had to indicate which of three alternatives corresponded with the new word (e.g., "point to the picture that sounds like 'clock' if you take away the /c/"). Finally, during *letter knowledge*, children were asked to read aloud 34 different letters presented on paper. On each task all correct answers were counted. Internal consistency for this task is high ( $\alpha > 0.90$ ; Vloedgraven & Verhoeven, 2007). A Principal Component Analysis showed that the four tasks loaded on one factor (phonological awareness) that explained 61% of the variance. The component loadings ranged from 0.57 (deletion) to 0.87 (segmentation). Factor scores were saved and used for further analyses.

**2.2.2.2. Word reading first grade.** The *Three-Minutes-Reading-Test* (Krom et al., 2010; Verhoeven, 1995) was used to assess children's word reading skills in first grade. This task consists of three cards with 150 high-frequency content words, presented in columns of 30 words. Children had to read aloud as many words as possible on each card within a time limit of 1 min. On each card, all correctly pronounced words were counted and the sum of the scores for the three cards was used. Internal consistency for this task is excellent ( $\alpha = 0.96$ ; Krom et al., 2010).

### 2.2.3. Early numeracy

**2.2.3.1. Number sense kindergarten.** To assess children's early number sense the *Number Sense Task*, version A (Van Luit & Van de Rijt, 2009), a standardized Dutch test suitable for children between 4 and 9 years of age, was used. The task consists of 45 items divided over nine different blocks that assess skills that are indicative of early numeracy (Desoete & Gregoire, 2006; Van Luit & Van de Rijt, 2009). The first four blocks are dedicated to Piagetian concepts: In the *comparison* block, the child had to compare the qualitative and quantitative aspects of several items (e.g., "On these pictures you see some men. Which of these men is the biggest?"). In the *classification* block, children had to group several items depending on specific criteria (e.g., "On which of these pictures you do not see a group of five?"). In the *correspondence* block, children had to compare absolute quantities in a one-to-one relation (e.g., "On this picture you see three busses. Which of these pictures has the same number of dots as the three busses you see here?"). In the *seriation* block, children had to order items on the basis of specific criteria (e.g., "On which picture do you see the apples arranged from big to small?"). The focus in the other blocks of this task is on counting skills: In the *counting* block, children had to count both forward and backwards, and use their knowledge of ordinal and cardinal aspects of the number system (e.g., "Count to twenty."). In the *synchronous and shortened counting* block, children had to count sequentially and then by intervals, using the structure of dice (e.g., "Here you see six groups of two dice. In which group you see ten dots?"). In the *resultative counting* block, children had to count structured, unstructured and covered quantities without using their fingers or hands (e.g., "How many pawns are there on the table?"). In the *applied knowledge of the number system* block, children had to apply knowledge of the number system in simple problems (e.g., "I have twelve cakes and I eat seven of them. How many cakes are left? Point to the picture that depicts the right answer."). Finally, in the *estimation* block, children had to indicate the location of a number on a number line (e.g., "Here you see a number line. On which place on this number line would you place the number nineteen?"). Items involved 2D images, graphic numbers, and 3D pawns. Some items requested children to draw lines between associated images or indicate the position of a number on a number line. The instructor read out aloud the instructions and the child worked independently on every item. Correct items were scored as one and sum scores were calculated for each block. The task has excellent reliability ( $\alpha = 0.93$ ; Van Luit & Van de Rijt, 2009). A Principal Component Analysis showed that all blocks loaded on one factor, except from the estimation block, which loaded on a separate factor. This block was therefore removed, resulting in a one-factor solution that explained 49% of the variance. Factor loadings ranged from 0.43 (comparison) to 0.83 (applied knowledge of the number system). Factor scores were saved and used for further analyses.

**2.2.3.2. Mathematics first grade.** Mathematical skills were assessed using *CITO Rekenen-Wiskunde, 2012* (Janssen et al., 2015), a standardized teacher-administered task that is part of the obligatory pupil monitoring system for schools in the Netherlands. This task consists of 52 items in the domains of basic arithmetic skills, elementary fraction and elementary geometry. The task takes about  $2 \times 40$  min to administer and includes both contextual problems (e.g., "4 children share 8 cookies together. Every child gets the same amount. How many

cookies does each child receive?") as well as non-contextual problems (e.g.,  $6 - 2 - 2 = ?$ ). Number of correct answers were counted. This task has excellent reliability ( $\alpha = 0.92$ ; Janssen et al., 2015).

### 2.3. Procedure

Testing sessions in kindergarten were conducted between March and May, and divided across three occasions, on subsequent days, to avoid test fatigue. Children were each randomly assigned to a specific test session order, but tests within each session were administered in a fixed order. Session one: *Day/Night task, Screening Instrument for Emerging Literacy*. Session two: *Flanker Fish task, Hearts & Flowers task and Number Sense task*. Session three: *Continuous Performance task and HTKS*. Each session lasted 30 to 40 min. Each child was tested individually in a private room by the first author or a trained research assistant (latter applies to 27 children's number sense). All measures, except the *Number Sense task*, were administered automatically on a computer or tablet. The *Number Sense task* was partly administered by the trained research assistant and this did not predict any significant variation in the task ( $\beta = -0.133$ ,  $p = .161$ ), indicating no administrator-effect. Instructions and feedback on practice trials were provided by the researcher, after which children worked independently, without receiving feedback, on the remaining of the tasks. Testing in first grade was part of the pupil monitoring system for schools in the Netherlands and carried out in June by the children's teacher.

### 2.4. Data analysis

Structural equation models (SEM), using MPlus software (Muthén & Muthén, 1998–2010), were used to analyze the data. SEM was used as it allows the simultaneous analysis of all our variables in one model, which better reflects the complexity of relationships between EF and different academic skills. Since our sample size is relatively small, we used several methods to analyze the data: First, associations between the variables were estimated using maximum likelihood parameter estimates with standard errors that are robust to the effect of outliers, non-normality, missing data and model misspecification (MLR; Yuan & Bentler, 2000; Yuan & Zhong, 2013). Second, the bootstrapping process procedure (Preacher & Hayes, 2004) was used to assess the 95% bias corrected confidence intervals of the standard errors of both direct and indirect effects. Finally, to reduce the complexity of the model and increase the ratio of estimated parameters to participants, we estimated the model using composite scores instead of latent variables. SES was controlled for in the model. When assessing overall model fit it is advised to report multiple model fit criteria, because sample size may have differential effects on fit indices (Bollen, 1990). We therefore report the following fit indices and criteria (Hu & Bentler, 1999):  $\chi^2/p > 0.05$ , Comparative Fit Index (CFI) and Tucker Lewis Index (TLI)  $\geq 0.95$ , Root Mean Square Error of Approximation (RMSEA)  $\leq 0.06$ , and Standardized Root Mean Square Residual (SRMR)  $\leq 0.08$ .

## 3. Results

### 3.1. Descriptive statistics and preliminary analyses

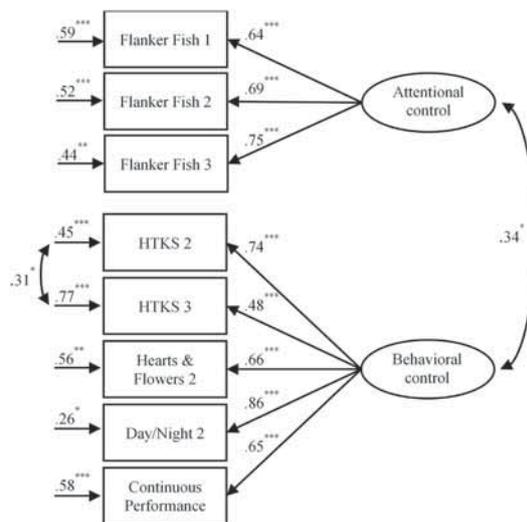
Before answering the research question, we first computed descriptive statistics. Table 1 shows the means and standard deviations for each measure. As can be seen, the first block of the *Hearts & Flowers*, *HTKS* and *Day/Night task* showed strong ceiling effects and were therefore omitted from further analyses. This implies that inhibition is involved in every block. Percentage of extreme scores ( $z > 3.29$ ; Field, 2009) was  $< 3.4\%$ . Deviations from normality and outliers were dealt with using MLR (Yuan & Bentler, 2000; Yuan & Zhong, 2013).

To investigate the underlying factor structure of EF, we first conducted an Exploratory Factor Analysis with Promax Rotation in Mplus.

**Table 1**  
Descriptive statistics for the executive functioning measures, phonological awareness and number sense in kindergarten and word reading and mathematics in first grade.

	Min	Max	M	SD	Skewness	Kurtosis
<b>Executive functioning kindergarten</b>						
<b>Flanker Fish task</b>						
Block 1	0.00	100.00	69.87	25.64	-0.72	-0.39
Block 2	5.88	100.00	65.49	20.98	-0.51	-0.16
Block 3	15.56	95.56	56.15	16.79	-0.18	-0.28
<b>Hearts &amp; Flowers task</b>						
Block 1	42.86	100.00	95.56	8.29	-3.37	16.36
Block 2	8.33	100.00	88.61	17.50	-2.46	6.79
Block 3	24.24	100.00	78.52	16.29	-1.00	0.60
<b>Head Toes Knees Shoulders task</b>						
Block 1	0.00	20.00	18.31	3.58	-3.66	14.48
Block 2	0.00	20.00	14.86	5.39	-1.54	1.41
Block 3	0.00	20.00	10.65	7.13	-0.26	-1.44
<b>Day/Night task</b>						
Block 1	12.50	100.00	89.77	12.33	-3.23	15.68
Block 2	0.00	100.00	85.74	21.41	-2.39	5.55
Continuous	-5.57	2.25	0.00	1.70	-0.93	0.55
<b>Performance task kindergarten</b>						
<b>Phonological awareness kindergarten</b>						
Phoneme blending	1.00	15.00	13.03	3.01	-1.90	3.08
Phoneme segmentation	3.00	15.00	11.52	3.36	-0.74	-0.62
Phoneme deletion	1.00	15.00	6.40	2.74	0.86	1.15
Letter knowledge	0.00	34.00	15.78	8.54	0.31	-0.56
<b>Number sense kindergarten</b>						
Comparison	1.00	5.00	4.56	0.75	-2.11	5.43
Classification	0.00	5.00	2.73	1.07	0.22	-0.22
Correspondence	1.00	5.00	4.02	0.92	-0.99	1.09
Seriation	0.00	5.00	3.80	1.09	-1.05	1.10
Counting	0.00	5.00	2.63	1.59	0.05	-1.31
Synchronous and shortened counting	0.00	5.00	2.71	1.39	-0.22	-0.84
Resultative counting	1.00	5.00	3.21	1.09	-0.43	-0.33
Applying knowledge of the number system	0.00	5.00	3.38	1.30	-0.90	0.48
Estimation	0.00	5.00	2.72	1.37	-0.14	-0.78
Word reading first grade	27	247.00	107.39	53.80	0.57	-0.56
Mathematics first grade	13	52.00	41.40	7.71	-1.39	2.13

The results showed a two-factor structure consisting of attentional control and behavioral control. The *Continuous Performance* task did not load significantly on the attentional control factor ( $\beta = -0.012$ ,  $p > .05$ ), but showed a significant factor loading of  $\beta = 0.68$  ( $p < .05$ ) on the behavioral control factor. Block 3 of the Hearts & Flowers task loaded significantly on both factors ( $\beta = 0.68$  and  $\beta = 0.35$ ) and was therefore omitted from further analysis. Based on these findings we estimated the measurement model, including the hypothesized two latent factors for attentional and behavioral control. The residuals of the HTKS blocks were allowed to correlate. This model showed a good fit with the data ( $\chi^2(18) = 18.127$ ,  $p = .447$ , CFI = 0.999, TLI = 0.999, RMSEA = 0.009, SRMR = 0.06) and is depicted in Fig. 1. Forcing the CPT to load on the attentional control factor led to poor model fit ( $\chi^2(18) = 65.148$ ,  $p < .001$ , CFI = 0.781, TLI = 0.660, RMSEA = 0.171, SRMR = 0.122) and the CPT was therefore kept as an indicator for the behavioral control factor. We performed a power analysis (Soper, 2018) in order to make sure that our sample size was large enough to detect true effects in the data. The results indicated that with 2 latent variables, 8–9 indicators, a probability level of 0.05, and a minimum power of 0.80, the sample size of 90 was large enough to detect anticipated factor loadings of 0.30. In addition, as communalities in our data range from 0.23 to 0.74, number of expected factors is low,



**Fig. 1.** Measurement model for attentional and behavioral control. Estimates provided are standardized coefficients.  
\* $p < .05$ . \*\* $p < .01$ . \*\*\* $p < .001$ .

and our models show a good fit with the data, it is likely that our sample has adequately recovered the population factor structure (MacCallum, Widaman, Preacher, & Hong, 2001; MacCallum, Widaman, Zhang, & Hong, 1999; Preacher & MacCallum, 2002). Nonetheless, to assure that a one-factor model did not fit the data better, we estimated a model where all indicators were allowed to load on one factor. The one-factor structure showed a poor model fit ( $\chi^2(19) = 62.216$ ,  $p < .001$ , CFI = 0.800, TLI = 0.705, RMSEA = 0.159, SRMR = 0.11). This suggests that a two-factor structure best represented the data. To reduce the complexity of the model and increase power composites based on the factor loadings for the two factors were calculated in Mplus and used for further analyses.

**3.2. Direct and indirect effects of EF on early literacy and early numeracy**

To investigate our research question on how attentional and behavioral control predict early literacy and early numeracy skills in kindergarten and first grade, we first computed Pearson correlations between attentional control, behavioral control, phonological awareness and number sense in kindergarten, and word reading and mathematics in first grade. As can be seen in Table 2, both attentional and behavioral

**Table 2**  
Correlations between attentional and behavioral control, phonological awareness and number sense in kindergarten, and word reading and mathematics in first grade.

	1.	2.	3.	4.	5.	6.
<b>Kindergarten</b>						
1. Attentional control	–					
2. Behavioral control	0.40***	–				
3. Phonological awareness	0.48***	0.54***	–			
4. Number sense	0.55***	0.68***	0.68***	–		
<b>First grade</b>						
5. Word reading	0.39***	0.17	0.64***	0.38***	–	
6. Mathematics	0.37***	0.63***	0.45***	0.60***	0.25*	–

\*  $p < .05$ .  
\*\*\*  $p < .001$ .

control show moderate to strong positive relations with the dependent variables, with the exception of behavioral control and word reading for which the correlation did not reach significance. Furthermore, phonological awareness was significantly related to number sense in kindergarten and word reading and mathematics in first grade. Number sense showed a strong positive correlation with first grade mathematics. Next, the independent variables were all screened for possible problems with multicollinearity. Tolerance statistics were all  $> 0.02$  and variance inflation factor values were all  $< 10$ , indicating no collinearity within our data (Field, 2009). Scatterplots for all correlations were inspected and showed no signs of non-linear patterns. We then performed a structural equation modelling analysis to test for direct and indirect effects while controlling for cross-domain relations between early literacy and numeracy development. Therefore, in this model, all pathways from attentional and behavioral control to early literacy and early numeracy skills in kindergarten and first grade were estimated. SES was included as a control variable. The model showed a good fit with the data ( $\chi^2(1) = 0.027$ ,  $p = .869$ , CFI = 1.000, TLI = 1.066, RMSEA = 0.000, SRMR = 0.002).

We ran an additional model using the bootstrap process procedure to evaluate the 95% bias corrected bootstrap confidence intervals. The results (see Fig. 2) indicate that both attentional and behavioral control positively predicted phonological awareness as indicated by the standardized bias-corrected 95% bootstrap confidence intervals of [0.150, 0.464] and [0.214, 0.555], respectively, as well as number sense (95% BC bootstrap CI [0.195, 0.439] and [0.384, 0.671], respectively). The direct effect of attentional control on first grade word reading did not reach significance (95% BC bootstrap CI [-0.25, 0.313]) and the effect of behavioral control was suppressed (95% BC bootstrap CI [-0.536, -0.016]). Attentional control did not have a significant effect on mathematics (95% BC bootstrap CI [-0.135, 0.235]). Behavioral control had a positive direct effect on first grade mathematics (95% BC bootstrap CI [0.077, 0.676]). Finally, while controlling for attentional and behavioral control, phonological awareness in kindergarten predicted first grade word reading (95% BC bootstrap CI [0.527, 0.922]) and number sense predicted mathematics one year later (95% BC bootstrap CI [0.02, 0.543]).

With regard to the indirect effects, there was a significant indirect effect of attentional ( $\beta = 0.22$ ) and behavioral control ( $\beta = 0.28$ ) on word reading via phonological awareness, as indicated by the standardized bias-corrected 95% bootstrap confidence intervals of [0.113, 0.359] and [0.145, 0.471], respectively. Furthermore, no significant indirect effect of attentional or behavioral control via number sense was found (95% BC bootstrap CIs [-0.019, 0.179] and [-0.006, 0.281], respectively).

## 4. Discussion

The aim of this study was to examine the extent to which attentional and behavioral control predict early literacy (i.e., phonological awareness in kindergarten and word reading in first grade) and early numeracy skills (i.e., number sense in kindergarten and mathematics in first grade).

### 4.1. Early literacy

Regarding early literacy, as expected, the results first of all indicated that both attentional and behavioral control uniquely predicted phonological awareness in kindergarten. The correlational analysis indicated that attentional control was related to later word reading, but behavioral control was not. The results from the SEM model indicated that the association between attentional control and first grade word reading was mediated by phonological awareness in kindergarten. Furthermore, although behavioral control was found to be unrelated to word reading in the correlational analysis, the results showed behavioral control to have an indirect effect on reading via its contribution to the development of phonological awareness in kindergarten. These findings are in line with results found by, for example, Van de Sande et al. (2013) and suggest that learning to read, to a relative large extent, is a cognitive attentional process that heavily depends on the acquisition of phonological awareness in kindergarten, which is initially developed through both attentional and behavioral control abilities.

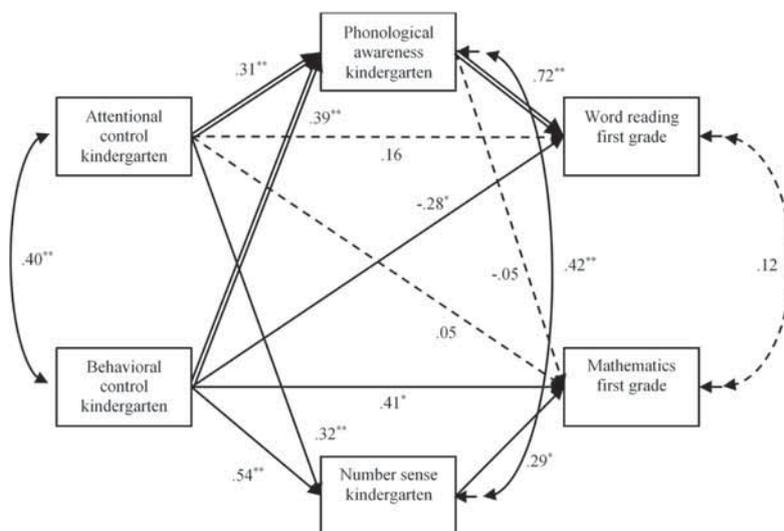


Fig. 2. Structural relations between attentional and behavioral control, phonological awareness, and number sense in kindergarten and word reading and mathematics in first grade. Significant indirect paths are shown with a double line. Estimates provided are standardized coefficients.

\* $p < .05$ . \*\* $p < .01$ .

#### 4.2. Early numeracy

Regarding early numeracy, the results partly confirmed our expectations. Both attentional and behavioral control uniquely predicted number sense in kindergarten, which is in line with earlier research (Becker et al., 2014; Cadima et al., 2015; Dulaney et al., 2015; Hubert et al., 2015; McClelland et al., 2014). Moreover, behavioral control appeared to have a strong direct effect on first-grade mathematics, even when children's number sense in kindergarten was controlled for. This is also in line with previous studies (e.g., von Suchodoletz & Gunzenhauser, 2013). One reason that might explain the fact that behavioral control is especially important for the development of early numeracy is that embodiment is an important part of numerical cognition (Fischer, 2012). Early numeracy and math activities in kindergarten and in the first years of formal schooling often include activities such as finger counting and actively comparing shapes and sizes of real objects, which require children to maneuver their bodies and learning materials and thus regulate their motor actions. For example, children need to be able to time the movement of specific fingers in congruence with the counting sequence. When comparing shapes and sizes they need to manipulate and move objects and measure the size with their hands or by moving a ruler. Compared to early mathematical learning activities, learning to decode does not involve such manipulation of objects, but rather concentrating on visual input on a piece of paper or blackboard. The development of mathematics, at least in the early years, can thus be thought of as a relative behavioral activity and may therefore place a relatively high demand on the inhibition and regulation of motoric responses. Indeed, children's motor skills are related to both behavioral control (Becker et al., 2014) and emerging mathematical skills (Becker et al., 2014; Reikeras, Moser, & Tonnessen, 2017; van Rooijen, Verhoeven, & Steenbergen, 2011). Although a significant association between attentional control and mathematics was found in the correlational analysis, after controlling for behavioral control in the final model, we did not find a direct effect of attentional control on first-grade mathematics. Associations between attentional control and mathematics have been reported in previous studies (e.g., Hassinger-Das et al., 2014). One possible explanation for this result is that the present study used a direct assessment of attentional control, which taps more selectively into attention as compared to teacher reports that were used in previous studies. The present results thus show that behavioral control predicts mathematics over and above the effect of attentional control, but not vice versa.

Although number sense and mathematics were strongly related, the association between the two reduced after behavior control was taken into account. It thus seems that the effect of number sense on mathematics is at least partly driven by their mutual reliance on behavioral control. Contrary to results from previous studies (e.g. Kleemans et al., 2011; Krajewski & Schneider, 2009; Purpura et al., 2011; Simmons & Singleton, 2008), there was no direct effect of phonological awareness on mathematics in the final model, notwithstanding the fact that we did find a significant correlation between the two. An explanation may be that in our model we controlled for both attentional control, behavioral control, and number sense.

The correlation between behavioral control and mathematics was relatively high (0.63). For example, Van der Ven et al. (2012) found lower correlations (ranging between 0.35 and 0.41) between a latent inhibition/shifting factor and mathematics in slightly older Dutch children. A possible explanation for why the correlation in the current study is higher is that their latent variable of inhibition/shifting did not include any gross motoric inhibition tasks such as the HTKS, which has shown correlations as high as 0.57 with mathematics when used as an observed variable (Gestsdottir et al., 2014). Also, Van der Ven et al. (2012) suggested that in younger children inhibition might be more strongly related to mathematics because young children's inhibitory skills are still relatively immature. Moreover, the correlation between word reading and mathematics was relatively low. Previous validation

studies in the Netherlands on other first grade samples also report low to moderate correlations between the word reading and mathematics test, and argue that this might be due to the fact that the word reading test is an efficiency measure, while the mathematics test is a measure of accuracy (Janssen et al., 2015). LeFevre et al. (2010) also found similar correlations between word reading and math.

#### 4.3. Limitations and suggestions for future research

Certain limitations of the present study should be taken into account. First, our sample was relatively small, which may result in problems with model misspecification, error in sampling variability, and the estimation of parameters. We applied several procedures (e.g., composite scores, MLR, and bootstrapping) to deal with these issues, and the results indicated relative stability across procedures with regard to the effects of attentional and behavioral control. However, still, significance levels should be interpreted while keeping the moderate sample size of this study in mind and replication with multiple samples would be needed to determine if these results are stable across samples. In relation to this, it is important to note that results regarding the effect of attentional and behavioral control on phonological awareness and word reading are in line with previous studies in other samples (Segers et al., 2016; Van de Sande et al., 2013), indicating that present findings are less likely to be sample specific effects.

Second, EF, phonological awareness and number sense were measured at the same time point in kindergarten. Although EF is regarded as a foundational skill that provides the basis for successful acquisition of later academic skills (Blair & Razza, 2007; McClelland & Cameron, 2012; Purpura et al., 2017), inferences about the direction of causal influences cannot be made from the present study. Including more time points in future research could provide a full longitudinal design and strengthen conclusions about the direction of effects (e.g., Fuhs, Nesbitt, Farran, & Dong, 2014; Welsh et al., 2010).

Third, the present study only assessed two specific aspects of EF, namely attentional and behavioral control. The majority of scholars agree that EF constitutes distinct, yet related, components, with inhibition, updating of working memory, and shifting being foundational components (Best et al., 2011; Huizinga et al., 2006; Miyake et al., 2000) although a clear distinction between inhibition and shifting is not always found in young children (Lee et al., 2013; Van der Ven et al., 2012). Relations between inhibition and mathematical performance tend to attenuate when working memory is included as an explanatory variable (Bull & Lee, 2014). In the present study we did not include specific working memory or shifting tasks. However, working memory and shifting were considered to be embedded in attentional and behavioral control, as the tasks that were used are complex tasks that require children to hold rules in mind and shift between rules and responses (Garon et al., 2008). Nevertheless, inclusion of multiple aspects of EF would certainly be informative in future studies for better understanding how specific aspects of EF support the development of early academic skills.

Fourth, our analysis revealed one aspect of attention. A recent study (Commodari, 2017) showed that aspects of attention differently relate to reading. By adding tasks aimed specifically at other aspects of attention future studies could provide a more detailed picture of the unique contributions of specific EF components for the development of early literacy and numeracy over time. Furthermore, we aimed at measuring each component with multiple tasks to avoid problems with task impurity. Our factor analyses revealed that the *Continuous Performance task* did not load on the attention factor as expected and therefore only the blocks of the *Flanker Fish task* were included in the latent factor for attentional control. This makes it difficult to ascertain whether the shared variance is from task characteristics or attentional control per se, although our relative high factor loadings and correlations with the variables of interest do suggest that task characteristics are not the only source of shared variance. Although continuous

performance tasks are often used as a measure of inattentiveness and sustained attention (e.g., Connors, 2001) (children need to focus on a tedious strain of stimuli for a longer period of time and thus inhibit attention being drawn to external distractors), the go/no-go nature of this task (children repeatedly need to inhibit the urge to press a button) might have drawn more heavily on inhibitory control than on the ability to keep focus. Future studies should include other tasks of attentional control that include the suppression of distractors. Finally, the present sample was a relative homogenous group of children as only four children spoke another language at home. Results might therefore not directly generalize to more diverse samples.

#### 4.4. Conclusion and practical implications

The results of the present study add to existing knowledge on the role of EF in academic skill development. First, the present findings underscore theories about the domain specific effects of EF on early literacy versus numeracy that have been proposed in the literature (Blair et al., 2008; Blair & Raver, 2015): EF allows the development of early literacy skills, such as phonological awareness, once this knowledge is automatized the contribution of EF diminishes. On the contrary, EF - especially behavioral control - keeps playing an important role in the development of mathematics, even though early number sense skills are controlled for. Second, the present study showed the unique effects of attentional and behavioral control in early literacy and numeracy by including both academic skills in one design and controlling for domain-specific and cross-domain relations between early literacy and early numeracy. Third, previous research found somewhat inconsistent results between EF and early literacy skills (e.g., Blair et al., 2015; Cameron Ponitz et al., 2009; Hubert et al., 2015). The results of the present study suggest that part of this inconsistency might be due to the fact that many of these studies measured behavioral aspects of EF. The ability to control attention seems a specific aspect of EF that is especially important for learning to read.

To conclude, the present study shows that although attentional and behavioral control overlap in some aspects, there are multiple routes through which each affects the development of early literacy and numeracy in kindergarten and first grade. While attentional control indirectly (via phonological awareness) predicts word reading in first grade, behavioral control keeps playing a direct role in the developmental trajectory from number sense in kindergarten to mathematics proficiency in first grade. From a practical point of view, it can be recommended to assess attentional and behavioral aspects of EF in kindergarten and first grade in order to be able to optimally support children's early academic development. Embedding exercises to support specific aspects of EF while training phonological awareness or number sense may be fruitful to further boost the effects of such activities (see e.g., van de Sande, Segers, & Verhoeven, 2018).

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## **Appendices**

## **Appendix 1 - Ani Banani Math Test**

## Appendices

### **Ani Banani Matte Test**

1	I dag er Ani Banani VELDIG tørst. Kan du gi ham den STØRSTE milkshaken? ( <i>'Kan du trekke milkshaken HELT over streken til Ani Banani?'</i> )
2	Ani Banani syns milkshaken var KJEMPEGOD og han har lyst på litt til. Kan du gi ham den NEST MINSTE milkshaken?
3	Ani Banani vil vite om du kan telle til 50. Kan du telle så langt for ham?
4	I dag er Ani Banani LITT sulten. Kan du gi ham fem bananer?
5	Ani Banani har vært ute og lekt og klatret masse i trærne, og nå har han blitt VELDIG sulten. Kan du gi ham 17 bananer?
6	Ani Banani har noen bananer i den ene kurven sin. Han har lyst på dobbelt så mange epler som han har bananer. Kan du gi ham dobbelt så mange epler i den andre kurven?
7	Hvor mange lekebiler har Ani Banani i lekekassen? ( <i>svaret er 7</i> )
8	Ani Banani har bygget med duploklosser. Hvor mange klosser har han brukt? ( <i>svaret er 15</i> )
9	Ani Banani skal ha bursdag. Kan du hjelpe til med å sette tallerkener på bordet slik at det blir 5 tallerkener på bordet?
10	Nå kommer det flere i Ani Banani sin bursdag. Kan du hjelpe til med å sette på flere tallerkener slik at det nå er plass til 7 tilsammen? Alle må få en tallerken hver.
11	Nå har Ani Banani funnet et puslespill. Kan du hjelpe ham å pusle sammen brikkene slik at det blir et fint bilde? ( <i>Begynn med å plassere øye til høyre i bildet.</i> )
12	Ani Banani liker å se på ulike figurer. Kan du hjelpe ham å finne trekanten? ( <i>'Dra trekanten over til Ani Banani'</i> )

## Appendices

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13	Nå er Ani Banani forvirret. Hvor har trekanten blitt av? Klarer du å hjelpe ham å finne trekanten nå?
14	Ani Banani har fått besøk av Mini Belini. Begge samler på klinkekuler. De snakker om hvem som har flest klinkekuler. Kan du trykke på den som du mener har flest klinkekuler?
15	Apekattene liker å perle. Kan du hjelpe Ani Banani å lage akkurat det samme mønsteret som Mini Belini? Når du trykker på en rute kommer det en perle. Hvis du vil ta den bort, kan du trykke en gang til. Prøv å lage AKKURAT det samme mønsteret som Mini Belini har.
16	Mini Belini har laget et nytt fint mønster. Kan du hjelpe Ani Banani en gang til med å lage det samme mønsteret som Mini Belini?
17	Ani Banani synes det er morsomt å telle baklengs eller bakover. For eksempel sier han noen ganger $5 - 4 - 3 - 2 - 1$ . Kan du telle baklengs fra 15 til 1? Begynn på 15 og tell deg nedover til 1.
18	Apekattene har fått epler. Kan du dele ut alle eplene og gi Ani Banani og Mini Belini like mange epler hver?