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Why do early mathematics skills predict later mathematics and reading achievement? The role of executive function

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ABSTRACT

A robust association between young children's early mathematical proficiency and later academic achievement is well established. Less is known about the mechanisms through which early mathematics skills may contribute to later mathematics and especially reading achievement. Using a parallel multiple mediator model, the current study investigated whether executive function (integration of working memory, inhibition, and cognitive flexibility) can explain the relations between early mathematics skills and elementary school mathematics and reading achievement. Data in this longitudinal study were collected from 243 children during the last year of early childhood education and care (kindergarten ages 5 and 6 years), 1 year later in first grade, and 5 years later when the children were in fifth grade. Background variables (maternal education, age, sex, and immigrant status), kindergarten baseline skills, and mediating effects of first-grade mathematics, phonological awareness, vocabulary, and possible omitted variables were controlled. Results showed that first-grade executive function mediated the effects of kindergarten mathematics on fifth-grade mathematics and on reading achievement. These findings suggest that executive function may work as a mechanism that may help to explain the frequently found strong association

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between children's early mathematics skills and later mathematics and reading achievement.

Introduction

The strongest predictors of children's academic achievement are their earlier academic skills (Duncan et al., 2007). Early mathematics skills, in particular, have strong predictive power and even predict later reading skills as strongly as, or even better than, domain-specific precursors of reading itself (Claessens, Duncan, & Engel, 2009; Claessens & Engel, 2013; Duncan et al., 2007; Pagani, Fitzpatrick, Archambault, & Janosz, 2010). In fact, Duncan et al. (2007) is one of the most cited studies during the past 20 years reporting the predictive power of mathematics. Although several theories exist regarding why children's literacy skills predict mathematics (Krajewski & Schneider, 2009; Simmons & Singleton, 2008), surprisingly few studies have examined potential explanations for why mathematics is such a strong predictor of later academic and especially reading achievement. The current study aimed to investigate whether executive function (EF) may explain the association between school-entry mathematics and academic achievement in fifth grade.

Early mathematics predicting later mathematics and reading achievement

The importance of children's early mathematics skills for later mathematics outcomes is well established (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Clements, Sarama, & Germeroth, 2016; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Purpura, Baroody, & Lonigan, 2013; Sarama & Clements, 2009). However, several studies have also found statistical predictions from children's early mathematics skills to early literacy skills (Purpura, Logan, Hassinger-Das, & Napoli, 2017) and later reading outcomes (Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007). A meta-analytic study using six longitudinal datasets demonstrated that early math skills have the strongest predictive power for later academic achievement and that early math skills are as predictive of later reading achievement as are early reading skills (Duncan et al., 2007). This highly cited study has been followed up by several studies (Claessens et al., 2009; Claessens & Engel, 2013; Pagani et al., 2010; Romano, Babchishin, Pagani, & Kohen, 2010) replicating the strong predictive power of early mathematics for both mathematics and reading. Experimental evidence for a pathway from mathematics to later language proficiency was found by Sarama, Lange, Clements, and Wolfe (2012), who tested the effects of a pre-kindergarten mathematics curriculum and found that children in the intervention group outperformed children in the control group on oral language skills. These studies are often used to argue for the importance of early mathematics in early childhood education and care. Yet, although the mechanisms through which early mathematics skills may contribute to later mathematics have been investigated in several studies (e.g., Hassinger-Das, Jordan, Glutting, Irwin, & Dyson, 2014; McKinnon & Blair, 2019; Nguyen et al., 2016; Van der Ven, Kroesbergen, Boom, & Leseman, 2012; Watts et al., 2015), the mechanisms explaining the pathway between mathematics and reading achievement are less well understood. Understanding the nature of this association is essential in order to gain insight into whether this association is causal—which would imply that mathematics interventions in themselves may be effective in promoting children's reading skills (as suggested by Sarama et al., 2012)—or whether something else actually explains this relation or that mathematics may only have been acting as a proxy.

Indeed, some scholars have suggested that the relation between mathematics and reading outcomes may be spurious or due to the procedural and conceptual nature of early mathematics skills (Duncan et al., 2007). Others also argue that the association between mathematics and reading achievement may be overestimated due to limitations of the statistical methods used in previous research and that other shared factors may explain why reading and mathematics achievement overlap (Bailey, Oh, Farkas, Morgan, & Hillemeier, 2020; Cirino, Child, & Macdonald, 2018; Schenke, Rutherford, Lam, & Bailey, 2016). For example, Cirino et al. (2018) found that phonological awareness, rapid automatic, and symbolic naming accounted for most of the overlap in mathematics and reading outcomes in first grade. Korpipaa et al. (2017) found that covariation between reading and mathematics skills is already fairly well established at the beginning of school and predicted by phonological awareness, letter knowledge, and counting and that working memory predicted the time-invariant covariation between first and seventh grades. One study investigated the role of mathematical language in the relation between early mathematics and early literacy skills and found that children's mathematical language skills mediated part of the relation between early mathematics ability and phonological awareness and definitional vocabulary in preschool children, suggesting that mathematics may have been acting as a proxy for mathematical language (Purpura, Logan, et al., 2017). The results from these studies emphasize the importance of including early literacy and language skills in the prediction from early mathematics to later reading achievement. Yet, other possible (confounding) mechanisms, such as mediation by EF, may also play a role.

Associations between EF and academic skills

EF can be 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, Chen, & Main, 2012). The main components of EF include the ability to maintain and update information in working memory (working memory), to inhibit automatic or prepotent responses (inhibition), and to flexibly shift attention (shifting) (Best & Miller, 2010; Diamond, 2013; Miyake & Friedman, 2012; Miyake et al., 2000).

The development of EF across early childhood manifests itself through the ability to perform increasingly complex tasks (e.g., Best & Miller, 2010; Garon, Bryson, & Smith, 2008). This is thought to allow children to acquire increasingly complex mathematics and reading skills. For example, EF may aid in the storage and retrieval of partial results, suppression of inappropriate strategies or irrelevant information from a word problem, and switching between operations, notations, and the steps of a complex multistep problem (Bull & Lee, 2014). Similarly, EF may help children to flexibly shift attention between the meaning of a word and its structural features, suppress incorrect or irrelevant interpretations, and maintain relevant information and exclude irrelevant information in working memory to successfully construct a coherent representation of a text (Butterfuss & Kendeou, 2018).

There is clear evidence that EF is related to both mathematics outcomes (Blair & Razza, 2007; Bull & Lee, 2014; Byrnes, Wang, & Miller-Cotto, 2019; Fuhs, Nesbitt, Farran, & Dong, 2014; Hernández et al., 2018; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Lenes, McClelland, ten Braak, Idsøe, & Størksen, 2020; McKinnon & Blair, 2019; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017; ten Braak, Kleemans, Størksen, Verhoeven, & Segers, 2018; Van der Ven et al., 2012; Welsh et al., 2010) and reading outcomes (Butterfuss & Kendeou, 2018; Byrnes et al., 2019; Connor et al., 2016; Lenes et al., 2020; Meixner, Warner, Lensing, Schiefele, & Elsner, 2019; Nouwens, Groen, Kleemans, & Verhoeven, 2021), although often more consistently to the former (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Blair & Razza, 2007; McClelland et al., 2014; Schmitt et al., 2017). EF may explain shared variance between kindergarten mathematics and reading (Blair & Razza, 2007) and is a significant propensity factor (together with prior academic skills) over and above antecedent factors (e.g., socioeconomic status, age) and opportunity factors (e.g., home literacy and numeracy environment) that can explain why some children have higher levels of academic skills than do others (Byrnes et al., 2019; Ribner, Harvey, Gervais, & Fitzpatrick, 2019). Moreover, EF is thought to facilitate learning from mathematics instruction (Ribner, 2020), and when EF is investigated as a moderator, the magnitude of the association between early mathematics and later mathematics varies as a function of early EF. This suggests that EF might work as a "buffer" and that children with limited initial math skills who have high levels of EF to some extent can "catch up" (Hernández et al., 2018; Ribner, Willoughby, Blair, & Family Life Project Key Investigators, 2017). EF likely predicts academic achievement trajectories through children's learning-related self-regulatory behaviors (Sung & Wickrama, 2018). Taken together, EF seems to play a significant role in the development of children's academic skills because it predicts both mathematics and reading and may function as a moderator of the relation between early and later skills.

EF as a mediator

EF might not only function as a predictor or moderator but also may play a mediating role in associations between early mathematics and later mathematics and reading achievement. Recent studies investigating the direction of relations show that mathematics often predicts EF over and above earlier EF skills as well (e.g., Cameron, Kim, Duncan, Becker, & McClelland, 2019; Fuhs et al., 2014; Hernández et al., 2018; McKinnon & Blair, 2019; Schmitt et al., 2017; ten Braak, Størksen, Idsoe, & McClelland, 2019; Welsh et al., 2010). For example, Schmitt et al. (2017) found evidence for bidirectional relations between mathematics and EF across preschool (over and above literacy skills) as well as correlated growth between mathematics and EF during the transition from preschool to kindergarten. Similarly, McKinnon and Blair (2019) found bidirectional associations between EF and mathematics achievement from kindergarten to first grade, with mathematics being a consistent predictor of EF over and above previous EF skills, measures of reading achievement, and teacher–child relationships. Math achievement also predicted EF in a longitudinal study across the early elementary school grades (Hernández et al., 2018). Results from a recent study (Cameron et al., 2019) also suggested that when children gain early mathematics skills (e.g., applied quantitative competencies), they are likely to make gains in EF and literacy as well. In line with these findings, scholars have suggested testing for mediating effects of EF in the development of academic skills (e.g., Schmitt et al., 2017). Thus, considering the predictive relation from mathematics to EF and the fact that EF is related to both mathematics skills (Bull & Lee, 2014) and reading skills (Butterfuss & Kendeou, 2018), EF may potentially be a mechanism that may help to explain why early mathematics is such a strong predictor of later academic achievement.

Relational developmental systems perspectives (Overton, 2015) may provide a framework for explaining such a mechanism. According to this perspective, the development of skills is seen as interrelated (Blair & Raver, 2015) and bidirectional (e.g., McClelland, Geldhof, Cameron, & Wanless, 2015). The progress children make in EF is thought to set the stage for concomitant progress in the growth of academic skills and vice versa (Blair & Raver, 2015). That is, EF might not only be a foundation for academic development; the development of academic skills may also promote EF. One theoretical explanation for a directional pathway from mathematics to EF is that the cognitive demands of mathematical learning may provide children with unique opportunities for the development of EF processes (Clements et al., 2016). Mathematics is considered to develop through a cumulative learning process (Sarama & Clements, 2009), and the increasingly complex math activities that children encounter likely place increasingly high demands on children's ability to update information in memory, inhibit impulses, and shift attention to and focus on the math problems at hand. This demand is also reflected in neuroscientific studies indicating that the prefrontal cortex, a brain region strongly associated with EF, plays a significant role in mathematics (Butterworth, Varma, & Laurillard, 2011). Thus, mathematical activities may provide affordances and scaffolding that allow children to further develop and strengthen EF (Clements et al., 2016). This suggests the hypothesis that part of the strong pathway between early mathematics and later mathematics and reading achievement may be explained by EF. That is, early mathematics skills may predict why some children have higher mathematics and reading achievement outcomes later on (in part) because they have acquired higher levels of EF.

A few studies have examined domain-general EF as a mediator between early and late mathematics, and mixed findings emerged. In one study investigating EF's mediating role in the association between first-grade and 15-years-of-age mathematics achievement, no significant mediation was found (Watts, Duncan, Clements, & Sarama, 2015). In contrast, two studies conducted in the kindergarten and first-grade years did find evidence for mediation. Results from McKinnon and Blair (2019) show that development of math achievement from the fall of kindergarten to the fall of first grade was mediated by EF in the spring of kindergarten. Similarly, spring kindergarten EF was a unique partial mediator underlying the relation between fall kindergarten number sense and first-grade mathematics skills in a sample of low-income children with mathematics difficulties

(Hassinger-Das et al., 2014), suggesting that EF plays a similar role in mathematics development across typically developing children and children at risk.

Compared with the role of EF in math development, the role of EF as a mediator between mathematics and reading achievement has received less attention. In addition, considering that the strength of relations between EF and mathematics and reading skills may vary depending on the timing of assessment (see also Bohlmann, Maier, & Palacios, 2015; Fuhs et al., 2014; McKinnon & Blair, 2019; Schmitt et al., 2017), there is a need for studies that investigate mediating pathways at other points of development. This is needed to obtain a more complete picture of the factors that contribute to the predictive strength of mathematics across development. Identifying the mechanisms by which mathematics and reading skills are related across time is important because it may guide the design of educational activities that can promote these skills.

The current study

A substantive body of research has demonstrated that early mathematics skills are predictive of later mathematics and reading achievement (Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007; Pagani et al., 2010; Romano et al., 2010). However, the mechanisms through which early mathematics may predict later academic outcomes, especially reading achievement, remain far from clear. As outlined earlier, a few recent studies have investigated possible explanations for why mathematics predicts reading, but other plausible pathways (e.g., where EF mediates this relation) have received less attention. In addition, considering that the variance accounted for in later reading by early mathematics skills tends to grow over time (Claessens & Engel, 2013), it is important to investigate these mechanisms in a longitudinal dataset.

Thus, the current study investigated whether EF (first grade) mediates the association between early mathematics (kindergarten) and later mathematics and reading achievement (fifth grade). Early literacy skills (vocabulary and phonological awareness) were controlled for to reduce possible bias in the estimates (Cirino et al., 2018; Korpipaa et al. 2017; Schenke et al., 2016). Based on the strong associations between mathematics and EF found in previous research (Allan et al., 2014; Blair & Razza, 2007; McClelland et al., 2014; Schmitt et al., 2017), it was hypothesized that EF would be a significant mediator over and above other (mediating) effects of early mathematics and literacy skills and when controlling for background variables (maternal education, age, sex, and immigrant status).

Method

Sample and procedure

This study is based on secondary analyses of an existing dataset covering kindergarten and first grade. The data were part of a larger research project called *Skoleklar* [ready for school]. In addition, data from the mandatory national school assessments, which in Norway are administered in fifth grade, were collected. The project was reported to and approved by the Norwegian Center for Research Data (NSD). A total of 287 children from 19 kindergartens from a municipality on the west coast of Norway were approached to participate in this project. Of those, 84.7% (243 children; 119 girls) were given consent from parents to participate. Data for the first time point were collected in the spring of kindergarten. The mean age of the children in kindergarten was 5.8 years (SD = 0.29, range = 5.3–6.3). From this sample, 31 children (12.8%) had at least one parent who was born outside of Norway, including 5 children (2.1%) for whom both parents were born in the European Union/European Economic Area (EU/EEA) (but outside of Scandinavia), United States, Canada, Australia, or New Zealand and 8 children (3.3%) for whom both parents came from either Asia, Africa, Latin America, Oceania (except Australia and New Zealand), or another country in Europe outside the EU/EEA. These latter 13 children were regarded as having an immigrant status in the current study. All children spoke Norwegian and were assessed in Norwegian. Of the mothers, 48.3% reported having 3 or more years of college/university education. Data were collected again 1 year later in the spring of first grade (8 schools). Children were assessed individually by a trained research assistant in a separate room. Tasks were administered on a tablet in a fixed order. The total administration time of the battery was approximately 45 min per child. The time frame for testing all children was at most 3 or 4 weeks. In the fall of fifth grade, data were collected from the mandatory national school assessments administered by teachers.

Measures

Kindergarten and first-grade measures

Executive function

EF was assessed with the Head–Toes–Knees–Shoulders (HTKS) task (McClelland et al., 2014), which is often referred to as a measure of (behavioral) self-regulation because it assesses the integration of working memory, inhibitory control, and cognitive flexibility in overt behavior. Research has demonstrated that the HTKS task is a reliable (α = .94) and valid measure that loads onto one EF factor together with these cognitive processes (Schmitt et al., 2017). Research has also shown that the task significantly predicts children's academic outcomes (McClelland et al., 2007, 2014; von Suchodoletz et al., 2013; Wanless et al., 2011) and has been used in diverse and international samples including Norwegian children (Størksen, Ellingsen, Wanless, & McClelland, 2015) and children in early elementary school (Day, Connor, & McClelland, 2015; Gestsdottir et al., 2014). Reliability could not be calculated in the current sample (only sum scores were available), but in a recent Norwegian study with a similar age group (Rege et al., 2019) the HTKS task showed a reliability of α = .87.

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 test 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 4 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 2 points when correct, 1 point when children made an incorrect movement but ended up with the correct response, and 0 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

Children's early mathematics skills were assessed with the Ani Banani Math Test (ABMT; ten Braak & Størksen, 2021). The ABMT is a short digital mathematics assessment including 18 items aimed to cover three areas of mathematics: numeracy, geometry, and problem solving. The items included counting of objects, counting back and forward, counting to 50, completing a puzzle, recognizing geometric shapes, copying figures, simple arithmetic reasoning, and comparing qualitative and quantitative aspects of objects. The task shows both predictive and discriminant validity, is a strong predictor of later mathematics achievement, and is significantly more strongly related to other mathematics assessments compared with measures of EF, working memory, and early literacy and language measures (ten Braak & Størksen, 2021). Reliability was α = .73 in kindergarten and α = .68 in first grade.

Expressive vocabulary

Children's expressive vocabulary was assessed with the Norwegian Vocabulary Test (NVT; Størksen, Ellingsen, Tvedt, & Idsøe, 2013). In this test, children were presented with 45 different pictures on a tablet screen. Children needed to tell the experimenter the name of the object that was depicted on the screen. Reliability was α = .84 in kindergarten and α = .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 (2016). The measure consisted of 12 blending items. The target word was auditorily presented in its individual phonemes by the experimenter, and children needed 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 α = .75 (Solheim, Brønnick, & Walgermo, 2013).

Fifth-grade measures

Mathematics and reading achievement

Mathematics and reading achievement were assessed through mandatory national assessment (Norwegian Directorate for Education and Training, 2016). The tests are conducted on a computer, and students are given ample time (90 min) to complete each assessment. For reading achievement, the questions are designed to assess three different reading comprehension skills, namely (a) find information in texts, (b) interpret and compare information, and (c) reflect on and evaluate the form and content of the texts. The test has five texts, and each text is followed by multiple-choice questions. There are five to seven items per text, with a total of 30 items. For mathematics, the test has 45 items and assesses three different aspects of mathematics: (a) numeracy and how students manage to use the four arithmetical operations, (b) measuring and geometry (e.g., length, area, volume, angle, mass, time, scale), and (c) statistics (e.g., ability to organize, analyze, present, and evaluate data, tables, and charts). All reliability estimates for the tests are α > .80 (Utdanningsdirektoratet, 2013, 2018).

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. Maternal education level was used as a proxy for socioeconomic status (SES) and 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 = all other children.

Analytic procedure

Rates of missing data were generally low (0.8%–4.1%) in kindergarten and first grade. In fifth grade, 34% of the data was missing. The new parent consent that was necessary for data collection in fifth grade explains most of this attrition. To account for missing data under the missing at random (MAR) assumption, the variable that was related to attrition (immigrant status) was included in the model and the full information maximum likelihood (FIML) estimator with robust standard errors (MLR) was used. Children were nested in 19 kindergartens and 8 schools. All intraclass coefficients (ICCs) were under .04 except for phonological awareness in kindergarten and first grade (ICC = .059 and ICC = .076, respectively). Therefore, analyses adjusting for potential nested effects were not used.

To investigate whether EF could account for the relation between early mathematics and later mathematics and reading skills, a parallel multiple mediator model with EF, mathematics, phonological awareness, and vocabulary as mediators was estimated using structural equation modeling (SEM) techniques in Mplus Version 8.2 (Muthén & Muthén, 1998–2010). In contrast to models in which each mediator is considered individually, this model allows for a simultaneous test of each mediating mechanism while accounting for the shared association between them. This method is especially useful when mediators are expected to correlate. Controlling for each mediator should reduce potential bias in the estimated mediation effects (Hayes, 2013). Indirect effects were tested using the bootstrapping process procedure (Preacher & Hayes, 2004), providing the 95% bias-corrected confidence intervals of the standard errors.

The modeling was performed stepwise. For the first two steps, saturated models where all dependent variables were regressed on all predictors were estimated. Hence, perfect model fit was obtained in each model.[1] First (Model 1), to investigate whether kindergarten mathematics significantly predicted mathematics and reading achievement in fifth grade, these were regressed on kindergarten mathematics while controlling for kindergarten EF, phonological awareness, vocabulary, maternal education, age, sex, and immigrant status.

Next, the full multiple mediator model (Model 2) was estimated in which first-grade EF, vocabulary, phonological awareness, and mathematics were added as mediators between kindergarten mathematics and fifth-grade mathematics and reading achievement. Mediators were allowed to correlate. Kindergarten EF, phonological awareness, and vocabulary were kept in the model as control variables (autoregressive effects) to reduce bias in the estimated effects of kindergarten mathematics on the mediators and fifth-grade outcomes.

Finally, one can argue that all (cognitive developmental) models likely omit one or more variables that are non-null in the population (Harring, McNeish, & Hancock, 2017). Even though Model 2 controls for several autoregressive effects and mediators, there may still be omitted variables that may cause the mediating effect to be upwardly biased. Specifically, there may be unmeasured factors that contribute to between-person differences on scores across kindergarten mathematics and first-grade EF tasks. Therefore, a phantom variable approach (Harring et al., 2017) was added to assess the model's sensitivity to external misspecification (Model 3). Specifically, we regressed kindergarten mathematics and first-grade EF onto a latent phantom variable with a mean of 0 and a variance of 1. The phantom variable was set to correlate with covariates and other kindergarten measures. A fixed parameter approach was used with path coefficients systematically set to the same constant magnitude of .10, .20, and .30, running a separate model for each value. That is, the phantom variable served as a placeholder for a variable that is potentially missing from the model.

Results

Preliminary analyses

Descriptive statistics for all variables are presented in Table 1. Correlations are presented in Table 2. Mathematics in kindergarten showed a strong positive association with mathematics achievement in fifth grade (r = .58), a moderate positive association with reading achievement in fifth grade (r = .49), and a moderate positive association with first-grade EF (r = .44). EF in first grade showed moderate positive associations with mathematics and reading achievement in fifth grade (r = .46 and r = .40, respectively). The mediators had moderate correlations with one another (ranging from r = .30 to r = .47). This demonstrates the utility of accounting for multiple mediators in reducing bias when assessing mediating pathways in mediation models.

Primary analyses

Kindergarten mathematics predicting fifth-grade academic achievement (Model 1)

Results from Model 1 showed that kindergarten mathematics was a unique predictor for mathematics (β = .48, p < .001) and reading achievement (β = .28, p < .001) in fifth grade. The model explained 42.7% of the variance in fifth-grade mathematics and 38.6% in reading achievement. See Table 3.

EF as a mediator (Model 2)

Model 2 explained 50.3% of the variance in fifth-grade mathematics and 41.8% in reading. Bias-corrected bootstrap confidence intervals (BC CIs) for the indirect effects based on 10,000 bootstrap samples showed that EF mediated the predictive association between kindergarten mathematics and both fifth-grade mathematics achievement (β = .039, standardized 95% BC CI [.006, .089]) and

[1] The reason we estimate path analyses in Mplus is because it allows for the use of FIML, which produces unbiased estimates while maintaining power in the case of missing data.

Table 1
Descriptive statistics for study variables.

Variable	*N*	*M*	*SD*	Skewness	Kurtosis	Min	Max
Kindergarten							
Mathematics	241	10.62	3.13	−0.32	−0.19	2	18
EF	241	52.22	20.14	−0.92	0.25	0	83
Vocabulary	241	26.35	5.69	−0.42	−0.16	10	39
PA	240	3.66	3.38	0.59	−0.91	0	12
First grade							
Mathematics	239	14.52	2.57	−1.01	1.18	5	18
EF	239	68.48	11.96	−2.18	8.37	1	84
Vocabulary	239	30.72	4.96	−0.63	0.44	14	42
PA	233	10.21	1.91	−1.75	3.98	1	12
Fifth grade							
NS reading	159	49.89	9.91	0.13	−0.65	26	74
NS mathematics	160	50.88	9.72	0.26	−0.24	28	78
Covariates							
Maternal education[a]	240	3.279	1.30	0.09	−1.538	1	5
Sex[b]	241	1.506	0.50	−0.025	−1.999	1	2
Age	242	5.787	0.29	0.063	−1.156	5.29	6.30
Immigrant status[c]	237	0.055	0.23	3.91	13.289	0	1

Note. Kindergarten and first-grade mathematics: Ani Banani Math Test. Executive function (EF): Head–Toes–Knees–Shoulders task. Vocabulary: Norwegian Vocabulary Test. PA: phonological awareness. NS: national school assessment.

[a] 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.

[b] 1 = girl, 2 = boy.

[c] 0 = nonimmigrant, 1 = immigrant.

reading (β = .037, standardized 95% BC CI [.003, .084]). In addition, mathematics significantly mediated the pathway from early mathematics to later mathematics achievement (β = .16, CI [.073, .260]). There were no other significant indirect effects from kindergarten mathematics to the fifth-grade outcomes. See Fig. 1.

Sensitivity to external misspecification (Model 3)

Adding a phantom variable to test for the robustness of the results to unmeasured factors that could contribute to differences on scores across kindergarten mathematics and first-grade EF tasks resulted in poor model fit, $\chi^2(7)$ = 98.304, p < .001, comparative fit index (CFI) = .898, Tucker–Lewis index (TLI) = .000, root mean squared error of approximation (RMSEA) = .232, standardized root mean squared residual (SRMR) = .137; $\chi^2(7)$ = 88.968, p < .001, CFI = .909, TLI = .086, RMSEA = .220, SRMR = .134; and $\chi^2(7)$ = 73.918, p < .001, CFI = .925, TLI = .254, RMSEA = .198, SRMR = .131, for models with phantom variable path magnitudes set to .10, .20, and .30, respectively. The pattern of results remained the same for all magnitudes, with a slight reduction in direct and indirect effects but no change in significance (see Table A1 in the Appendix for an overview of the estimates). However, considering that the models did not fit the data well, Model 2 remains the preferred specification.

Discussion

This study aimed to investigate whether EF may be part of the explanation for why early mathematics skills predict better academic achievement in elementary school. Several studies have found that early mathematics predicts later mathematics and reading (Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007; Pagani et al., 2010; Romano et al., 2010). However, few studies have tried to explain this relation. Specifically, the prediction from early mathematics to reading warranted further investigation. Some studies have investigated the role of literacy and language in the relation between early mathematics and later reading (e.g., Cirino et al., 2018; Korpipaa et al. 2017; Purpura, Logan, et al., 2017; Schenke et al., 2016), and some studies have looked at moderating effects (Ribner et al., 2017) or mediating effects (Hassinger-Das et al., 2014; McKinnon & Blair, 2019; Watts et al.,

Table 2
Correlations among kindergarten mathematics, mediators, fifth-grade reading and mathematics achievement, and covariates.

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Kindergarten														
1.	Mathematics	–													
2.	EF	.48***	–												
3.	Vocabulary	.46***	.35***	–											
4.	PA	.40***	.38***	.40***	–										
	First grade														
5.	Mathematics	.67***	.48***	.39***	.40***	–									
6.	EF	.44***	.39***	.32***	.21**	.47***	–								
7.	Vocabulary	.42***	.33***	.81***	.33***	.39***	.30***	–							
8.	PA	.35***	.31***	.39***	.40***	.36***	.32***	.35***	–						
	Fifth grade														
9.	NS reading	.49***	.33***	.48***	.34***	.51***	.40***	.44***	.23***	–					
10.	NS mathematics	.58***	.27***	.40***	.25***	.60***	.46***	.39***	.22**	.67***	–				
	Covariates														
11.	Maternal education[a]	.29***	.12*	.28***	.20**	.33***	.22**	.31***	.16**	.36***	.36***	–			
12.	Sex[b]	−.21**	−.31***	−.14	−.35***	−.18*	−.11	−.13	−.38***	−.10	−.04	−.09	–		
13.	Age	.18**	.14*	.14*	.21**	.12	.07	.12	.06	.04	.01	.04	−.04	–	
14.	Immigrant status[c]	−.06	−.08	−.39***	−.09	−.09	.01	−.45***	−.14*	−.26	.01	−.15*	.12	−.02	–

Note. Kindergarten and first-grade mathematics: Ani Banani Math Test. Executive function (EF): Head–Toes–Knees–Shoulders task. Vocabulary: Norwegian Vocabulary Test. PA: phonological awareness. NS: national school assessment.

[a] 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.

[b] 1 = girl, 2 = boy.

[c] 0 = nonimmigrant, 1 = immigrant.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

Table 3
Estimates of kindergarten mathematics predicting fifth-grade academic achievement while controlling for EF, vocabulary, PA, and covariates (Model 1).

Variable	NS mathematics			NS reading		
	β	*SE*	*p*	*β*	*SE*	*p*
Kindergarten						
Mathematics	.485	.080	<.001	.276	.073	<.001
EF	.005	.078	.948	.043	.075	.567
Vocabulary	.204	.083	.014	.269	.071	<.001
PA	−.048	.081	.552	.047	.078	.543
Covariates						
Maternal education[a]	.191	.068	.005	.180	.071	.011
Sex[b]	.004	.066	.953	−.020	.066	.760
Age	−.098	.057	.087	−.073	.058	.210
Immigrant status[c]	.191	.068	.005	−.089	.053	.090

Note. Kindergarten mathematics: Ani Banani Math Test. Executive function (EF): Head–Toes–Knees–Shoulders task. Vocabulary: Norwegian Vocabulary Test. PA: phonological awareness. NS: national school assessment.
[a] 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.
[b] 1 = girl, 2 = boy.
[c] 0 = nonimmigrant, 1 = immigrant.

2015) of EF in the development of mathematics. However, the results were mixed for the latter, and although the association between EF and mathematics is well established, the role of EF as a mediator in the prediction from early mathematics to later reading was less clear despite theoretical and empirical substantiation for such a relation. The current study is novel in that it examined the mediating role of EF between children's early mathematics and both later mathematics and reading achievement in a longitudinal dataset crossing a 5-year age span while controlling for several mediating effects of early literacy skills and covariates.

As expected, and in line with previous research (Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007; Pagani et al., 2010; Romano et al., 2010), children's mathematics skills in kindergarten predicted mathematics and reading achievement 5 years later over and above the effects of kindergarten EF, phonological awareness, vocabulary, and child background variables. Second, and in line with the hypothesis, EF significantly mediated these relations even when controlling for prior skills, mediating effects of early mathematics and early reading indicators, and possible omitted variables. Thus, results point to an explanatory role for EF in the relation between early mathematics and both mathematics and reading. This is in line with developmental systems perspectives (Overton, 2015) and the theoretical framework where development of skills is seen as interrelated (Blair & Raver, 2015) and bidirectional (e.g., McClelland et al., 2015). The results suggest that high proficiency in kindergarten mathematics may set the stage for concomitant progress in EF skills, which in turn may result in higher academic achievement. EF may facilitate learning from instruction and encourage children to learn more over time (Ribner, 2020; Sung & Wickrama, 2018). Thus, the effect may represent a reinforcing process wherein children with good math skills receive more opportunities to develop EF, which in turn facilitates and encourages learning-related behavior and further academic development. In contrast, children with low math skills might not be receiving these opportunities, may struggle to keep up with the increasingly complex math activities to be tackled at school, and may end up with less bright opportunities for academic development. While acknowledging that the current study is correlational and that the design does not allow for confirming causality, the results lend support to the hypothesis that high-quality mathematics education in early childhood education and care may help to develop academic skills through its relation with EF (Clements et al., 2016).

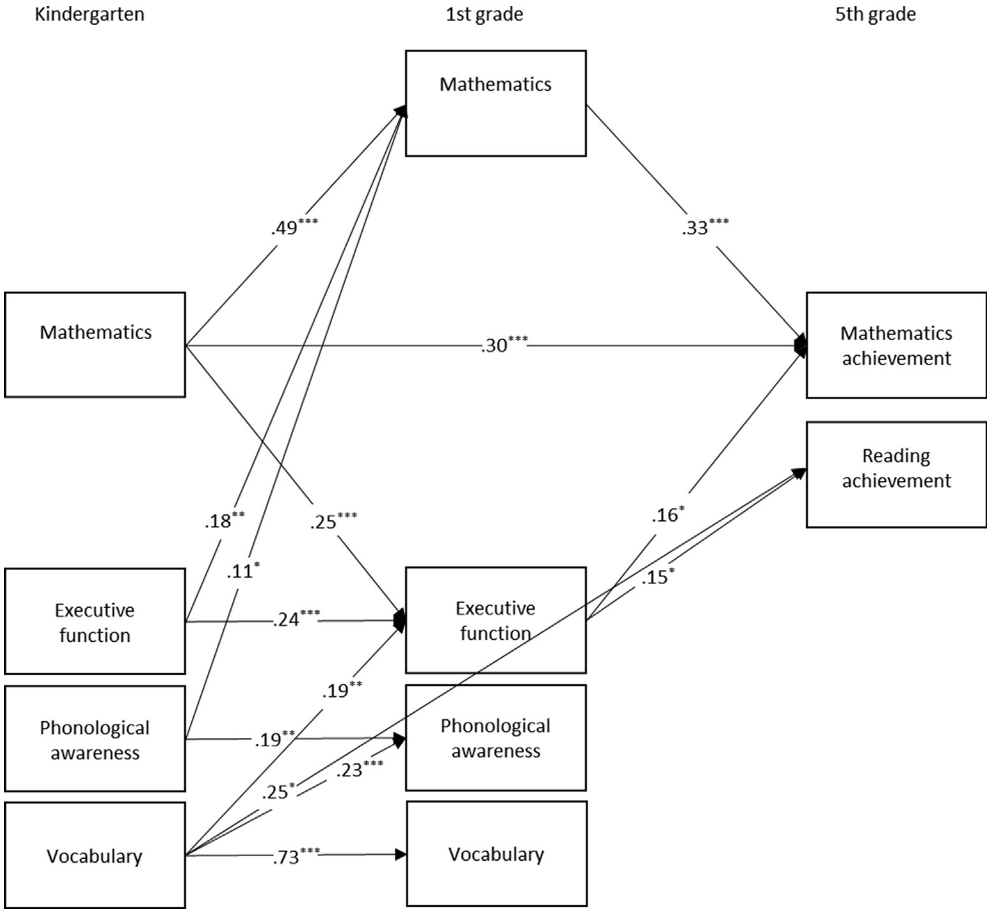

Fig. 1. Parallel multiple mediator model (Model 2) predicting fifth-grade achievement from kindergarten skills through first-grade mediators. Covariates (maternal education, age, sex, and immigrant status), correlations between the mediators, and nonsignificant paths ($p > .05$) were included in the model but are not depicted for reasons of clarity. Estimates provided are standardized coefficients. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Mediating effect of EF for mathematics

The mediating effect of EF for mathematics was small but significant, with 7.8% of the total effect being attributable to the indirect effect through EF. These results are in line with results from Hassinger-Das et al. (2014) and McKinnon and Blair (2019) and suggest that EF plays a unique role in the relation between early and later mathematics. EF may be especially important for children with weak initial mathematics skills because they are likely to have more trouble in keeping up with the increasingly complex and cognitively demanding instructions and activities in formal school, which in turn puts an increasing demand on EF. This combination of low mathematics and EF skills may then create a cycle of failure (Hassinger-Das et al., 2014).

The results are different from those of Watts et al. (2015), who did not find a mediating role for EF in the association between first-grade and 15-years-of-age mathematics achievement. Measurement differences may be one explanation for this difference. That is, the HTKS task as used in the current study may tap into more complex EF skills compared with some of the separate EF tasks (i.e., Memory for Sentences, Continuous Performance Test) used in Watts et al.'s study. The difference may also be due to EF being measured at a later time point (i.e., third and fourth grades). In general, the time span in the study by Watts et al. was much longer (children in the current study were about 10 years old at the last measurement), which may have attenuated some of their effects. It may also be that EF is a much stronger predictor during the first years of schooling when children need to use EF to regulate to the new learning activities and formal context in school. Finally, Watts et al. (2015) controlled for several other mediators such as math self-concept of ability and school placements (e.g., gifted and talented programs).

Although EF significantly mediated the association between kindergarten mathematics and fifth-grade mathematics achievement, the direct effect remained relatively strong. Children's early mathematics skills in kindergarten seem to be a particularly stable predictor for their later mathematics over and above effects of EF, language, literacy, and child background variables. In addition, correlations with fifth-grade achievement appear to be remarkably similar for kindergarten and first- grade assessments. Together with a significant indirect pathway through mathematics at the second time point, this reflects the cumulative and hierarchical nature of mathematics development where increasingly complex skills build on top of each other (Sarama & Clements, 2009), and early informal skills function as a foundation for long-term success or difficulty (Aunola et al., 2004; Jordan et al., 2009; Purpura et al., 2013).

An important note is that the results regarding mathematics (including the strong direct effect and the estimated indirect effect via first-grade mathematics being larger than the other estimated indirect effects) also show that prior math-specific knowledge seems to be much more important than EF. This was also highlighted in a recent study conceptualizing EF as one of the propensity factors predicting children's academic achievement but finding EF to be much less important than prior skill levels (Byrnes et al., 2019). Nevertheless, as developmental systems perspectives assume, and the current findings also suggest, skills likely develop through dynamic and continuous bidirectional coactions, and promoting a combination of EF and academic skills in early childhood education and care likely renders the biggest impact on children's further development.

Mediating effect of EF for reading

As outlined in the Introduction, the association between early mathematics and later reading outcomes has been found in several studies, but surprisingly few studies have tried to explain this particular association. Purpura, Logan, et al. (2017) found an explanatory role of mathematical language skills for the association between early mathematics and later literacy but did not incorporate EF into the model. The current study adds to this by showing that across a 5-year span EF can explain at least part of the predictive association between early mathematics and later reading achievement. Given that Schmitt, Purpura, and Elicker (2019) found a bidirectional association between EF and mathematical language, future research should elucidate whether both act as unique mediators.

Although the indirect effect was small in magnitude, a considerable percentage of the total effect for fifth-grade reading was attributable to the indirect effect through EF (12.9%). In contrast to the mathematics achievement outcome, the direct association between kindergarten mathematics and later reading achievement that was found in Model 1 (while controlling for kindergarten EF, mathematics, and covariates) was rendered nonsignificant when EF was included as a mediator. Notably, given that kindergarten mathematics predicted fifth-grade reading achievement through first-grade EF while controlling for kindergarten EF, this effect cannot be explained away by the correlation between EF and mathematics at the first wave of testing. These results also suggest that the direct relation between early mathematics and later reading outcomes, as found in previous studies that did not include mediating effects of EF (e.g., Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007), has likely been overestimated and can be explained in part by EF. Thus, there does not seem to be anything specific with early mathematics that may directly help children with their reading achievement. Rather, and again consistent with developmental systems perspectives (Overton,

2015) wherein development of skills is seen as interrelated (Blair & Raver, 2015) and bidirectional (e.g., McClelland et al., 2015), high proficiency in kindergarten mathematics may set the stage for successful EF development, which in turn may help children to develop their reading skills in school.

Limitations and suggestions for future research

Despite this study's strengths, including the longitudinal multiple mediator design that allows a test of mediating effects of EF while controlling for prior skills and mediating effects of literacy and other possible omitted variables, some limitations of this study should be noted. First, although the study aimed to test a causal pathway, the correlational nature of the data cannot prove a causal relation and the study's findings provide only suggestive evidence of causality. The existence of unmeasured variables correlated with both early mathematics and the outcome variables do not allow for unambiguous causal inferences. Recent concerns have been raised regarding the interpretation of longitudinal correlational data (Bailey, Duncan, Watts, Clements, & Sarama, 2018) and cross-lagged panel models (Berry & Willoughby, 2017). The current study's design did not allow for a deconstruction of within- and between-child variation. Future research should use methodological approaches that can tease these apart (e.g., Berry & Willoughby, 2017; Hamaker, Kuiper, & Grasman, 2015) and provide a more rigorous test of skill-building theories (Bailey et al., 2018).

Experimental manipulation of early mathematics skills often generates much smaller effects (Bailey et al., 2018; Watts et al., 2018). Despite the inclusion of several covariates in the model, the exclusion of other unmeasured variables could still have led to some upward bias in the estimates. For example, this study could not assess the role of mathematical language (Purpura, Logan, et al. 2017), math self-concept or school placement programs (Watts et al., 2015), learning disabilities (Hassinger-Das et al., 2014), or other skills known to explain the overlap between mathematics and reading such as rapid automatic and symbolic naming (Cirino et al., 2018) and letter knowledge (Korpipaa et al. 2017). This study could also not account for the quality or context of the educational environments that children experienced in school. Given that formal schooling aims to influence children's development of the skills considered in this study, controlling for measures of educational quality or context may have further reduced possible bias. However, the phantom variable approach that was added to assess the model's sensitivity to external misspecification does suggest that the effects are seemingly robust to omitted variable bias. Nevertheless, future studies should include these variables or test the robustness of results for potential effects of other unmeasured confounders through sensitivity analyses (e.g., Harring et al., 2017; VanderWeele, 2016). In addition, the limited time available for testing did not allow for additional measures, such as receptive language and multiple measures of EF, to be included. Subsequently, the use of single measures of each construct does not enable the control for measurement error, which again may have downwardly biased some estimates.

Relatedly, it is difficult to determine whether mediation between kindergarten mathematics and later achievement represents EF as a causal mediator, a confounder, or both. There could be a number of reasons for mediation. Statistically, mediation and confounding are identical. However, conceptually, considering that we modeled this longitudinally, it is unlikely that EF in first grade would be a confounder (defined as having an effect on both independent and dependent variables) "causing" kindergarten mathematics. Moreover, EF in kindergarten was controlled for, rendering unlikely the hypothesis that mathematics predicts academic outcomes because of its association with EF at a previous time point. Nevertheless, EF and other plausible causes of previous and later EF are likely not perfectly captured by EF measures, and so confounding might still be an issue.

The nature of the mathematics measures in the current study did not allow for investigation of subdomains. Some work has found that numeracy skills (Purpura & Lonigan, 2013) and mathematics skills more broadly (Milburn, Lonigan, DeFlorio, & Klein, 2019) are separable into distinct domains. Future research could benefit from more specific measures covering different math and reading domains because EF has been shown to relate differently to different sub-academic domains (Purpura, Schmitt, & Ganley, 2017).

The indirect effects were also relatively small, which is somewhat inherent to indirect effects given the mathematical nature of the mediation. Nevertheless, the coefficients for the pathways are in line with effects published in previous studies (e.g., Claessens et al., 2009; Duncan et al., 2007; Pagani et al., 2010), and the effects of .15 and .16 from EF in first grade to reading and mathematics several years later are also within a similar range compared with other longitudinal studies on EF (e.g., Birgisdottir, Gestsdottir, & Geldhof, 2020; Hernández et al., 2018; Morgan, Farkas, Hillemeier, Pun, & Maczuga, 2019; Ribner et al., 2017).

Regarding other pathways, the effect of first-grade mathematics is likely smaller compared with the total effect of kindergarten mathematics because the first-grade path has an autoregressor as a statistical control, but the kindergarten path does not. In addition, the included autoregressor effect for vocabulary was relatively strong, leaving little variance to be accounted for by mathematics.

Finally, no data were available at time points between first and fifth grades. Results may have been different if the time frame had been shorter. Nevertheless, we consider the longitudinal nature of the dataset as a great opportunity to assess the underlying mechanisms of the long-term relations that have been reported in previous research (e.g., Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007).

Conclusions

With its longitudinal design, crossing a 5-year age span, the inclusion of several covariates, and control for other mediating effects, the current study may help to clarify why previous work (e.g., Claessens et al., 2009; Claessens & Engel, 2013; Duncan et al., 2007) has often found early mathematics to be such a prominent predictor of later academic achievement. As such, findings from this study highlight the importance of including indicators of EF in models investigating early predictors of later achievement. Ultimately, a better understanding of the complex and interdependent relations between the development of EF, mathematics, and reading may inform early childhood practice on where difficulties may arise and where to apply resources.

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Appendix A

Table A1.

Table A1
Changes in standardized path estimates from kindergarten mathematics to first grade EF and indirect effects via EF to fifth grade achievement outcomes for different magnitudes of phantom variable paths using fixed parameter approach.

	Phantom variable path magnitude			
	.00	.10	.20	.30
Standardized path estimate	.249	.244	.213	.180
Indirect effect to mathematics	.039 [.006, .089]	.039 [.006, .088]	.034 [.005, .081]	.029 [.003, .072]
Indirect effect to reading	.037 [.003, .084]	.037 [.004, .085]	.032 [.003, .077]	.027 [.002, .068]

Note. Values in the ".00" column correspond to the estimates of the original model (Model 2). The 95% bias-corrected bootstrap confidence intervals are within square brackets. N.B. Data model fit indices for all models including the phantom variable paths were poor, and estimates might not be trustworthy.

References

Allan, N. P., Hume, L. E., Allan, D. M., Farrington, A. L., & Lonigan, C. J. (2014). Relations between inhibitory control and the development of academic skills in preschool and kindergarten: A meta-analysis. *Developmental Psychology, 50*(10), 2368–2379.

Aunola, K., Leskinen, E., Lerkkanen, M.-K., & Nurmi, J.-E. (2004). Developmental dynamics of math performance from preschool to Grade 2. *Journal of Educational Psychology, 96*(4), 699–713.

Bailey, D. H., Duncan, G. J., Watts, T., Clements, D. H., & Sarama, J. (2018). Risky business: Correlation and causation in longitudinal studies of skill development. *American Psychologist, 73*(1), 81–94.

Bailey, D. H., Oh, Y., Farkas, G., Morgan, P., & Hillemeier, M. (2020). Reciprocal effects of reading and mathematics? Beyond the cross-lagged panel model. *Developmental Psychology, 56*(5), 912–921.

Berry, D., & Willoughby, M. T. (2017). On the practical interpretability of cross-lagged panel models: Rethinking a developmental workhorse. *Child Development, 88*, 1186–1206.

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development, 81*(6), 1641–1660.

Birgisdottir, F., Gestsdottir, S., & Geldhof, G. J. (2020). Early predictors of first and fourth grade reading and math: The role of self-regulation and early literacy skills. *Early Childhood Research Quarterly, 53*, 507–519.

Blair, C. (2016). Developmental science and executive function. *Current Directions in Psychological Science, 25*(1), 3–7.

Blair, C., & Raver, C. C. (2015). School readiness and self-regulation: A developmental psychobiological approach. *Annual Review of Psychology, 66*(1), 711–731.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647–663.

Bohlmann, N. L., Maier, M. F., & Palacios, N. (2015). Bidirectionality in self-regulation and expressive vocabulary: Comparisons between monolingual and dual language learners in preschool. *Child Development, 86*(4), 1094–1111.

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8*(1), 36–41.

Butterfuss, R., & Kendeou, P. (2018). The role of executive functions in reading comprehension. *Educational Psychology Review, 30*(3), 801–826.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science, 332*(6033), 1049–1053.

Byrnes, J. P., Wang, A., & Miller-Cotto, D. (2019). Children as mediators of their own cognitive development in kindergarten. *Cognitive Development, 50*, 80–97.

Cameron, C. E., Kim, H., Duncan, R. J., Becker, D. R., & McClelland, M. M. (2019). Bidirectional and co-developing associations of cognitive, mathematics, and literacy skills during kindergarten. *Journal of Applied Developmental Psychology, 62*, 135–144.

Cirino, P. T., Child, A. E., & Macdonald, K. T. (2018). Longitudinal predictors of the overlap between reading and math skills. *Contemporary Educational Psychology, 54*, 99–111.

Claessens, A., Duncan, G., & Engel, M. (2009). Kindergarten skills and fifth-grade achievement: Evidence from the ECLS-K. *Economics of Education Review, 28*(4), 415–427.

Claessens, A., & Engel, M. (2013). How important is where you start? Early mathematics knowledge and later school success. *Teachers College Record, 115*(6).

Clements, D. H., Sarama, J., & Germeroth, C. (2016). Learning executive function and early mathematics: Directions of causal relations. *Early Childhood Research Quarterly, 36*, 79–90.

Connor, C. M., Day, S. L., Phillips, B., Sparapani, N., Ingebrand, S. W., McLean, L., ... Kaschak, M. P. (2016). Reciprocal effects of self-regulation, semantic knowledge, and reading comprehension in early elementary school. *Child Development, 87*(6), 1813–1824.

Day, S. L., Connor, C. M., & McClelland, M. M. (2015). Children's behavioral regulation and literacy: The impact of the first grade classroom environment. *Journal of School Psychology, 53*(5), 409–428.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*(1), 135–168.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., ... Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446.

Fuhs, M. W., Nesbitt, K. T., Farran, D. C., & Dong, N. (2014). Longitudinal associations between executive functioning and academic skills across content areas. *Developmental Psychology, 50*(6), 1698–1709.

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin, 134*(1), 31–60.

Gestsdottir, S., von Suchodoletz, A., Wanless, S. B., Hubert, B., Guimard, P., Birgisdottir, F., ... McClelland, M. (2014). Early behavioral self-regulation, academic achievement, and gender: Longitudinal findings from France, Germany, and Iceland. *Applied Developmental Science, 18*(2), 90–109.

Hamaker, E. L., Kuiper, R. M., & Grasman, R. P. P. P. (2015). A critique of the cross-lagged panel model. *Psychological Methods, 20*(1), 102–116.

Harring, J. R., McNeish, D. M., & Hancock, G. R. (2017). Using phantom variables in structural equation modeling to assess model sensitivity to external misspecification. *Psychological Methods, 22*(4), 616–631.

Hassinger-Das, B., Jordan, N. C., Glutting, J., Irwin, C., & Dyson, N. (2014). Domain-general mediators of the relation between kindergarten number sense and first-grade mathematics achievement. *Journal of Experimental Child Psychology, 118*, 78–92.

Hayes, A. F. (2013). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York: Guilford.

Hernández, M. M., Eisenberg, N., Valiente, C., Spinrad, T. L., Johns, S. K., Berger, R. H., ... Southworth, J. (2018). Self-regulation and academic measures across the early elementary school grades: Examining longitudinal and bidirectional associations. *Early Education and Development, 29*(7), 914–938.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*(3), 850–867.

Korpipää, H., Koponen, T., Aro, M., Tolvanen, A., Aunola, K., Poikkeus, A.-M., ... Nurmi, J.-E. (2017). Covariation between reading and arithmetic skills from Grade 1 to Grade 7. *Contemporary Educational Psychology, 51*, 131–140.

Krajewski, K., & Schneider, W. (2009). Exploring the impact of phonological awareness, visual–spatial working memory, and preschool quantity–number competencies on mathematics achievement in elementary school: Findings from a 3-year longitudinal study. *Journal of Experimental Child Psychology, 103*(4), 516–531.

Kroesbergen, E. H., Van Luit, J. E. H., Van Lieshout, E. C. D. M., Van Loosbroek, E., & Van de Rijt, B. A. M. (2009). Individual differences in early numeracy: The role of executive functions and subitizing. *Journal of Psychoeducational Assessment, 27*(3), 226–236.

Lenes, R., McClelland, M. M., ten Braak, D., Idsøe, T., & Størksen, I. (2020). Direct and indirect pathways from children's early self-regulation to academic achievement in fifth grade in Norway. *Early Childhood Research Quarterly, 53*, 612–624.

McClelland, M. M., & Cameron, C. E. (2012). Self-regulation in early childhood: Improving conceptual clarity and developing ecologically valid measures. *Child Development Perspectives, 6*(2), 136–142.

McClelland, M. M., Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., & Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Developmental Psychology, 43*(4), 947–959.

McClelland, M. M., Cameron, C. E., Duncan, R., Bowles, R. P., Acock, A. C., Miao, A., & Pratt, M. E. (2014). Predictors of early growth in academic achievement: The Head–Toes–Knees–Shoulders task. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00599.

McClelland, M. M., Geldhof, G. J., Cameron, C. E., & Wanless, S. B. (2015). Development and self-regulation. In W. F. Overton, P. C. M. Molenaar, & R. M. Lerner (Eds.), *Handbook of child psychology and developmental science* (pp. 523–565). Hoboken, NJ: John Wiley.

McKinnon, R. D., & Blair, C. (2019). Bidirectional relations among executive function, teacher–child relationships, and early reading and math achievement: A cross-lagged panel analysis. *Early Childhood Research Quarterly, 46*, 152–165.

Meixner, J. M., Warner, G. J., Lensing, N., Schiefele, U., & Elsner, B. (2019). The relation between executive functions and reading comprehension in primary-school students: A cross-lagged panel analysis. *Early Childhood Research Quarterly, 46*, 62–74.

Milburn, T. F., Lonigan, C. J., DeFlorio, L., & Klein, A. (2019). Dimensionality of preschoolers' informal mathematical abilities. *Early Childhood Research Quarterly, 47*, 487–495.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Science, 21*(1), 8–14.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100.

Morgan, P. L., Farkas, G., Hillemeier, M. M., Pun, W. H., & Maczuga, S. (2019). Kindergarten children's executive functions predict their second-grade academic achievement and behavior. *Child Development, 90*(5), 1802–1816.

Muthén, L. K., & Muthén, B. O. (1998–2010). Mplus user's guide (6th ed.). Los Angeles: Muthén & Muthén.

Nguyen, T., Watts, T. W., Duncan, G. J., Clements, D. H., Sarama, J. S., Wolfe, C., & Spitler, M. E. (2016). Which preschool mathematics competencies are most predictive of fifth grade achievement? *Early Childhood Research Quarterly, 36*, 550–560.

Norwegian Directorate for Education and Training. (2016). Nasjonal prøve i leseforståelse 5 trinn: Veileder for lærere [Mandatory assessment test in reading comprehension, Grade 5: Guidelines for teachers]. Oslo, Norway: Author. Retrieved from https://www.udir.no/eksamen-og-prover/prover/nasjonale-prover/.

Nouwens, S., Groen, M. A., Kleemans, T., & Verhoeven, L. (2021). How executive functions contribute to reading comprehension. *British Journal of Educational Psychology, 91*(1), 169–192.

Overton, W. F. (2015). Process and relational developmental systems. In W. F. Overton & P. C. M. Molenaar (Eds.), Handbood of child psychology and developmental science, Vol. 1: Theory and method (7th ed., pp. 9–62). Hoboken, NJ: John Wiley.

Pagani, L. S., Fitzpatrick, C., Archambault, I., & Janosz, M. (2010). School readiness and later achievement: A French Canadian replication and extension. *Developmental Psychology, 46*(5), 984–994.

Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods Instruments & Computers, 36*(4), 717–731.

Purpura, D. J., Baroody, A. J., & Lonigan, C. J. (2013). The transition from informal to formal mathematical knowledge: Mediation by numeral knowledge. *Journal of Educational Psychology, 105*(2), 453–464.

Purpura, D. J., Logan, J. A. R., Hassinger-Das, B., & Napoli, A. R. (2017). Why do early mathematics skills predict later reading? The role of mathematical language. *Developmental Psychology, 53*(9), 1633–1642.

Purpura, D. J., & Lonigan, C. J. (2013). Informal numeracy skills: The structure and relations among numbering, relations, and arithmetic operations in preschool. *American Educational Research Journal, 50*(1), 178–209.

Purpura, D. J., Schmitt, S. A., & Ganley, C. M. (2017). Foundations of mathematics and literacy: The role of executive functioning components. *Journal of Experimental Child Psychology, 153*, 15–34.

Rademacher, A., & Koglin, U. (2019). The concept of self-regulation and preschoolers' social–emotional development: A systematic review. *Early Child Development and Care, 189*(14), 2299–2317.

Rege, M., Størksen, I., Solli, I., Kalil, A., McClelland, M., Lenes, R., ... Hundeland, P. (2019). Promoting child development in a universal preschool system: A field experiment impressum. CESifo Working Paper No. 7775. Available at https://ssrn.com/abstract=3434830.

Ribner, A. D. (2020). Executive function facilitates learning from math instruction in kindergarten: Evidence from the ECLS-K. *Learning and Instruction, 65*, 101251. https://doi.org/10.1016/j.learninstruc.2019.101251.

Ribner, A., Harvey, E., Gervais, R., & Fitzpatrick, C. (2019). Explaining school entry math and reading achievement in Canadian children using the Opportunity-Propensity framework. *Learning and Instruction, 59*, 65–75.

Ribner, A. D., Willoughby, M. T., Blair, C. B., & Family Life Project Key Investigators. (2017). Executive function buffers the association between early math and later academic skills. Frontiers in Psychology, 8. http://doi.org/10.3389/fpsyg.2017.00869.

Romano, E., Babchishin, L., Pagani, L. S., & Kohen, D. (2010). School readiness and later achievement: Replication and extension using a nationwide Canadian survey. *Developmental Psychology, 46*(5), 995–1007.

Sarama, J., & Clements, D. H. (2009). *Early childhood mathematics education research*. New York: Routledge.

Sarama, J., Lange, A. A., Clements, D. H., & Wolfe, C. B. (2012). The impacts of an early mathematics curriculum on oral language and literacy. *Early Childhood Research Quarterly, 27*(3), 489–502.

Schenke, K., Rutherford, T., Lam, A. C., & Bailey, D. H. (2016). Construct confounding among predictors of mathematics achievement. *AERA Open, 2*(2). https://doi.org/10.1177/2332858416648930.

Schmitt, S. A., Geldhof, G. J., Purpura, D. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology, 109*(8), 1120–1140.

Schmitt, S. A., Purpura, D. J., & Elicker, J. G. (2019). Predictive links among vocabulary, mathematical language, and executive functioning in preschoolers. *Journal of Experimental Child Psychology, 180*, 55–68.

Simmons, F. R., & Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia, 14*(2), 77–94.

Solheim, O. J., Brønnick, K., & Walgermo, B. R. (2013). Kartlegging av leseferdighet 1-3-trinn (Assessment of literacy skills grade 1-3). Retrieved from www.fhi.no. https://www.udir.no/eksamen-og-prover/prover/rammeverk-for-kartleggingsprover-pa-1.-4.-trinn/

Størksen, I., Ellingsen, I. T., Tvedt, M. S., & Idsøe, E. M. C. (2013). Norsk vokabulartest (NVT) for barn i overgangen mellom barnehage og skole: Psykometrisk vurdering av en nettbrettbasert test. *Spesialpedagogikks forskningsdel, 4*(13), 40–54.

Størksen, I., Ellingsen, I. T., Wanless, S. B., & McClelland, M. M. (2015). The influence of parental socioeconomic background and gender on self-regulation among 5-year-old children in Norway. *Early Education and Development, 26*(5-6), 663–684.

Sung, J., & Wickrama, K. A. S. (2018). Longitudinal relationship between early academic achievement and executive function: Mediating role of approaches to learning. *Contemporary Educational Psychology, 54*, 171–183.

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.

ten Braak, D., & Størksen, I. (2021). Psychometric properties of the Ani Banani Math Test. *European Journal of Developmental Psychology, 18*(4), 610–628.

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.

Utdanningsdirektoratet. (2013). Nasjonale prøver 2013—Fagmiljøenes analyse av prøvene. Retrieved from https://www.udir.no/tall-og-forskning/finn-forskning/rapporter/Nasjonale-prover-2013—fagmiljoenes-analyse-av-provene/.

Utdanningsdirektoratet. (2018). Rammeverk for kartleggingsprøver på 1–4 trinn. Retrieved from https://www.udir.no/eksamen-og-prover/prover/rammeverk-for-kartleggingsprover-pa-1.-4.-trinn/#.

Van der Ven, Sanne H. G., Kroesbergen, Evelyn H., Boom, Jan, & Leseman, Paul P. M. (2012). The development of executive functions and early mathematics: A dynamic relationship. *British Journal of Educational Psychology, 82*(1), 100–119.

VanderWeele, Tyler J. (2016). Mediation analysis: A practitioner's guide. *Annual Review of Public Health, 37*(1), 17–32. https://doi.org/10.1146/annurev-publhealth-032315-021402.

Von Suchodoletz, A., Gestsdottir, S., Wanless, S. B., McClelland, M. M., Birgisdottir, F., Gunzenhauser, C., & Ragnarsdottir, H. (2013). Behavioral self-regulation and relations to emergent academic skills among children in Germany and Iceland. *Early Childhood Research Quarterly, 28*(1), 62–73. https://doi.org/10.1016/j.ecresq.2012.05.003.

Wanless, S. B., McClelland, M. M., Acock, A. C., Cameron Ponitz, C., Son, S. H., Lan, X. Z., Morrison, F. J., Chen, J. L., Chen, F. M., Lee, K., Sung, M., & Li, S. (2011). Measuring Behavioral Regulation in Four Societies. Psychological Assessment, 23(2), 364–378. https://doi.org/10.1037/a0021768.

Watts, Tyler W., Duncan, Greg J., Chen, Meichu, Claessens, Amy, Davis-Kean, Pamela E., Duckworth, Kathryn, ... Susperreguy, Maria I. (2015). The role of mediators in the development of longitudinal mathematics achievement associations. *Child Development, 86*(6), 1892–1907.

Watts, Tyler W., Duncan, Greg J., Clements, Douglas H., & Sarama, Julie (2018). What is the long-run impact of learning mathematics during preschool? *Child Development, 89*(2), 539–555.

Welsh, Janet A., Nix, Robert L., Blair, Clancy, Bierman, Karen L., & Nelson, Keith E. (2010). The development of cognitive skills and gains in academic school readiness for children from low-income families. *Journal of Educational Psychology, 102*(1), 43–53.

Zhou, Qing, Chen, Stephen H., & Main, Alexandra (2012). Commonalities and differences in the research on children's effortful control and executive function: A call for an integrated model of self-regulation. *Child Development Perspectives, 6*(2), 112–121.