Early Numeracy Development as a Foundation of Mathematics Achievement in Primary Education

Veronique Dierkx[1], Bernadette van de Rijt[1], Dave Hessen[2], Hans van Luit[1], Sietske van Viersen[1]

[1] Department of Development and Education of Youth in Diverse Societies (DEEDS), Utrecht University, Utrecht, the Netherlands

[2] Department of Methodology and Statistics of the Faculty of Social Sciences at Utrecht University

*Correspondence concerning this article should be addressed to Veronique Dierkx (vm.dierkx@gmail.com; +31 683450233).

Abstract

Purpose: This study aimed to investigate the 1) development of early numeracy (EN) between Kindergarten and Grade 1, 2) parental factors influencing this development, and 3) its predictive value for mathematics achievement mid-primary school. **Method:** The sample included 1252 children whose EN was measured bi-annually across six time points. **Results:** Latent growth curve modeling revealed non-linear growth in EN, with stronger effects of time throughout Kindergarten and a flattening curve in Grade 1, without reaching ceiling. Lower maternal education level and migration background were associated with lower EN at baseline, but these children also show greater improvement over time. Higher baseline EN and growth positively predict mathematics achievement in mid-primary school. **Conclusions:** Findings confirm significant EN development throughout early grades, but learning gains are not optimal in the current informal setting. Implications for early screening and intervention to address insufficient foundational skills, essential for later mathematics achievement, are addressed.

Keywords: Early Numeracy; Latent Growth Curve Analysis; Maternal Education and Migration Background; Mathematics Achievement; Primary Education

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In the Netherlands, the average mathematics level that children attain by the time they leave primary school has been declining for multiple consecutive years (Inspectie van het Onderwijs, 2022). According to the reference levels set up by the Dutch Ministry of Education, Culture and Science, 93% of children reached the 1F level for mathematics (i.e., the fundamental level, the minimum level children should reach at the end of primary school), and only 42% of the children who were leaving primary school reached the 1S level (i.e., the target level, needed to proceed to the higher levels of secondary education; Inspectie van het Onderwijs, 2022). This decrease in math achievement is alarming as math performance in primary education has been linked to future educational performance (Ginsburg et al., 2006; Siegler et al., 2012) and influences multiple factors in later life, such as financial success (Morgan et al,, 2009). As mathematics is a hierarchical skill (Hwang, 2020), children build their mathematical competence by accumulating knowledge obtained in informal and formal contexts (Kutaka et al., 2023). The current decrease in mathematics achievement at the end of primary school may thus result from ineffective early numeracy development in early years, leaving children with an insufficient foundation to build their knowledge on when formal mathematics instruction commences (van Luit, 2019). The current study aimed to investigate the development of early numeracy during early school years and how this may vary based on parental socioeconomic background factors. In addition, the predictive role of early numeracy development for math achievement in mid-primary education was also assessed. With the results of these research aims we hope to gain vital insight into how education in informal educational settings contributes to early numeracy outcomes.

Early Numeracy

Early numeracy (EN) refers to a set of skills needed to work with the number-word sequence and to make relational statements in a numerical context (Aunio & Niemivirta, 2010). EN covers multiple components that capture both counting skills and Piaget's traditional number development conditions (Raghubar & Barnes, 2017; van Luit & van de Rijt, 2020). van de Rijt and van Luit (1999) discern between the primary understanding of amounts, acoustic counting, asynchronic counting, synchronic counting, resultative counting, and shortened counting, which also describe the development of children's counting skills in phases (Aunio & Niemivirta, 2010). Around the age of 2, children become aware of the fact that numbers are linked to quantities but are still unable to distinguish them (Aunio & Niemivirta, 2010; Gelman & Gallistel, 1986). Subsequently, children start counting objects, ordering them, and subsequently start resultative counting around the age of 5, and shortened counting around age 5.5 to 6, meaning they recognize how numbers form quantities (e.g., groups of five) and use these numbers to count (Kleemans et al., 2012; van Luit & van de Rijt, 2020). Children are then able to use their counting skills for tasks such as measuring and estimating quantities (Kroesbergen et al., 2009; Toll & van Luit, 2014).

Additionally, the four Piagetian conditions for logical thinking (i.e. conservation, classification, correspondence, and seriation) are also part of EN and develop partly in tandem with counting skills (Aunio et al., 2004). The ability to operate the number–word sequence for whole numbers, and to use that ability in problem solving, increases substantially throughout EN development. It is important to recognize that in EN development, the ability to make relational statements is necessary to correctly solve tasks that require the counting of objects. For instance, to get a correct answer in an object counting task (which requires number–word sequence skills), the child needs to know what objects are to be counted (i.e., classification skills) and count all the included items once and only once (i.e., one-to-one correspondence). In addition, depending on the task, the child might need to decide based on the counting results which of the sets of objects has more or less than the others (i.e., comparison and seriation skills).

The development of EN starts roughly at birth and continues until around the start of Grade 1, when formal mathematics instruction starts (Kroesbergen et al., 2012; Li et al., 2018; Raghubar & Barnes, 2017). EN thus initially develops through informal education at home and in preschool/kindergarten (Jordan et al., 2022; Kroesbergen et al., 2009; Toll & van Luit, 2014). A sufficient level of EN is essential for children to benefit optimally from formal mathematics education in Grade 1 and onwards without problems (Namkung et al., 2019). Accordingly, monitoring numerical skills from a young age is of considerable importance to track EN development and discover potential issues in time (Kroesbergen et al., 2012). Moreover, McDonald et al. (2021) suggest early detection of problems with EN development through assessment in kindergarten could help teachers to focus their efforts towards weaker performing children. Previous research has shown that deficiencies in specific EN components can be effectively overcome using targeted interventions (Mononen et al., 2014; Nelson & McMaster, 2019; van Luit & Schopman, 2000). Hence, monitoring EN development is key to implement interventions timely and avoid that children lag too far behind while receiving formal mathematics education without the proper foundation (Clements et al., 2017; van de Rijt & van Luit, 1998). However, despite this knowledge, there is a clear lack of studies using longitudinal data to assess individual variation in EN development and its predictive value for later math achievement.

Early EN monitoring is difficult in the Netherlands, as most schools do not have a dedicated EN curriculum to support and monitor the development of EN. Children attend Kindergarten from the age of 4 and enter Grade 1 around age 6. Although screening on pre-literacy skills is common practice, there has been strong resistance against also screening children's numerical abilities during Kindergarten. Despite earlier attempts, schools have not been required to consistently screen children on their numeracy skills for over a decade now. Moreover, some years ago the Dutch Ministry of Education, Culture and Science decided that group tests in Kindergarten years had to be entirely removed from the student tracking systems.

Importantly, failing to monitor EN during early grades puts specific groups of children at increased risk of later math difficulties. This includes children who initially enter kindergarten with a lower EN level, for example those whose parents have a migration background (Aunio & Niemivirta, 2010). These children have been shown to perform more poorly due to various external factors (Henfield et al., 2008). Previous research that focused on implementing a math curriculum for minority students showed that instruction increased the math levels of these children and could resolve the achievement gap (Davis & Farran, 2018; Olszewski-Kubilius, 2006). This suggests that the lack of a formalized EN curriculum may have more negative consequences for these children in particular. Optimizing both the screening and instruction of EN in Kindergarten could help minimize the gap in foundational skills before the onset of formal mathematics instruction.

EN Growth Trajectories

To assess the extent to which children are currently able to benefit from informal education to develop their EN and to identify the potential need for early screening and interventions, it is important to gain more insight into growth trajectories of EN. Preferably, this development is mapped across Kindergarten (age 4 and 5; i.e., Years 1 and 2; Li et al., 2018; Torbeyns et al., 2002) and into the transitional year of Grade 1 (age 6 to 7) when formal mathematics instruction starts (Aunio & Niemivirta, 2010). However, current studies on growth in EN often cover a limited age range/focus on shorter periods and findings are mixed.

Studies conducted in Kindergarten and Grade 1 show different growth trajectories depending on the years or the set of numeracy skills investigated (Anders et al., 2012; Salaschek et al., 2014). Anders et al. (2012) measured EN on three occasions between the ages of 3 and 5 years and found linear growth trajectories in EN, meaning the scores on the EN measurements increased at a constant rate across the timepoints. Similarly, Toll and van Luit (2014) found linear growth in EN across the first two years of kindergarten, with the average starting age of the children being 4 years. Results by Salaschek et al. (2014) also confirmed linear EN growth, but they only assessed numerical abilities throughout Grade 1. Several other studies also found linear growth trajectories, but testing for nonlinear patterns was explicitly avoided there to facilitate interpretation of the growth trajectories. As such, it is unclear whether more complex models might have fit better for assessing EN growth (Clarke et al., 2008; Kohli et al., 2015; Salaschek et al., 2014). Most importantly, few of these studies have examined the growth trajectories in EN from the start of Kindergarten up until, or even beyond, the start of formal instruction in Grade 1. At this point, children must have fully developed their EN and growth rates may decrease as they approach ceiling levels (Torbeyns et al., 2002).

In contrast, other studies did find non-linear patterns of growth in EN (Hojnoski et al., 2018; Little et al., 2021; Namkung et al., 2019; Xenidou-Dervou et al., 2018). Schmitt et al. (2017) conducted a longitudinal study with four measurements of EN in preschool and Kindergarten (average starting age 4 years) and found positive quadratic EN growth, indicating that EN levels initially increased at a faster rate and slower across later timepoints. Namkung et al. (2019) found quadratic growth trajectories for informal and formal mathematics achievement in children during two years between Kindergarten and the end of Grade 1. Interestingly, positive increasing quadratic growth was found for formal mathematics skills and positive decreasing quadratic growth for informal mathematics skills (Namkung et al., 2019). This means that growth in formal mathematics skills was initially more shallow and later accelerated, while the growth rates in informal mathematics skills were initially higher and then flattened out. This corresponds with the expected mastery of EN around Grade 1, whereas children have only just started learning formal mathematics at the age at which they were assessed. Whether most children enter Grade 1 with fully developed EN, or necessarily extend this development into Grade 1 (possibly hampering early mathematical development), thus remains unclear.

Predictors of Baseline Levels and Growth in EN

Multiple studies have looked at factors that might influence baseline levels and growth trajectories in EN. From studies including cognitive predictors, we know for example that higher working memory and intelligence scores contribute positively to EN development (Noël, 2009; Stock et al., 2009). However, studies including environmental factors are more limited. Yet, we know that external factors in the direct environment of children can influence both baseline levels at school entry and subsequent growth trajectories of EN (Crane, 1996; Daucourt et al., 2020).

An environmental factor that has been suggested to influence EN levels of children is parental education. Using a latent growth curve analysis on EN with multiple predictors, Anders et al. (2012) demonstrated that maternal education level, parental native language status, gender, and SES contributed positively to baseline levels of EN as well as EN growth trajectories between children ages 3 to 5 years. Children whose mothers had obtained a higher education, whose parents spoke the native language, and who had a higher SES, had higher baseline EN scores upon entering preschool. Maternal education had no effect on the growth trajectory in EN, while the other predictors were all positively associated with the linear effect of time, indicating that children who scored higher on these predictors showed more growth between ages 3 to 5. In addition, a longitudinal study assessing EN in preschool and Kindergarten that found that higher parental education (the average of both parents) resulted in higher EN scores measured at age 5 (Slusser et al., 2019).

Furthermore, parental migration background has also been suggested to influence EN development (Blevins-Knabe, 2016). Previous research on parental influences in the home environment of four-year-old children, where children first informally develop their EN, suggests that a migration background is associated with less optimal conditions for EN development, which has a negative influence on learning in this environment (Niklas et al., 2016). Parental factors such as education level and migration background, often operationalized by using information from the primary caregiver (i.e., generally the mother), are thus important to consider when assessing EN development during early school years. More specifically, it is essential to learn whether these factors only influence baseline levels of EN, or also hamper growth, to establish to what extent informal EN instruction in Kindergarten is sufficient to counter these effects.

Predictive Value of EN for Later Mathematics Achievement

From studies on the foundational role of EN, we know that EN at various points during early development predicts later mathematics achievement (Claessens et al., 2009; Duncan et al., 2007; Jordan et al., 2009; Krajewski & Schneider, 2009; Skwarchuk et al., 2014). Baseline EN levels upon school entry have been shown to positively predict later mathematics achievement (Aunio & Niemivirta, 2010; Devlin et al., 2022), with higher EN levels in Kindergarten resulting in higher mathematics achievement in Grade 1. The same holds for EN levels in Kindergarten year two, which positively predict mathematics achievement in Grade 3 (Krajewski & Schneider, 2009), and EN levels at the beginning of Grade 1 positively predicting mathematics achievement in Grade 3 (Kiss et al., 2019). Furthermore, Duncan et al. (2007) found the EN level upon school entry to be more predictive of later reading and mathematics achievement than reading and attentional skills (Duncan et al., 2007).

Additionally, a limited number of studies showed that growth trajectories in EN may predict mathematics achievement. A study conducted in Kindergarten measured four EN components at three occasions and found that linear growth in EN predicted early mathematics achievement at the end of Kindergarten (Clarke et al., 2008). Keller-Margulis et al. (2008) found early growth in mathematical competencies in Grade 1 to be more positively predictive of mathematics achievement two years later than later growth, highlighting the importance of growth trajectories in early learning. Another study showed that linear growth in children's early number competence between Kindergarten and Grade 1 positively predicted mathematics achievement in Grade 3 (Jordan et al., 2009). This means that more growth in EN was associated with higher mathematics achievement, which is in line with the design and findings by Watts et al. (2014). However, studies that assess the predictive value of EN growth between Kindergarten and Grade 1 with a *comprehensive* EN test are limited. Research is thus warranted, as assessment of baseline levels or only measuring some EN components might not suffice to identify children at risk of poor EN development as well as later math achievement. More frequent monitoring over multiple years may be needed to inform decisions about intervention and to prevent adverse effects on later mathematics achievement (Salaschek et al., 2014).

The Present Study

In this study, we assessed EN development at six time points between mid-Kindergarten year 1 and the end of Grade 1 using a comprehensive test covering both counting skills and Piagetian concepts. Additionally, maternal education level and migration background were assessed as environmental factors. The main aims of the study were to investigate 1) growth patterns in EN between the start of Kindergarten and the end of Grade 1, explicitly including the transition from informal to formal instruction, 2) effects of environmental predictors on baseline levels and growth in EN, capturing learning gains in at-risk populations, and 3) the predictive value of baseline levels of and growth in EN for mathematics achievement in mid-primary education. We hypothesized a) non-linear growth in EN between mid-Kindergarten year 1 and the end of Grade 1, with trajectories indicating stronger initial growth and decreasing growth towards the end of Grade 1 as scores reach the asymptote, b) lower maternal education level and migration background predicting lower baseline levels of and growth in EN, and c) baseline levels of and growth in EN both predicting mathematical ability in mid-primary education, with both higher baseline levels and higher growth rates resulting in higher mathematics achievement.

Method

Participants

The sample consisted of 1252 children (n_{girls} = 614; 49%) ranging in age from 49 to 90 months (*SD* = 10.66; 4 to 7.5 years) at the time of the first assessment. Data were collected in three cohorts across three grades: Kindergarten year 1, Kindergarten year 2 and Grade 1, with two timepoints per grade, and each cohort starting in a different grade in a cohort-sequential design (see Table 1; Scammacca et al., 2020). Data were collected at 35 Dutch primary schools between the springs of 2019 and 2021 over six timepoints. To achieve a representative sample, the selection of schools was based on national data about the distribution of schools and the ratio of cities versus smaller towns per province, as provided by the Dutch Central Statistical Office (CBS, 2018a; 2018b). Special education schools were not included. Ethical approval was provided by the Faculty Ethical Review Board of XXXX (FERB project number XXXX). Parents provided written consent for data collection of EN and gathering background information on mathematics achievement and environmental factors separately.

Table 1

Number of Participants per Starting Moment and Timepoint

	Age in months		Early Numeracy						
	M	*SD*	T1 Middle KG1	T2 End KG1	T3 Middle KG2	T4 End KG2	T5 Middle G1	T6 End G1	% attrition
Cohort 1	56.8	0.50	414	392	339	221	236	258	38%
% girls			51.4%	51.5%	54.0%	53.4%	53.8%	53.9%	
Cohort 2	68.3	4.51			423	408	344	218	48%
% girls					47.2%	47.8%	48.3%	44.0%	
Cohort 3	80.7	4.77					415	386	7%
% girls							48.4%	49.0%	
Total			414	392	761	629	995	863	

Note. T = Timepoint; KG = Kindergarten; G = Grade. The starting sample is the sum of the bottom cells for the three cohorts at T1, T3, and T5 (*N* = 1252; not the row with Totals)

Instruments

Early numeracy

EN was measured using the *Early Numeracy Test 3* (ENT3; Utrechtse Getalbegrip Toets 3, 2022; van Luit & van de Rijt, 2020). The ENT3 is the third edition of a standardized test designed to measure children's EN. It aims to establish a child's level of EN to tailor teaching or to propose interventions, which both could help foster the child's future mathematical skills (Nelson & McMaster, 2019). The ENT3 consists of 50 questions that test 10 components of EN, with five items per component (see Appendix C for example items; van Luit & van de Rijt, 2020). The difficulty level of the items increased per component, so each component starts with an easy item and ends with the most difficult one. All items were scored dichotomously (0 = incorrect, 1 = correct). The total score was the sum of the scores on all items, with a maximum of 50. This total raw score was used in the analyses. The ENT3 has high internal consistency (Cronbach's $\alpha = .94$ at the first measurement occasion over all cohorts and .93 at the second measurement occasion) and reliability (test-retest $r = .90$).

Mathematics achievement

Mathematics achievement was measured by the LVS 3.0, a Dutch national standard test battery, administered in the middle and end of every school year (i.e., January/June; CITO, 2001). Here, the CITO mathematics scores from the end of Grade 2 were used to determine mathematics achievement in mid-primary school, as this test result was available for children from all cohorts and assured equal content of the test for all children. The test contained 56 exercises, including both arithmetic and word problems with a supporting picture. Four topics are covered at the end of Grade 2; numbers and number relations, addition and subtraction, multiplication and division, and measurement, time, and money. The raw test score (number of correct answers) was used in the current study. Mathematics scores were obtained for 203 children (16.2% of total EN sample).

Background information

Data about parents' background, including education level and migration background, were collected via a questionnaire distributed by the school. This information was collected for fathers and mothers separately. Building on previous studies, only maternal education level and migration background were included as predictors in this study. Mothers typically spend more time with the child at home during early years and might thus have a larger influence on their child's EN development (Giannelli & Rapallini, 2016). Maternal education levels were divided into three categories: low education (= 0; maximum of vmbo-gt [preparatory secondary vocational education]) or lower grades of havo/vwo [higher general secondary education/preparatory academic education]), intermediate education (= 1; maximum mbo 2-4 [secondary vocational education] or havo-vwo), and higher education (= 2; minimum hbo [higher professional education]), in line with guidelines of the Central Statistical Office (CBS, 2018b). Migration background was categorized as no migration background (0) vs. migration background (1), for which no distinction was made based on the country or region of origin.

Procedure

Data were collected between February 2019 and June 2021. Children were tested outside the classroom by student assistants from the bachelor program Pedagogical and Educational Sciences of [blocked for review] who were trained in the use of the ENT3). The test was administered individually during a 30-minute session, using a paper guide, additional materials such as dice and plastic pawns, and scoring sheets. Children received a sticker afterwards as a reward for completing the test. Data on children's mathematics achievement were retrieved from school records.

Analyses

Growth trajectories in EN were assessed using latent growth curve modeling in R version 4.2.2 (R Core Team, 2023) using the lavaan package version 0.6.13 (Rosseel, 2012) for structural equation modeling. Previous studies with similar methodology indicate that the sample size was sufficient for this statistical approach (Xenidou-Dervou et al., 2018). The analyses were conducted in three consecutive steps: Firstly, the shape of the growth curves in EN was determined by testing linear and nonlinear growth trajectories to find the best fitting model based on generally used indices of a good model fit: nonsignificant $\chi2$, root-mean-square error of approximation (RMSEA) < .05 (<.08 is acceptable) with a 90% confidence interval (CI) with lower limit ≤ .05 and upper limit of ≤ .08 (upper limit < .10 is acceptable), comparative fit index (CFI) > .95 (>.90 is acceptable), standardized root-mean-square residual (SRMR) < .05 (< .08 is acceptable); Browne & Cudeck, 1992; Kline, 2015). The baseline model included the six timepoints at which children were tested on their EN as indicators (ENT3 measures at T1- T6), an initial status factor (i.e., baseline level, with factor loadings fixed at 1 for all timepoints), and a linear growth factor (i.e., representing a linear effect of time, with factor loadings 0, 1, 2, 3, 4, 5, indicating equivalent intervals between the six timepoints). Residual covariances between the six consecutive timepoints were also added to the baseline model. In the case of an insufficient fit of the baseline model, a non-linear quadratic growth factor (i.e., representing a quadratic effect of time, with factor loadings, 0, 1, 4, 9, 16, 25) was added to the model to improve the fit, provided that this growth trajectory was more appropriate for the representation of EN growth (Kline, 2015).

Secondly, predictors were added to the model one by one. This was done by regressing the latent growth factors onto the predictors maternal education level (i.e., 0 = low education; 1 = intermediate education; 2 = higher education) and migration background (i.e., 0 = no migration background; 1 = migration background; see Figure 2).

Thirdly, the latent growth factors (baseline level and effect[s] of time) were used to predict mathematics achievement in mid-primary school (Grade 2). This was done by regressing the mathematics scores (end Grade 2) onto the growth factors (Figure 3). If possible, the mathematics scores would also be directly regressed onto the predictors to assess whether there was an additional direct effect of maternal education level and/or migration background on later mathematics achievement.

Results

Data screening

Outlier analyses showed no significant univariate or multivariate outliers. At each timepoint, there was missing data for EN (see attrition rates in Table 2) as well as for the predictor variables of maternal education level and migration background (624 and 683 cases respectively), and mathematics achievement (1049 cases). For the latent growth curve modeling, missing data were handled using Full Information Maximum Likelihood (FIML) estimation. This was also the case for the model with predictors, for which the sample size could still be considered large and data were missing at random (mainly due to school dropout; van Luit & van de Rijt, 2020). However, the model with mathematics achievement was tested on a smaller sample (N = 203), as there was too much missing data on the specific combination of predictors and mathematics achievement to run the model (see below). Descriptives for EN, maternal education level and migration background, and mathematics achievement are provided in Table 2.

Table 2

Descriptives of Total EN Scores per Timepoint, Predictors, and the Outcome Measure.

Measure	*N*	*M*	*SD*	Min	Max	%
EN T1	414	17.06	7.52	0	38	
EN T2	392	22.17	8.24	1	43	
EN T3	761	28.39	8.01	2	48	
EN T4	629	33.65	7.39	5	49	
EN T5	996	38.21	5.81	10	49	
EN T6	863	41.27	5.02	21	50	
Education level						
Low	17					3.0
Average	248					43.6
High	304					53.4
Migration background	133					21.2
Math achievement	203	189.8	30.9	93	283	

Note. EN = early numeracy; T = timepoint.

Correlations

Table 3 shows the correlations between the EN scores across the six timepoints, as well as maternal education level and migration background, and mathematics achievement. The EN scores on all six timepoints were moderately to strongly correlated with each other ($p < .01$). This indicates that individual differences in EN are highly stable across development. Maternal education level and migration background showed a very small but significant negative correlation, indicating that mothers' migration background is associated with a slightly lower education level. For maternal education level, correlations with EN were small to moderate and positive, and significant for timepoints 3 to 6, indicating that higher EN scores are associated with higher maternal education levels between mid-Kindergarten year 2 and the end of Grade 1. In addition, maternal migration background showed small but significant negative correlations with EN at timepoints 3 to 6, suggesting that maternal migration background is weakly associated with lower EN scores between mid-Kindergarten year 2 and Grade 1. Correlations between EN and mathematics achievement were

Table 4

Pearson's Correlations between EN Timepoints, Predictors and Mathematics Achievement.

Measure	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. EN T1	-								
2. EN T2	.83**	-							
3. EN T3	.74**	.77**	-						
4. EN T4	.71**	.72**	.79**	-					
5. EN T5	.57**	.60**	.73**	.73**	-				
6. EN T6	.62**	.60**	.70**	.69**	.73**	-			
7. Education level	.14	.14	.30**	.28**	.26**	.29**	-		
8. Migration background	−.11	−.06	−.21**	−.18**	−.18**	−.19**	−.13**	-	
9. Math achievement	.55**	.62**	.39**	.34**	.35**	.32**	.29**	−.07	-

Note. EN = early numeracy; T = timepoint.**p* < .05. ***p* < .01

significant ($p < .01$) and moderate for timepoints 1 and 2, and weak for timepoints 3 to 6, suggesting that EN levels in Kindergarten year 1 are more strongly associated with later mathematics achievement than EN levels in mid-Kindergarten year 2 and Grade 1. Finally, mathematics achievement showed a moderate positive correlation with maternal education level ($p < .01$), indicating that a higher education level in mothers is associated with higher mathematics achievement in their children.

Latent Growth Curve Modeling

The baseline model, including a linear effect of time, could not be fitted due to several negative residual covariances between the EN indicators. Therefore, the residual covariances were all fixed at zero. This adjusted baseline model had a poor fit, $\chi2(16) = 473.49$, $p < .001$, RMSEA = .15, 90% CI [.14 - .16], CFI = .83, SRMR = .13. Based on the potential shape of growth trajectories as indicated by the literature, a quadratic effect of time (modeling nonlinear growth), was added to the model. This model had a significantly better fit than the previous model, $\Delta\chi2\ (4) = 361.22$, $p < .001$, and demonstrated an acceptable fit: $\chi^2(12) = 112.27$, $p < .001$, RMSEA = .08, 90%CI [.07 - .10], CFI = .96, SRMR = .06.

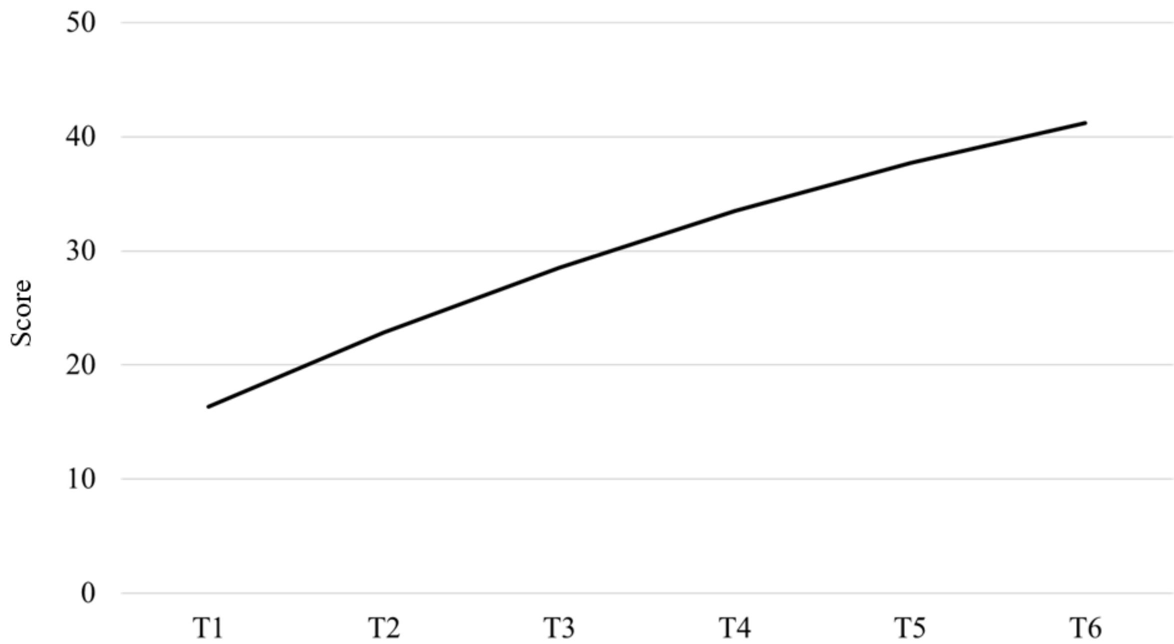
For the baseline level, the variance was significant, 56.07, *SE* = 4.16, $p < .001$, meaning that the children showed significant variability in EN mid-Kindergarten year 1 (T1). The variances for the linear and the quadratic effects of time were both significant, 6.81, *SE* = 1.47, $p <.001$ and 0.19, SE = .04, $p < .001$ respectively, suggesting that linear and non-linear growth trajectories varied significantly between children. Additionally, there is a moderate negative covariance between the baseline level and linear effect of time, −0.30, *SE* = 2.05, $p < .01$, indicating that the effect of time was smaller for children with higher baseline levels (i.e., slower growth). The strong negative covariance between the linear and quadratic growth factors indicates that the quadratic effect of time was smaller for children with growth trajectories that were characterized by a stronger linear effect of time (i.e., growth trajectories flatten less towards the end of Grade 1). In total, the model with both linear and quadratic growth factors explained about 79.4% of observed total variance in EN growth between mid-Kindergarten year 1 and end Grade 1.

Subsequently, the predictors were added to the model by regressing the latent growth curve factors on maternal education level and migration background. The model demonstrated good fit: $\chi^2(18) = 117.90$, $p = < .001$, RMSEA = .07, 90% CI [.06 - .08], CFI = .96, SRMR = .05. As displayed in Figure 2, maternal education level had a significant small positive effect on the baseline level but not the linear and quadratic effects of time. When controlling for maternal migration background, children with mothers with a higher education level thus had higher baseline levels of EN but not a more accelerated growth trajectory. Similarly, maternal migration background had a significant but very small negative effect, on the baseline level but not on the linear and quadratic effects of time. When controlling for maternal education level, children with a mother with a migration background thus had slightly lower baseline levels of EN at the start of the study, but not less accelerated growth trajectories. In fact, the model with the predictors also contained a moderate negative covariance between the baseline level and linear effect of time, indicating that children of mothers with a low education level and a migration background have lower baseline levels but actually show a more accelerated growth trajectories. The strong negative covariance between the linear and quadratic effects of time indicates that also in case of a low maternal education level and a migration background, the quadratic effect of time was smaller for children with growth trajectories that were characterized by a stronger linear effect of time (i.e., growth trajectories flatten less towards the end of Grade 1). Combined, the two predictors explained 6.8% of the variance in the baseline level, 1.2% of the variance in the linear growth factor and 2.6% in the quadratic growth factor. EN development across the six time points, as based on the means estimated by the model, is displayed in Figure 1.

The model is displayed in Figure 2 and an overview of the parameter estimates is provided in Appendix A.

Figure 1

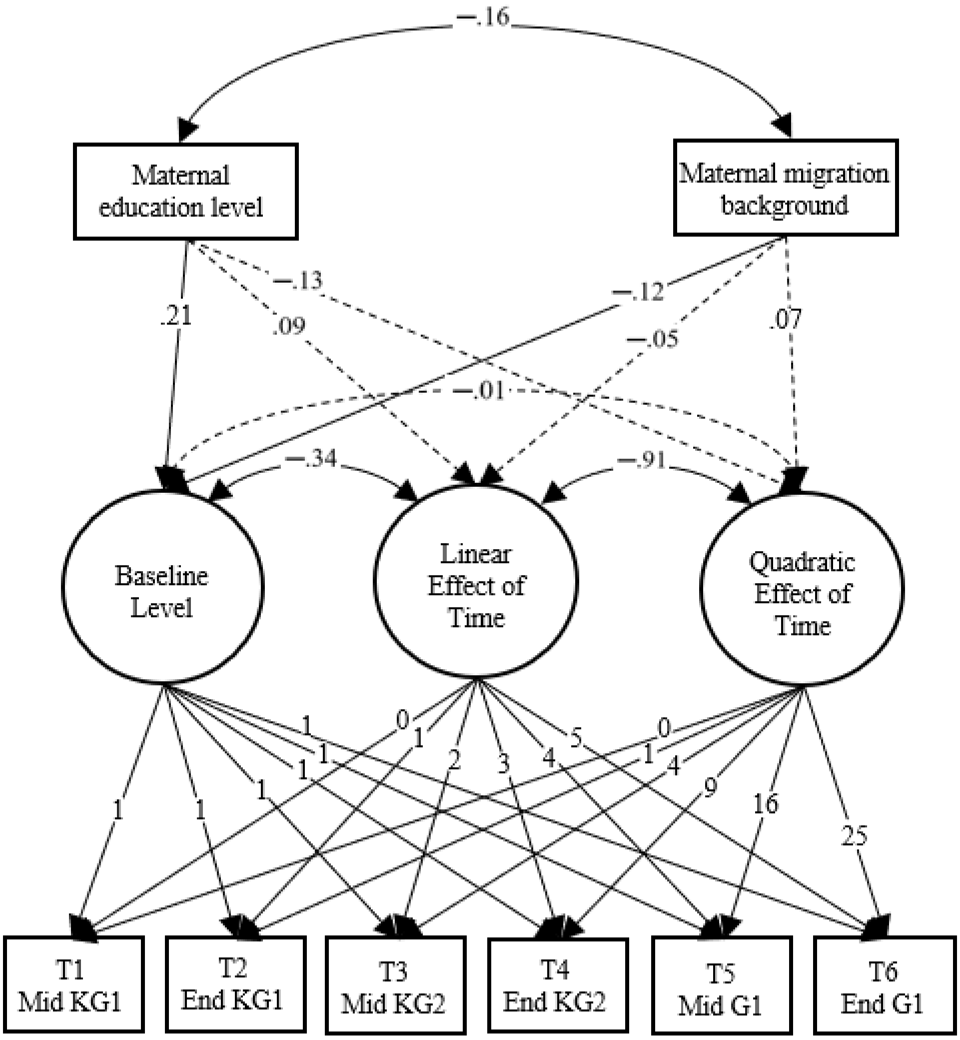
Estimated Mean EN Scores across the Six Timepoints in the Model.



Note. EN = early numeracy; T = timepoint. The maximum score on the ENT3 is 50.

Figure 2

Latent Growth Curve Model of EN with Maternal Education Level and Migration Background as Predictors.



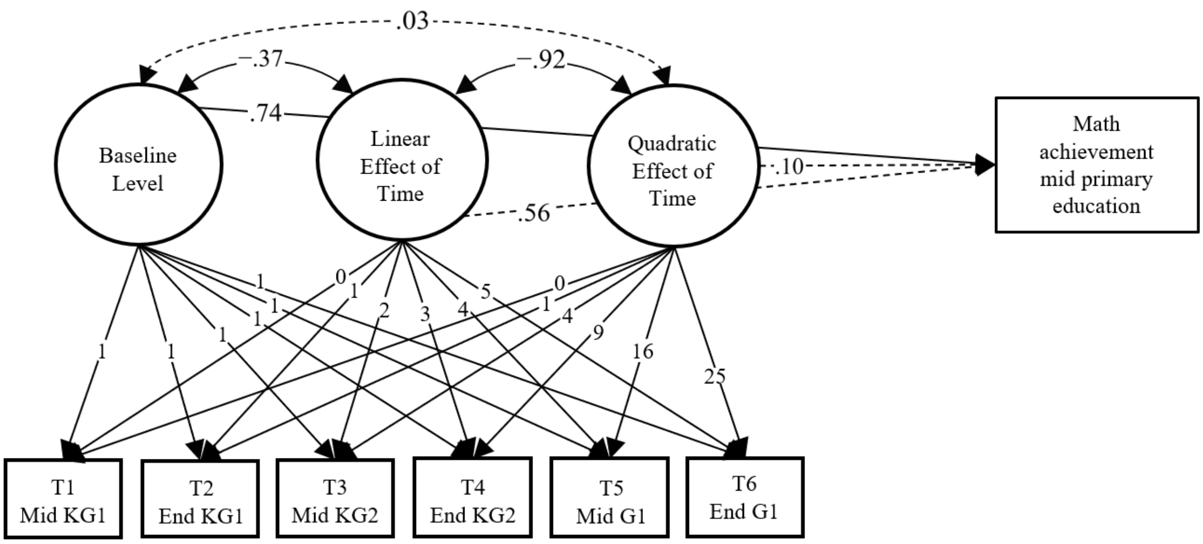
Note. T = Timepoint; KG = Kindergarten; G = Grade. Significant effects ($p < .05$) are visualized by solid lines. Error terms are not shown.

For the final model, mathematics achievement in mid-primary education was added as an outcome measure. As data on mathematics achievement were only available for part of the sample, the final model was fitted on a smaller subsample ($N = 203$). The representativity of the subsample was also checked for gender, migration background and region. The subsample slightly differed in terms of migration background and spread over the four regions of the Netherlands as compared to the national average (CBS, 2018a, CBS, 2018b). Predictor variables were not included in the final model due to the substantial amount of combined missing values. The fit of this final model was acceptable, $\chi^2(14) = 106.95$, $p = < .01$, RMSEA = .07, 90% CI [.06 - .09], CFI =.97, SRMR = .06.

The baseline level had a large positive effect on mathematics achievement mid-primary school. This indicated that higher baseline levels of EN resulted in higher later mathematics achievement. The positive effect of the linear effect of time on mathematics achievement was large, though not significant in this sample. The final model explained 42.6% of the variance in mathematics achievement and is displayed in Figure 3. A complete overview of the parameter estimates is provided in Appendix B.

Figure 3

Latent Growth Curve Model of EN with Mathematics Achievement as Outcome Measure.



Note. T = timepoint; KG = Kindergarten; G = Grade. Significant effects ($p < .05$) are visualized by solid lines. Error terms are not shown.

Discussion

This study investigated the early numeracy (EN) development of children to gain more insight into how education in informal educational settings contributes to (variation in) EN outcomes and its predictive value for later math achievement. EN was measured longitudinally, using a comprehensive test, across six timepoints between mid-Kindergarten year 1 and the end of Grade 1 in three cohorts of children. The main aims of the study were to gain insight into 1) growth patterns in EN between the mid-Kindergarten year 1 and the end of Grade 1, explicitly including the transition from informal to formal instruction, 2) effects of the environmental factors material education level and migration background on baseline levels and growth trajectories in EN, capturing learning gains in at-risk populations, and 3) the predictive value of baseline levels of and growth in EN for mathematics achievement in mid-primary education. The hypotheses regarding nonlinear growth, a positive influence of maternal education level, a negative influence of maternal migration background, and the prediction of later mathematics achievement by EN initial levels *and* growth curves were largely confirmed.

Regarding growth trajectories for EN, the results showed that EN development is characterized by strong initial growth throughout Kindergarten and subsequently decreasing growth towards the end of Grade 1. This was in line with our expectations and consistent with earlier findings by Hojnoski et al. (2018) and Namkung et al. (2019). Other studies that assessed growth trajectories during the Kindergarten years found a stable increase in EN throughout this period, which is also confirmed by our results (Anders et al., 2012; Toll & van Luit, 2014, see also Braeuning et al., 2020). The faster growth during early time points suggests that the Kindergarten environment provides new opportunities for children to informally learn and develop EN compared to the home and/or preschool/daycare environment(s). The less substantial growth in Grade 1 was also in line with our expectations, as children are supposed to have (largely) mastered the skills measured with the ENT3 by the end of Kindergarten year 2.

However, it is important to note that the decreased growth rates in Grade 1 are not due to a ceiling effect in the measurement of EN. None of the children reached the maximum score at T5, and only 9 children (1.0%) reached the maximum scores at T6. More importantly, only 46.8% of the children obtained at least an 80% score (40 points) on the ENT3 test by mid-Grade 1 and only 28.2% of the children obtained at least a 90% score (45 points) by the end of Grade 1, which would be considered EN levels indicative of a sufficient foundation (see Toll & Van Luit, 2014 for a similar score development throughout Kindergarten year 1 and 2 on a different sample using the ENT-R, the previous version of the ENT3). It thus seems that, for most children, EN was not sufficiently (and certainly not optimally) developed at these points in time. Similar findings were reported by Navarro et al. (2012), who found no ceiling effect in EN for children between ages 5 and 7 years, and Hampton et al. (2012), who observed linear growth in EN throughout Grade 1. Our findings thus suggest that many children may not have a proper foundation to start receiving formal mathematics instruction from Grade 1 onwards, and also do not develop these foundational skills further up to a sufficient level while also already receiving formal mathematics instruction. A formal EN curriculum might help optimize learning gains in this regard.

Concerning environmental factors predicting EN baseline levels and growth trajectories, maternal education level positively influenced baseline EN levels mid-Kindergarten year 1 but did not influence the trajectory of EN development. This suggests that, controlling for maternal migration background, children whose mothers had higher education levels scored higher on EN in mid-Kindergarten year 1, but did not show different growth trajectories. This is contrasting with previous research by Anders et al. (2012). They found maternal education level to be associated with EN growth, suggesting that higher maternal education resulted in faster EN growth in children. Yet, they found this effect in the presence of a small (and nonsignificant) positive covariance between the baseline and linear growth factors, whereas this covariance is negative in our study.

Similarly, maternal migration background negatively influenced baseline EN levels, indicating that children whose mothers had a migration background had lower EN levels in mid-Kindergarten year 1 when controlling for maternal education level. This is in line with our expectations based on previous studies (Blevins-Knabe, 2016; Niklas et al., 2016). Yet, the effect is rather small. This is encouraging, though against our expectations, as recent figures on the Dutch context have shown that, especially during the pandemic, children of parents with a migration background experienced larger learning losses in mathematics than children of parents without a migration background (Haelermans, et al., 2021; Inspectie van het Onderwijs, 2022). We also found that the migration background did not influence growth in EN, however. In fact, our finding of a small negative covariance between the baseline level and linear growth trajectory indicated that, also when controlling for maternal education level and migration background, children with lower baseline EN levels do show accelerated growth trajectories and thus catch up to some extent. Although children with lower baseline levels do not lag even further behind, but instead seem to benefit from more or less informal education in the school context, they do not close the gap as much as would be desired.

Concerning the predictive value of baseline levels and growth trajectories of EN on mathematics achievement, both baseline EN levels mid-Kindergarten year 1 and the linear effect of time were moderately to strongly related to children's mathematics achievement in mid-primary school. This is in line with our expectations and confirms earlier studies showing that higher baseline EN levels (Aunio & Niemivirta, 2010) are associated with higher later mathematics achievement. Importantly, although stronger flattening of the growth curve was expected to be associated with higher later mathematics achievement, we did not find an effect of quadratic growth on later mathematics achievement. Also, the mean growth curve as predicted by the model did not run as close to the asymptote towards the end of Grade 1 as we had expected.

Taken together, the findings suggest that the EN development of children between Kindergarten year 1 and Grade 1 follows the expected trajectory, but resulting levels achieved at the end of Grade 1 are not optimal and should be improved. These findings could contribute to lower mathematics achievement in mid-primary school and might (partly) explain the overall trend of declining mathematics achievement in the Netherlands. Given that part of this data were collected during the COVID-19 pandemic, this might account for the lower EN levels to some extent (Engzell et al., 2021; Haelermans et al., 2021; Nationaal Cohortonderzoek Onderwijs, 2021). However, adverse effects of the pandemic on growth, also via relevant environmental factors, are not evident in the current study. This suggests that the influence of the pandemic within the current study may be considered limited (see e.g., Toll & van Luit, 2014, for similar results).

Limitations

A clear limitation of the current study is the substantial amount of missing data in the predictors and the outcome measure. Due to the structure of the data collection, consisting of three cohorts that varied in the timepoints for which data were collected, and attrition (and re-entry) of schools and children throughout the study (partly due to COVID-19), this resulted in a large number of combined missing values. Accordingly, some effects could not be assessed and the final model, including later mathematics achievement, could only be tested on a subset of the sample, also affecting statistical power. However, using FIML estimation in our analyses is an adequate solution for dealing with missingness. Moreover, the data for the current study were collected in the context of the validation and norming of the new ENT3 test (van Luit & van de Rijt, 2020). Extensive checks have been performed to assure that the sample was representative of the targeted population and averages and percentages for relevant descriptive variables were all found to lie close to the national average (van Luit & van de Rijt, 2020).

Furthermore, as the data were collected partly during the COVID-19 pandemic, it would have been of major added value to also collect data about factors influenced heavily by these circumstances. Examples would be an indication of the amount of missed instruction time, applied instructional formats, contact hours, etc. Unfortunately, schools were not able to provide much information about how their education functioned throughout the pandemic, and available data were not detailed and systematic enough to analyze potential effects. Hence, although the effect of the pandemic on EN growth seems limited, the interpretation of our findings should be considered with some caution.

Implications and Future Research

Regarding theoretical implications, the current study has been the first to assess growth patterns in EN in a large sample over three consecutive years, starting when children enter school in Kindergarten year 1 and including the transitional phase of Grade 1 when children combine their informal development of EN with formal instruction in mathematics (Aunio & Niemivirta, 2010). As EN consists of multiple components that all have their own average age of onset (van Luit & van de Rijt, 2020), the transitional phase is vital to take into account, as not all components will have been fully mastered by the time children enter Grade 1. Through this approach, we have been able to establish the EN levels that children reach at the end of Kindergarten year 2 as well as illustrate how much further their EN still develops during Grade 1 alongside the formal mathematics instruction they then receive. These findings provide important information about variation in the extent to which children (with lower and higher baseline levels and from various backgrounds) benefit from the current informal EN curriculum as well as the necessity to identify children that need additional support or targeted intervention in their EN development. As illustrated, this can be done through a comprehensive test, covering all relevant aspects of EN, that can also be used to find specific gaps in children's EN.

Concerning practical implications, the current study suggests that the EN level of children in Grade 1 is not optimal and needs to be improved. There are several possible approaches to attain improvements in EN. One option would be to implement formal EN instruction *in Grade 1*, to assure that all children reach a sufficient EN level and are consecutively able to benefit from formal instruction in mathematics. A second option would be the implementation of a formal EN curriculum *from the start of Kindergarten*. The informal EN curriculum that is currently in place is apparently not sufficient to raise children's EN levels, and a formal curriculum before children reach Grade 1 could ensure a smoother transition to formal mathematics instruction. Ideally, this option would be combined with early screening on EN. Although early testing is controversial in the Dutch Kindergarten years, there is widespread consensus on the necessity and benefit of early screening and targeted intervention on precursors of literacy in early grades (see e.g., van Viersen et al., 2018; Zijlstra et al., 2021). Given the theoretical basis for EN as a foundational skill and the hierarchical nature of mathematics, similar importance should be given to early screening on EN. As with precursors of literacy development, if issues in EN are identified early there is still time to intervene and increase children's level. Moreover, early interventions have been shown to be effective in improving mathematics achievement (Bryant et al., 2011; Mononen et al., 2014; van Luit & Schopman, 2000). Hence, despite understandable apprehension towards early testing, early screening on EN should also be considered. It should be stressed, however, that both a formal EN curriculum *and* early screening can be implemented using play and age-appropriate activities; it does not mean that children are necessarily subjected to strict test situations and rigid instructional settings.

Future studies should replicate our findings on EN development in cohorts unaffected by the pandemic. Additionally, studies could focus on the specific growth trajectories of separate EN components within a population sample and reveal whether or not reaching a sufficient level of EN at the end of Grade 1 might be due to specific EN components lagging behind. If specific gaps are identified, interventions could be targeted accordingly (Hojnoski et al., 2018; Milburn et al., 2019), but adjustments to the curriculum should also be considered. As previous research also suggests that various EN components are predictive of different mathematics skills at a later age, very specific interventions could be implemented based on results of screening (Desoete et al., 2009; Litkowski et al., 2020). In addition, growth trajectories in EN and separate components could be assessed for the lowest performing children as well, including a range of cognitive and contextual predictors that might influence their development (including retrospective use of later diagnosis of dyscalculia or learning disability). Previous research has suggested that lower performing children show different growth curves, meaning interventions might need to be adapted accordingly (Aunio et al., 2015; Desoete et al., 2012; Dowker et al., 2005).

To summarize, EN development in young children is nonlinear between the start of Kindergarten and the end of Grade 1 and extends beyond the start of formal math instruction at the beginning of Grade 1. Children with lower baseline levels show faster growth, indicating that they benefit from the informal EN instruction within the school context. This also holds for children with lower maternal education levels and/or migration background. Given the predictive value of both baseline levels and growth in EN for math achievement in mid-primary grades, and the seemingly suboptimal levels of EN when formal math instruction starts, it is vital to not only increase efforts for early monitoring and intervention of EN development, but first and foremost to improve the quality of the EN curriculum and ensure all children are able to benefit optimally for maximum learning gains.

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