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Numeracy skills in young children as predictors of mathematical competence

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Abstract

As mathematical competence is linked to educational success, professional achievement, and even a country's economic growth, researchers have been interested in early predictors for quite some time. Although there have been numerous studies on domain-specific numerical abilities predicting later mathematical competence in preschool children, research in toddlers is scarce, especially regarding additional influential aspects, such as domain-general cognitive abilities and the children's social background. Using a large-scale dataset, the present study examined predictive effects of numeracy skills in 17-month-olds for later mathematical achievement. We found small, positive effects, even when controlling for child-related variables (i.e., age and sex) and the children's social background (i.e., maternal education and household language). Additionally, we compared results with a domain-general categorization task and found no distinct effect on mathematical competence. The present results are discussed with regard to the specificities of the dataset, as well as implications for future studies on predictors of mathematical competence.

KEYWORDS
cognitive development, mathematical competence, numeracy skills

BACKGROUND

Over the last few decades, research has provided ample evidence supporting a basic understanding of numerosity in children below 3 years of age (e.g., Cordes & Brannon, 2009; Starkey & Cooper, 1980; Wynn, 1992). A number of studies have shown that infants discriminate between various small number sets and pay attention to the number ratio of displayed objects (for a review, see Cantrell & Smith, 2013). Also, there is mounting evidence that Wynn's (1992) original findings on early arithmetic skills, namely that 5-month-old infants have basic addition and subtraction skills, are reliable (for a meta-analysis, see Christodoulou et al., 2017). Given that differences in basic numerical understanding appear to remain relatively stable during early childhood, it is therefore not surprising that researchers expect early numeracy skills to be predictive of later mathematical competence (Feigenson et al., 2013). However, meta-analyses reveal that most studies on the predictive effects of early numerical understanding on later mathematical competence focus on children aged 5 years and above (Chen & Li, 2014; Schneider et al., 2017, 2018). Existing studies that focus on younger children are still rare, limited in sample size (Ceulemans et al., 2015; Starr et al., 2013), and often lack important controls. Therefore, the present study uses a large-scale dataset to investigate the relationship between early numeracy skills – that is, early number perception and sensitivity to numerical changes in 17-month-old toddlers – and later mathematical competence, while controlling for the children's social background and early domain-general cognitive abilities.

Numeracy skills in early childhood

Mathematical competence is linked to educational success (Aubrey et al., 2006; Duncan et al., 2007), the solving of daily problems (Stacey, 2012), professional achievement (Organisation for Economic Co-operation & Development, 2005), and even to a country's economic growth (National Mathematics Advisory Panel, 2008; Organisation for Economic Co-operation & Development, 2010). Thus, it is not surprising that researchers want to identify how precursor abilities such as early numeracy skills development in young children. Numeracy skills are a central concept of early perception, processing, and reasoning about numbers (Feigenson et al., 2004). They are a widely researched concept and are also referred to as quantitative abilities, numerical reasoning, or numerical abilities (Antell & Keating, 1983; Bynner & Parsons, 1997; Geary, 2000; Starkey, 1992; Van de Rijt & Van Luit, 1999).

From a theoretical perspective, cognitive models of the development of numerical understanding in young children argue that infants perceive numerosity non-verbally and approximately, using basic perceptual cues (Mix et al., 2002). In particular, Clements et al. (2019) assume that infants start to quantify rigid objects with a general pre-attentive process that individuates discrete objects, while a specific number-related estimator simultaneously stores information about the quantity of the objects. Thus, two different cognitive systems are actively involved in the processing of numerical information: an analog magnitude system, which helps infants to discriminate between continuous number ratios of different sets of objects, and an object file system, which helps infants to represent an exact and discrete number of objects (Cordes & Brannon, 2008). With this theoretical approach, it can be reasoned that: (I) the understanding of numbers and quantities already starts in infancy; (II) numerical understanding is related to attentional processes, general perceptual skills, and more specific encoding processes of quantitative information; and (III) attention and attentional shifts to numerical stimuli comprising different numerical relations may indicate numerical understanding.

Attention to numerical stimuli is often examined using visual familiarization or habituation–dishabituation tasks. Such tasks are useful for investigating a broad range of cognitive skills in early childhood such as general visual or auditory discrimination and/or categorization skills (e.g., Arterberry & Bornstein, 2002). They present children with a series of either identical (i.e., information processing tasks) or similar (i.e., categorization tasks) stimuli. Observable behavioural responses such as looking behaviour, head turning (e.g., Lipton & Spelke, 2003), or the sucking rate (e.g., Antell & Keating,

Statement of contribution

What is already known on the subject?

- Numeracy skills in preschool children predict later mathematical competence.
- Predictive effects for children under 3 years have seldom been examined.
- Existing studies often have small samples and do not control for the children's social background.

What the present study adds?

- Large-scale data are used to analyse the predictive effects of early numeracy skills at 17 months on later mathematical competence.
- The study controls for the children's social background and early domain-general cognitive abilities.

1983) are recorded and used as a basis for calculating various measures of early information processing skills (for reviews, see Colombo & Mitchell, 2009; Kavšek, 2013). For the familiarization or habituation phase, measures of attentional decrement are used, which are interpreted as reflecting general information processing skills (e.g., Colombo et al., 2004). For the dishabituation phase, novelty measures are used. They are assumed to capture discriminatory memory performance or attention recovery (e.g., Friedman et al., 1970; Laucht et al., 1994). Habituation–dishabituation tasks are used for studying cognitive development (Rose et al., 2009) and the predictive effects of early cognitive measures for later competencies (Bornstein et al., 2013).

Domain-specific tasks are used to study a child's reaction in the dishabituation phase (novelty effect), showing how previous information is encoded, retrieved, and compared to the novel stimulus (e.g., Rose et al., 2012). Thus, domain-specific tasks assessing early numeracy skills usually habituate children to certain numerosity or ratio of quantities and investigate their reaction to novel quantitative information in the dishabituation phase (e.g., Antell & Keating, 1983; Ceulemans et al., 2015; Feigenson et al., 2013; Starr et al., 2013; Wynn, 1992). This reaction or novelty effect is generally interpreted as a basic form of numerical understanding, even though the effects are often confounded with space, contour shape, or density (Cantrell & Smith, 2013; Cordes & Brannon, 2008 for a critical discussion).

Early numeracy skills and mathematical competence

Mathematical competence is often conceptualized as a cognitive resource and as readiness to master challenges associated with the domain of mathematics (Niss & Højgaard, 2019). It involves, for example, the handling of operations with quantities, understanding of relationships between numbers, and geometrical or statistical understanding. Such definitions are compatible with the mathematical frameworks of the PISA and TIMSS studies (Lindquist et al., 2017; Organisation for Economic Co-Operation & Development, 2003). In these studies, mathematical competence, or mathematical literacy, also plays a fundamental role in preparing young people for everyday activities as well as for vocational challenges. Thus, mathematical competence enables a person to apply abstract mathematical operations in everyday contexts (Ojose, 2011), for example when describing, explaining, and predicting phenomena (Stacey, 2012).

Accumulated evidence suggests that there is a certain degree of continuity in mathematical development (for a review, see Siegler, 2016), as early interindividual differences are high (Duncan et al., 2007) and remain rather stable during the first years of schooling (Bailey et al., 2014; Jordan et al., 2009). Even earlier, namely at the age of 3–5, mathematical knowledge and numeracy skills – such as advanced counting skills, counting with cardinality, and subitizing (see below) – are strong predictors of later mathematics achievement (Nguyen et al., 2016; Watts et al., 2014). This highlights the notion that the association between numeracy skills and mathematical competence develops early on in life and remains rather stable. For example, some authors argue that subitizing – namely, the ability to immediately perceive a small number of objects without explicitly counting them – is related to the immediate and intuitive perception of numerosity or is simply a basic encoding mechanism before formal counting is acquired (Clements et al., 2019). According to the subitizing model of Clements et al. (2019), this ability is related to how children form number-related schemes by abstracting numbers and integrating this information into a counting-based verbal system. While several studies have investigated the associations between the numeracy skills of preschool children and their later mathematical competence in elementary school (e.g., Aunio & Niemivirta, 2010; Fuhs & McNeil, 2013; Krajewski & Schneider, 2009; Nguyen et al., 2016), studies of even younger children are relatively scarce.

Two notable studies investigated the predictive effects of very early numeracy skills and later mathematical competence but their findings were not as straightforward as the findings on numeracy in later childhood. Starr et al. (2013) studied the approximate number system in 6-month-old infants using a numerical change detection task (Libertus & Brannon, 2010). The authors presented the children with a sequence of slides with varying quantities of black dots. In one task, there was always the same amount of dots, whereas in the other task the numbers of dots switched between 10 and 20. Weber fraction scores were calculated to identify children with a higher number sense, that is, a higher discrimination skill for the numerical change. The scores predicted standardized mathematics test scores at 3.5 years of age ($r = .28$, $p < .05$). The standardized mathematics test featured tasks such as counting, number comparison, number knowledge, and basic calculation (Ginsburg & Baroody, 2003). The second study investigated number discrimination using a habituation task (Ceulemans et al., 2015). In this study, 8-month-old infants were shown sets of slides with different arrays of dots. In a test phase, the children were shown alternating slides of the familiar and novel stimuli. The difference in looking times was dichotomized, with children who looked at the novel stimulus for a longer time being categorized as having successfully discriminated between the presented magnitudes. However, the authors did not find an effect of number discrimination on the children's performance in a standardized cardinality test administered at 4 years of age. They only found a positive effect of number discrimination at 24 months on later cardinality scores and concluded that infancy might be too early for measures of number discrimination to predict later cardinality and, thus, that future research should focus more on toddlers.

Taken together, there is evidence for an association between early numeracy skills and later mathematical competence but the findings related to very young children are mixed and rare. The study by Starr et al. (2013) found a weak but significant correlation that was robust, even when general cognitive abilities were controlled for. The study by Ceulemans et al. (2015) did not identify effects in 8-month-old children but in 24-month-olds. Although the studies had well-controlled experimental designs, both drew on small samples, a fact Ceulemans et al. (2015) pointed out as a central shortcoming of previous research. Further, only Starr et al. (2013) included measures of early domain-general information processing which should be related to both early numeracy skills and later mathematical competence.

The present study

The present study investigates the predictive relationship between early numeracy skills and mathematical competence in young children. Hereby, we address several shortcomings of previous studies. First, only a few studies have investigated numeracy skills in children below 3 years of age and later mathematical competence. As early numeracy skills in preschool-age have been shown to be positively associated with later number knowledge, arithmetical knowledge, and complex mathematical problem solving (Aunio & Niemivirta, 2010; Chu et al., 2016), the present study extends this limited body of literature to toddlers.

Second, many studies on early numeracy skills use domain-specific tasks, for example, measures of numerical discrimination (e.g., Cordes & Brannon, 2009; Xu & Arriaga, 2007). However, they often do not include more domain-general tasks, unlike studies on preschool children (Chu et al., 2016; Passolunghi & Lanfranchi, 2012). The ability to abstract patterns (Amit & Neria, 2008) and form structural knowledge about numerical relations constitutes the basis for acquiring mathematical competence (Jonassen et al., 1993; Sfard, 1991). Thus, both domain-specific numeracy skills as well as more general cognitive abilities may contribute to task performance (Clements et al., 2019).

Lastly, research on whether numeracy skills in infancy predict later mathematical competence is typically conducted in small laboratory studies. It has been discussed whether a series of studies with small samples might lead to an overestimation of the actual effect at the population level (Maxwell, 2004; Oakes, 2017). Further, previous studies were conducted on rather homogenous samples and did not consider children's social background. Indeed, Fuhs and McNeil (2013) argue that the numeracy skills of preschool children (4–6 years of age) from low-income families could be more weakly associated with mathematical competence because these children might not have fully integrated numeracy skills in the larger context of mathematical competence. Their findings supported their initial expectation that social background is already an influencing factor for this age group. Furthermore, a longitudinal study on the effect of learning environments on the development of numeracy skills in preschool (i.e., counting, identification of numbers, knowledge of shapes, and understanding of early mathematical concepts, such as addition or subtraction) found household language and maternal education to be associated with the children's initial numeracy levels and their development of numeracy skills (Anders et al., 2012).

Therefore, the present study used a large-scale dataset to address these issues, controlling for central variables that have a meaningful impact on how young children develop mathematical competence. In particular, drawing on existing literature, we controlled for children's sex (Aunola et al., 2004) and age (Siegler & Braithwaite, 2017). Furthermore, we included the following social background characteristics: maternal education, as it influences a child's learning environment in formative years (Anders et al., 2012; Aunio & Niemivirta, 2010; Melhuish et al., 2008); household language, as the mathematical competence test was administered in German and mathematical achievement is usually correlated with language skills (Martiniello, 2009).

Research questions

Taken together, over the last few decades, research has been conducted to determine whether early numeracy skills are predictive of later mathematical competence, yet findings on early childhood are still limited. We used data from a large-scale study, which allowed us to additionally test and control for potential influences of the children's social background. In particular, our study had three main goals. First, we investigated whether early numeracy skills in 17-month-old children are predictive of mathematical competence at the age of 4 years. For that, we looked at the children's novelty effect in a numerical visual habituation–dishabituation task. We hypothesized that the novelty effect would be positively associated with later mathematical competence, even when controlling for general attention in the habituation phase. Second, we investigated whether important aspects of the children's social background influence this relationship. Many previous studies did not control for such aspects, but we suspected that the effect of numeracy skills on mathematical competence would be robust, as studies with older children confirm that domain-specific precursors are relevant for acquiring mathematical skills. Finally, we additionally used data of a domain-general categorization task with non-numerical stimuli to test whether the effect on mathematical competence is really due to domain-specific early numeracy skills.

METHOD

Sample

The Newborn Cohort of the National Educational Panel Study (NEPS SC1; Blossfeld et al., 2011) is a longitudinal dataset from a representatively drawn sample of N = 3481 infants born in Germany between February and July 2012 (Weinert et al., 2016). Each year, both the target children (observational tasks or competence tests) and their parents (parental interviews and questionnaires) take part in the survey. Over the course of the first years, about 80% of the target children were regularly assessed (Zinn et al., 2020). By design, only about half (N = 1893) of the original sample was asked to take part in the habituation–dishabituation tasks at the second measurement point (children aged on average 17 months); after dropout, N = 1510 parents participated in the study. Most of them (98.28%) gave informed consent for the habituation–dishabituation tasks and a total of N = 1315 children successfully finished the tasks, after child-related disturbances and technical errors were excluded. The mathematical competence test was administered at the fifth measurement point when children were on average 4 years old, which means there was a further longitudinal dropout. This study included all children who participated in the mathematical competence test from the subsample at the second measurement point and who also successfully participated in the habituation–dishabituation tasks (N = 871 children; 50.63% female).

Assessment of early numeracy skills

At the second measurement point, a visual habituation–dishabituation task with numerical stimuli was administered. The task was based on Cooper's (1983) method for assessing children's attention towards and discrimination of numerical changes, which have been suggested to be central precursor abilities for later mathematical competence (e.g., Feigenson et al., 2013). Cooper (1983) showed 10–12-month-old children two different arrays of dots. In the habituation phase, one array always featured more dots, while in the dishabituation phase the other array featured more dots. Thus, it was tested whether the children could process numerical changes. In the present study, all children were presented with the same stimulus material in the same sequence (fixed trial procedure); thus, surface area, perimeter, and density were not manipulated. All children were presented with a habituation phase, a subsequent dishabituation phase, and an attention control phase. The stimulus pictures (trials) in the habituation and dishabituation phases were presented for 10 s each, with an intertrial interval of 2 s. In the end, two additional and vastly different pictures were shown (attention control phase). We used these trials to check for outliers, possibly indicating that some children had fallen asleep or were not paying attention at all. As these control trials did not contain numerical stimuli, we did not include them in the present analyses. In the habituation phase, the stimulus sequence consisted of four pictures with varying amounts of identical cartoon sheep on the left side and identical bears on the right side were used. Instead of simple dots, this rather child-friendly stimulus material was chosen, as the household setting could have potentially distracted the children from boring pictures (the stimulus material was pretested; Freund, 2012). In Cooper's (1983) study, there were five familiar trials (i.e., the habituation phase), one (novel) reversed dishabituation trial and one trial with an equal ratio. Because the children in the original experiment were younger (10–12-month-olds), we expected the current number of habituation trials to be sufficient. The ratio of sheep and bears in the four trials of the habituation phase was always below the subitizing threshold, namely 3:2 (trial 1), 4:3 (trial 2), 3:1 (trial 3), and 4:2 (trial 4), respectively. As a fixed-trial procedure was used, this sequence was the same for all children, with no repetition of any trial. Thus, in the habituation phase, there were always more sheep than bears, while the first dishabituation picture reversed that ratio (2:4) and the second dishabituation picture had a balanced ratio (3:3). The total area and contour length varied between the trials. Each trial was accompanied by a short three-note auditory cue to attract children's attention. The task was administered by trained interviewers in the children's homes using a laptop (Weinert et al., 2017). The task lasted 94 s in total, not counting a pause interval of about 10 s between the numerical and the categorization task. The child's looking behaviour was recorded, and coding was performed offline using Mangold INTERACT software. For every single coding frame (30 frames per second), coders had to rate the children's looking behaviour (on/off target); the reliability was good, κ = .93. The present study used the accumulated sum of looking times for each trial, which ranged from 0 to 10 s. Looking times were not truncated, so there was no cut-off criterion for short looking times.

Children who discriminated between trials of the habituation and trials of the dishabituation phase were expected to look at the stimulus material for a longer time in the latter. In other words, they were expected to dishabituate to the novel stimulus which displayed a change in the number relation (Johnson & Zamuner, 2010). As the response to the novel stimulus reflected how the previous habituation phase was encoded (Kavšek, 2013), the novelty effect was defined as the difference in manifest looking times between the first dishabituation trial and the last habituation trial. We only used the first trial as this was the most discrepant to the habituation pictures (inverse number relation) and because using only the first novel stimulus had been shown to be the most robust (Kavšek, 2004). Higher values represent a strong reaction towards the dishabituation stimulus, indicating a large novelty response. In addition, we defined total time looking at the target during the habituation phase as another commonly used measure (e.g., Colombo et al., 1987). Hereby, we wanted to control for the children's general attention (Colombo et al., 2010).

Assessment of domain-general cognitive abilities

In addition to the numerical habituation–dishabituation task, a general habituation–dishabituation task with categorical stimuli was used. The task was also administered at the second measurement point, and the experimental setup, as well as the procedure, were similar to the numerical task – both tasks mirror the standard procedure of fixed-trial experiments in infant habituation. The only differences between both tasks were the number of trials in the habituation phase (i.e., nine pictures instead of four) and the stimulus material (i.e., categorical but not numerical). The higher number of trials in the habituation phase was deemed necessary for the children to form an adequate mental representation of the stimulus category. The original series of experiments from which this task was adapted had the same number of habituation trials – with the exception of the dishabituation phase having a novelty preference design (Zhang, 2007). The pictures presented in the habituation phase featured one round-shaped cartoon bug each which mainly differed with regard to highly specific details as well as the colour scheme; the pictures in the dishabituation phase featured rectangular-shaped cartoon bugs which differed with respect to many features from the habituation bugs. As in the numerical task, this sequence was the same for all children, with no repetition of any trial. We used the same approach to the data and the same measures as in the numerical task, namely the novelty effect and total looking time. The categorization task was always administered before the numerical task, and there was an additional dropout of $N = 64$ cases, mostly due to child-related reasons associated with the start of the tasks. The task lasted 154 s in total.

Assessment of mathematical competence

Children's mathematical competence was assessed at the fifth measurement point (children aged 4 years) with an adapted version of the Kieler Kindergartentest (Grüßing et al., 2013) developed specifically for implementation in the NEPS (Neumann et al., 2013). The test was administered on a tablet computer and consisted of 20 verbally administered questions that assess age-appropriate knowledge on the following content areas: sets, numbers, and operations (I), units and measuring (II), space and shape (III), change and relationships (IV), and data and chance (V; Jordan et al., 2015). The reliability of the test was acceptable (EAP/PV reliability = 0.70 and weighted likelihood estimators [WLE] reliability = 0.67). Due to the broad performance distribution, it was expected to accurately measure person abilities in high- and low-ability regions (Petersen & Gerken, 2018). The present analyses used WLE as an estimated score of individual competence (Warm, 1989).

Control variables

As child characteristics, we included sex (50.63% female) and age at the fifth measurement point; the children's social background was indicated by maternal education and household language. All control variables are reported for the final sample of $N = 871$ children.

For *maternal education*, we used the International Standard Classification of Education (ISCED), which classifies a broad range of institutional and professional qualifications in ascending levels, with higher scores representing higher educational degrees. This study uses an adapted version of ISCED 1997 (United Nations Educational Scientific & Cultural Organization, 2012) with a total of 10 categories, sorted in ascending order from no formal qualification to doctorate/habilitation.

For *household language*, we used a dichotomized variable. Children were grouped into primarily German (87.37%) and primarily non-German speaking households. If the parents reported at least once during the first five measurement points that the household language was primarily not German, the children were grouped into the latter category.

Statistical analyses

To examine associations between early measures of the numerical task and mathematical competence as well as between the control variables and mathematical competence, correlations were computed (Pearson correlation, point biserial correlation, and phi correlation, respectively). Furthermore, we conducted stepwise multiple linear regression analyses. We started with the novelty effect as the sole predictor of mathematical competence. The total looking time during the numerical task (habituation phase), individual child characteristics (i.e., sex and age), and the characteristics of the child's social background (i.e., maternal education and household language) were then added stepwise. In the last step, we calculated a similar multiple regression analysis, additionally including measures of the general categorization task, and then compared both final models with a Wald test. As preterm birth is generally associated with higher rates of mathematics learning disabilities (Simms et al., 2013; Taylor et al., 2009), we initially analysed children born preterm separately ($N = 46$) but found no effect on the association between their early numeracy skills and later mathematical competence. Thus, we report collapsed data for all children. There was a certain degree of missing values for the general categorization task (7.35%). However, as there was no correlation with the control variables, these values were regarded as missing at random, and full information maximum likelihood (FIML) was chosen to estimate the values. The calculations were performed in STATA© release 16 (StataCorp, 2019). The discussed findings are statistically significant at the $\alpha \leq .05$ level unless otherwise noted.

RESULTS

Table 1 displays descriptive information regarding the children's age, maternal education, mathematical competence (fifth measurement point), early numeracy skills, early categorization skills (i.e., novelty effects assessed at the second measurement point), and all control variables.

Because of the relatively high degree of dropout and the reduced sample at the second measurement point (by design), we conducted several analyses testing for potential bias in the data. First, we compared the children in our final sample ($N = 871$) with the rest of the initial sample of NEPS SC1 ($N = 2610$) regarding their social background. A Welch's t-test revealed a significant difference between the final sample ($M = 7.01$, $SD = 2.46$) and the rest of the cohort ($M = 5.85$, $SD = 2.93$; $t(1753.22) = -11.53$, $p < .001$) regarding maternal education. A proportion test also revealed a significant difference between the final sample ($M = 0.13$, SE = 0.01) and the rest of the cohort ($M = 0.24$, SE = 0.01; $z = 7.09$, $p < .001$) regarding household language, indicating that children in the final sample were less likely to come from primarily non-German speaking households. Next, we investigated differences in individual

TABLE 1 Descriptive overview of mathematical competence, early numeracy skills, and control variables

	N	Mean	Median	*SD*	Min	Max
Mathematical competence	871	0.07	0.03	1.02	−2.85	3.19
Numeracy skills	871	0.04	0	2.89	−9.27	9.63
Numerical task: total looking time (seconds)	871	30.36	31.97	7.30	1.80	40.16
General categorization task: Novelty effect	807	0.07	0	2.43	−7.60	9.93
General categorization task: Total looking time (seconds)	807	70.40	72.65	12.24	12.60	90.27
Child age (months; second measurement point)	871	17.02	17.02	0.59	15.77	18.95
Child age (months; fifth measurement point)	871	50.06	50.10	1.57	45.74	53.67
Maternal education	871	7.12	8	2.42	0	10

Note: Variables mathematical competence and maternal education refer to the fifth measurement point; numeracy skills, categorization skills, and total looking times of the children were assessed at the second measurement point.

child characteristics. As expected, there was an age difference between the final sample and the rest of the cohort, which was due to the habituation–dishabituation tasks being assessed several weeks after the parental interview at the second measurement point. There were no differences regarding the children's sex, $X^2(1, N = 3481) = 1.22, p = .27$. Importantly, the effects were also found when children in the final sample were compared only to the children who were selected by design to participate at the second measurement point.

Table 2 shows the correlations between mathematical competence at the age of 4, numeracy skills and categorization skills at 17 months, as well as all control variables. In line with our expectation, there was a positive correlation between early numeracy skills, as measured by numerical habituation–dishabituation task at 17-months of age, and the mathematical competence test at 4 years ($r = .07$, $p = .03$). In addition, there were significant correlations between mathematical competence and age ($r = .19, p < .001$), sex ($r = .08, p = .01$), maternal education ($r = .17, p < .001$), and household language ($r = −.15, p < .001$). The association between mathematical competence and total looking time was marginally significant for the numerical habituation task. There were no significant correlations between early numeracy skills and the control variables.

We conducted multiple linear regression analyses (Table 3) to predict mathematical competence based on early numeracy skills (Model 1.1). Total looking time for the numerical task (Model 1.2), individual child characteristics, and indicators of the child's social background (Model 1.3) were added stepwise. The exclusion of all children born preterm ($N = 46$) resulted in virtually identical effects and the model fits with the effect of numeracy skills in Model 1.1 being only marginally significant. Thus, collapsed results are reported.

In all models, early numeracy skills were a stable, significant predictor of later mathematical competence. Total looking time in the numerical task also predicted mathematical competence. For the control variables, standardized coefficients show that the children's age, maternal education, and household language each had a stronger predictive effect on mathematical competence than early numeracy skills. The overall explained variance was 10%.

To analyse the degree to which domain-general cognitive abilities might account for the effect of the numerical task, again multiple linear regression analyses were conducted (Table 4). Model 2.1 included early numeracy skills and total looking time for the numerical task as well as the novelty effect and total looking time for the general categorization task at 17 months to predict mathematical competence at the age of 4. In Model 2.2, individual child characteristics and indicators of the child's social background were added. The exclusion of all children born preterm ($N = 46$) resulted in virtually identical effects and model fits; only numeracy skills in Model 2.1 and total looking time for the numerical task in Model 2.2 were marginally significant. Thus, collapsed results are reported.

In both models, the measures of the general categorization task had no significant effect, while the effects of the numerical task remained significant. Based on Model 2.2, a Wald test was calculated to

TABLE 2 Correlations between early numeracy skills (age 17 months), mathematical competence (age 4 years), and all control variables ($N = 871$)

	Mathematical competence	Numeracy skills	Numerical task: total looking time	General categorization task: novelty effect[1]	General categorization task: total looking time[a]	Child age	Child sex	Maternal education
Numeracy skills	**.07***							
Numerical task: total looking time	.07	**−.19****						
General categorization task: novelty effect[a]	.04	.03	.03					
General categorization task: total looking time[a]	.06	−.005	**.31****	−.05				
Child age	**.19****	−.04	−.04	−.05	−.01			
Child sex	**.08***	−.05	.02	.06	−.002	.03		
Maternal education	**.17****	−.01	.06	**.08***	.06	−.01	.05	
Household language	**−.15****	−.05	−.01	−.02	.02	.05	−.02	**−.27****

Note: $*p < .05$; $**p < .01$. Child sex (1 = male and 2 = female); household language (0 = primarily German and 1 = primarily another language).

[a]$N = 807$.

TABLE 3 Summary of multiple linear regression analyses for variables predicting mathematical competence ($N = 871$)

	Model 1.1			Model 1.2			Model 1.3		
	B	SE *B*	β	*B*	SE *B*	β	*B*	SE *B*	β
Numeracy skills	.03	.01	.07*	.03	.01	.09*	.03	.01	.10**
Numerical task: total looking time				.01	.005	.08*	.01	.005	.08*
Child sex							.15	.07	.07*
Child age							.13	.02	.20**
Maternal education							.06	.01	.14**
Household language							−.34	.10	−.11**
R^2			.015			.01			.10
ΔR^2						.007			.09
F for change in R^2						5.79*			20.40**

Note: *$p < .05$, **$p < .01$; $N = 871$ for all models. Child sex (1 = male and 2 = female); household language (0 = primarily German and 1 = primarily another language).

TABLE 4 Summary of multiple linear regression analyses for variables predicting mathematical competence ($N = 871$)

	Model 2.1			Model 2.2		
	B	SE *B*	β	*B*	SE *B*	β
Numeracy skills	.03	.01	.09*	.03	.01	.09**
Numerical task: total looking time	.01	.01	.07	.01	.005	.07*
General categorization task: novelty effect	.01	.01	.03	.01	.01	.02
General categorization task: total looking time	.003	.003	.04	.003	.03	.03
Child sex				.14	.07	.07*
Child age				.13	.02	.20**
Maternal education				.06	.01	.13**
Household language				−.35	.10	−.11**
R^2			.01*			.10**

Note: *$p < .05$, **$p < .01$; $N = 871$ for all models; FIML was used for $N = 64$ missing values in the general categorization task. Child sex (1 = male and 2 = female); household language (0 = primarily German and 1 = primarily another language).

further investigate the effect of both measures. The null hypothesis could not be rejected when the novelty effect and total looking time for the general categorization task were simultaneously set equal to zero ($\chi^2 = 1.42$, $p = .50$). This indicated that the inclusion of these variables did not significantly improve model fit. Further, a robustness check was conducted without including the $N = 64$ children with missing values in the general categorization task. There were negligible differences in effect size and no differences in significance for all variables. Thus, only results with estimated missing values are reported in Table 4.

DISCUSSION

Previous studies on numeracy skills have seldom investigated the predictive effects of numeracy skills in toddlers for later mathematical competence; those that did failed to control for the children's social background and/or more domain-general cognitive abilities (Ceulemans et al., 2015; Starr et al., 2013). Thus, the aim of the present study was to investigate whether early numeracy skills in 17-month-old children are predictive of later mathematical competence at the age of 4 years. A visual habituation–dishabituation task with numerical stimuli was used, and we defined the novelty effect (i.e., attention to numerical changes) as a measure of numeracy skills and total looking time as a measure of general attention. We expected numeracy skills to be positively associated with later mathematical competence. Indeed, we found a significant predictive effect of early numeracy skills on later mathematical competence, even when controlling for general attention, individual child characteristics (i.e., sex and age), and indicators of the child's social background (i.e., maternal education and household language). The effect of the domain-specific precursor was small but comparable to the effects previously found (Ceulemans et al., 2015; Starr et al., 2013). Overall this effect was robust but smaller than the effect of age, maternal education, or household language. Altogether, the explained variance indicated that other, possibly more influential mechanisms still need to be explored. In particular, we compared the results with a model that also considered a general categorization task with a similar experimental design and procedure to the numerical task. Measures of this task were not predictive of mathematical competence, and numeracy skills remained significant when these measures were controlled for.

Researchers investigating children's numeracy skills typically habituate children to a specific ratio (e.g., Ceulemans et al., 2015; Xu & Arriaga, 2007) or to objects in an arithmetic relation (e.g., Wynn, 1992). Thus, the numerical habituation–dishabituation task in NEPS SC1 deviates from more common methods with an approach that has not been frequently used since Cooper's (1983) original study. The numerical habituation–dishabituation task habituated the children to a series of different ratios, favoring one of two presented stimulus types (i.e., sheep), while the dishabituation phase-shifted the numerical relation in favor of the other stimulus type (i.e., bears). Cooper (1983) argues that in the first year of life infants learn the concept of 'more' by combining numerosity and basic arithmetic operations, which he sees as the start of number development and of more complex mathematical operations. Likewise, the present study showed a predictive effect of numeracy skills on later mathematical competence. Thus, we argue that this approach is useful for examining the longitudinal effects of early numeracy skills on educational achievement.

Our study draws on a comparably large sample, which is why we were able to control for the children's social background. As aspects of the children's social background have been shown to be related to the early development of mathematical competence (e.g., Fuhs & McNeil, 2013), we included maternal education and household language as control variables. Overall, both variables had a stronger effect on mathematical competence than children's early numeracy skills in toddlerhood. Previous research on social disparities documents robust effects of children's social background (e.g., parental education and household income) on the early quantitative knowledge of children in preschool age (Aunio & Niemivirta, 2010; Halle et al., 2009), so these findings were expected. Interestingly, both variables were not correlated with early numeracy skills in toddlerhood. However, we do not rule out associations, as the focus of the present study was not to investigate social disparities in early numeracy skills, especially given that sample attrition was associated with the children's social background. It is possible that the numerical habituation–dishabituation task assessed children's more basic attention towards numerical changes, which already develop within the first year of life (Clements et al., 2019). This basic attentional measure might not be influenced by their social background as much as more formal mathematical knowledge such as counting and number knowledge (Jordan & Levine, 2009). Still, future research should investigate this topic more thoroughly, as at least one previous study already found social disparities in early quantitative knowledge at the age of 24 months (Halle et al., 2009).

Studies examining early numeracy skills in infants and toddlers with habituation–dishabituation tasks have been criticized for overinterpreting their findings (Cordes & Brannon, 2008; Quinn, 2008). Therefore, a careful interpretation of the present findings seems reasonable, especially because the effects – as in previous studies – were small. Further, the sequence of stimulus pictures was not randomized, and the total area or contour shape was not controlled for. As the stimulus material of the categorization task which we used as a measure of general cognitive ability did not differ with regard to space, contour shape, or density, we cannot rule out these confounding factors. In addition, as the children in the sample were aged 17 months on average, they were relatively old compared to other studies using habituation–dishabituation tasks. Furthermore, due to the test design of NEPS SC1, we cannot rule out sequence effects, as the numerical task and the general categorization task were always administered in the same order.

Lastly, the household setting could be a reason why the effects were small and why our findings might not be completely comparable to controlled settings in baby laboratories. Even though great attention was paid to the training of interviewers and the experimental setup was strictly specified and controlled with a computer, the observational setting could have differed depending on the characteristics of the household. For instance, there could have been different room lighting or the task could have been administered at different times of the day, possibly influencing the children's attention. Also, the living situation might have differed with regard to room space and traffic noise. Note, however, that this applies to both habituation tasks and that both the interviewers and the video raters reported few such cases. Nevertheless, for habituation–dishabituation tasks, there have been extremely few comparison studies; one short report found that looking time and habituation decrement were comparable between household and laboratory settings (Bornstein & Ludemann, 1989). Still, we believe that observing children in their homes can increase the ecological validity of such tasks. However, given the myriad of possible influences in children's homes, future research should compare different observational settings more thoroughly.

A central problem is that the numerical and general categorization tasks were not directly comparable, as both had a different number of stimulus pictures in the habituation phase (4 vs. 9 trials). Thus, the numerical tasks may have not included enough trials for children to habituate properly. In addition, as already mentioned, the tasks were administered in a fixed order, with the numerical task always coming after the general categorization task. This was deemed necessary because NEPS SC1 focuses on inter-individual group differences. We consequently cannot control for sequence effects, especially regarding children's general attention. Indeed, although initial looking times for both tasks were comparable, looking times for the numerical task tended to decrease more strongly and faster, but this could also be due to the stimulus material.

Owing to the considerable longitudinal dropout, we tested for potential bias in the final sample. We found that the mothers of children who successfully participated in the habituation–dishabituation tasks and for whom mathematical competence test scores were available had higher education levels on average and that their household language was more likely to be German. Thus, considering these variables, the final sample is not representative of the initial NEPS SC1 sample (for more information on sample attrition, see Zinn et al., 2020). Consequently, although the present sample is still larger (and probably more heterogeneous) than those of typical laboratory studies, results should not readily be generalized to the whole population. Given the ongoing debate about replicability and biased sampling in developmental studies (e.g., Fernald, 2010), future research should draw on more diverse samples and/or investigate the causes of sample attrition and participation as a function of children's social background.

Lastly, we only included a broad, dichotomous indicator of the children's household language, focusing on the comparison of children raised in primarily German-speaking households with children raised in households where another language was primarily spoken. The mathematical competence test was administered in German, which is why children from German-speaking households could have had an advantage. Thus, the validity of the measure could vary depending on children's language proficiency, although care was taken to use simple instructional language and to reduce the verbal demands as far as possible. Indeed, a previous study on German children in elementary school showed that German language skills had an effect on mathematical competence development over and above socioeconomic background and basic cognitive abilities (Paetsch et al., 2016). Still, because we used WLE scores, as provided by the NEPS, which showed negligible differential item functioning between children with and without migration background and, thus, acceptable test fairness (Petersen & Gerken, 2018), we do not consider this limitation critical for the main findings of our analyses. Of course, other studies focus on the role of language in the development of mathematical competence; however, this was not the aim of the present study.

The current study focused on whether the numeracy skills of 17-month-old children predict their mathematical competence at the age of 4 years. A robust relationship between toddlers' early numeracy skills and mathematical competence was found, even when controlling for sex, age, maternal education, and household language. The effect was generally small, and most control variables had larger effects on mathematical competence. Nevertheless, the inclusion of an attentional measure and a categorization task ruled out potential alternative explanations regarding domain-general cognitive abilities. We conclude that the adapted approach presented here should be compared to other numeracy tasks in studies investigating the development of mathematical competence. In addition, future studies should investigate possible associations between a child's social background and his or her developing numeracy skills more thoroughly.

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CONFLICTS OF INTEREST

All authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Maximilian Seitz: Conceptualization; Formal analysis; Writing – original draft. **Sabine Weinert:** Conceptualization; Funding acquisition; Project administration; Supervision; Writing – review & editing.

DATA AVAILABILITY STATEMENT

This paper uses data from the National Educational Panel Study (NEPS): Starting Cohort Newborns, https://doi.org/10.5157/NEPS:SC1:6.0.0. From 2008 to 2013, NEPS data were collected as part of the Framework Program for the Promotion of Empirical Educational Research funded by the German Federal Ministry of Education and Research (BMBF). As of 2014, NEPS has been carried out by the Leibniz Institute for Educational Trajectories (LIfBi, Bamberg) in cooperation with a nationwide network. Data of the numerical habituation–dishabituation task was also collected by the NEPS but coded by the project ViVA and will be added to the NEPS scientific use files. The data are available on reasonable request to the authors.

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