Besser, Nadine; Weinert, Sabine; Dornheim, Dorothea; Lehrl, Simone

# Reciprocal development of numeracy, mathematical language, and general language skills from age 2 ½ to 4 years : A cross-lagged panel perspective

Date of secondary publication: 14.08.2026

Version of Record (Published Version), Article

Persistent identifier: urn:nbn:de:bvb:473-irb-116816x

**Primary publication**

Besser, Nadine; Weinert, Sabine; Dornheim, Dorothea; u. a. (2026): Reciprocal development of numeracy, mathematical language, and general language skills from age 2 ½ to 4 years : A cross-lagged panel perspective, in: Learning and Individual Differences, Amsterdam [u.a.]: Elsevier Science, Vol. 131, No. 102991, pp. 1–12, doi: 10.1016/j.lindif.2026.102991.

Learning and Individual Differences 131 (2026) 102991

Contents lists available at ScienceDirect

# Learning and Individual Differences

journal homepage: www.elsevier.com/locate/lindif

# Reciprocal development of numeracy, mathematical language, and general language skills from age 2 ½ to 4 years: A cross-lagged panel perspective

Nadine Besser [a,*], Sabine Weinert [a,1], Dorothea Dornheim [a,1], Simone Lehrl [b,2]

[a] Department of Developmental Psychology, Otto-Friedrich-University of Bamberg, Germany
[b] Department of Education, University of Education Weingarten, Germany

ARTICLE INFO

*Keywords:*
Numeracy
General language
Mathematical language
Toddlers
Reciprocal development

ABSTRACT

This study examines reciprocal relations between toddler's numeracy and their language skills in “Germany” ($N = 389$, $M = 31.46$ months, $SD = 3.34$, 52.8% male) across three time points (collected between 2021 and 2023) while controlling for potential influencing factors. Cross-lagged panel models revealed that between ages 2½ and three years numeracy ($\beta = 0.19$, $p < .010$) and general language ($\beta = 0.25$, $p < .010$) development mutually predicted each other and both fostered later mathematical language ($\beta = 0.16$–$0.18$, $p < .010$). From three to four years, mathematical language predicted numeracy ($\beta = 0.21$, $p < .050$) and general language ($\beta = 0.32$, $p < .010$) development, while numeracy predicted mathematical language development ($\beta = 0.19$, $p < .010$). The results highlight the intertwined yet distinct roles of numeracy and general and math-specific language skills in early development.

## Educational relevance statement

This study extends existing research by examining early numeracy development together with both general language and mathematical language in 389 children from ages two-and-a-half to four. The findings demonstrate that these skills are linked through reciprocal relations that differ across early childhood. Between two-and-a-half and three years, general language and numeracy skills are related to each other's development, and both are associated with mathematical language development, whereas from around age three onward mathematical language is related to numeracy and general language development. The results suggest that promoting everyday language use in toddlers and, as they get older, the use of mathematical language, can be a promising way to support the development of language as well as numeracy skills.

## 1. Introduction

The development of foundational numeracy skills is a gradual and multifaceted process that begins early in children's lives, well before formal schooling starts (e.g., Mix, 2009; Sarama & Clements, 2009; Sarnecka & Carey, 2008). However, a considerable amount of children face significant challenges in acquiring early numeracy skills and lag behind their peers (e.g., Cahoon et al., 2024; Lehrl et al., 2020; Liu et al., 2025). Although early individual differences remain rather stable across time, it is widely recognized that early numeracy development does not occur in isolation, but rather in interaction with other cognitive and academic domains. Dehaene's (Dehaene, 1992; Dehaene et al., 2003) triple-code model of numerical cognition outlines distinct but interconnected systems for processing numerical information, including the processing of non-symbolic quantity information (i.e., analog code), which is supposed to be related to children's acquisition of number words (i.e., verbal code) and number symbols (i.e., visual code). Although each pathway uniquely contributes to early numeracy, prior research has consistently highlighted the linguistic pathway as the strongest predictor of early mathematical performance (Peng et al., 2020). Traditionally, this pathway has been examined through general language abilities, such as general vocabulary knowledge (e.g., LeFevre et al., 2010) and morpho-syntactic skills (e.g., Bonifacci et al., 2016). General language abilities are regarded as a foundation for children's progress in mathematics, since they support the use of mathematical terms, the communication of ideas, and the construction and retrieval of mathematical representations from long-term memory (“medium

* Corresponding author at: Otto-Friedrich-University of Bamberg, Markusplatz 3, 96047, Bamberg, Germany.
*E-mail addresses:* nadine.besser@uni-bamberg.de (N. Besser), sabine.weinert@uni-bamberg.de (S. Weinert), dorothea.dornheim@uni-bamberg.de (D. Dornheim), simone.lehrl@ph-weingarten.de (S. Lehrl).
[1] Otto-Friedrich-University of Bamberg, Markusplatz 3, 96047, Bamberg, Germany.
[2] University of Education Weingarten, Kirchplatz 2, 88250, Weingarten, Germany.

https://doi.org/10.1016/j.lindif.2026.102991
Received 3 February 2026; Received in revised form 16 July 2026; Accepted 4 August 2026
Available online 10 August 2026

function hypothesis"; Dehaene, 1992; Peng et al., 2020). In addition, language is assumed to contribute to the ability to reason about mathematical concepts and to develop strategies for solving problems ("thinking function hypothesis"; Peng et al., 2020; Vygotsky, 1989). However, emerging evidence suggests that language use in mathematical contexts (e.g., mathematical terms)—often referred to as mathematical or domain-specific language—may play a particularly crucial role (Peng et al., 2020; Turan & De Smedt, 2022). Nevertheless, it remains unclear whether the associations, often examined predictively in children from three years onwards, also apply to younger age groups and while controlling for autoregressive effects and concurrent associations. Furthermore, research has shown that the benefits are not unidirectional, but that general and mathematical language and numeracy skills might mutually strengthen each other's development (e.g., Chan et al., 2025; Chen et al., 2025; Peng et al., 2020). This is consistent with models of mutualism. These models assume that cognitive abilities have positive interactions and promote each other's long-term development (e.g., Kievit, 2020; Van Der Maas et al., 2006). Furthermore, research on language development has shown that a conceptual understanding (for example, regarding numeracy skills, an understanding of numbers or cardinality) facilitates the acquisition of meanings (e.g., of relational words, sentence structures that contain such words, or mathematical terms) (e.g., Bloom, 2000). Despite the potential significance of both general and mathematical language for numeracy skill development, research exploring the dynamic interplay of these three constructs at an early age remains limited. The present study aims to address these gaps by examining the cross-lagged associations between (1) math-related vocabulary and numeracy skills in children from age 2 ½ years onwards and (2) by additionally modeling their relation to general language skills over time.

## 2. Development of early numeracy skills and the importance of language

Research has consistently shown that children's language proficiency is strongly associated with their mathematical skills during the preschool years (Napoli & Purpura, 2018; Peng et al., 2020; Purpura & Reid, 2016). Purpura and Ganley (2014) demonstrated that language skills significantly predicted performance across a wide range of early numeracy tasks in preschool aged children. Furthermore, these associations are believed to emerge even before preschool age, as language is assumed to play a pivotal role in differentiating the symbolic number system—which typically starts to emerge as early as 18 to 24 months of age (Mix, 2009)—from the more basic, non-symbolic system responsible for approximate quantity discrimination, which is believed to be present already in infancy (Libertus & Brannon, 2010; Xu & Spelke, 2000). It is assumed, that language skills significantly impact the development of numerical understanding, as children rely on language—especially number-related vocabulary—to enhance and structure their grasp of quantities (Spelke, 2003). Consistent with this view, cardinality has been shown to be closely tied to general language skills, as children's understanding of cardinal numbers is associated with receptive and expressive vocabulary size between the ages of 2.5 and 5 years (Negen & Sarnecka, 2012). More recent evidence further suggests that general vocabulary size contributes to the acquisition of number words as early as age three, and even at 30 months children's ability to learn and retain new words predicts their "knower level" (e.g., knowing that the number 1 also represents quantity 1; Sarnecka & Carey, 2008) in number knowledge tasks (Horn et al., 2021). Horn et al. (2021) also argued that language and numeracy skills at the age of two-and-a-half-years rely on a shared strategy of forming one-to-one correspondences—assigning novel words to objects and assigning numbers to quantities. This shared mechanism might suggest that the relation between language and numeracy may not be purely unidirectional but instead provides a foundation for reciprocal influences between both domains from early in life. Beyond that, cross-lagged longitudinal path models (controlling for age and gender) demonstrate that phonological processing skills and basic number knowledge in 5- to 6-year-old children predict each other's development over the course of a year (Chen et al., 2025). Even though the findings should be interpreted with some caution in this context, since the characteristics measured relate to metalinguistic skills, they nevertheless suggest that not only do general language skills predict the development of numeracy skills, but that, conversely, numeracy skills might also predict the development of general language skills. This mutualism is also supported by a meta-analysis by Peng et al. (2020): General language skills—including vocabulary, phonological awareness, rapid automated naming, and oral comprehension—predicted later mathematical performance after controlling for initial mathematical skills, and likewise, mathematical performance predicted later general language when controlling for initial language skills. Theoretical assumptions suggest that language provides a scaffold for the development of number concepts by offering the linguistic structure needed to frame number as a category (Carey, 2009; Purpura & Logan, 2015). Once established, these conceptual foundations of numbers may, in turn, facilitate the acquisition of specialized mathematical vocabulary that organizes quantitative and spatial relations in early childhood (Hornburg et al., 2018, 2024). This reciprocal perspective is consistent with broader research on academic language, which highlights how language proficiency enables access to increasingly abstract, discipline-specific registers (e.g., Uccelli et al., 2015). Together, these findings and theoretical assumptions point to a dynamic and potentially reciprocal relation between early language and numeracy development. Nevertheless, whether such reciprocal associations can be reliably identified in early childhood development remains unresolved.

### 2.1. The specific role of mathematical language

In contrast to general language skills, specific academic domains such as numeracy are characterized by a highly specialized vocabulary (Purpura & Reid, 2016; Snow & Uccelli, 2009). As such, understanding and using this content-specific mathematical language is crucial for successfully engaging with mathematical concepts and problem-solving tasks. Empirically, numerical terms are usually intentionally excluded from the assessment of mathematical language to rule out the possibility that children's knowledge of numbers—as a foundation of their numeracy skills—is also measured as part of their mathematical language skills. Therefore quantitative (e.g., "much", "little") and spatial (e.g., "over", "under") words are focused and the items of mathematical language are set in a predominantly non-numerical context (e.g., Purpura et al., 2017; Purpura & Logan, 2015). Empirically, as early as age three, children's mathematical language is related to numeracy skills (e.g., Bleses et al., 2023; King & Purpura, 2021; Kung et al., 2019; Payne, 2024). For example, studies found that children who had higher mathematical language skills performed better in numeracy tasks (e.g., Purpura et al., 2017; Purpura & Logan, 2015). Mathematical language also contributes to stronger growth in numeracy skills for children with lower initial numeracy skills (Toll & Van Luit, 2014a). Moreover, the analyses by Bleses et al. (2023) indicate that the associations between mathematical language and numeracy skills are much stronger compared to those between general language and numeracy, particularly in lower-achieving children. In addition, a recent meta-analysis demonstrates a positive correlation between mathematical language and numeracy skills for children between the ages of three and a half and eleven and a half (the average age was 6 years), which was even stronger than the correlation between general language and numeracy skills (Zhu et al., 2026). Hornburg et al. (2024) found that general language predicted concurrent numeracy skills but not numeracy skills assessed 5 months later, while mathematical language predicted later numeracy skills. Further findings indicate that the relation between general language and numeracy skills is mediated by mathematical language (e.g., Ho et al., 2025; Toll & Van Luit, 2014b). Mathematical language also mediates the positive relation between the home numeracy environment (e.g., King & Purpura, 2021) and both children's mathematical language and their numeracy skills and can be improved through interventions (e.g., Besser et al., 2025; Bleses et al., 2021; Purpura et al., 2017). Conversely, a recent study with a sample of U.S. kindergarten children (mean age 5.9 years) revealed that number ordering and number line estimation skills at time 1 significantly predicted spatial language development during the next six weeks, indicating that numeracy skills might support the development of mathematical language (Chan et al., 2025). Beyond that, the reciprocal relations between mathematical language and numeracy skills were not further empirically tested (Zhu et al., 2026). An additional gap is that, to the best of our knowledge, only three studies have examined the mathematical language and numeracy skills of children under the age of three (Besser et al., 2025; Bleses et al., 2021; Slot et al., 2020). This represents a significant research gap as comparatively stable individual differences in mathematical and linguistic abilities are already observable by the age of three (e.g., Liu et al., 2025; Purpura & Reid, 2016) and thus must have developed beforehand. The results of Bleses et al. (2021) demonstrated that even at the age of two years, mathematical language and numeracy skills, both based on teacher ratings, can be improved through intervention. This result was confirmed by the analyses of Besser et al. (2025) and significantly extended through a direct measurement of skills: the children ($M$ = 2.6 years) whose teachers took part in a professional development training on math-specific interaction quality developed higher mathematical language and numeracy skills than both, the children in a comparison intervention group (training on global interaction quality) and a control group (no training) (Besser et al., 2025). However, only one of these studies examined autoregressive and cross-lagged relations between different school-readiness skills (including general language, mathematical language and numeracy skills) in under-three-year-olds (Slot et al., 2020). The results revealed, among others, that general language skills of children being 25 months old predicted mathematical language and numeracy development during the next seven months but not vice versa. Group comparisons also highlighted that general language skills predicted numeracy and mathematical language development, particularly in very young children between 12 and 24 months of age ($\beta = 0.34$, $p < .001$) but not in children between 24 and 36 months of age ($\beta = 0.16$, n.s.). However, these analyses were based on teacher ratings. Moreover, mathematical language and numeracy skills were not included separately in the analyses but as a composite indicator of mathematical skills, leaving no conclusions about the mutual relation between the development of mathematical language and numeracy skills at this young age.

### 2.2. The present study

Existing research has repeatedly shown that mathematical language skills predict numeracy skills from the age of three onwards. Further studies demonstrated that numeracy and mathematical language skills are not only closely related, but that their association seems to be stronger than that between general language and numeracy skills. However, these studies mostly examined predictive relations rather than conducting cross-lagged analyses. Due to the high stability of these measures, solely predictive analyses remain inconclusive as to whether the findings may be attributable to stability. Furthermore, the studies were mostly conducted with children aged three years and older. Yet, it is important to consider earlier phases of development, as significant differences in numeracy and mathematical language skills are already observable at the age of three years, indicating that their origin must be earlier. However, studies also demonstrate that numeracy and general language are closely related and predictive of each other. Yet, only a few studies examined all three constructs in a longitudinal model and even less considered autoregressive effects and concurrent associations between the constructs (as in a cross-lagged panel model [CLPM] for example). Since mathematical language is a form of language, the question remains whether the relations found between mathematical language and numeracy might in fact be attributable to general language. Therefore, there is a lack of deeper insights into the reciprocal development of numeracy and mathematical as well as general language skills, especially for children under the age of three. To address these gaps, we investigated the mutual and longitudinal prediction of early numeracy and mathematical as well as general language skills on each other's development in 2 ½ year old children across time to determine whether the existing findings could also be extended to a younger age group and to examine all three constructs simultaneously across time. In other words, we considered the cross-lagged paths for all three skills across the three measurement points (for example, from T1 to T2: numeracy T1—general language T2; numeracy T1—mathematical language T2; general language T1—numeracy T2; general language T1—mathematical language T2; mathematical language T1—numeracy T2; mathematical language T1—general language T2; the same applies for T2 to T3). This allows us to gain insights into whether early numeracy and general and mathematical language skills promote each other's development or whether one skill functions as a prerequisite for the development of the other skill. We hypothesized that between ages two-and-a-half and three years children who demonstrated higher levels of general and mathematical language would also demonstrate higher levels of later numeracy skills and vice versa. As children's language develops, their vocabulary becomes increasingly differentiated and domain-specific (e.g., Kauschke & Hofmeister, 2002). Previous research with children aged three years and older has consistently demonstrated that mathematical language is uniquely associated with numeracy and explains variance beyond general language (e.g., Purpura & Reid, 2016; Toll & Van Luit, 2014b; Zhu et al., 2026). Building on these findings, we hypothesized that between ages three and four years, mathematical language would play a more prominent role than general language in predicting subsequent numeracy development. Drawing on mutualism models that assume that reciprocal interactions between cognitive domains change over the course of development (Kievit, 2020; Van der Maas et al., 2006), and based on findings that show that both concept development (Bloom, 2000) and language (Kauschke & Hofmeister, 2002) become increasingly specific, we investigated exploratively whether numeracy skills would increasingly predict the development of mathematical language rather than that of general language as mathematical concepts become more differentiated. We tested these hypotheses and assumptions within one model thus also considering the simultaneous cross-sectional interrelation between constructs.

## 3. Methods

### 3.1. Sample and design of the overall study

The present analyses use data from the longitudinal project EarlyMath ((Lehrl et al., 2024; Linberg et al., 2019), which is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). The focus of the project is to analyze children's numeracy and mathematical language development and influencing factors from the age of two-and-a-half-years onwards (Fig. 1). Two cohorts (cohort 1: $N$ = 191 children from $N$ = 50 childcare centers; cohort 2: $N$ = 217 children from $N$ = 45 childcare centers) have participated in the project since 2020 with three measurement points: time 1 (T1) and time 2 (T2) with approximately 4 months in between and time 3 (T3) approximately one year after T2. The total of $N$ = 408 children and $N$ = 95 childcare centers were from the two main regions Upper Franconia and Upper Bavaria in Bavaria (Germany). As part of the EarlyMath project, between T1 and T2, the participating teachers (one per childcare center) either received two days of professional development training on mathematical (math-specific intervention group MIG; $N_{\text{children}}$ = 131) or general (general intervention group GIG; $N_{\text{children}}$ = 141) interaction quality or took part in a 90-min information event without training (control group CG; $N_{\text{children}}$ = 136). Detailed information about the intervention (impact period: 2 months) and the study design can be found at (Lehrl

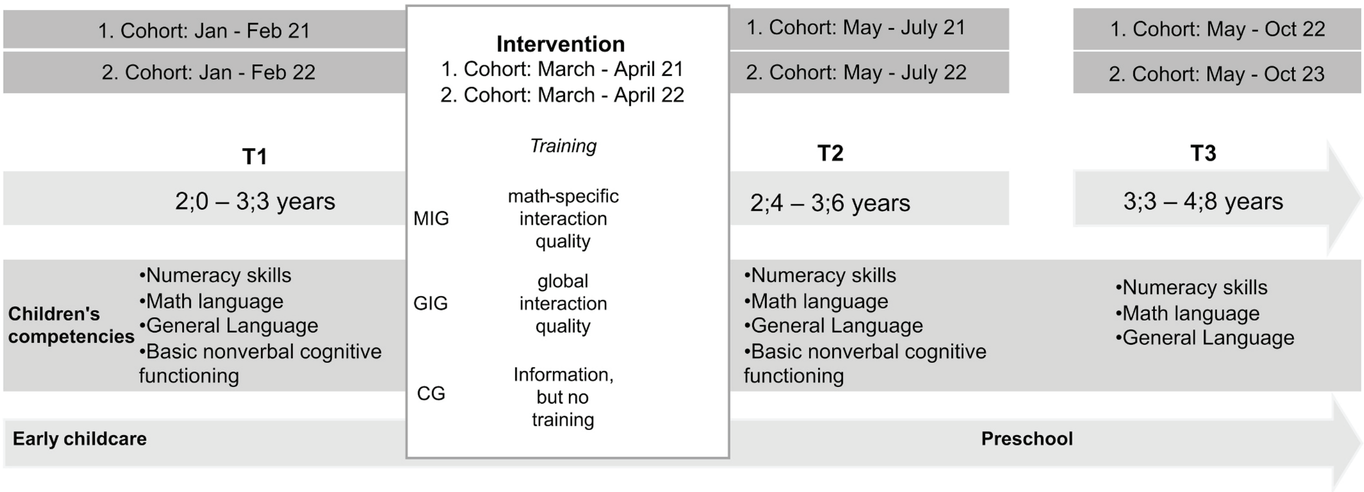


**Fig. 1.** Overall design of the EarlyMath study. T1 = First measurement point; T2 = Second measurement point; T3 = Third measurement point.

et al., 2024). The Institutional Review Board of the University of Bamberg approved the EarlyMath project and the study was conducted in accordance with the Ethical Principles of Psychologists and Code of Conduct of the American Psychological Association (2017).

### 3.2. Participants

Collecting demographic data is a balancing act between (1) important information on sample characteristics and (2) sensitive personal data about individuals. Therefore, we have only collected the most necessary demographic data, which on the one hand allows us to contextualize the results and on the other hand does not overly intrude on the privacy of the participating children and their families. For recruitment all childcare centers in the targeted regions that care for children under the age of three ($N = 848$ in Cohort 1 and, by expanding the region, an additional $N = 501$ in Cohort 2) were first identified and then contacted initially by e-mail and then by telephone. One teacher per participating early childcare center was allowed to take part in the project and distributed the information material and confirmation of participation to all parents of the children in our target age range (2;6–2;11). After the parents had given their informed consent, an average of four children (range: 1–8 children) per early childcare center took part in the project. Since some of these children fell outside our target age range, we expanded the target age range to 2;0–3;3 years. Nevertheless, we had to exclude 19 of the initial 408 children from the analysis because they were still too far outside the age limits ($N = 9$) or they had only data at T3 ($N = 10$). At the first measurement point (see Table 1 for a descriptive summary), the 389 children (52.8% male) were $M = 31.46$ months old ($SD = 3.34$, range = 24–39 months). The children's family language was in most cases German (77.7%), followed by at least one other language besides German (22.3%). Most parents were highly educated (71.5% with at least one parent holding a college degree), while under one third of the parents indicated vocational education (28.5%). The monthly net income of all household members averaged $M =$ €4.000 to less than €5.000 ($SD =$ €2.000; range: less than €1.000 to €8.000 and more), however 37% of parents did not answer this question at T1. The participating families thus fall within the middle range of the net household income in Germany in 2021. While couples with children had an average net household income of €5.600, single parents had an average of around €3.100 (Federal Statistical Office, 2021). Between T1 and T2, $N = 52$ children dropped out of the analyses (13%). At T3 (i.e., one year after T2), data from $N = 192$ children were available (attrition rate T1–T3: 49%). Selectivity analyses revealed that the dropout groups (completers (T1–T3), late dropouts (T1 and T2 only), early monotone dropouts (T1 only), and children with intermittent missingness (T1 and T3 only)) did not differ in terms of their performance test scores (i.e., numeracy skills, mathematical and general language), their family language, their intervention group, or their gender. However, evidence of an age difference between the groups was found: children who dropped out between T2 and T3 (i.e., late dropouts) were slightly older at T1 ($M = 32.1$, $SD = 3.31$) than children who participated at all three measurement points ($M = 30.9$, $SD = 3.25$). The remaining pairwise comparisons were not significant.

### 3.3. Assessment of children's early numeracy skills and their general and mathematical language

The examiners were students who either already had or were about to complete a bachelor's degree in psychology or educational science. To guarantee standardized yet joyful task administration, they attended a six-hour online training with video feedback, which was conducted by the project's research assistants. After that the examiners tested the children at T1 and T2 (average interval of four months) and at T3 (one year after T2). The test sessions (30 to 40 min per test session; at least two sessions on two consecutive days) were coordinated with the participating teachers. To give the children the opportunity to get to know the examiners when not in the test situation, the examiners took part during breakfast and/or the morning circle. Participation in the project and each test session was voluntary. The tasks and tests were conducted in a standardized yet engaging way. A stuffed sheep named Woolly assisted the examiners to keep the children motivated and focused. The examiners were blind concerning the intervention group.

### 3.4. Measures

A variety of age-appropriate tasks and tests measured the numerical, verbal and basic nonverbal cognitive competencies of the children. The tasks assessing general and mathematical language, numeracy skills and included controls are presented below (see Table 1 for a descriptive summary). A detailed description of the further tests can be found in (Lehrl et al., 2024).

#### 3.4.1. Numeracy skills

Four subscales (on verbal counting, counting objects, cardinality [give-n], cardinality [point-to-x]) comprise the numeracy skills construct; the scores were aggregated (sum scores) per child across all subscales (see Table 1 for an overview on item numbers, internal consistencies, and descriptives). Confirmatory factor analyses revealed a unidimensional structure (Chi-square $\chi^2 = 255.49$, $p < .001$; robust CFI $= 0.94$; robust RMSEA $= 0.15$ 90% CI [0.09; 0.23]; SRMR $= 0.06$).

**Table 1**
Descriptive information on the analysis variables and control variables (sum scores[1]).

| | N | M | SD | $\rho_{KR20}$ | Range | |
|---|---|---|---|---|---|---|
| | | | | | Potential | Actual |
| Numeracy (T1) | 334 | 13.09 | 6.35 | 0.84 | 0–48 | 0–35 |
| Verbal Counting | 333 | 2.11 | 2.13 | 0.83 | 0–10 | 0–9 |
| Counting objects | 333 | 1.99 | 1.90 | 0.78 | 0–10 | 0–7 |
| Give-N | 331 | 3.63 | 1.73 | 0.67 | 0–14 | 0–11 |
| Point-to-X | 301 | 5.99 | 3.14 | 0.73 | 0–14 | 0–12 |
| Numeracy (T2) | 342 | 17.29 | 8.16 | 0.89 | 0–55 | 0–41 |
| Verbal Counting | 340 | 3.11 | 2.34 | 0.84 | 0–10 | 0–9 |
| Counting objects | 341 | 3.06 | 2.11 | 0.80 | 0–10 | 0–8 |
| Give-N | 341 | 4.69 | 2.28 | 0.78 | 0–17 | 0–15 |
| Point-to-X | 324 | 6.83 | 4.14 | 0.84 | 0–18 | 0–17 |
| Numeracy (T3) | 192 | 31.15 | 10.48 | 0.98 | 0–55 | 6–55 |
| Verbal Counting | 192 | 6.06 | 1.95 | 0.93 | 0–10 | 0–10 |
| Counting objects | 192 | 5.53 | 2.09 | 0.92 | 0–10 | 0–9 |
| Give-N | 192 | 9.16 | 4.43 | 0.96 | 0–17 | 0–17 |
| Point-to-X | 192 | 9.09 | 5.20 | 0.96 | 0–18 | 0–18 |
| Mathematical language[a] (T1) | 308 | 8.97 | 3.48 | 0.67 | 0–21 | 0–19 |
| Mathematical language[a] (T2) | 324 | 13.94 | 4.64 | 0.71 | 0–31 | 0–26 |
| Mathematical language[a] (T3) | 180 | 21.19 | 4.53 | 0.98 | 0–31 | 7–30 |
| General language[b] (T1) | 310 | 13.00 | 7.09 | 0.91 | 0–44 | 0–33 |
| General language[b] (T2) | 318 | 17.17 | 8.14 | 0.93 | 0–44 | 0–37 |
| General language[b] (T3) | 192 | 15.81 | 7.28 | 0.96 | 0–36 | 0–30 |
| Control variables | | | | | | |
| Age in months (T1) | 389 | 31.46 | 3.34 | | | 24–39 |
| Age in months (T2) | 337 | 35.63 | 3.25 | | | 29–43 |
| Nonverbal basic cognitive functioning (T1)[c] | 305 | 3.19 | 2.12 | 0.78 | 0–10 | 0–9 |
| Nonverbal basic cognitive functioning (T2)[c] | 317 | 4.26 | 2.15 | 0.77 | 0–10 | 0–10 |
| Family language[d] | 299 | 1.7 | 0.45 | | 1–2 | 1–2 |
| Intervention group[e] | 389 | 2.0 | 0.80 | | 1–3 | 1–3 |

Notes. T1 = T1 = First measurement point; T2 = Second measurement point; T3 = Third measurement point; ρKR20 = Kuder–Richardson-Coefficient 20 (internal consistency); Give-N = Give-a-number task (Sarnecka & Carey, 2008; Wynn, 1990); Point-to-X = Point-to-x task (Wynn, 1992); [a]PALM = Preschool Assessment of the Language of Mathematics (PALM; Purpura & Logan, 2015), [b]TROG-D (Bishop, 2003; Fox-Boyer et al., 2020; Weinert & Ebert, 2017); [b] Sprachentwicklungstest für zweijährige Kinder = [Language development test for two-year-old children] (Grimm, 2016); [c]German version of the subtest categories of the SON-R 2 ½-7 (Tellegen et al., 1998; Tellegen et al., 2007); [d]1 = At least one other language than German, 2 = German; [e]1 = Control group, 2 = General intervention group, 3 = Math-specific intervention group. [1] Note that the sum-scores are partially based on different numbers of items as some tasks were extended by more easy or difficult items due to the age-related skill development of the children.

*Verbal counting* (adapted from Mix, 2009; Wynn, 1990, 1992): Woolly, the sheep, asked the children to count as far as they could (starting at 1) twice in a row and helped them at T1 and T2 by counting to 3 in the beginning. The children received one point for correctly reciting the number word series up to 1, 2, 3, 5, 7, 10, 15, 20, 30, more than 30 respectively. For example, three points were given for counting to three, and six points were given for counting to 10.

*Counting Objects* (adapted from Mix, 2009; Wynn, 1990, 1992)*:* Woolly had collected stones and asked the children to help him count them. He then placed ten stripes of glass nuggets in front of the children one after the other (quantities: 1, 2, 3, 5, 7, 10, 15, 20, 30, 50). If the initial item (3 glass nuggets) was not solved correctly, Woolly presented first one glass nugget and then two glass nuggets. Woolly continued until either the child solved all other items correctly or failed on two stripes in a row (discontinuation criterion). He did likewise, if the initial item (3 glass nuggets) was solved correctly. The children received one point for each correctly solved item. Children who successfully solved the initial item (3 glass nuggets) were awarded points 1 and 2 as well, so that a total of 10 points could be scored.

*Give-a-number task* (Sarnecka & Carey, 2008; Wynn, 1990): Woolly requested that the children feed him by placing the specified number of wooden cubes onto a plate. At the start, Woolly showed an example with one piece of food. Then, the numbers 1 to 7 were asked twice in sequence, but not directly after each other, except for the number 1 (1, 1, 2, 3, 2, 3, 4, 5, 4, 5, 6, 7, 6, 7). After T1, 3 items were added (8, 9, 10) to account for the children's age-related skill development. The task ended when the children either completed all the items or gave three consecutive incorrect answers (discontinuation criterion). The children earned one point for each correctly given number.

*Point-to-x task* (Wynn, 1992): Woolly asked the children to tap at a specific number of objects from two different quantities. In a vertical layout, two quantities of identical objects were shown on picture cards (e.g., one cat vs. two cats). The quantities ranging from 1 to 8 (1 vs. 2, 2 vs. 3, 3 vs. 4, and so on) were presented twice with various objects. After T1, 4 items were added (8 vs. 9, 9 vs. 10) to account for the children's age-related skill development. The items were shown in increasing order until the children either completed all tasks or failed four consecutive times (discontinuation criterion). The children received one point for each correct quantity they identified by tapping on it. Table 1 presents an overview of the number of items, internal consistencies, and descriptives per assessment wave for each variable.

### 3.4.2. *General language*

To measure the children's general language skills, a sentence comprehension test was administered (German version of the Test for Reception of Grammar (TROG-D; Bishop, 2003; Fox-Boyer et al., 2020 shortened; see Weinert & Ebert, 2017)). An examiner presented a sentence together with four colored pictures and the children were asked to select the picture that best matched the sentence. The further the children progressed, the more difficult the items became. The children received one point for each correctly solved item. The analyses are based on the children's sum scores. To avoid floor effects, the TROG-D (Bishop, 2003; Fox-Boyer et al., 2020 shortened; see Weinert & Ebert, 2017) was supplemented at the first two measurement times with a comparable item set (8 items) suitable for two year old children from the Sprachentwicklungstest für zweijährige Kinder [Language development test for two-year-old children] (Grimm, 2016), as the TROG-D (Bishop, 2003; Fox-Boyer et al., 2020 shortened; see Weinert & Ebert, 2017) is only normed from the age of three years. Children were able to score up to eight points more on T1 and T2 than on T3(see Table 1 for number of items, internal consistencies, and descriptives per assessment wave).

### 3.4.3. *Mathematical language*

The mathematical language skills of the children were assessed using a shortened (21 items), German version of the Preschool Assessment of the Language of Mathematics (PALM; Purpura & Logan, 2015). The children were asked to either identify various mathematical terms related to unspecified quantities (e.g., “a bit,” “more”) and spatial prepositions (e.g., “up,” “in front”) on picture cards (e.g., “Where are more dots?”) or to perform actions with wooden cubes (e.g., “Take away many blocks.”). We expanded the tasks to include a total of 6 items covering geometry, which involved either shapes (e.g., “Point to the triangle.”) or three-dimensional objects (e.g., “Point to the cube.”). To ensure that the concepts of “numeracy skills” and “mathematical language skills” are explicitly separated, the PALM intentionally avoids the use of numerals. After T1, a total of 10 items were added to account for the children's age-related skill development. These items included both quantitative and spatial items from the original measure, whose discriminatory power suggested that they might be too difficult for children under three years of age (e.g., “a little”, “behind”) as well as additional, more challenging geometric items (e.g., “cylinder”) that we used to expand the measure. The PALM has no discontinuation criterion, and one point was awarded for each correctly solved item. The analyses were based on the children's sum scores (see Table 1 for item numbers, internal consistencies, and a summary of descriptives per assessment wave).

#### 3.4.4. Control variables

The development of numeracy skills, as well as that of general language and mathematical language, can be influenced by contextual factors, such as the children's age (e.g., Peng et al., 2020), their basic nonverbal cognitive functioning (e.g., Libertus et al., 2024), or their family language (e.g., Méndez et al., 2019). To rule out the possibility that the results could be attributed to other factors rather than the relations between general and mathematical language and numeracy skills, we controlled for children's age at T1 (for paths between T1 and T2) and T2 (for paths between T2 and T3) and children's basic nonverbal cognitive functioning at T1 (for paths between T1 and T2) and T2 (for paths between T2 and T3) (German version of the subtest categories of the Snijders-Oomen Nonverbal Intelligence Test 2,5–7 years (SON-R 2 ½-7); Tellegen et al., 1998; Tellegen et al., 2007). In the first part of the SON-R 2 ½-7 (see Table 1 for item numbers, internal consistencies, and a summary of descriptives per assessment wave), picture cards must be sorted into two groups according to specified categories (e.g., candies and flowers). Participants must identify the categories themselves based on examples. If the items in the first part are completed successfully, the second part requires matching two out of five additional picture cards to three picture cards that share a common characteristic. Between all measurement points we also controlled for children's language spoken at home (only German vs. at least one other language than German). In addition, while focusing on longitudinal relations among numeracy and language constructs, the three-group intervention assignment (control group, general intervention, math-specific intervention) was statistically controlled for using two dummy variables (reference group: control group) (see Table 1 for a summary of descriptives per assessment wave).

### 3.5. Statistical analyses

Reciprocal effects between numeracy and general and mathematical language skills, were examined by conducting a *Cross-lagged Panel Model* (CLPM), which controlled for children's age, their basic nonverbal cognitive functioning, their home language and the intervention group assignment. The model was estimated in R version 4.4.3 (R Core Team, 2024) with lavaan version 0.6-19 (Rosseel, 2012). To account for the nesting of children within different childcare centers we used cluster-robust standard errors (Savalei, 2014; Savalei & Rosseel, 2022). Missing values were handled using the maximum likelihood estimation with robust (Huber-White) standard errors and a scaled test statistic ("MLR"). Since the time intervals between measurement points were not equal, all autoregressive and cross-lagged paths were estimated separately for each interval. No equality restrictions were imposed over time. For the estimated models, goodness of fit was evaluated using three practical fit indices. First, the robust comparative fit index (CFI; Brosseau-Liard & Savalei, 2014), then the robust root mean square error of approximation (RMSEA; Brosseau-Liard et al., 2012), and the standardized root mean square residual (SRMR). Models with CFI $\geq$ 0.95, RMSEA $\leq$0.08, and SRMR $\leq$0.10 are considered "acceptable," whereas models with CFI $\geq$ 0.97, RMSEA $\leq$0.05, or SRMR $\leq$0.05 are considered "good" fit (e.g., Schermelleh-Engel et al., 2003). Since the conventions established for correlations should not be applied to lagged effects, we use the following values as benchmarks: 0.03 (small effect), 0.07 (medium effect), and 0.12 (large effect) (Orth et al., 2024).

## 4. Results

Tables 1 and 2 present the descriptive statistics and the correlations of the analyzed variables. The children improved their numeracy skills (T1: $M = 13.09$, $SD = 6.34$; T2: $M = 17.28$, $SD = 8.16$; T3: $M = 31.15$, $SD = 10.48$), their mathematical language (T1: $M = 8.97$, $SD = 3.48$; T2: $M = 13.94$, $SD = 4.64$; T3: $M = 21.19$, $SD = 4.53$), and their general language (T1: $M = 13.00$, $SD = 7.09$; T2: $M = 17.17$, $SD = 8.13$; T3: $M = 15.81$, $SD = 7.28$) skills from T1 to T3. The correlations in Table 2 indicate that there are significant relations between all child measures across the three time points, both within and across domains and between the control variables. The stabilities of the measures were strong (numeracy: $r_{T1-T2} = 0.52, p < .001, r_{T2-T3} = 0.55\ p < .001$; mathematical language: $r_{T1-T2} = 0.60$, $p < .001$, $r_{T2-T3} = 0.58$, $p < .001$; general

**Table 2**
Correlations between the analysis variables ($N = 141–389$).

| | Numeracy | | | Mathematical language | | | General language | | |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (09) |
| (01) Numeracy T1 | – | | | | | | | | |
| (02) Numeracy T2 | 0.518*** | – | | | | | | | |
| (03) Numeracy T3 | 0.419*** | 0.553*** | – | | | | | | |
| (04) Math language T1 | 0.510*** | 0.400*** | 0.353*** | – | | | | | |
| (05) Math language T2 | 0.470*** | 0.506*** | 0.510*** | 0.598*** | – | | | | |
| (06) Math language T3 | 0.424*** | 0.443*** | 0.544*** | 0.534*** | 0.578*** | – | | | |
| (07) General language T1 | 0.444*** | 0.460*** | 0.475*** | 0.602*** | 0.504*** | 0.499*** | – | | |
| (08) General language T2 | 0.442*** | 0.490*** | 0.374*** | 0.458*** | 0.580*** | 0.421*** | 0.543*** | – | |
| (09) General language T3 | 0.367*** | 0.330*** | 0.331*** | 0.420*** | 0.484*** | 0.437*** | 0.376*** | 0.480*** | – |
| Control variables | | | | | | | | | |
| (10) Age T1 | 0.388*** | 0.314*** | 0.272*** | 0.273*** | 0.225*** | 0.212** | 0.295*** | 0.214*** | 0.184* |
| (11) Age T2 | 0.381*** | 0.339*** | 0.274*** | 0.250*** | 0.289*** | 0.183* | 0.306*** | 0.214*** | 0.146+ |
| (12) Nonverbal basic cognitive functioning T1[a] | 0.315*** | 0.330*** | 0.216*** | 0.245*** | 0.274*** | 0.258** | 0.275*** | 0.326*** | 0.281*** |
| (13) Nonverbal basic cognitive functioning T2[a] | 0.307*** | 0.378*** | 0.260*** | 0.233** | 0.325*** | 0.271*** | 0.255*** | 0.385*** | 0.145 |
| (14) Family language[b] | 0.074 | 0.101 | 0.270*** | 0.231*** | 0.303*** | 0.240*** | 0.212*** | 0.293*** | 0.200* |
| (15) Intervention group[c] | 0.007 | 0.084 | 0.144** | 0.042 | 0.161** | 0.031 | 0.036 | 0.023 | 0.032 |

Notes. T1 = First measurement point; T2 = Second measurement point; T3 = Third measurement point; [a]German version of the subtest categories of the SON-R 2 ½-7; Tellegen et al., 1998; Tellegen et al., 2007; [b]1 = At least one other language than German, 2 = German; [c]1 = Control group, 2 = General intervention group, 3 = Math-specific intervention group.

*** $p < .001$.

** $p < .010$.

* $p < .050$.

+ $p < .100$.

language: $r_{T1\text{-}T2} = 0.54$, $p < .001$, $r_{T2\text{–}T3} = 0.48$, $p < .001$). Additionally, the concurrent relations between the variables were primarily in the medium to high range (numeracy—mathematical language: $r_{T1} = 0.51$, $p < .001$; $r_{T2} = 0.51$, $p < .001$; $r_{T3} = 0.54$, $p < .001$; numeracy—general language: $r_{T1} = 0.44$, $p < .001$; $r_{T2} = 0.49$, $p < .001$; $r_{T3} = 0.33$, $p < .001$; mathematical language—general language: $r_{T1} = 0.60$, $p < .001$; $r_{T2} = 0.58$, $p < .001$; $r_{T3} = 0.44$, $p < .001$).

### 4.1. Results of cross-lagged panel modeling with numeracy and mathematical and general language skills

Fig. 2 presents the results of the CLPM including all three constructs (numeracy, mathematical and general language skills), in which non-significant paths were removed to simplify the figure. The model fitted the data well ($\chi^2 = 85.66$, $df = 31$, $p < .001$, Robust CFI = 0.97, Robust RMSEA = 0.08, 90% CI [0.06; 0.11], SRMR = 0.04). The autoregressive paths were significant for numeracy as well as for general and mathematical language skills across the three measurement times (with β ranging between 0.29 and 0.40, all $p < .001$). This indicates that children who demonstrated comparatively higher numeracy and general and mathematical language skills at the age of about two-and-a-half-years also did so at the age of three and four years. There were several significant cross-lagged effects between the domains: General language at T1 predicted both the development of numeracy skills (β = 0.25, $p < .001$) and mathematical language (β = 0.18, $p < .010$) in children between T1 and T2, indicating that children who have higher general language skills at the age of two-and-a-half-years demonstrate a more pronounced change of individual differences in numeracy and mathematical language skills during the next months. Likewise, numeracy skills at T1 proved to be predictive of the development in both mathematical (β = 0.16, $p < .001$) and general language skills (β = 0.19, $p < .001$). At T2, however, numeracy skills predicted the development of mathematical language (T3) (β = 0.19, $p < .010$), but not general language skills. When considering the cross-lagged effects of mathematical language, it was significantly associated with both the development of numeracy skills (β = 0.21, $p < .050$) and general language skills (β = 0.32, $p < .001$) from T2 to T3 but not from T1 to T2. This indicates that children who have higher mathematical language skills at the age of three years also demonstrate higher general language and numeracy skills at the age of four years (controlled for autoregressive effects and controls), but not between two-and-a-half and three years. With respect to the control variables considered in the CLPM, significant simultaneous associations were observed for all control variables included as well as some predictive relations particularly between T1 and T2 (for details see Table S1 in the online supplement).

### 4.2. Additional analyses

Since we were interested in whether the relations between mathematical language and numeracy skills could also be replicated for younger children under the age of three, we additionally estimated a two-component model that accounted only for mathematical language

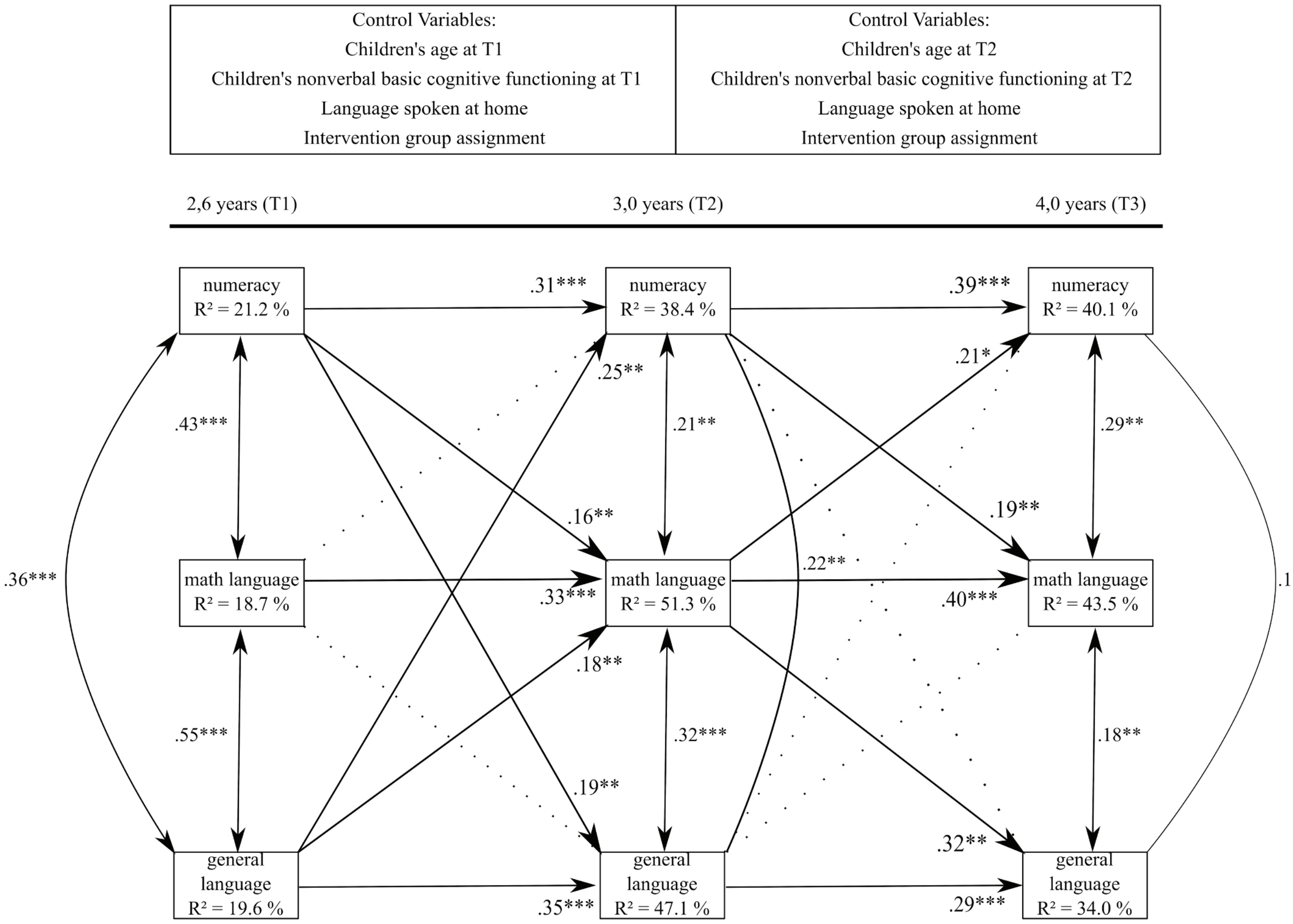


**Fig. 2.** Standardized estimates of the cross-lagged panel model. Only significant coefficients are presented (on solid lines). T1 = First measurement point; T2 = Second measurement point; T3 = Third measurement point.
***$p < .001$, **$p < .010$, *$p < .050$.

and numeracy skills (since existing research on the relations between numeracy and mathematical language often treats general language as a control variable or does not consider it at all). These results (see Fig. S2 in the online supplement) revealed that mathematical language predicted the development of numeracy skills even between the ages of two and a half and three, when general language was not included in the model. A further model that only considered general language and numeracy skills (see Fig. S3 in the online supplement) demonstrated that, even when mathematical language was excluded, general language predicted the development of numeracy skills between the ages of two and a half and three, but not beyond that.

We also conducted sensitivity analyses to rule out the possibility that our results might be reduced to general intervention effects. To that end, we conducted the analyses in the pure control group; that is, no intervention was conducted in this group. This subgroup revealed the same pattern as the overall sample: Between the ages of two and a half and three, numeracy and general language skills predicted each other's development, and both predicted the development of mathematical language skills. Between the ages of three and four, however, numeracy skills and mathematical (rather than general) language skills predicted each other's development. In addition, mathematical language skills also predicted the development of general language skills, but not vice versa (for details see Fig. S1 in the online supplement). This overall result was also confirmed by the findings of a multi-group (CG, GIG, MIG) CLPM with robust estimation (MLR) and cluster-robust standard errors. A freely estimated model (all paths group-specific; robust CFI = 0.96, robust RMSEA = 0.10, SRMR = 0.06) was compared with a model in which all autoregressive and cross-lagged paths were set equal across groups (robust CFI = 0.96, robust RMSEA = 0.09, SRMR = 0.07). The scaled chi-square difference test (Satorra-Bentler) was marginally significant, $\Delta\chi^2(36) = 51.28$, $p < .100$. As shown by the group-specific standardized path coefficients of the freely estimated model (see Table S2 in the online supplement), the differences between the groups mainly relate to the autoregressive paths.

## 5. Discussion

In this study, we investigated the reciprocal relations between early numeracy and mathematical as well as general language skills of children, starting when they were younger than three years at the first measurement point and following them up to preschool age. Previous studies have investigated either the mutual relations between numeracy and general language skills or the predictive associations between mathematical language and numeracy skills. Furthermore, most of the studies were conducted with children over the age of three and direct measures of skills are sparse in children under the age of three. This study expands on existing research in several ways. Firstly, we analyzed direct measures (instead of adult ratings) of skills in children being two-and-a-half-year-old (and onwards), which allowed us to, secondly, expand existing findings on the prediction of numeracy skills by mathematical language to a younger age group. Thirdly, the study extends beyond predictive approaches by examining longitudinal effects while controlling for stabilities as well as for concurrent relations between the skills. Furthermore, general language was also included in the model, which, fourthly, allows us to examine the reciprocal relations between numeracy skills and general as well as mathematical language skills simultaneously in a single model. We expected that all skills would be closely intertwined between two-and-a-half and three years of age and that both language measures would predict numeracy skills, while numeracy skills would only predict the specific language (mathematical language). Conversely, we expected that between three and four years of age, mathematical language and numeracy skills would be bidirectionally intertwined, while general language would only be associated to mathematical language.

The CLPM revealed robust autoregressive stability in all constructs between two-and-a-half and three years and between three and four years. Furthermore, skills were significantly correlated at each measurement point. Several significant cross-lagged relations were found, indicating that earlier skills were associated with later skills, even when controlling for autoregressive and concurrent relations (and control variables).

Our aim was to investigate whether the findings that numeracy skills are predicted by mathematical language could also be replicated in a younger age group (under three years of age), or whether these findings rather reflect general language skills. Our results suggest that the development of numeracy skills between the ages of two and a half and three is predicted by general language rather than mathematical language (controlling for autoregressive effects, concurrent associations, and important controls). Conversely, between the ages of three and four, mathematical language skills—but not general language—predicted the development of numeracy skills. Although we can replicate existing findings for children between the ages of three and four (e.g., Bleses et al., 2023; King & Purpura, 2021; Kung et al., 2019) we were unable to extend this to younger children between the ages of two and a half and three. From a theoretical point of view, as general language is considered an important prerequisite for the acquisition of number word series, counting skills and numerical understanding, it is to be expected that general language particularly influences the development of numeracy skills in the very early phases (Toll & Van Luit, 2014b). From around 24 and 30 months of age (or even earlier), grammatical skills support the acquisition of words (e.g., Borovsky, 2022; Caglar-Ryeng et al., 2019; Dionne et al., 2003), in particular verbs and relational terms, which are important in syntax, and foster the acquisition of numeracy skills (e.g., counting, cardinality) and mathematical language (e.g., much, little, over, under). General language at the age of two-and-a-half-years appears to be a steppingstone for learning more complex specific language terms, i.e., mathematical language, and more complex numerical relations (“bootstrapping”). On the other hand, mathematical language is central as it enables children to understand and express numerical concepts, such as the comparison of quantities and the assignment of number words to quantities (Barner et al., 2009; Zhu et al., 2026). Our results demonstrate that mathematical language predicted numeracy and general language skills once a certain level of skill had been reached (at three years of age), suggesting that by this point, mathematical vocabulary had expanded to such an extent that it could also contribute to the understanding of both more complex sentences, in which increasingly quantitative and spatial terms were used and more complex numerical tasks, which, for example, involve a deeper understanding of quantities and natural numbers. Thus, for the expansion and differentiation of early numeracy skills during development, mathematical language gains importance compared to general language, as it is necessary to be able to understand and solve increasingly complex numeracy tasks (e.g., Hornburg et al., 2024; Purpura et al., 2011; Purpura & Reid, 2016). Our additional analyses, which revealed that mathematical language—in a model that did not simultaneously account for general language—predicted the development of numeracy skills between the ages of two and a half and three, while general language—in a model that did not simultaneously account for mathematical language—predicted the development of numeracy skills between the ages of two and a half and three, but not between the ages of three and four, strengthen our assumptions that young children between the ages of two and a half and three require general language to acquire both specialized language (such as mathematical language) and numeracy skills. Once these skills have reached a certain level, specialized language becomes crucial for the development of both general language and numeracy skills.

Another objective of this study was to investigate whether the relation between numeracy and language skills might also be reciprocal, that is, whether numeracy skills might also predict the development of general and/or mathematical language skills. Our findings demonstrate that numeracy skills at age two and a half predicted the development not only of mathematical language but also of general language over the course of six months. Between the ages of three and four, however, numeracy skills significantly predicted mathematical language but not general language skills. These findings contribute to the discussion about the developmental dynamics between numeracy and language skills, as they suggest that early representations of quantities and numbers are not only stimulated by language but may also promote general and mathematical language development themselves. The assumption that numeracy skills could contribute to language development is theoretically reasonable. For example, Dehaene et al. (2003) postulate a parietal-linguistic interface in which the intraparietal sulcus (IPS) and the angular gyrus connect numerical and linguistic processes. If numerical representations are established and differentiated in the early years, they can serve as a semantic anchor that makes it easier to access verbal concepts (e.g., relational terms), even beyond pure number words. Similarly, Pinhas et al. (2014) demonstrated that the neural response to number word–quantity incongruities is modulated by cardinal competence. Bugden et al. (2021) complement this perspective by demonstrating that the functional specialization of the left IPS for numeral-quantity mappings increases with age and experience, suggesting an increasingly close interconnection between quantity and language representations. The idea of concept formation, i.e., higher mental processes in which generalized categories and relations are formed from perceived, coded, and stored information (e.g., Carey, 2009; Spelke, 2017), suggests that early established representations of quantities and relations serve as a conceptual basis to which, for example, spatial and quantitative language (such as “more than”, “between”) can be linked. Similar to the word learning process, in which the acquisition of word meanings is understood as the mapping of concepts and words (e.g., Bloom, 2000), children can link new words to existing numerical concepts (which in turn be influenced by the mapping process), facilitating the acquisition of mathematical and general language. Of course, with respect to general language (as measured via sentence comprehension), it is an open question, how an advanced understanding of quantitative and relational concepts promotes general language, e.g., via domain general relational reasoning, or symbolic mapping, or whether it helps to understand more complex sentence structures that include quantitative and relational terms. However, it should be noted that the formation of numerical concepts might itself be influenced by parental or teacher's language input and that (verbal) number knowledge is an integral part of early numeracy and numeracy assessment.

From the age of three onward, although numeracy skills continued to predict the development of mathematical language, they no longer predicted general language development in the present sample. This might be explained by the interwoven nature of these two aspects of language. General language served as a stepping stone between the ages of two and a half and three—a mechanism that was postulated, for example, by Bloom (2000)— only to be “superseded” by mathematical language once a certain skill level was reached, which is consistent with research showing that, starting at age three, mathematical rather than general language skills predict numeracy skills (Purpura & Reid, 2016; Toll & Van Luit, 2014b; Zhu et al., 2026). At the same time, such a mechanism might also apply to the reverse path—from numeracy to language skills. Early on, numeracy skills—beyond the development of mathematical language—were predictive of the development of general language (as indicated by comprehension of increasingly difficult sentence structures). However, once a certain level of general language was reached, numeracy skills were no longer predictive of its further development; rather, they influenced the development of specialized mathematical language, which in turn promoted general language development. This pattern can be framed within mutualistic models of cognitive development, where certain abilities develop in part through positive, reciprocal interactions, such that a child's level of performance in one domain determines the rate of growth in another area (Kievit, 2020; Van Der Maas et al., 2006). Furthermore, mutualism models postulate not only that such interactions exist, but they also suggest that these interactions change in strength and nature over the course of development, including sensitive phases in which cross-domain interactions differ in scope or nature (Kievit, 2020). To our knowledge, this reverse pathway—from early numeracy skills to general language and, simultaneously, to mathematical language—has not yet been analyzed, which is why future longitudinal studies might further examine these aspects.

In summary, the CLPM demonstrated robust autoregressive stability and reciprocal relations between numeracy, mathematical and general language skills between the ages of two-and-a-half and four years. These patterns reflect both stable and changing interindividual differences. The close interconnection of numeracy skills and mathematical and general language is consistent with the current literature that assumes close links between these domains already in early childhood (e.g., Peng et al., 2020; Purpura & Ganley, 2014; Toll & Van Luit, 2014b). Our results expand on and differentiate these findings by indicating that although these associations are already present in children between two-and-a-half and three years of age, the specific pathways change over time. Note that pure correlations—even across time—could be due to stabilities of interindividual differences. Yet, when controlling for those stabilities (as well as for other variables), the (cross-lagged) effects in the CLPM still showed mutual relations between language and numeracy development with general language skills being particularly closely related in the earlier phases and mathematical language in the later phases in early childhood.

While general language functions primarily as the basis for the development of individual differences in numeracy and mathematical language in earlier phases, mathematical language gains importance with increasing age (or age-related competencies) and might be positively associated with higher levels of numeracy skills over time. Importantly our results cannot be reduced to general effects of nonverbal cognitive functioning or other control variables (family language, age and intervention group assignment) additionally considered in the models but extend beyond these factors. This suggests a specific, reciprocal developmental relation of numeracy skills and general, and from age three onward particularly mathematical, language skills.

### 5.1. Strengths and limitations

The strengths of this study are its longitudinal design with three measurement points of direct assessments of general and mathematical language as well as numeracy skills in children from the age of two-and-a-half-years. Our study thus extends the (limited) previous work by examining the mutual relations in a joint model and in younger children, thereby modeling both, interrelations between constructs at each measurement point as well as stabilities within each skill across time. Finally, drawing on empirical findings, we included influential control variables to increase the specificity of the effects examined.

Some limitations exist in this study. First, since this was originally an intervention study, it might seem plausible that the relations between the three skills were altered by the intervention. However, robustness checks of the results demonstrated that (1) they could be replicated in the control group (i.e., the children who were not exposed to the intervention) and that (2) the cross-lagged paths did not differ substantially between the three intervention groups. Nevertheless, further studies should be conducted with samples without intervention to confirm the results. The unequal time intervals between T1 and T2 (6 months) and between T2 and T3 (12 months) were also part of the original design. This was addressed in the analyses by estimating the autoregressive and cross-lagged paths separately for both intervals and by not imposing equality restrictions across time. Our conclusions therefore primarily focus on the existence of relations within the respective intervals, rather than on a direct comparison of the magnitude of the effects across intervals. Future studies with continuous-time models or designs with equal measurement intervals could further contribute to strengthening the comparability of the estimated relations across intervals. Second, as is typical in longitudinal studies, there were missing values, especially at the third measurement point (one year after the first two assessments). Therefore, the findings of this study are based on partially estimated values. However, we tried to improve the generalizability of the findings by using the maximum likelihood estimation with robust (Huber-White) standard errors. Selectivity analyses indicated that children who dropped out between T2 and T3 were slightly older at T1 than children with complete data across all three measurement points. This age-related selectivity may reflect that older children were more likely to have transitioned to school by the third measurement point and were therefore more difficult to reach. However, age was included as a covariate in the analyses, so that age-related differences were statistically controlled for. Furthermore, the dropout groups did not differ in terms of performance data at T1, so there was no evidence of performance-related bias in the sample. Third, this is a German sample, and only a few children with lower social status (SES) or a migrant background were included. This might be because the children were recruited through early childcare centers, that are known to have lower attendance rates of children under the age of three from low SES or migrant families in Germany (Autor:innengruppe Bildungsberichterstattung, 2026). Furthermore, particularly motivated parents with a higher level of education might have given their consent for their children to participate, or because other factors had a deterrent effect (e.g., language barrier). Although we controlled for language spoken at home, further studies could systematically differentiate monolingual from bilingual children. In addition, further studies need to investigate whether the mutual relations between numeracy and general and mathematical language skills are also found in two-year-old children from other countries and from more diverse samples.

### 5.2. Practical implications

The results indicate that general language skills form an important basis for the development of numeracy and mathematical language skills between two and a half and three years of age, while mathematical language appears to be particularly important for the development of numeracy skills from around the age of three. The findings underscore the relevance of early, systematic language support as a basis for the development of numeracy skills. This foundation may be fostered by parents or teachers, for example, by creating playful, language-based interactions (e.g., during dialogic reading sessions; Ergenekon & Işıkoğlu, 2026; Purpura et al., 2017). With respect to early numeracy and mathematical language, these interactions could focus on e.g., quantities, sizes, and relations, embedding general and mathematical language in the context of mathematical learning opportunities, for example, through counting while reading books or comparing quantities while cooking. Furthermore, the results indicate that mathematical language promotes numeracy development with increasing age. Therefore, mathematical language such as "more", "bigger", or "below" should be incorporated into everyday activities at home or in the childcare center. In this context, activities such as sorting games, building activities with spatial concepts, or solving simple quantity problems together offer opportunities for learning. The results also provide important links for further research: they confirm the assumption that general and—from three years on—mathematical language are key drivers of numeracy development. Future studies should therefore model linguistic mechanisms—such as lexical depth, syntactic complexity, or adult input quality—more systematically as mediating processes. Moreover, the differentiated cross-lagged effects over time indicate dynamic developmental relations between domains that might also hint to sensitive developmental windows in very early phases of development: General language seems to have an earlier effect, mathematical language a comparatively later one in early childhood. Research should specifically identify these time (or developmental) windows to derive age- and developmentally appropriate support strategies.

### 5.3. Conclusion

This study provides substantial indications that numeracy skills and general, and from age three onward particularly mathematical, language skills are closely intertwined in early childhood. By considering children under the age of three and direct measures of numeracy and language skills, it demonstrates that language, and from age three onward particularly mathematical language, contributes to numeracy development and that—overall—there are mutual interrelations between numeracy and early language development, even when controlling for autoregressive effects, concurrent associations, and important controls. The study thus provides empirical evidence for a deeper understanding of the specific role of (mathematical) language and delivers findings that provide a basis for better understanding the intertwining of language and numeracy in early childhood.

## CRediT authorship contribution statement

**Nadine Besser:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Sabine Weinert:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Dorothea Dornheim:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Simone Lehrl:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

## Funding

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 416593881.

## Declaration of competing interest

None declared.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lindif.2026.102991.

## Data availability

The data necessary to reproduce the analyses presented here will be made available to the scientific community in a repositorium soon (after the main assessments are finished).

The analytic code necessary to reproduce the analyses and the materials necessary to attempt to replicate the findings presented in this paper can be provided by the first author on request.

The analyses presented here were not preregistered.

## References

American Psychological Association. (2017). Ethical principles of psychologists and code of conduct. https://www.apa.org/ethics/code.

Bildungsberichterstattung, Autor:innengruppe (2026). *Bildung in Deutschland 2026: Ein indikatorengestützter Bericht mit einer Analyse zu Bildungsungleichheiten nach sozialer Herkunft (Education in Germany 2026: An Indicator-Based Report Analyzing Educational Inequalities by Social Background)* (1st ed.). wbv Media https://doi.org/10.3278/9783763980253.

Barner, D., Chow, K., & Yang, S.-J. (2009). Finding one's meaning: A test of the relation between quantifiers and integers in language development. *Cognitive Psychology, 58* (2), 195–219. https://doi.org/10.1016/j.cogpsych.2008.07.001

Besser, N., Linberg, A., Dornheim, D., Weinert, S., Roßbach, H.-G., & Lehrl, S. (2025). Fostering toddlers' numeracy and mathematical language skills through a professional development intervention on interaction quality in toddler classrooms. *Early Childhood Research Quarterly, 72*, 44–55. https://doi.org/10.1016/j.ecresq.2025.02.004

Bishop, D. (2003). *Test for reception of grammar, TROG-2.* Pearson Assessment.

Bleses, D., Jensen, P., Slot, P., & Justice, L. (2021). Low-cost teacher-implemented intervention improves toddlers' language and math skills. *Early Childhood Research Quarterly, 53*, 64–76. https://doi.org/10.1016/j.ecresq.2020.03.001

Bleses, D., Moos, M., Purpura, D. J., & Dale, P. S. (2023). General and math vocabulary contributions to early numeracy skills in a large population-representative sample. *Frontiers in Developmental Psychology, 1*. https://doi.org/10.3389/fdpys.2023.1279691

Bloom, P. (2000). *How children learn the meanings of words*. The MIT Press. https://doi.org/10.7551/mitpress/3577.001.0001

Bonifacci, P., Tobia, V., Bernabini, L., & Marzocchi, G. M. (2016). Early literacy and numeracy skills in bilingual minority children: Toward a relative independence of linguistic and numerical processing. *Frontiers in Psychology, 7*, Article 1020. https://doi.org/10.3389/fpsyg.2016.01020

Borovsky, A. (2022). Lexico-semantic structure in vocabulary and its links to lexical processing in toddlerhood and language outcomes at age three. *Developmental Psychology, 58*(4), 607–630. https://doi.org/10.1037/dev0001291

Brosseau-Liard, P. E., & Savalei, V. (2014). Adjusting incremental fit indices for nonnormality. *Multivariate Behavioral Research, 49*(5), 460–470. https://doi.org/10.1080/00273171.2014.933697

Brosseau-Liard, P. E., Savalei, V., & Li, L. (2012). An investigation of the sample performance of two nonnormality corrections for RMSEA. *Multivariate Behavioral Research, 47*(6), 904–930. https://doi.org/10.1080/00273171.2012.715252

Bugden, S., Park, A. T., Mackey, A. P., & Brannon, E. M. (2021). The neural basis of number word processing in children and adults. *Developmental Cognitive Neuroscience, 51*, Article 101011. https://doi.org/10.1016/j.dcn.2021.101011

Caglar-Ryeng, Ø., Eklund, K., & Nergård-Nilssen, T. (2019). Lexical and grammatical development in children at family risk of dyslexia from early childhood to school entry: A cross-lagged analysis. *Journal of Child Language, 46*(6), 1102–1126. https://doi.org/10.1017/S0305000919000333

Cahoon, A., Simsek, E., Gilmore, C., & Simms, V. (2024). The cognitive and numerical predictors of early mathematical achievement: A latent growth curve analysis. *Journal of Cognition and Development, 0*(0), 1–21. https://doi.org/10.1080/15248372.2024.2434036

Carey, S. (2009). *The origin of concepts*. Oxford University Press.

Chan, J. Y.-C., Vieites, V., & Wang, J.(J.) (2025). The links between quantitative versus spatial language knowledge and numeracy skills in kindergarten children. *Cognitive Development, 74*, Article 101560. https://doi.org/10.1016/j.cogdev.2025.101560

Chen, X., Ma, C., Yang, Z., & Yang, X. (2025). Bidirectional relationships between phonological processing and basic number knowledge in kindergarten children: A longitudinal study. *BMC Psychology, 13*(1), 49. https://doi.org/10.1186/s40359-025-02375-y

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*(1), 1–42. https://doi.org/10.1016/0010-0277(92)90049-N

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3), 487–506. https://doi.org/10.1080/02643290244000239

Dionne, G., Dale, P. S., Boivin, M., & Plomin, R. (2003). Genetic evidence for bidirectional effects of early lexical and grammatical development. *Child Development, 74*(2), 394–412. https://doi.org/10.1111/1467-8624.7402005

Ergenekon, E., & Işıkoğlu, N. (2026). Examining the impact of dialogic reading interventions with math picture books. *Cognitive Development, 78*, Article 101685. https://doi.org/10.1016/j.cogdev.2026.101685

Federal Statistical Office, & DESTATIS. (2021). Nettoeinkommen privater Haushalte nach Haushaltstyp [Net Income of Private Households by Household Type]. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Einkommen-Konsum-Lebensbedingungen/_Grafik/_Interaktiv/einnahmen-ausgaben-haushaltstypen.html.

Fox-Boyer, A., Bäumer, T., Müller, M., & Merzbecher, S. (Eds.). (2020). *TROG-D: Test zur Überprüfung des Grammatikverständnisses* [*Test to evaluate grammar comprehension*] (8. Auflage). Schulz-Kirchner Verlag.

Grimm, H. (2016). *SETK-2—Sprachentwicklungstest für zweijährige Kinder (2;0–2;11 Jahre). Diagnose rezeptiver und produktiver Sprachverarbeitungsfähigkeiten* [*Language development test for two-year-old children (2;0-2;11 years). Diagnosis of receptive and productive language processing skills*] (2nd ed.). Hogrefe.

Ho, J. C.-S., Cheung, S. K., McBride, C., Purpura, D. J., Ng, M. C. Y., & Ho, A. P. L. (2025). Relation between general vocabulary knowledge and early numeracy competence: The mediating role of mathematical language. *Journal of Experimental Child Psychology, 252*, Article 106145. https://doi.org/10.1016/j.jecp.2024.106145

Horn, P., Fritzsche, T., Ehlert, A., & Adani, F. (2021). Tapping into the interplay of lexical and number knowledge using fast mapping: A longitudinal eye-tracking study with two-year-olds. *Infant Behavior and Development, 64*, Article 101573. https://doi.org/10.1016/j.infbeh.2021.101573

Hornburg, C. B., King, Y. A., Westerberg, L., Schmitt, S. A., & Purpura, D. J. (2024). The roles of mathematical language and emergent literacy skills in the longitudinal prediction of specific early numeracy skills. *Journal of Experimental Child Psychology, 244*, Article 105959. https://doi.org/10.1016/j.jecp.2024.105959

Hornburg, C. B., Schmitt, S. A., & Purpura, D. J. (2018). Relations between preschoolers' mathematical language understanding and specific numeracy skills. *Journal of Experimental Child Psychology, 176*, 84–100. https://doi.org/10.1016/j.jecp.2018.07.005

Kauschke, C., & Hofmeister, C. (2002). Early lexical development in German: A study on vocabulary growth and vocabulary composition during the second and third year of life. *Journal of Child Language, 29*(4), 735–757. https://doi.org/10.1017/S0305000902005330

Kievit, R. A. (2020). Sensitive periods in cognitive development: A mutualistic perspective. *Current Opinion in Behavioral Sciences, 36*, 144–149. https://doi.org/10.1016/j.cobeha.2020.10.007. Sensitive and Critical Periods.

King, Y. A., & Purpura, D. J. (2021). Direct numeracy activities and early math skills: Math language as a mediator. *Early Childhood Research Quarterly, 54*, 252–259. https://doi.org/10.1016/j.ecresq.2020.09.012

Kung, M., Schmitt, S. A., Zhang, C., Whiteman, S. D., Yang, F., & Purpura, D. J. (2019). The role of mathematical language in mathematics development in China and the US. *International Journal of Educational Research, 95*, 131–142. https://doi.org/10.1016/j.ijer.2019.02.008

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development, 81*(6), 1753–1767. https://doi.org/10.1111/j.1467-8624.2010.01508.x

Lehrl, S., Ebert, S., Blaurock, S., Rossbach, H.-G., & Weinert, S. (2020). Long-term and domain-specific relations between the early years home learning environment and students' academic outcomes in secondary school. *School Effectiveness and School Improvement, 31*(1), 102–124. https://doi.org/10.1080/09243453.2019.1618346

Lehrl, S., Linberg, A., Dornheim, D., Besser, N., Baron, F., Klemm, J., … Weinert, S. (2024). *Frühe mathematische Entwicklung und die Bedeutung von Interaktionsqualität in Kindertageseinrichtungen: Ein Methodenbericht zur Konzeption und Umsetzung des EarlyMath Projekts*. OSF. https://doi.org/10.31219/osf.io/wy9um

Libertus, M., Miller, P., Zippert, E. L., Bachman, H. J., & Votruba-Drzal, E. (2024). Predicting individual differences in preschoolers' numeracy and geometry knowledge: The role of understanding abstract relations between objects and quantities. *Journal of Experimental Child Psychology, 247*, Article 106035. https://doi.org/10.1016/j.jecp.2024.106035

Libertus, M. E., & Brannon, E. M. (2010). Stable individual differences in number discrimination in infancy. *Developmental Science, 13*(6), 900–906. https://doi.org/10.1111/j.1467-7687.2009.00948.x

Linberg, A., Lehrl, S., Dornheim, D., Weinert, S., & Roßbach, H.-G. (2019). *Mathematical Development and the Impact of Interactionquality in Early Childcare: Frühe mathematische Entwicklung und die Bedeutung von Interaktionsqualiät in Kindertageseinrichtungen*.

Liu, Y., Peng, P., & Yan, X. (2025). Early numeracy and mathematics development: A longitudinal meta-analysis on the prediction nature of early numeracy. *Journal of Educational Psychology.*. https://doi.org/10.1037/edu0000925

Méndez, L. I., Hammer, C. S., Lopez, L. M., & Blair, C. (2019). Examining language and early numeracy skills in young Latino dual language learners. *Early Childhood Research Quarterly, Cross-Domain Development of Academic and Cognitive Skills, 46*, 252–261. https://doi.org/10.1016/j.ecresq.2018.02.004

Mix, K. S. (2009). How Spencer made number: First uses of the number words. *Journal of Experimental Child Psychology, 102*(4), 427–444. https://doi.org/10.1016/j.jecp.2008.11.003

Napoli, A. R., & Purpura, D. J. (2018). The home literacy and numeracy environment in preschool: Cross-domain relations of parent–child practices and child outcomes. *Journal of Experimental Child Psychology, 166*, 581–603. https://doi.org/10.1016/j.jecp.2017.10.002

Negen, J., & Sarnecka, B. W. (2012). Number-concept acquisition and general vocabulary development. *Child Development, 83*(6), 2019–2027. https://doi.org/10.1111/j.1467-8624.2012.01815.x

Orth, U., Meier, L. L., Bühler, J. L., Dapp, L. C., Krauss, S., Messerli, D., & Robins, R. W. (2024). Effect size guidelines for cross-lagged effects. *Psychological Methods, 29*(2), 421–433. https://doi.org/10.1037/met0000499

Payne, T. (2024). The math talk learning environment: Testing an early childhood math intervention. *Early Childhood Research Quarterly, 66*, 224–233. https://doi.org/10.1016/j.ecresq.2023.10.012

Peng, P., Lin, X., Ünal, Z. E., Lee, K., Namkung, J., Chow, J., & Sales, A. (2020). Examining the mutual relations between language and mathematics: A meta-analysis. *Psychological Bulletin, 146*(7), 595–634. https://doi.org/10.1037/bul0000231

Pinhas, M., Donohue, S. E., Woldorff, M. G., & Brannon, E. M. (2014). Electrophysiological evidence for the involvement of the approximate number system in preschoolers' processing of spoken number words. *Journal of Cognitive Neuroscience, 26*(9), 1891–1904. https://doi.org/10.1162/jocn_a_00631

Purpura, D. J., & Ganley, C. M. (2014). Working memory and language: Skill-specific or domain-general relations to mathematics? *Journal of Experimental Child Psychology, 122*, 104–121. https://doi.org/10.1016/j.jecp.2013.12.009

Purpura, D. J., Hume, L. E., Sims, D. M., & Lonigan, C. J. (2011). Early literacy and early numeracy: The value of including early literacy skills in the prediction of numeracy development. *Journal of Experimental Child Psychology, 110*(4), 647–658. https://doi.org/10.1016/j.jecp.2011.07.004

Purpura, D. J., & Logan, J. A. R. (2015). The nonlinear relations of the approximate number system and mathematical language to early mathematics development. *Developmental Psychology, 51*, 1717–1724. https://doi.org/10.1037/dev0000055

Purpura, D. J., Napoli, A. R., Wehrspann, E. A., & Gold, Z. S. (2017). Causal connections between mathematical language and mathematical knowledge: A dialogic reading intervention. *Journal of Research on Educational Effectiveness, 10*(1), 116–137. https://doi.org/10.1080/19345747.2016.1204639

Purpura, D. J., & Reid, E. E. (2016). Mathematics and language: Individual and group differences in mathematical language skills in young children. *Early Childhood Research Quarterly, 36*, 259–268. https://doi.org/10.1016/j.ecresq.2015.12.020

R Core Team. (2024). *R: A language and environment for statistical computing* (Version R 4.4.1) [Computer software]. R Foundation for Statistical Computing.

Rosseel, Y. (2012). lavaan: An *R* package for structural equation modeling. *Journal of Statistical Software, 48*(2). https://doi.org/10.18637/jss.v048.i02

Sarama, J., & Clements, D. H. (2009). *Early childhood mathematics education research: Learning trajectories for young children*. Routledge. https://doi.org/10.4324/9780203883785

Sarnecka, B. W., & Carey, S. (2008). How counting represents number: What children must learn and when they learn it. *Cognition, 108*(3), 662–674. https://doi.org/10.1016/j.cognition.2008.05.007

Savalei, V. (2014). Understanding robust corrections in structural equation modeling. *Structural Equation Modeling: A Multidisciplinary Journal, 21*(1), 149–160. https://doi.org/10.1080/10705511.2013.824793

Savalei, V., & Rosseel, Y. (2022). Computational options for standard errors and test statistics with incomplete normal and nonnormal data in SEM. *Structural Equation Modeling: A Multidisciplinary Journal, 29*(2), 163–181. https://doi.org/10.1080/10705511.2021.1877548

Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). Evaluating the fit of structural equation models: Tests of significance and descriptive goodness-of-fit measures. *Methods of Psychological Research, 8*(2), 23–74.

Slot, P. L., Bleses, D., & Jensen, P. (2020). Infants' and toddlers' language, math and socio-emotional development: Evidence for reciprocal relations and differential gender and age effects. *Frontiers in Psychology, 11*. https://www.frontiersin.org/articles/10.3389/fpsyg.2020.580297.

Snow, C. E., & Uccelli, P. (2009). The challenge of academic language. In *The Cambridge handbook of literacy* (pp. 112–133). Cambridge University Press. https://doi.org/10.1017/CBO9780511609664.008.

Spelke, E. S. (2003). What makes us smart? Core knowledge and natural language. In , *Boston ReviewLanguage in mind: Advances in the study of language and thought* (pp. 277–311). https://doi.org/10.7551/mitpress/4117.001.0001

Spelke, E. S. (2017). Core knowledge, language, and number. *Language Learning and Development, 13*(2), 147–170. https://doi.org/10.1080/15475441.2016.1263572

Tellegen, P. J., Laros, J. A., & Peterman, F. (2007). *SON-R 2½-7: Nonverbaler Intelligenztest* [*Nonverbal Intelligence Test*]. Hogrefe Verlag GmbH & Co. KG.

Tellegen, P. J., Winkel, M., Wijnberg-Williams, B. J., & Laros, J. A. (1998). *Snijders-Oomen Nonverbal Intelligencetest 2,5–7 years (SON-R 2,5-7)*. Swets Test Publishers.

Toll, S. W. M., & Van Luit, J. E. H. (2014a). Explaining numeracy development in weak performing kindergartners. *Journal of Experimental Child Psychology, 124*, 97–111. https://doi.org/10.1016/j.jecp.2014.02.001

Toll, S. W. M., & Van Luit, J. E. H. (2014b). The developmental relationship between language and low early numeracy skills throughout kindergarten. *Exceptional Children, 81*(1), 64–78. https://doi.org/10.1177/0014402914532233

Turan, E., & De Smedt, B. (2022). Mathematical language and mathematical abilities in preschool: A systematic literature review. *Educational Research Review, 36*, Article 100457. https://doi.org/10.1016/j.edurev.2022.100457

Uccelli, P., Galloway, E. P., Barr, C. D., Meneses, A., & Dobbs, C. L. (2015). Beyond vocabulary: Exploring cross-disciplinary academic-language proficiency and its association with reading comprehension. *Reading Research Quarterly, 50*(3), 337–356. https://doi.org/10.1002/rrq.104

Van Der Maas, H. L. J., Dolan, C. V., Grasman, R. P. P. P., Wicherts, J. M., Huizenga, H. M., & Raijmakers, M. E. J. (2006). A dynamical model of general intelligence: The positive manifold of intelligence by mutualism. *Psychological Review, 113*(4), 842–861. https://doi.org/10.1037/0033-295X.113.4.842

Vygotsky, L. S. (1989). Concrete human psychology. *Soviet Psychology, 27*(2), 53–77.

Weinert, S., & Ebert, S. (2017). In V. Mall, F. Voigt, & N. H. Jung (Eds.), *2. Entwicklungsstörungen und chronische Erkrankungen: Diagnose, Behandlungsplanung und Familienbegleitung* (pp. 13–33). Band: Schmidt-Römhild.

Wynn, K. (1990). Children's understanding of counting. *Cognition, 36*(2), 155–193. https://doi.org/10.1016/0010-0277(90)90003-3

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology, 24*(2), 220–251. https://doi.org/10.1016/0010-0285(92)90008-P

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition, 74*(1), B1–B11. https://doi.org/10.1016/s0010-0277(99)00066-9

Zhu, T., Luo, H., & Zhang, L. (2026). Examining the relationship between mathematics-specific language and mathematical abilities in children: A three-level meta-analysis. *Educational Psychology Review, 38*(1), Article 48. https://doi.org/10.1007/s10648-026-10139-2