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Predicting children's emerging understanding of numbers

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Abstract

How do children construct a concept of natural numbers? Past research addressing this question has mainly focused on understanding how children come to acquire the cardinality principle. However, at that point children already understand the first number words and have a rudimentary natural number concept in place. The question therefore remains; what gets children's number learning off the ground? We therefore, based on previous empirical and theoretical work, tested which factors predict the first stages of children's natural number understanding. We assessed if children's expressive vocabulary, visuospatial working memory, and ANS (Approximate number system) acuity at 18 months of age could predict their natural number knowledge at 2.5 years of age. We found that early expressive vocabulary and visuospatial working memory were important for later number knowledge. The results of the current study add to a growing body of literature showing the importance of language in children's learning about numbers.

KEYWORDS
natural number concept, numerical cognition, cognitive development, language, working memory

1 | INTRODUCTION

The natural numbers (1, 2, 3, …) are an important part of everyday life in most modern societies. They are the foundation upon which much of mathematics is built (Rips et al., 2008) and are among the first mathematical concepts that young children encounter. A solid understanding of the natural numbers is important for children's later learning of mathematics. Preschoolers who know how to label a set of objects with the right number word show more sophisticated arithmetic strategies when starting school compared to children who do not yet have this skill (Chu et al., 2018).

When children, around the age of two, begin to understand the natural numbers, they do so in a series of predictable steps (Carey, 2009; Sarnecka & Carey, 2008). It begins with memorizing the count-list for the number words (Sarnecka & Carey, 2008). At this point, the number words carry little meaning and are not part of a numerical concept. Instead, they are arbitrary words similar to other rhymes (e.g., eeny, meeny, miny, moe; or the Alphabet). Soon, however, the child begins to attach numerical meaning to the number words. Childrent's knowledge of number words is often evaluated with the "Give-N" task (Wynn, 1992). The task measures the child's *knower level* by asking them to give an experimenter a specific number of objects. According to the logic of the task, a child knows the cardinality (i.e., the number of elements in a set) of "one" if they can give the correct number of objects when asked for one object, but fails when asked for any other number, such as two or three. A child who knows the cardinality of one is called a "one-knower". Over a period of several months, children go from being one-knowers to becoming two-knowers, three-knowers, four-knowers, and, eventually, cardinal-principal knowers (CP-knowers). The transition to being a CP-knower is marked by children coming to understand the cardinality principle; that the cardinality of the set is given by the last word uttered when counting it (Carey, 2009).

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That children progress through the number-knower-levels is well documented (e.g., Lee & Sarnecka, 2010; Sarnecka & Lee, 2009). However, there is little consensus in the literature about how a natural-number concept is constructed as children move from one level to the next (see e.g., Rips et al., 2008 for an overview of the debate). In fact, some suggest the stage-like development is an artifact produced by the Give-N coding scheme (Barner & Bachrach, 2010) and that children may have more number-knowledge than captured by the task (Barner & Bachrach, 2010; Baroody et al., 2017; Le Corre et al., 2006; O'Rear et al., 2020; K. Wagner et al., 2019). For example, children can display number-knowledge through gesture before being able to verbalize that knowledge (Gunderson et al., 2015).

Furthermore, even though children show a rudimentary understanding of the natural numbers already from a young age (Gilmore et al., 2007), the existing literature has mainly focused on the shift from understanding the first three or four number words to becoming a CP-knower (e.g., van Marle et al., 2016). In contrast, very few efforts have been made at understanding how children come to learn the first few number words. That is, what predicts the earliest stages of children's learning about numbers?

Several factors have been suggested, both on empirical (e.g., Negen & Sarnecka, 2012; Sarnecka et al., 2007; Starr et al., 2013; Wang & Feigenson, 2019) and theoretical (Barner, 2017; Carey, 2009; Leslie et al., 2008; Spelke, 2017) grounds, as important for children's understanding of natural numbers. The main factors that have been identified are: experience with language (Barner, 2017; Carey, 2009; Gibson et al., 2020; Negen & Sarnecka, 2012; Sarnecka et al., 2007; Spelke, 2017), the approximate number system (Leslie et al., 2008; Spelke, 2017; Starr et al., 2013) and, to a lesser extent, visuospatial working memory or object tracking ability (Carey, 2009; Purpura & Ganley, 2014; Spelke, 2017). Notably, the role of these factors has mainly been investigated in children who are subset-knowers or CP-knowers. However, it is unclear to what extent they are also involved in children's learning about the first number words. In the following, we review the support for each of the three main factors having a role in the development of number-knowledge.

1.1 | Language

Several theoretical accounts (e.g., Barner, 2017; Carey, 2009; Spelke, 2017) have emphasized the role of language in the development of number-knowledge. Specifically, experience with quantifiers (e.g., *many, more, few*), singular-plural morphology (e.g., *car, cars*), and the count-list is thought to support children's understanding of the first number words. The role of language has also been corroborated in empirical studies, indicating that language plays a role in learning to understand numbers (Negen & Sarnecka, 2012; Purpura & Ganley, 2014; Purpura & Reid, 2016), both in terms of children's own language ability and in terms of specific numerical language input. For example, in preschoolers, expressive vocabulary correlates with number word knowledge, independent of the child's age (Negen & Sarnecka, 2012).

RESEARCH HIGHLIGHTS

- We tested which factors predict the earliest stages of children's learning about natural numbers.
- Children's expressive vocabulary, visuospatial working memory, and Approximate Number System acuity were assessed at 18 months of age.
- At 30 months of age, children's understanding of the natural numbers was assessed using the Give-N task.
- We found that early expressive vocabulary and visuospatial working memory predicted children's later natural number knowledge.

Further, studies investigating parental number-talk have provided evidence for a role of specific numerical language input in learning number words. Several studies have found that the way in which parents use number words and counting when interacting with their young children correlates with children's early number knowledge (Casey et al., 2018; Gunderson & Levine, 2011; Levine et al., 2010). For example, Levine et al. (2010) measured parents' number-talk in the home environment at 5 time-points between 14 and 30 months of age. They found substantial variation in how much number-talk parents engaged in, and this variation predicted children's understanding of number words at 46 months of age, even after controlling for socioeconomic status (Levine et al., 2010).

Training studies add further support to the role of specific number related language experiences, in the form of language input from caregivers, in learning about natural numbers (Gibson et al., 2020; Mix et al., 2012; O'Rear & McNeil, 2019; Posid & Cordes, 2018). Gibson et al. (2020), for example, manipulated parents' number-talk by creating picture books that prompted parents to count and use number words to label either small (1–3) or large (4–6) sets of objects together with their 2-to-4-year-old children. Compared to a control condition, children who had been read the small numbers picture book had moved up more knower-levels after the intervention (Gibson et al., 2020). Gibson and colleagues argue that this finding shows that number-talk, that is, directed to the child's knower-level, or level directly above, is most beneficial for children's learning (Gibson et al., 2020). This, and other training studies (Gibson et al., 2020; Mix et al., 2012; O'Rear & McNeil, 2019; Posid & Cordes, 2018), shows that language experience, in the form of hearing number words used to count and label sets of objects, has a significant causal impact on children's developing number knowledge.

Indirect evidence for the role of language can be found in cross-cultural studies (Almoammer et al., 2013; Barner et al., 2009; Le Corre et al., 2016; Sarnecka et al., 2007). For example, children who speak a language (e.g., English or Russian) with a singular/plural distinction (one dog – two dogs) become one-knowers earlier than children who do not (e.g., Japanese) (Sarnecka et al., 2007). Such findings suggest that differences in language structure, and thereby in language input children receive, influences their number-knowledge development. Nevertheless, the developmental progression of natural number-knowledge is remarkably similar across cultures and languages. For example, Tsimane children, who live in an indigenous foraging-farming society in the Bolivian rainforest, learn the first number words in a similar developmental trajectory, although somewhat delayed, relative to children living in the United States, Russia, and Japan (Piantadosi et al., 2014).

Taken together, the current literature indicates that both language ability and specific numerical language experiences might play a role in in children's developing natural number concept. However, to our knowledge, no previous study has investigated the predictive role of early language ability for the earliest stages of children's learning about numbers.

1.2 | The approximate number system

Influential theories have posited that natural number learning is supported by a cognitive system known as the approximate number system (ANS) (Gallistel & Gelman, 1992; Spelke, 2017). The ANS is an innate cognitive system that represents the numerosity of sets as approximate mental magnitudes (Feigenson et al., 2004; Izard et al., 2009). According to one theoretical account, (Gallistel & Gelman, 1992) number words acquire meaning by being mapped onto these approximate mental magnitude representations. Because there are individual differences in how precise these representations are, it can be expected that children with more precise representations would benefit when mapping out the meanings of number words. Other theoretical accounts instead posit that approximate mental magnitude representations are mapped onto number words *after* children have learned the cardinality principle (Carey, 2009) and therefore do not play a role in the initial learning of number words.

There is evidence that the acuity of ANS representations is related to math achievement more generally in children (Mazzocco et al., 2011) and adults (Halberda et al., 2008). A number of studies have also investigated the more specific relation between ANS acuity and number word learning (e.g., van Marle et al., 2016; van Marle et al., 2014; Wagner & Johnson, 2011). For example, van Marle et al. (2014) tested 3- to 4-year-old children on ANS acuity and several quantitative tasks (e.g., verbal counting, Give-N, numeral recognition, and number comparison) at the beginning of the school year and general math achievement at the end of the school year. ANS acuity was significantly correlated with end-of-year math achievement, even after controlling for background factors and children's cognitive ability. Furthermore, children's performance on the Give-N was a key mediator of this relation, indicating that the ANS may play a role learning the meaning of number words. In another study, van Marle et al. (2016) tested 3- to 4-year-olds at two time points during the school year and found that ANS acuity predicted whether or not children would become CP-knowers on the Give-N task between the two time-points. Similarly, Wagner and Johnson (2011) also found a concurrent correlation between 3- and 5-year-olds' performance on an ANS task and their performance on a version of the Give-N that was independent of age (Wagner & Johnson, 2011). Wagner and Johnson (2011) also studied the responses of subset-knowers to large numbers outside of their knower-level range and found evidence that ANS representations are mapped onto large number words before children become CP-knowers. However, others have argued that these types of findings are an artefact created by the choice of statistical test (Wagner et al., 2019) and when non-parametrical tests are employed, there is no evidence that ANS representations are mapped onto large number words before children become CP-knowers (Wagner et al., 2019).

Other work has suggested that the relation between ANS acuity and number word learning is more complicated. Shusterman et al. (2016) followed 3- to 4-year-olds over a 6-month period and assessed ANS acuity, Give-N and mappings between ANS representations and number words using a rapid estimation task. They found that increases in ANS acuity were related to the acquisition of the cardinality principle (i.e., becoming a CP-knower on the Give-N) but not to shifts between subset-knower-levels (Shusterman et al., 2016). This indicates that the possible relation between ANS acuity and number word learning might not be as straightforward as one might think. ANS representations could be involved in constructing the meaning of number words, but learning about symbolic numbers can also affect ANS representations. The relation may therefore be bidirectional. Studies have addressed this potential bidirectionality by assessing children ability to map from ANS representations to number words (i.e., by quickly presenting visual displays of dots and asking the child to say the correct number word without counting) and by assessing the mapping from number words to ANS representations (i.e., rapidly tapping the table the correct number of times after hearing a number word) (Odic et al., 2015). Results from these kinds of tasks indicate that the relation between ANS representations and number words might not be bidirectional early in development and that the mapping direction from number words to ANS representations might develop first (Odic et al., 2015). However, to our knowledge, it remains untested whether ANS representations are used by children in the earliest stages in number word learning.

1.3 | Object tracking and visuospatial working memory

According to one influential theoretical account of number word learning (Carey, 2009), the object tracking system, which can also be construed as visuospatial working memory (Carey, 2009), is thought to play a key role in children's initial learning about number words. The object tracking system helps us keep track of objects in the environment by attaching indexes, or tags, to individual objects (Scholl & Pylyshyn, 1999; van Marle et al., 2016). The system can then keep track of the indexes even as objects move through space and out of sight (van Marle et al., 2016). Studies have shown that infants can simultaneously track around three objects and adults four objects (Feigenson & Carey, 2005). According to Carey (2009), when children learn the meaning of the first number words, they map the verbal number word label to representations of small sets of individual objects originating in the object tracking system. Children do this by creating working memory models from the object tracking system representations and storing them in long-term memory.

There is some empirical support for a role of the object tracking system, or visuospatial working memory, in children's number word learning. van Marle et al. (2016) tested 3- to 4-year-olds' object tracking ability, ANS acuity, and knower-level using the Give-N at the beginning and end of the schoolyear. Object tracking ability was tested using a *magic box task* where children watched an experimenter hide 0, 1, or 2 objects in a box and then either add or remove an object. The content of the box was then revealed and contained either a correct or incorrect number of objects and children were asked if a magic trick had been performed on the box (i.e., to gage if the child noticed that an object was missing or had been added). Results showed that at the beginning of the school year both object tracking ability and ANS acuity predicted if children were CP-knowers or non-CP-knowers (i.e., pre-knowers or subset-knowers), but at the end of the school year only ANS acuity, and not object tracking ability, significantly predicted CP-knower status and whether or not children had become CP-knowers during the schoolyear. The results were interpreted as the object-tracking system initially being used to map out the meaning of number words, together with the ANS, but that its role diminishes over time (vanMarle et al., 2016).

Working memory, especially visuospatial working memory, is clearly important for math ability in general (e.g., (Bull et al., 2008; Hawes & Ansari, 2020; Judd & Klingberg, 2021; Krajewski & Schneider, 2009; Purpura & Ganley, 2014; Raghubar et al., 2010), but only a few studies have looked specifically at the relation to children's knower-level progression. This is perhaps surprising given that object tracking and visuospatial working memory is argued to be the basis for children's initial mappings between number words and quantities (Carey, 2009). Object tracking ability in general has been well studied in young children (Cheung & Le Corre, 2018; Feigenson, 2005; Feigenson & Carey, 2003; Wang & Feigenson, 2019), but studies relating it to knower-level progression has mainly focused on the shift to becoming cardinal principle knower (van Marle et al., 2016). Thus, the question remains; does visuospatial working memory/object tracking ability, predict the earliest stages of children's number word learning?

1.4 | The current study

In the current study we investigated which factors predict the earliest stages of children's learning of number words. We used data from a longitudinal study that was not originally designed to answer our specific research questions, but includes assessments of our variables of interest. Children's vocabulary, visuospatial working memory, and ANS acuity were measured at 18-months of age and their number-knower-level, procedural knowledge of the counting procedure and general cognitive ability were measured at 2.5 years of age. We explored the following research questions: (a) Does vocabulary, visuospatial working memory and ANS acuity predict the earliest stages of children's learning of number words? and (b) If we are able to predict children's number-knower-level, are the predictors specific to children's knower-level progression or do they also predict a more general cognitive ability or general number knowledge?

2 | METHOD

2.1 | Participants

In total, 118 (50% female) children and their caregivers participated in the current study as part of a larger longitudinal project. Ages for the assessments included in the current study were 18 months (M = 544 days; SD = 12 days, min = 524 days, max = 583 days,) and 30 months (M = 912 days; SD = 13.6 days, min = 887 days, max = 974 days). At the 18 month time-point, 104 children were tested and at the 30 month time-point 92 children were tested. Because the 30 month time-point is when our main outcome measure (number-knower-levels) was assessed, we only report data from these 92 children. However, the exact number of participants for each task varies because of failure to complete the task, either due to fussiness of the child or the caregivers not completing our questionnaires (see table 1 for exact numbers for each task). Missing data was handled using full information maximum likelihood estimation in the analyses.

The study was approved by the local ethics committee (Regionala Etikprövningsnämnden dnr: 2013/423). We obtained written consent from caregivers prior to the start of the study and at each lab visit. Families received a gift voucher (worth approximately 30 euros) at each lab visit. A full description of all tasks administered in this project is available on Databrary (Gredebäck et al., 2019). Three manuscripts with data from the project have been published to date targeting the link between motor development and action prediction and action evaluation in 6- to 10-month-olds and the relation between these processes and later executive control at 18 months, and the relation between attachment quality and gaze following (Astor et al., 2020; Gredebäck et al., 2018; Marciszko et al., 2019).

2.2 | Tasks and measures

2.2.1 | Vocabulary at 18 months

Children's vocabulary was assessed by parents at 18 months using the Swedish short version of the MacArthur-Bates Communicative Development Inventories (CDI) (Eriksson, 2017; Fenson, 2007). The assessment included 90 items of, for example, animal names (e.g., dog, cow, and cat), food items (e.g., sandwich, sausage), and names of people (e.g., mom, grandfather). For each item, caregivers were asked to indicate if their child could understand the word or understand and say the word. From this assessment we extracted a receptive vocabulary score (how many words does the child understand) and an expressive vocabulary score (how many words can the child say).

TABLE 1 Descriptive statistics

	Vocabulary expressive 18 m	Vocabulary receptive 18 m	WM 18 m	ANS 18 m	Knower-level 30 m	Counting 30 m	Blocks 30 m	Matrix 30 m
N	81	81	85	78	92	92	91	91
Mean	23.5	60.9	2.85	0.53	0.76	1.72	5.90	2.73
Median	18	64	2.75	0.50	0	0.0	6	2
SD	21.1	14.9	0.63	0.20	1.01	2.06	2.34	2.26
Min	0	23	1.50	0.04	0	0	2	0
Max	83	86	4.00	0.97	4	6	12	7

2.2.2 | Visuospatial working memory at 18 months

We assessed children's visuospatial working memory using a hide and seek task (Garon et al., 2008; Marciszko et al., 2019). This task is similar to that used by van Marle et al. (2016) to measure children's object tracking ability but it is construed as measuring visuospatial working memory. Children were presented with a miniature chest of drawers with four different colored drawers. The task started with two warm-up trials where a toy was hidden in one of the drawers and the child was encouraged to search for it immediately. We then conducted four test trials. A test trial started with the experimenter hiding a toy in one of the drawers, in full view of the child, and then covering the chest with a curtain. After 5 s, the experimenter uncovered the chest and presented it to the child and asked the child to search for the toy. The child was allowed to make four search attempts before the experimenter revealed the location of the toy. On each of the test trials the toy was hidden in a different drawer, according to a fixed order. On each test trial children could receive a score between 0 (did not find the toy) and 4 (found the toy on the first attempt). We calculated a mean score over all four test trials for every child. Interrater reliability was excellent (*kappa* = 0.96). Note that data from this task has previously been published on (Marciszko et al., 2019).

2.2.3 | ANS change detection 18 months

We measured children's ANS acuity using a numerical change detection paradigm, originally created by Libertus and Brannon (Libertus & Brannon, 2010) but here adapted to be suitable for eye-tracking and repeated trials (Schröder et al., 2020). Infants were seated in their caregiver's lap, approximately 60 centimeters from the screen of a Tobii TX300 Eye Tracker set to 60 Hz (Tobii Technology AB, www.tobii.com), which records the reflection of near infra-red light in the pupils and corneas of both eyes (precision = 0.5°, spatial resolution < 0.3°). Prior to the presentation of our stimuli a standard 5-point calibration (Gredebäck et al., 2010) was conducted and caregivers were instructed not to point, comment or influence their child in any way.

On each 10 s trial, children were presented with two streams of images showing black dots on a white background, one on the right side of the screen and one on the left side of the screen. Each image was presented for 500 ms with 300 ms blank screen between images. One stream showed images where the number of dots alternated between images (e.g., 10 and 20 dots) (numerically changing stream) whereas the other stream showed images with the same number of dots (e.g., always 10 dots) (non-changing stream). The dots varied randomly in size (diameter ranging between 0.4 to 1.25 visual degrees) and the dots in each stream were presented in a 10 × 10 visual degree area. The distance between the centers of the streams was 24 visual degrees. To make sure that other cues besides number were not used, the average size of the dots was equated between the two streams on half of all images and the cumulative area of the dots in each image was equated between the two streams on the other half. Additionally, we counterbalanced across trials which side the changing stream was presented. We varied the difficulty of the paradigm between trials by varying the numerical distance between the two numbers shown in the numerically changing stream. Children were shown trials where the ratio between the two numbers were 1:2, 2:3, and 3:5. Two trials per ratio were presented. For each trial we calculated the proportion looking time to the numerically changing stream (compared to the total looking time to both streams). In order to remove noise, we only considered at trial to be valid if children had looked at the screen for at least 25% of the trial and had looked at each stream for at least 200 ms. The dependent variable was the average proportion score over all trials.

2.2.4 | Number knower level at 30 months

We measured children's number knower level using the Give-N task (Wynn, 1992). Children were seated in front of an experimenter and introduced to a puppet and a box of 10 small objects. The child was told that the puppet loves the particular object and that the experimenter would soon tell the child how many objects to put on a plate and give to the puppet. The first trial started by the experimenter asking the child to give the puppet "one" object. Once the child had made their response, the experimenter asked: "is that one object?" the child then had the possibility to modify their response. The experimenter then gave the object(s) to the puppet, without giving feedback on if the response was correct or not, and said "thank you". If the child had made a correct response the experimenter proceeded to ask the child to give the puppet "two" objects and then "three" objects and so on. If the child made an incorrect response, the experimenter asked the child to give the puppet the number of objects that the child had previously succeeded on. For example, if the child correctly gave the puppet "two" objects but failed to correctly give "three" objects, the experimenter would again ask for "two" objects and, given a correct response, then ask for "three" objects. If a child failed to correctly give "one" object, the experimenter would again ask for "one" object. The experimenter was instructed to test the child on the highest number that they could correctly give and the number above that three times. So, if a child correctly gave "two" objects but not "three" the experimenter attempted to conduct three "two object" trials and three "three object" trials. The experimenter could also change object type in between trials to keep the child interested. Our dependent variable was the child's knower-level (pre, one, two, three, four or CP-knower) estimated using the procedure specified by Negen, Sarnecka, and Lee (Negen et al., 2012). We used this classification procedure because it uses all available data to inform the classification.

2.2.5 | Counting procedure at 30 months

In this task we measured children's ability to perform the counting routine correctly. Children were presented with a line of buttons that were glued to a surface and asked by an experimenter to count how many there were. There were six trials where children were first asked to count two buttons, then three and so on up to six. On each trial children could receive help from the experimenter if they did not initiate counting or if they counted incorrectly. If this happened, the experimenter first pointed to the button on the right and said "one". If the child still did not count the experimenter again pointed to the rightmost button and said "one" and continued to point at the following buttons but without counting out loud. Our dependent variable was the highest count word children got to in any of the trials while correctly following the counting rules (pointing to one object at a time, not skipping any object or counting it twice, and reciting the count words in the correct order). This yielded a possible score between zero and six.

2.2.6 | Blocks at 30 months

This task was inspired by the NEPSY (Korkman et al., 1998) block construction assessment but adapted to be suitable for our age group. We measured children's ability to reconstruct three-dimensional block designs from a model. Children were seated opposite an experimenter who demonstrated building a specific configuration of red and white blocks which the children were then asked to copy. The task started with a practice trial where the experimenter placed a red and a white block next to each other and asked the child to copy. On this trial children received feedback on their performance and the experimenter corrected their figure if it was wrong. Next followed seven test trials where children did not receive feedback. At the start of each trial, children were given the exact number of blocks needed. Additionally, the experimenter described the configuration while they were building it. For example, "Now I am placing a red block here, and a white one on top of it." Each test trial consisted of a different configuration. For each trial, children received one point if they copied the figure correctly within 30 s and an additional point if their figure was also the mirror-image of the experimenter's figure (i.e., they translated the spatial relation between the figure and the experimenter to their own perspective). Our dependent variable was total score on the task ranging from 0 to 14.

2.2.7 | Matrix reasoning at 30 months

In this task we measured children's ability to complete a pattern. Children were presented with a matrix consisting of three pictures and a blank square and asked to complete the matrix by choosing the correct picture from four options. The task started with a practice trial where the child was shown a matrix picturing three blue pencils and then asked to help the experimenter by finding which pencil belonged in the fourth blank square. On this trial children received feedback on their performance and an explanation, for example, "These three pencils are blue, this pencil is also blue, therefore it belongs here". Children were then presented with six test trials where they did not receive feedback. Children could receive one point per trial (including the practice trial) for a correct answer and our dependent variable was total score on the task with possible scores ranging from 0 to 7.

3 | RESULTS

3.1 | Number-knower-levels

Fifty-one percent of the children were classified as pre-number-knowers, meaning that they did not yet reliably understand any number words, 33% were one-knowers, 9% were two-knowers, 4% were three-knowers and 3% were four-knowers. No children in our sample were classified as cardinal-principle-knowers.

3.2 | Descriptive statistics and zero order correlations

In the vocabulary assessment (MCDI), caregivers respond to each item by indicating if the child can understand the word, if they can understand and say the word, or if they cannot understand or say the word. The receptive vocabulary variable therefore contains a subset of words that children can also express which means that the receptive and expressive vocabulary variables are not independent. We therefore decided to only use the expressive vocabulary variable in the following analyses. However, the pattern of results was identical when using the receptive vocabulary variable instead (see supplementary materials for these analyses and results).

We first calculated zero order correlations for all variables of interest. Correlations and descriptive statistics for all predictor variables

TABLE 2 Zero order correlations

		Knower-level 30 m	Language expressive 18 m	Visuospatial working memory 18 m	ANS 18 m	Counting 30 m	Blocks 30 m	Matrix 30 m
Knower-level 30 m	Pearson's r	—						
	p-value	—						
Language expressive 18 m	Pearson's r	0.220*	—					
	p-value	0.048	—					
Visuospatial working memory 18 m	Pearson's r	0.199	−0.131	—				
	p-value	0.067	0.256	—				
ANS 18 m	Pearson's r	0.071	−0.133	0.035	—			
	p-value	0.536	0.270	0.764	—			
Counting 30 m	Pearson's r	0.375***	0.248*	−0.027	0.112	—		
	p-value	< .001	0.025	0.809	0.328	—		
Blocks 30 m	Pearson's r	0.247*	−0.170	−0.032	0.261*	0.294**	—	
	p-value	0.018	0.132	0.769	0.022	0.005	—	
Matrix 30 m	Pearson's r	0.256*	−0.005	−0.035	0.198	0.132	0.243*	—
	p-value	0.014	0.961	0.752	0.085	0.212	0.021	—

Note. * p < .05, ** p < .01, *** p < .001.

can be found in Tables 1 and 2. Children's number-knower-level was significantly correlated with expressive vocabulary at 18 months ($r_{(79)} = 0.220$, $p = 0.048$, 95% CI [0.002, 0.42]), procedural knowledge of the counting routine at 30 months ($r_{(90)} = 0.375$, $p < 0.001$, 95% CI [0.18, 0.54]) performance on the block task at 30 months ($r_{(89)} = 0.247$, $p = 0.018$, 95% CI [0.04, 0.43]), and performance on the matrix reasoning task at 30 months ($r_{(89)} = 0.256$, $p = 0.014$, 95% CI [0.05, 0.44]). Expressive vocabulary at 18 months was also significantly correlated with counting ability at 30 months ($r_{(79)} = 0.248$, $p = 0.025$, 95% CI [0.03, 0.44]) and ANS acuity at 18 months was correlated with the blocks task at 30 months ($r_{(75)} = 0.261$, $p = 0.022$, 95% CI [0.04, 0.46]). Finally, at 30 months performance on the blocks task was significantly correlated with counting ability ($r_{(89)} = 0.294$, $p = 0.005$, 95% CI [0.09, 0.47]) and performance on the matrix reasoning task ($r_{(89)} = 0.243$, $p = 0.021$, 95% CI [0.04, 0.43]).

3.3 | Regression analyses

In order to account for missing data and sparse data matrices we analyzed our data using regression models with full information maximum likelihood (FIML) estimation. Models were run in R (version 1.4.1103) using the *lavaan* package (version 0.6-5) (Rosseel, 2012). All variables were entered as continuous variables. We investigated our research questions in two steps. We first test how expressive vocabulary, visuospatial working memory and ANS acuity, measured at 18 months, predict children's number knowledge at 30 months. We then assess how specific these variables are in predicting number knowledge by running regression models with the significant predictors from the first model but with performance on the blocks and matrix reasoning tasks as the dependent variables. We then test if the significant predictors also predict children procedural knowledge of the counting routine.

3.3.1 | Model 1–predicting children's number-knower-level

To investigate if children's number-knower-level can be predicted from their expressive vocabulary, ANS acuity, and visuospatial working memory we ran a regression model using FIML estimation with knower-level as the dependent variable and expressive vocabulary, ANS acuity and visuospatial working memory at 18 months as independent variables. The resulting model (see Table 3) showed that expressive vocabulary ($\beta = 0.27$, $p = 0.014$) and visuospatial working memory ($\beta = 0.23$, $p = 0.025$) at 18 months were significant predictors of children's number-knower-level at 30 months, while children's ANS acuity ($\beta = 0.094$, $p = 0.372$) was not[1]. However, it is important to note that visuospatial working memory was not significantly correlated at the zero-level order with children's knower-level. The fit of the model was $R^2 = 0.11$.[2]

3.3.2 | Model 2a and 2b–testing the specificity of predictors on cognitive ability

Our first model showed that children's number-knower-level at 30 months could be predicted from expressive vocabulary and visuospatial working memory at 18 months. We next asked how specific our

TABLE 3 Regression results from model 1. Children's number-knower-level

Predictor	B	Std.Err	z-value	*p*-value	β	fit
Intercept	−0.823	0.574	−1.434	0.152		
Language 18 m	0.013	0.005	2.46	0.014	0.266	
WM 18 m	0.363	0.162	2.24	0.025	0.227	
ANS 18 m	0.484	0.542	0.892	0.372	0.094	
						$R^2 = 0.11$

TABLE 4 Regression results from model 2a. Performance on blocks task

Predictor	B	Std.Err	z-value	*p*-value	β	fit
Intercept	6.96	1.256				
Language 18 m	−0.020	0.012	−1.620	0.105	−0.179	
WM 18 m	−0.204	0.406	−0.502	0.616	−0.055	$R^2 = 0.033$

TABLE 5 Regression results from model 2b. Performance on matrix reasoning task

Predictor	B	Std.Err	z-value	*p*-value	β	fit
Intercept	3.10	1.231	2.52			
Language 18 m	−0.001	0.012	−0.097	0.923	−0.011	
WM 18 m	−0.120	0.397	−0.303	0.762	−0.034	$R^2 = 0.001$

infant variables were in predicting number understanding. That is, do early vocabulary and visuospatial working memory predict other cognitively demanding tasks that do not rely on number understanding as well? Zero-order correlations indicated that number-knower-level was related to performance on both the Matrix reasoning and Blocks tasks measured at 30 months. It is therefore possible that early vocabulary and working memory predict a more general cognitive ability instead of something, that is, unique to the Give-N. We therefore ran two additional models with the significant predictors from our first model but this time our outcomes were performance on Matrix reasoning and Blocks tasks measured at 30 months. The resulting models showed that neither expressive vocabulary nor working memory at 18 months significantly predicted performance on the block task or the matrix reasoning task (all *ps* > 0.1, see table 4 and table 5). This indicates that expressive vocabulary and visuospatial working memory are more closely related to children's number knowledge than general cognitive ability.

3.3.3 | Analyses of procedural knowledge of counting routine

We next investigated if expressive vocabulary and visuospatial working memory specifically predict children's performance on the Give-N or if they also predict other number knowledge, in this case procedural knowledge of the counting routine. In order to correctly carry out the counting routine, children need to learn to follow certain rules. They must recite the count-list in the correct order and count each item only once (Gallistel & Gelman, 1992). This can be achieved without having a conceptual understanding of numbers, unlike the Give-N where children need to have some kind of concept of numbers. Zero-order correlations showed that children's procedural knowledge of the counting routine at 30 months was significantly related to their knower-level at 30 months ($r_{(90)} = 0.375$, $p < 0.001$, 95% CI [0.18, 0.54]) and expressive vocabulary at 18 months ($r_{(79)} = 0.248$, $p = 0.025$, 95% CI [0.03, 0.44]) . We therefore asked if expressive vocabulary and visuospatial working memory are more closely related children's conceptual understanding of numbers (i.e., their knower-level) or their procedural understanding of counting (i.e., their ability to carry out the counting routine).

3.3.4 | Model 3a–testing the specificity of predictors on number-knowledge

We ran a regression model using FIML estimation with performance on the counting task as the dependent variable and expressive vocabulary and visuospatial working memory as predictors. The resulting model showed that expressive vocabulary ($\beta = 0.241$, $p = 0.024$), but not visuospatial working memory ($\beta = 0.000$, $p = 0.998$), was a significant predictor of procedural knowledge of counting (see table 6). The results therefore suggest that expressive vocabulary predicts both conceptual and more procedural knowledge of numbers whereas visuospatial working memory is more closely related to performance on the Give-N.

TABLE 6 Regression results from model 3a. Performance on counting task

Predictor	B	Std.Err	z-value	*p*-value	*β*	fit
Intercept	1.160	1.043	1.113			
Language 18 m	0.024	0.010	2.254	0.024	0.241	
WM 18 m	0.001	0.337	0.002	0.998	0.000	$R^2 = 0.058$

TABLE 7 Regression results from model 3b. Children's number-knower-level

Predictor	B	Std.Err	z-value	*p*-value	*β*	fit
Intercept	0.315	0.159	1.981			
Language 18 m	0.007	0.005	1.325	0.185	0.142	
Counting 30 m	0.167	0.049	3.409	0.001	0.339	$R^2 = 0.159$

TABLE 8 Regression results from model 3c. Performance on counting task

Predictor	B	Std.Err	z-value	*p*-value	*β*	fit
Intercept	0.800	0.314	0.011			
Language 18 m	0.017	0.010	1.704	0.088	0.174	
Knower-level 30 m	0.683	0.200	3.419	0.001	0.335	$R^2 = 0.169$

3.3.5 | Model 3b and 3c–exploratory follow-up analyses testing the relation between expressive vocabulary, procedural knowledge of counting and knower-level

In order to follow up the finding that early expressive vocabulary predicted both later conceptual and procedural knowledge of numbers, we decided to conduct exploratory, analyses to further elucidate the relation between these three variables. Note that this was not originally included in our research questions. We first tested if expressive vocabulary predicts children's knower-level while controlling for procedural counting knowledge. The resulting model showed that when controlling for performance on the counting task, expressive vocabulary was no longer a significant predictor of children's knower-level ($\beta = 0.142$, $p = 0.185$, see table 7). However, to shed further light on the relation between these three variables, we ran a final model testing if expressive vocabulary predicted performance on the counting task while controlling for children's knower-level. The resulting model showed that when controlling for knower-level, expressive vocabulary was no longer a significant predictor of children's counting performance ($\beta = 0.174$, $p = 0.088$, see table 8). This indicates that expressive vocabulary predicts variance, that is, common to both knower-level progression and procedural knowledge of counting.

4 | DISCUSSION

How do children come to understand the natural numbers? Most research efforts aimed at answering this question have been directed towards understanding how children come to acquire the cardinality principle (e.g., van Marle et al., 2016). However, at that stage children already have a rudimentary natural number concept in place and understand the first number words. The question therefore remains; what gets children's learning about natural numbers off the ground? Based on previous empirical findings and theoretical accounts of number learning we identified three candidate factors, language ability, ANS acuity, and visuospatial working memory, and tested if they predict the earliest stages of children's number word learning.

Our results showed that expressive vocabulary is important for children's learning of number words. Children with a larger expressive vocabulary at 1.5 years of age had come further in their number word learning when they were 2.5 years old. This finding is in line with research showing a concurrent relation between vocabulary size and number-knower-level (Negen & Sarnecka, 2012). Here, we extend these findings by showing that early vocabulary longitudinally predicts the earliest stages of number learning.

We found that children's general vocabulary predicted how far they had progressed through the knower-levels. However, it might be that it is specific aspects of language that drives learning. Research with slightly older children has found that math specific language ability (e.g., knowledge of words like "most", "fewest", etc.) and not general language ability predicts early math skills (Hornburg et al., 2018; Purpura & Reid, 2016) and that number knowledge can be improved by increasing children's exposure to mathematical language (Purpura et al., 2017). Similar ideas can be found in theoretical accounts of number learning. Several theoretical accounts propose that experience with singular/plural morphology and quantifiers in language (e.g., some, all, many) (Barner, 2017; Carey, 2009; Spelke, 2017) and experience with the number words in the count-list (Barner, 2017; Carey, 2009) play a role in constructing a natural number concept. Because 18-month-old children do not have a large vocabulary yet, we are not able to distinguish between their math-specific vocabulary and their general vocabulary. The results of the current study therefore do not allow us to draw conclusions about which aspects of language matters the most. However, our findings indicate that even if math specific language ability is important at a later age, general vocabulary plays a role in getting learning about natural numbers off the ground.

Our results also showed that expressive vocabulary was not only related to children's later understanding of number words but also to their procedural knowledge of how to perform the counting routine. In order to correctly perform the counting routine, children must be able to recite the count-list in the correct order and count each item once and only once by giving one number word to each counted item (Gallistel & Gelman, 1992). This routine can be carried out without necessarily requiring any conceptual understanding of numbers, unlike the Give-N task. We found that children who had a larger expressive vocabulary at 1.5 years of age were better able to carry out the counting routine at 2.5 years of age. Further, when controlling for counting routine performance, expressive language ability was no longer a significant predictor of children's knower-level, indicating that expressive vocabulary might be more closely related to children's procedural rather than conceptual understanding of numbers and counting. However, when controlling for children's knower-level, expressive vocabulary did not significantly predict children's counting routine performance. We interpret this pattern of results as indicating that expressive language ability predicts variance, that is, common to both knower-level progression and procedural knowledge of the counting routine. In the current study we are not able to fully investigate the relation between knower-level progression and procedural knowledge of counting. However, previous intervention studies suggest that practicing the counting routine, through shared book reading with a parent, helps children's knower-level progression (Gibson et al., 2020). In order to more fully understand the role of language in the development of number knowledge future studies should assess language ability, both general and mathematical, knower-level progression and counting knowledge at several time points during the first years of life and assess in which order these develop.

We further found that visuospatial working memory predicted children's later knowledge of number words. Children with better visuospatial working memory performance at 1.5 years of age had progressed further in the number-knower-levels at 2.5 years of age. One previous study has shown that visuospatial working memory, or object tracking ability, could predict if children were CP-knowers or non-CP-knowers at the beginning of the schoolyear but not at the end of the schoolyear (van Marle et al., 2016). We extend this finding by showing that visuospatial working memory longitudinally predicts children's knower-level progression, even before children start making the shift to becoming CP-knowers.

There are several ways in which visuospatial working memory could affect children's performance on the Give-N task. According to one theoretical account (Carey, 2009), children who have not yet grasped the cardinality principle use the object tracking system, or visuospatial working memory, to create mental models of small sets which they then use to pick out and correctly label small sets with number words. However, it has also been suggested that children with large working memory capacity are better placed to make the most out of learning opportunities more generally and therefore become more skilled in many different areas (Bull et al., 2008). Although we cannot completely discount this explanation, we found that early visuospatial working memory did not significantly predict their spatial or reasoning ability, indicating that visuospatial working memory is more closely related to knower-level progression than children's general cognitive ability. We also found that visuospatial working memory did not predict children's procedural knowledge of counting. This suggests that early visuospatial working memory is more related to knower-level progression than general number skills. However, another possibility is that working memory is not related to children's number knowledge per se but rather that the Give-N has significant working memory demands (see Baroody et al., 2017, for a similar suggestion). Under this account, visuospatial working memory becomes related to number knowledge through task demands rather than through a true relation between the constructs. To resolve this issue, future studies would need to investigate if early visuospatial working memory is also related to number knowledge in tasks that have lower working memory demands.

We found that children's ANS acuity at 1.5 years was not related to their later knowledge of number words. It has previously been shown that ANS acuity at 6 months predicts standardized math scores at 3.5 years of age (Starr et al., 2013) and that ANS acuity concurrently relates to understanding of cardinality in 3- to 4-year-olds (van Marle et al., 2014, 2016). The main difference between these studies and the current study is that we tested children at a younger age who were just beginning to learn the first few number words. Therefore, one alternative is that children do not initially use ANS representations when mapping out the meaning of number words, but that once they have progressed further in their number learning ANS representations could become involved in understanding the cardinality principle or ANS representations are mapped to natural number representations after children have acquired the cardinality principle (Le Corre & Carey, 2008). Others have instead suggested that the association between ANS representations and number word knowledge, or math achievement more generally, can be explained by task demands. In ANS stimuli, strong incongruency effects are sometimes introduced which creates an attentional bias which the participant must inhibit to respond correctly (Fuhs & Mcneil, 2013; Lindskog et al., 2021). The association between ANS and math performance could therefore in part be driven by individual differences in inhibitory control (Gilmore et al., 2013). This possibility is further supported by findings that ANS training interventions mainly affect performance on trials with strong incongruency effects (Fuhs et al., 2016). Further weakening the claim that ANS representations play a causal role in number word learning is the failure to replicate key findings. For example, training studies have claimed that receiving brief ANS training leads to improvement in arithmetic fluency (Hyde et al., 2014; Park & Brannon, 2013; Park et al., 2016), but recent empirical work on both adults (Szkudlarek et al., 2021) and children (Bugden et al., 2021) has shown that this effect cannot be replicated, calling into question the causal role of the ANS in symbolic math.

If the relationships between early vocabulary, visuospatial working memory and later number knowledge turn out to be causal, it suggests a number of ways in which young children could be supported in their discovery of numbers. First, parents and others working with toddlers could encourage children's vocabulary development. This could be done through exposure to child-directed speech (Weisleder & Fernald, 2013) or dialogic book-sharing (Dowdall et al., 2020). When it comes to visuospatial working memory, it is less clear from the existing literature what can be done to support toddlers' visuospatial working memory. Finally, our results suggest that interventions targeting ANS acuity (e.g., Park et al., 2016) may not be beneficial in supporting young children's emerging number understanding.

The current study has a few limitations. First, given our correlational design we can only speculate about causality. Perhaps expressive language ability and visuospatial working memory do not support children's learning about natural numbers and the observed correlations are instead caused by a third, unknown variable. Secondly, we only assessed children's understanding of natural numbers using the Give-N. This task has been criticized for not capturing the full extent of children's number knowledge (O'Rear & McNeil, 2019; Wagner et al., 2019) and perhaps underestimates children's understanding of cardinality (Baroody et al., 2017). Third, to be certain that ANS representations are not involved when learning the first number words other methods of measuring ANS acuity should also be further evaluated. It is possible that our adaptation of the numerical change detection task made the task more difficult, which could mean that it also captured abilities other than ANS.

5 | CONCLUSIONS

The results of the current study suggest that children draw upon their vocabulary and their visuospatial working memory when mapping out the meaning of the first number words. We did not see an effect of early ANS acuity, but we cannot rule out that it matters for children's number learning at some stage. There are, of course, many other factors that could be important for children's learning that we have not been able to address in the current study. However, our results add to a growing body of literature showing that language ability and language experiences play a role in children's understanding of numbers, even at the very early stages of language and number learning.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

CONFLICT OF INTEREST

The authors declare that we have no conflicts of interest.

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ENDNOTES

[1] To check the robustness of these findings we reran the model as an ordinal regression using the Lavaan package in R with MICE to account for missing data. The resulting model showed that expressive vocabulary was a significant predictor (β=.013, p= .036), visuospatial working memory was just above threshold for significance (β=.372, p=.055) and ANS acuity was not a significant predictor (β=.565, p=.423).

[2] We also reran the regression model using an alternative method of coding the Give-N, where the highest set size a child can correctly provide is taken as their knower-level. The resulting model showed the same pattern of results, although the p-values differ slightly. Expressive vocabulary remained a significant predictor (β = .018, p = .007), visuospatial working memory became non-significant (β = .422, p = .063), and ANS acuity was a non-significant predictor (β = .382, p = .605).

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