Early exposure to language (in any modality) supports number concept development: Insights from deaf children acquiring signed and spoken language

Emily Carrigan

University of North Carolina – Greensboro

Anna Shusterman

Wesleyan University

Marie Coppola

University of Connecticut

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Abstract
One of the best predictors of future academic attainment is children's level of rudimentary number skills at school entry. However, a pervasive mathematics achievement gap exists between deaf/hard-of-hearing and typically hearing students. In typically hearing children, acquiring a count list, as well as other linguistic abilities, has been shown to influence early numeracy and successful later mathematics achievement. However, most deaf and hard-of-hearing children experience delays in exposure to fully accessible and/or inadequate linguistic input. Here we examine the impact of language modality and the timing of language exposure on the development of the cardinality principle (CP) in 55 children with typical hearing and 121 deaf and hard-of-hearing children ages 3.1-7.6 years (100 girls and 76 boys) who were learning spoken English and/or American Sign Language (ASL) and who reflected a range of racial, ethnic, and socioeconomic backgrounds. A logistic regression found that the developmental timing of language exposure (from birth vs. later) and age each independently predicted children's mastery of the cardinality principle, but modality (English vs. ASL) and socioeconomic status did not. Older children, and those in the early-language group, were more likely to have achieved CP-knower status than children in the later-language group. These results demonstrate that spoken English and/or ASL effectively support number development, as long as exposure begins early. These findings add to the growing evidence that early access to language is essential for age-appropriate linguistic and cognitive development for deaf and hard-of-hearing children.

Keywords: deaf/hard-of-hearing, cardinal principle, language, number cognition, sensitive period, experience-dependent development

Introduction

One of the best predictors of future academic attainment is children's level of rudimentary number skills at school entry. However, a pervasive achievement gap exists between deaf/hard-of-hearing and typically hearing (typically hearing) students in math and other Science, Technology, Engineering, and Mathematics (STEM) disciplines at all stages of development, as well as in levels of educational and professional attainment. Hearing loss has historically been associated with weaker mathematics performance (Hyde, Zevenbergen, & Power, 2003; National Council of Teachers of the Deaf Research Committee (U.K.), 1957; Wood, Wood, & Howarth, 1983), although a child's actual hearing level itself does not predict mathematics performance (Nunes & Moreno, 1998). While research on number understanding in deaf and hard-of-hearing preschoolers in the U.S. is scarce, the "math gap" between deaf and hard-of-hearing and typically hearing children has been documented early in development, before formal schooling has begun (Kritzer, 2009). Many developed nations with strong infrastructure for special education nevertheless report at least a one-year lag in mathematical attainment in deaf and hard-of-hearing individuals of varying ages (e.g., Traxler, 2000). These delays have a cascading effect: the proportion of deaf and hard-of-hearing people in STEM disciplines is very small (0.13–0.19%) relative to the general population (11–15.3%) (NCSES 1996, 2004, 2009, 2011).

In typically hearing children, the acquisition of a count list, as well as other linguistic abilities, has been shown to influence early numeracy and successful math instruction (e.g., Jordan et al., 2009). Therefore, mathematical success depends upon language acquisition (Vukovic & Leseaux, 2013; Slusser, Ribner & Shusterman, 2019). However, the majority of deaf and hard-of-hearing children experience delays in exposure to fully-accessible language input (Mitchell & Karchmer, 2004), in addition to inadequate linguistic input. The input can be inadequate for multiple reasons, including but not limited to degraded sign language input from non-fluent models, or aural rehabilitation that does not provide sufficient access to spoken language (e.g., Hall et al., 2019). Given this, we argue that it is critical to assess the effect of language experience on the development of number skills and mathematical achievement in deaf and hard-of-hearing children. We use the term *language experience* to encapsulate two aspects of language acquisition: the modality of the language the child is learning (signed vs. spoken), and the age at which a child begins to have access to language.[1]

Here we assess how differences in *language experience* affect the development of basic symbolic number representation in deaf and hard-of-hearing children. We find that early access to language predicts age-typical development of numerical cognition,

[1] While clearly important, we did not measure the quality of children's language input, or other variables that are known to influence language development (see Carrigan & Coppola, 2020 for discussion).

regardless of whether children are learning signed (American Sign Language, ASL) or spoken language (English); in other words, language modality has no effect on the development of numerical cognition. In contrast, the developmental timing of a child's access to language does influence number concept development, with those exposed to language from birth outperforming those whose access begins later.

The development of number cognition

An extensive body of literature has documented that humans represent information about quantity in both symbolic and non-symbolic ways (for a review see Feigenson et al., 2004). Two non-symbolic cognitive systems allow us to either precisely represent small quantities (sets of up to 3 objects), or to approximately represent larger quantities (for the purposes of this system, sets of 4 objects or more are considered "large"). The small-exact system is often referred to as the "parallel individuation" or "object file" systems reflecting the purported function of this system in representing and tracking individual objects, and the large-approximate system is often referred to as the "analog magnitude system" or "Approximate Number System" (ANS). These two systems are termed non-symbolic because they do not rely on the use of any symbols (e.g., number words or Arabic numerals)—newborn infants and non-human animals can represent quantity using these systems (e.g., Hyde, 2011).

To precisely or exactly represent quantities larger than 3, researchers argue that we make use of linguistic symbols: number words (Carey, 2009; Spelke, 2011). typically hearing children learn number words—usually as part of the count list (e.g.,*"one", "two", "three"*)—before they understand what those number words mean. Although a two-year-old child might be able to reliably count to ten, they are often nevertheless unable to correctly produce, label, or point to a specific set size, even for small quantities (Sarnecka & Lee, 2009). Carey's (2009) bootstrapping hypothesis posits that children first learn the number words in the count list as placeholders, initially devoid of meaning; evidence shows that between the ages of 2 and 4 years, children slowly associate those placeholders with the exact quantities they represent (for example, Fuson, 1988; Wynn, 1990). In typically hearing children, variability in language input influences the timeline in which the meanings of number words are acquired (Gunderson & Levine, 2011; Gibson et al., 2020). By extension, the extreme variability in deaf and hard-of-hearing children's language experience should have even more dramatic effects on how quickly and how well these children learn the meaning of number words.

Language and cognitive development in deaf/hard-of-hearing children

Deaf and hard-of-hearing children have variable language experiences, which leads to non-uniform, and generally worse, language development outcomes. Fewer than 10% of deaf and hard-of-hearing children in the U.S. are born to deaf parents who use ASL (Mitchell & Karchmer, 2004), and thus very few acquire a language at home from birth as all typically hearing children do. Most parents of deaf and hard-of-hearing children are encouraged instead to pursue spoken language and listening for their children, using assistive technologies (e.g., hearing aids and cochlear implants), speech therapy, and speechreading (see Humphries et al., 2017 and Kite, 2020 and references therein). While some deaf and hard-of-hearing children acquire expressive and receptive spoken language skills in the typical-hearing range, a large number do not, even with early use of state-of-the-art cochlear implants (Dettman et al., 2016). Niparko et al. (2010), for example, found that on average, significant gaps between typically hearing and deaf and hard-of-hearing children who received early cochlear implants were not eliminated in the 3 years following implantation. deaf and hard-of-hearing children who use cochlear implants also show consistently and significantly lower vocabulary scores (e.g., Costa et al., 2019, Carrigan & Coppola, 2020; see Lund, 2016 for a meta-analysis). Further, the time necessary to identify hearing loss, consider options, be fitted for or be deemed eligible for assistive technologies, and receive interventions and training (that may not result in age-typical spoken language abilities), means that the vast majority of deaf and hard-of-hearing children will experience delayed or inadequate exposure to language.

Degraded exposure to either spoken or signed language affects eventual language competency in both modalities. For example, deaf and hard-of-hearing individuals who began learning ASL in childhood or adolescence performed more poorly than native signers on various linguistic tasks (Newport, 1990; Mayberry & Eichen, 1991). Early exposure to *any* accessible language ensures a solid first language developmental trajectory, provides a foundation for more complete acquisition of a second language (Mayberry et al., 2002), and supports age-typical cognitive development, including reading (Mayberry, 2010). As with typically hearing children (e.g., Levine et al., 2016), early language development is critical for deaf and hard-of-hearing children's later cognitive and academic success (e.g., Young et al., 2002). The many aspects of language children begin to acquire in the first year of life, such as word segmentation, foundational vocabulary, and grammar can influence development of basic cognitive skills, including theory of mind (e.g., Garfield et al., 2001, Schick et al., 2007), executive function (Hauser et al., 2008, Hall et al., 2018, Figueras et al., 2008, Botting et al., 2017), and working memory (Marshall et al., 2015). Earlier access to language allows deaf and hard-of-hearing children to eventually develop age-appropriate academic skills like reading and writing (e.g., Clark et al., 2016, Lederberg et al., 2013, Daza et al., 2014, Dostal & Wolbers, 2014), language-based (Henner et al. 2016, Novogrodsky et al., 2017) and non-linguistic analogical reasoning (Bandurski & Galkowski, 2004) and mathematics skills (Kelly & Gaustad, 2007, see review by Gottardis, Nunes, & Lunt, 2011).

Does language experience affect the development of foundational number representations?

Several studies have found relationships between typically hearing children's approximate number skills and mathematical achievement and that training on tasks involving, for example, non-symbolic comparison, can improve arithmetic performance (e.g., Hyde et al., 2014, Libertus et al., 2011, Halberda et al., 2008). Szücs & Myers (2017), however, suggest that this relationship is bidirectional, and some researchers propose that the causality is reversed, that is, that gains in approximate number representations are the result of symbolic number development (Goffin & Ansari, 2019; Shusterman, Slusser, Halberda, & Odic, 2016). Research with deaf and hard-of-hearing children finds the ANS to be intact relative to typically hearing peers (summarized in Bull, 2008). Therefore, it is unlikely that differences in ANS are at the root of deaf and hard-of-hearing children's subsequent challenges with mathematics. Nevertheless, given the uncertainty about the role of the ANS in number acquisition, it is important to consider how later exposure to language might interact with non-symbolic cognitive systems to alter the course of learning for deaf and hard-of-hearing children.

Full understanding of number concepts and the ability to use numbers functionally relies on building symbolic, exact representations of quantities larger than three, which goes beyond the parallel individuation system (in terms of numerosity) and beyond the ANS (in terms of exactness; Carey & Barner, 2019). Spaepen, Coppola, Spelke, Carey and Goldin-Meadow (2011) found that deaf adult homesigners in Nicaragua who did not have access to linguistic input, and who did not develop a count sequence on their own, struggled to exactly represent quantities larger than 4. The authors interpret their findings in support of Carey's (2009) bootstrapping hypothesis. Results from deaf signers who began learning Nicaraguan Sign Language at different ages also corroborate these findings and interpretation (Flaherty & Senghas, 2011).

Prior work investigating the development of number cognition in preschool- and school-aged deaf and hard-of-hearing children is limited, and generally finds that they underperform their typically hearing peers in symbolic tasks (e.g., Leybaert & Van Cutsem, 2002; Nunes & Moreno, 1998). Bull (2008) summarizes findings suggesting that deaf and hard-of-hearing children show comparable non-symbolic skills to typically hearing children, but show significant variability in performance on mathematical tasks that depend on symbolic numerical representations. In their best-evidence synthesis review, Gottardis et al. (2011) found that deaf and hard-of-hearing children underperformed typically hearing children in all studies using standardized measures (n=13), and in seven out of ten non-standardized measures, noting that studies of deaf and hard-of-hearing children's number development and math achievement often do not systematically examine the children's language backgrounds.

While some studies speculate that deaf and hard-of-hearing children's reduced access to incidental number talk at home might contribute to this difference (Pagliaro & Kritzer, 2010), no single study has directly evaluated the role played by both language modality and the timing of language exposure in deaf and hard-of-hearing children's number representations. Shusterman et al. (2012) found that deaf and hard-of-hearing children who were acquiring spoken language via assistive devices, and who were not learning sign language, knew the meanings of significantly fewer number words than did same-aged typically hearing peers. This finding is consistent with the hypothesis that delayed exposure to language negatively affects children's number development, but it cannot disentangle the effects of deafness from the effects of late timing. Secada's (1984) unpublished dissertation is the single prior study that directly compared 15 deaf and hard-of-hearing children learning ASL from birth from deaf parents to 15 typically hearing children learning English on a battery of tasks assessing language, counting, and number cognition. Secada's findings indicate that deaf and hard-of-hearing and typically hearing children show broadly similar patterns of number development when exposed to accessible language from birth, noting that the small sample size warrants further research.

The central aim of the present work is to de-confound deafness and language experience in order to better understand the root of the mathematics gap between deaf and hard-of-hearing and typically hearing children. Additional goals are to:

1. replicate the finding that the later onset of exposure to spoken language negatively influences the development of children's number knowledge (Shusterman et al., 2012);
2. replicate the finding that a signed language (ASL) can support children's early number knowledge (Secada, 1984); and
3. expand our knowledge about the effects of later exposure to language to include signed in addition to spoken language.

We compare numeracy development in preschool- and early school-aged typically hearing and deaf and hard-of-hearing children with typical language development (those who receive early spoken or signed language input) to that of deaf and hard-of-hearing children with delayed or incomplete language development (spoken or signed language input that occurs later and/or is of variable quality). Although some previous work has discussed the importance of a child's language input generally, this work is the first to systematically examine, in a single study, the role of language modality and the timing of language exposure in young deaf and hard-of-hearing children's development of number concepts. Further, it is one of only a handful of studies to examine number knowledge development in preschool-aged deaf and hard-of-hearing children. In the present study we take two approaches, resulting in two outcome measures, that offer complementary perspectives on the development of children's number concepts: 1) asking children to create sets for quantities 1-6 using the Give-a-Number (Give-N) task (Schaeffer et al., 1974; Wynn, 1990) allows us to characterize which number meanings they have acquired and whether they have acquired the cardinal principle (CP); and 2) asking children to create sets for larger quantities between 7 and 16, which indexes how well children can apply their CP knowledge with (larger) numbers that they encounter less often (following Sarbh, 2013). We predict that early, rich access to either spoken or signed language will equally support the development of symbolic number representations, but later or incomplete access to language in either modality will hinder the development of such representations.

Methods

Participants

The participants were 176 children (100 girls) aged 3.1 to 7.6 (m=5.0, sd=1yr) who were recruited from educational programs throughout the U.S. (Table 1). The "English early" group comprised typically hearing children who were exposed to spoken English from birth. The "ASL early" group comprised deaf and hard-of-hearing children who were exposed to ASL from birth by at least one deaf signing parent. The two "later" groups comprised deaf and hard-of-hearing children whose exposure to English (via assistive listening technology) or ASL (at a signing school), began after birth or was disrupted by hearing loss at some point after birth. Barratt's (2006) measure based on parents' education level and occupation was used to collect family socioeconomic status (SES) information.

Table 1

Participant Demographic Information

	English early (N=55)	ASL early (N=38)	English later (N=50)	ASL later (N=33)
Age (years)				
Mean (SD)	4.8 (0.7)	5.0 (1.2)	5.0 (1.0)	5.5 (1.1)
Median [Min, Max]	4.8 [3.2, 6.5]	4.8 [3.4, 7.6]	5.0 [3.1, 6.6]	5.9 [3.1, 7.5]
Sex				
Girls	34 (61.8%)	24 (63.2%)	24 (48.0%)	18 (54.5%)
Boys	21 (38.2%)	14 (36.8%)	26 (52.0%)	15 (45.5%)
Race				
White	39 (70.9%)	33 (86.8%)	37 (74.0%)	19 (57.6%)
Mixed	6 (10.9%)	1 (2.6%)	4 (8.0%)	3 (9.1%)
Asian	2 (3.6%)	0 (0%)	1 (2.0%)	4 (12.1%)
Black or African American	1 (1.8%)	1 (2.6%)	3 (6.0%)	1 (3.0%)
Other/Missing	7 (12.7%)	3 (7.9%)	5 (10.0%)	6 (18.2%)
Ethnicity				
Not Hispanic or Latino	40 (72.7%)	24 (63.2%)	34 (68.0%)	22 (66.7%)
Hispanic or Latino	4 (7.3%)	1 (2.6%)	7 (14.0%)	7 (21.2%)
Prefer not to answer/Missing	11 (20.0%)	13 (34.2%)	9 (18.0%)	4 (12.1%)
SES				
Mean (SD)	53.3 (11.4)	46.1 (16.5)	47.6 (15.4)	40.2 (17.8)
Median [Min, Max]	54.5 [8, 66]	52.0 [11, 66]	53.0 [3, 66]	44.0 [8, 62]
Age of Language Exposure (years)				
Mean (SD)	0	0	1.9 (1.4)	3.4 (1.1)
Median [Min, Max]	0	0	1.50 [0, 5.8]	3.1 [1.5, 5.8]
Missing	0 (0%)	0 (0%)	11 (22.0%)	0 (0%)

Procedure

Participants were tested individually in a distraction-free environment, in their preferred language by a deaf, fluent ASL user or a hearing English speaker[2]. The instructions were carefully developed to be comparable across the two languages by a team of deaf and hearing users of both languages.

The experimenter presented each child with 20 small rubber fish and placed a bowl on the table (Figure 1, left) and explained that the fish enjoy swimming with their friends in the "pond" but that not they cannot all fit at the same time. On each trial, the experimenter asked the child to put **X** *(the target number of)* fish in the bowl. If the child spontaneously counted while generating the set, the experimenter looked away to avoid cueing the child.

After the child stopped putting fish in the bowl, the experimenter lined up the fish on the table and asked, "Is that **X**?" If the child responded "No," the experimenter asked the child to fix it to make it **X**. Once the child responded "Yes," the experimenter asked "Can you count and make sure there are **X?**" for all trials greater than 1 (Figure 1, right). The experimenter provided positive feedback regardless of the child's accuracy.

Figure 1

Give-a-Number Materials and Task Example

Note. The rubber fish and the bowl ("pond") used in **Give-a-Number** (left). A signer, age 4.7 years, signs the ASL number "8" while counting during the "count and fix" procedure (right).

[2] Per their preference, four children (2 in the ASL early group and 2 in the ASL later group) were tested by a hearing experimenter using English or a combination of English and ASL.

Quantities 1 through 6 were requested three times each in a fixed random order. Children who succeeded on at least two trials for the quantity 6 were also tested once each on quantities 7, 9, 10, 12, and 16[3]. All interactions were video recorded.

Coding and Analyses

Research assistants who were fluent in the language of testing coded the number of fish the child first put into the bowl (the "initial response") and the number of fish in the set after the child engaged in the counting/checking procedure (the "final response"). All responses were scored for accuracy; in accord with previous literature, we report final responses[4]. For quantities 1 through 6, the child was considered to "know" a number if they provided a correct set size for that number on at least 2 of the 3 trials (following Wynn, 1990)[5]. For the quantities 7, 9, 10, 12, and 16, the child was considered to "know" a number if they provided a correct set size for that number on that trial. If a child responded correctly for a given quantity (e.g., two) on at least 2 out of 3 trials, but also gave that same number of fish (2 fish) on requests for other quantities (like three, four, etc.), they did not receive credit for knowing that number.

We analyzed two primary dependent measures. The first was drawn from children's performance on Give-N trials asking for quantities 1-6. Many studies assess children's number knowledge in an ordinal way—using the concept of "knower-level" (e.g., Wynn, 1990, 1992; Sarnecka & Lee, 2009). This measure reflects the highest quantity for which children can reliably produce a correct set size. Children who can correctly produce sets of 5 or 6 (often the highest values assessed in this type of task) are considered to have developed the CP, an understanding of how counting reflects or relates to the quantities of sets.

The distribution of participants' 'highest set size produced correctly' at each of the smaller quantities was highly skewed, possibly because the participants ranged in age from 3.1 to 7.6 years old, with a mean age of 5. Children generally acquire the CP around the time they learn the meanings of "five" and "six" (sometime around the age of 4 years) (e.g., Fuson, 1988; Wynn, 1990, 1992). For this reason, we elected to analyze the data in a binary way. Children who produced accurate sets for both quantities 5 and 6 on at least 2 out of 3 trials were classified as "CP-knowers." In previous literature, correctly producing a set for 5 has been taken as evidence that a child has mastered

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[3] Nineteen participants who did not succeed on at least two trials of 6 were accidentally tested on set sizes 7, 9, 10, 12, and 16; they were excluded from the analyses of Give-N large trials.

[4] The "initial response" differed from the "final response" for 5-20% of participants for set sizes 1-6 because children made changes during the confirmation questions, usually (in 97% of cases) resulting in a correct "final response". This proportion was comparable across participant subgroups.

[5] Occasionally a child was only presented with a single trial of one or more quantities between 1 and 6 (due to experimenter error or to the child's non-compliance). In such cases, the "highest number known" was calculated from available responses (provided the participant received at least one trial on four different quantities).

the CP; however, a small subset of participants in the current study (n=13) correctly produced sets on at least 2 out of 3 trials for 5 but not for 6. In order to be conservative about whether a child had achieved the CP, here we considered these children "Non-CP-knowers" (see Table 3 for frequency information).

The second dependent measure assessed quantities larger than 6, specifically 7, 9, 10, 12, and 16, for a total of 135 children from the original sample. We analyzed children's Give-N performance on these larger quantities separately because prior work demonstrates that children might not make the cardinality generalization for quantities at the higher end of their recited count list (e.g., Davidson, Eng & Barner, 2012). Further, a number of factors led us to analyze children's performance on these larger quantities as percent correct. First, it is atypical to see children who are 7-knowers (e.g., Carey, 2009). Second, the process of learning number words beyond "six" seems to be much less protracted than learning number words up to six (Piantadosi et al., 2014; LeCorre & Carey, 2007). Third, it is possible that Give-N performance for larger quantities reflects children's practicing the application of their knowledge of the CP with less-often-encountered (i.e., higher) numbers. The fact that children do not universally perform at ceiling on these values supports this interpretation (see results).

Results

We evaluated whether children's performance on the two dependent measures described above (whether they are CP-knowers, and percent correct on trials between 7 and 16) varied according to the timing of their language experience: early (i.e., from birth vs. later, or language modality: ASL (signed) vs. spoken English. Because children's age and SES have been shown to influence number cognition development (e.g., DeFlorio & Beliakoff, 2015; Elliott & Bachman, 2018) we also included them as predictors (code available at https://github.com/emlini/SLaM-Give-N). To achieve sufficient power to detect group differences, Green (1991) suggests a sample size greater than 104 plus the number of individual predictors in the model (in this case, 4), for a total of 108; our sample size of 176 meets this criterion.

For trials assessing quantities 1-6, a logistic regression model (all assumptions met) predicting membership in the "CP-knower" category fit the data significantly better than a null model ($p<0.001$), and showed that language timing and age were significant predictors, but language modality and SES were not (Table 2). Children in the early-language group were 2.23 times more likely to have achieved CP-knower status than children in the later-language group, controlling for age (Figure 2). Children's likelihood of achieving CP-knower status also increased by 3.97 with each year they aged, independent of language timing. An added interaction term between age and language timing was not significant, and did not improve model fit. Taken together, these findings suggest that children in the later-language group are at a disadvantage relative to children in the early-language group with respect to becoming a CP-knower, and that this effect can persist until age 7 years.

Table 2

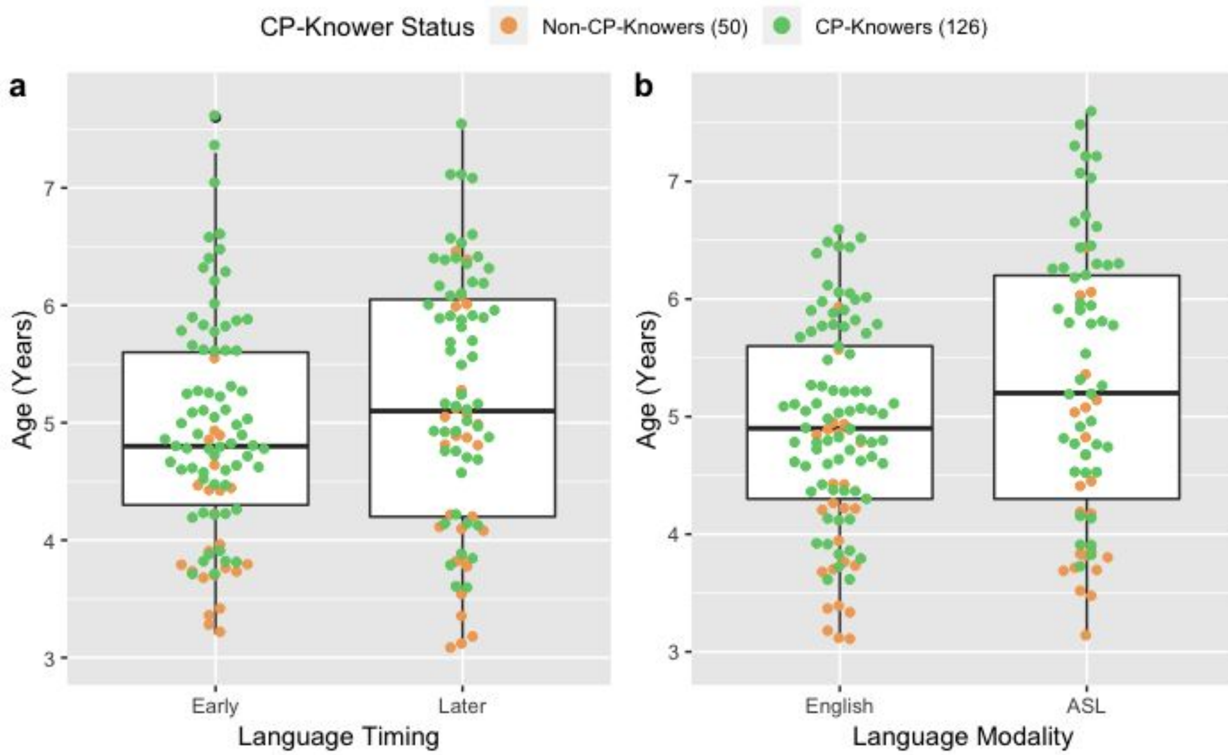
Logistic Regression Predicting CP-knower Status

	Dependent variable:
	CP-Knower Status
Socioeconomic Status (SES)	0.024 (0.014)
Language Modality (ASL)	-0.614 (0.411)
Age (Years)	1.379** (0.248)
Timing of Language Exposure (early)	0.801* (0.405)
Constant	-7.031** (1.508)
Observations	176
Akaike Inf. Crit.	172.718

Note. The coefficients for each variable are followed by the standard error in parentheses. *$p<0.05$; **$p<0.01$

Figure 2

Age of Cardinal Principle-Knower Achievement by Language Timing and Language Modality



Note. Each circle represents one child; the solid horizontal line indicates the median age for all children in that group (i.e., including both Non-CP-knowers and CP-knowers). Panel (a, left) demonstrates that, all things being equal, later-exposed children become CP-knowers at older ages than do early-exposed children, evidenced by the greater proportion of CP-knowers (green circles) above the median age of CP-knower achievement in the later group. In contrast, panel (b, right) shows that the distributions of CP-knowers and non-CP-knowers by age are similar for children acquiring ASL and those acquiring spoken English.

Table 3

CP- and non-CP-knowers by Language Timing and Language Modality

	Language Timing		Language Modality	
	Early	Later	English	ASL
Age range (mean)	3.16 -7.58 (4.83)	3.08-7.5 (5.17)	3.08-6.58 (4.83)	3.08-7.58 (5.25)
Non-CP-knowers (orange circles in Figure 2)	23 (25%)	27 (33%)	27 (26%)	23 (32%)
CP-knowers (green circles in Figure 2)	70 (75%)	56 (67%)	78 (74%)	48 (68%)
Total	93 (100%)	83 (100%)	105 (100%)	71 (100%)

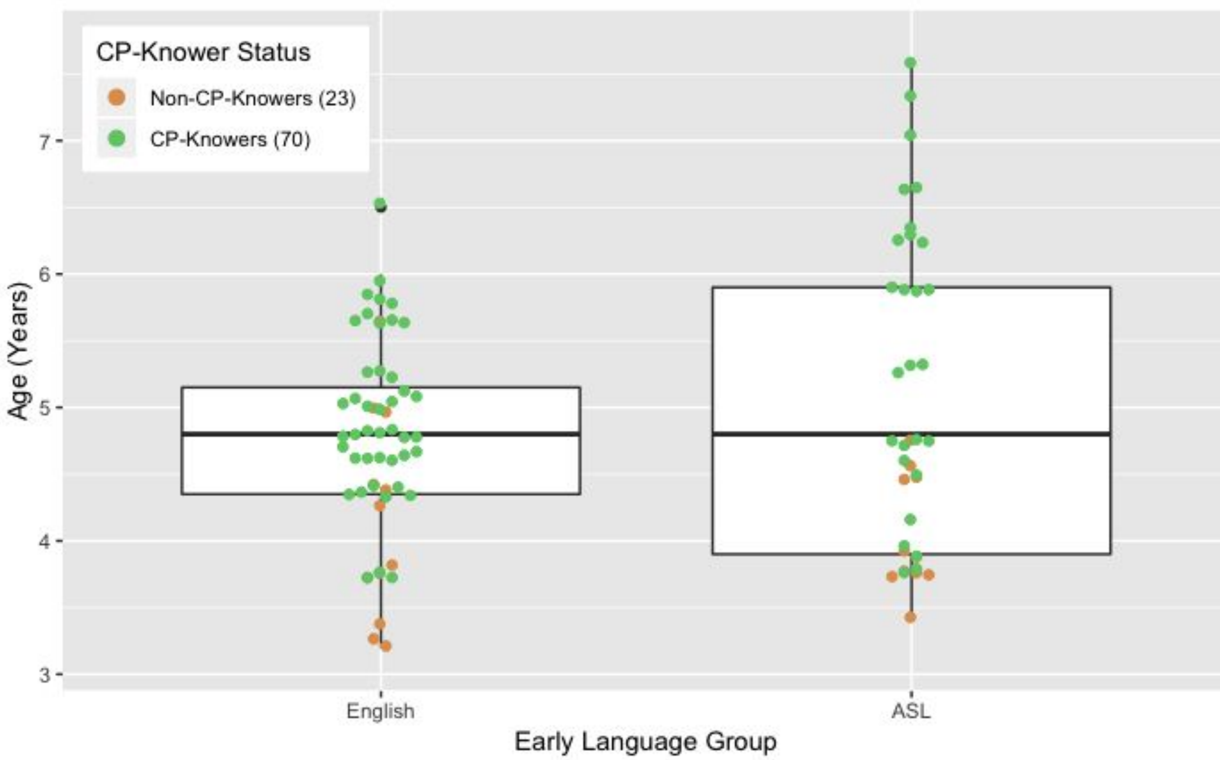
We conducted additional analyses to determine whether different distributions of age and SES across the timing and modality groups impacted performance. The later-exposed groups were significantly older (*m*=5.17) than the early-exposed groups (*m*=4.83) (Wilcoxon rank sum test, *W*=3095, *p*=0.02). Also, the participants using ASL (*m*=5.25) were significantly older than the English-speaking participants (*m*=4.83) (*W*=3021.5, *p*=0.03). In contrast to prior work finding that older typically hearing children tend to be CP-knowers, we found that the relatively older children in the later-exposed group were not more likely to be CP-knowers, supporting our conclusion that later, incomplete, or degraded exposure to language negatively affects number knowledge development.

Although children acquiring English had significantly higher SES (m=50.6) than children acquiring ASL (m=43.3) (*W*=4515.5, *p*=0.02), modality did not significantly predict CP-knower achievement. The SES of the early-exposed groups was significantly higher (m=50.3) than the later-exposed groups (m=44.7) (*W*=4764, *p*=0.007). A model with SES removed was not significantly different from the model including SES, according to a Likelihood Ratio Test, $X^2(1)=3.27$, $p=0.07$, indicating that SES was not a significant predictor of CP-knowing. However, a model with timing removed was significantly different from the model including timing, $X^2(1)=4.03$, $p=0.04$. These comparisons and other measures of model fit indicate that differences in timing, rather than differences in SES, predict CP-knowing.

We found no differences in CP-knower achievement between the English early and ASL early groups (Figure 3), $X^2(1)=0.29$, $p=0.59$, suggesting that language modality alone, in the context of language input from birth, does not affect CP-knower status.

Figure 3

Ages of CP-Knower Achievement by Language Modality for Early Language Groups



Note. Each circle represents one child; the solid horizontal line indicates the median age for all children in that group (i.e., including both Non-CP-knowers and CP-knowers). The distributions of CP-knowers and non-CP-knowers are similar for children acquiring ASL or spoken English from birth, in that the non-CP-knowers are generally among the youngest children across both groups.

Next we asked whether these predictors influenced children's ability to accurately generate sets for larger quantities (7, 9, 10, 12, and 16) (Figure 4). An ordinal logistic regression model including age, language timing, language modality, and SES was a better fit for the data than a null model, and indicated that age and language timing, but not language modality or SES, significantly predicted children's ability to generate sets for larger quantities (Table 4).

Table 4

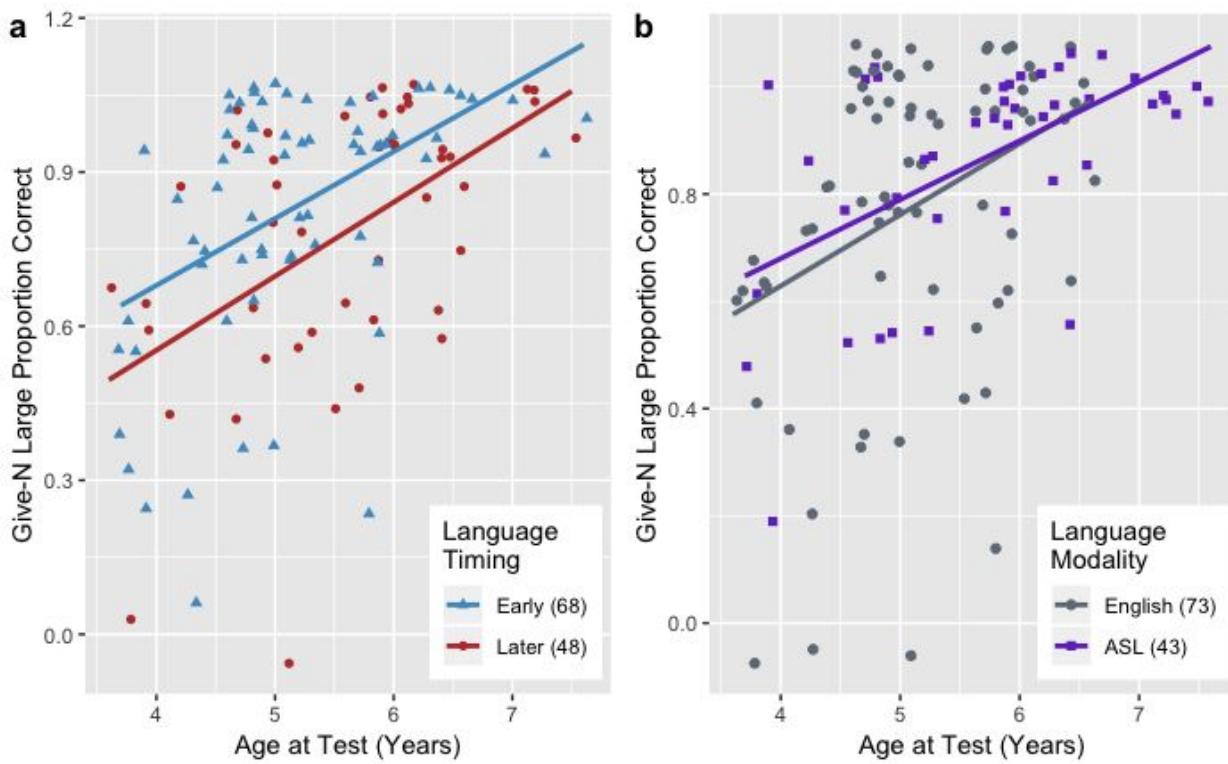
Ordinal Logistic Regression Predicting Give-N Large Performance

	Dependent variable:
	Give-N Large Proportion Correct
Socioeconomic Status (SES)	0.014 (0.008)
Language Modality (ASL)	0.210 (0.251)
Age (Years)	0.843** (0.149)
Timing of Language Exposure (later)	-0.553** (0.240)
Observations	116

Note. Coefficients and standard errors for ordinal logistic regression model predicting performance on Give-N larger quantity trials (7, 9, 10, 12, and 16). Language timing and age each independently predicted performance, but language modality and SES did not. Older children, and those in the early-language group, were more likely to respond correctly to larger quantity trials than children in the later-language group. $^{*}p<0.05$; $^{**}p<0.01$

Figure 4

Performance on Give-N for quantities 7, 9, 10, 12, and 16 by Language Timing and Language Modality



Note. Proportion correct is lower on average for children in the later language timing group relative to the children in the early group (panel a, left). However, children in the ASL group perform, on average, approximately equivalently relative to the English group (panel b, right).

Discussion

This work is the first to systematically assess how the timing of children's access to language *and* the modality of the language they learn affect children's acquisition of number concepts. To recap, our main findings are that age and the timing of their exposure to language (from birth vs. later) both significantly predict the likelihood that children are CP-knowers. In contrast, neither the modality of the language they are learning nor their family's SES significantly predicted CP knowledge. In accord with Secada (1984), native-signing deaf and hard-of-hearing children and English-speaking typically hearing children had comparable early number representations. The findings from these models suggest that, with respect to becoming a CP-knower, children with later exposure to language are at a disadvantage relative to children who experience language from birth. Further, this effect is apparent in some 7 year-old children in our sample. Importantly, these results demonstrate that deafness itself does not impede the development of numerical cognition, and serve as a reminder that the factors of language modality, the timing of language exposure, and hearing status should be kept separate in study design and analysis.

These findings have significant implications for both theories of number cognition development and for intervention and practice with deaf and hard-of-hearing children. Children's language experience is important for numerical cognition development (e.g., Gibson et al., 2020), and exact number representation is tied to the learning of specific, ordered words representing large, exact numerosities (i.e., the count sequence; Frank, Everett, Fedorenko, & Gibson, 2008, Spaepen et al., 2011). The present work highlights that adequate language experience is necessary for this development to proceed as expected. With sufficient accessible input to a signed language, spoken language, or both language modalities, children's early number cognition develops age-appropriately. When language access is inadequate or the timing is significantly disrupted, as it is for the "later" language group in the present work, number cognition development is also disrupted.

Our results suggest that this disruption goes beyond a delay in becoming a CP-knower. Our testing protocols, combined with the effect of timing on CP-knower achievement, resulted in fewer CP-knowers in the later exposed group. This meant that fewer children exposed to language later completed Give-N trials with larger quantities. Even still, there is an effect of timing on performance on these trials, suggesting that CP-knowers in the "later" language group struggle more in applying their knowledge of counting and cardinality to larger set sizes.

The effect of inadequate language experience is evident in some children older than 7 years in our sample. Literature examining mathematics achievement suggests that deaf and hard-of-hearing students are often unable to recover from this early disruption in number cognition development, though longitudinal studies are needed to discern the specific causal trajectories. These long-term disruptions may be the result of educational systems serving deaf and hard-of-hearing students that are unable to provide the additional support needed to compensate for the early deprivation, or they may be indicative of a sensitive period of development for these foundational number concepts. While discerning the underlying causes will enhance our theoretical understanding of this development, it is more ethical and expedient to simply prevent differences from emerging in the first place by ensuring adequate access to early language for deaf and hard-of-hearing children.

The finding that sign language equally supports achievement of the CP is novel and should have a significant impact on the clinical recommendations made to parents of deaf and hard-of-hearing children. For the 95% of deaf and hard-of-hearing children who are less likely to get early and full access to their first language, messages from clinicians and early intervention providers have a large influence on parents, and should strive to be informed by scientific evidence. Many hearing parents of deaf and hard-of-hearing children who do not know a sign language will likely want their child to learn spoken language. Data collected from deaf and hard-of-hearing children using cochlear implants across a period of almost a decade have demonstrated similar findings (Authors, in prep), suggesting that the promise of technological improvements in hearing technology to offer deaf and hard-of-hearing a developmental path comparable to typically hearing children has not been realized. The current findings and this context suggest that it would be prudent for parents to expose their deaf and hard-of-hearing child to sign language as well, to ensure an adequate language foundation that supports number knowledge development. Emerging research shows that parents do not need to be fluent signers in order to support the development of age-appropriate sign language skills and the cognitive abilities that depend on these language skills (Henner, Novogrodsky, Caldwell-Harris, & Hoffmeister, 2019, p. 103; Caselli et al., 2019; 2021).

Limitations

While examining the variability of language learning circumstances experienced by deaf and hard-of-hearing children offers important insights into the role of language in the development of number cognition, this approach has limitations. First, in contrast to research with typically hearing children, there are hard limits on sample size, given the low incidence of deafness in the population (approximately 2-3 children per 1,000; CDC, 2010). Second, while directly comparable ASL and English language measures would be ideal, such measures are not available. However, children’s knowledge of the meanings of the number words does in some sense reflect their language development.

In sum, we found that early access to a natural language in either modality supports age-appropriate development of number concepts and mastery of the cardinality principle, while children with later access to language, on average, showed later and more variable achievement of the CP. This work simultaneously underscores the importance of early access to language for age-typical development of number cognition, and demonstrates the impact of a lack of such early and full access. It also highlights the need for researchers to decouple language from hearing status in research designs (Hall et al., 2018), and to build the evidence base upon which clinicians and practitioners can depend to inform parents about the consequences of their decisions about their deaf and hard-of-hearing child’s language and educational opportunities.

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