Delayed first language exposure negatively impacts object tracking: Evidence from deaf and hard-of-hearing children

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Abstract

Most deaf and hard-of-hearing children are born to hearing parents, often delaying exposure to their first language, which negatively influences not only development of language, but also development of many other aspects of cognition, including exact representations of large quantities. The core knowledge view of numeracy predicts that delays in language exposure should not affect non-verbal representations of small quantities (1–3). This study is the first to investigate effects of modality (spoken vs. signed language) and timing of language experience (early, from birth vs. later) on small quantity object tracking. We adapted the "Mr. Elephant" task (Shusterman et al., 2017) and examined whether children succeeded on trials involving quantities 2 and 3. A logistic regression found that timing and socioeconomic status significantly predicted Mr. Elephant performance, while modality and age did not. Later-exposed children were *less* likely to succeed on the task than Early-exposed children. For an exploratory follow-up, two measures of language were added into the analysis: Highest Count, which records children's recitation of the count list, and Give-a-Number ('Give-N'), which assesses children's understanding of number word meanings. This logistic regression found that timing and Give-N performance significantly predicted Mr. Elephant performance, but socioeconomic status and

Highest Count did not. For every successive Give-N quantity answered correctly, children were more likely to succeed on Mr. Elephant. These results show that the timing of children's language exposure and their knowledge of number word meanings affect small quantity object tracking, suggesting that language contributes to the development of small-quantity representations.

Keywords

numerical cognition, development, object tracking, deaf/hard-of-hearing, language

Introduction

Deaf and hard-of-hearing (DHH) students historically are reported to underperform in mathematics compared to typically-hearing peers (Gottardis et al., 2011; Traxler, 2000; Wollman, 1965); however, the reasons behind this have not been fully investigated. It is well documented that early language skills and experiences are related to later mathematical success: counting abilities in kindergarten predict later mathematical skills (e.g., Jordan et al., 2009); children's number word knowledge fully mediates the relationship between general vocabulary and early mathematics achievement (Slusser et al., 2019); and the number talk that primary caregivers engage in with their children predicts (e.g., Levine et al., 2010) and in fact drives (Gibson et al., 2020) children's knowledge of cardinal number meanings.

However, the literature suggests that one of the subsystems for representing quantity, parallel individuation, does not rely on language. Parallel individuation is an object tracking system that allows representations of small sets (1–3) without language (Carey, 2009). This object tracking system has been shown to be present in a wide range of participants and conditions: infants and toddlers (Feigenson et al., 2002; Feigenson & Carey, 2003), adults performing nonverbal tasks (Gallistel & Gelman, 2000; Gelman & Cordes, 2001; Frank et al., 2008), adults without language input (Spaepen, 2008), adults and children who use a language without a counting system (Gordon, 2004; Frank et al., 2008; Butterworth et al., 2008), and a variety of non-human animals (Gelman & Cordes, 2001) including monkeys (Wood et al., 2008), horses (Uller & Lewis, 2009), and fish (Piffer et al., 2012). Evidently, language should not be necessary for the ability to represent small sets and track small quantities.

Furthermore, language modality—specifically using a spoken or signed language—should also not affect core subsystems for representing quantity, including representing approximate number magnitude and small quantity object tracking. Children acquiring American Sign Language (ASL) from birth from their deaf signing parents (i.e. native signers) achieve the same language milestones and follow the same patterns as children acquiring spoken language (Meier, 2016; Mayberry & Squires, 2006; Meier, 2002; Newport & Meier, 1985). Additionally, children who acquire ASL from birth perform similarly to typically-developing hearing children in various areas of cognitive development including executive functioning (M.L. Hall et al., 2017) and theory of mind (Schick et al., 2007). With regard to mathematics specifically, one small study found that when the ability to recite the count list was controlled for, native-signing DHH children and native English-speaking children showed comparable number knowledge (Secada, 1984). DHH children who receive sign language input from birth at home and hearing children who receive spoken language input from birth at home also perform equivalently on verbal, numerical and spatial reasoning tasks (Bandurski & Galkowski, 2004). Given this evidence, neither hearing level nor the signed modality can explain the findings that DHH students underperform in mathematics.

Therefore, we must consider other aspects of DHH children's language experience, specifically when they begin receiving substantial access to their first language, which we will refer to as language timing. Most DHH children are born to hearing parents who do not know sign language (Mitchell & Karchmer, 2004), delaying exposure to their first language.

Furthermore, many parents are encouraged by medical professionals to focus on spoken language acquisition through assistive technology such as hearing aids and cochlear implants, instead of sign language (Mauldin, 2016).

Timing of access to a first language can affect language acquisition, whether the language being acquired is signed or spoken. Deaf children acquiring spoken language via cochlear implants show a great deal of variability in spoken language development, even among early-implanted children (Lund, 2016; Niparko et al., 2010). Furthermore, children with cochlear implants show delays in number processing and mathematical skills, regardless of the age of implantation (Pixner et al., 2014; Edwards et al., 2013). Deaf adults who acquired ASL as a second language (e.g., they were born hearing, learned English, then became deaf later in childhood and learned ASL) performed better on an ASL sentence processing task compared to deaf adults who acquired ASL at the same age but as their first language (e.g., they had delayed access to their first language) (Mayberry & Kluender, 2018; Mayberry, 1993). Timing of first language acquisition can even influence how the brain responds to language. Deaf adults with later first language exposure showed more activation in posterior visual brain regions and less in anterior language regions when watching ASL sentences in an MRI task (Mayberry et al., 2011). Timing of first language access also affects other aspects of numerical and cognitive development. Children with later exposure to a first language achieve cardinal principle-knower status later than children whose language exposure began at birth, regardless of modality (Carrigan et al., in prep). The benefits of early exposure to ASL for DHH children include better performance on analogical reasoning tasks (Henner et al., 2016) and better theory of mind abilities (Schick et al., 2007). Timing of first language access is crucial because when DHH children have no or delayed exposure to sign language, they can be at risk for experiencing long-term language deprivation, which can have significant negative neurological, educational, and developmental consequences (W. C. Hall et al., 2017).

Early number knowledge is important for later mathematical achievement (Duncan et al., 2008; Jordan et al., 2009), and difficulty with basic numeracy skills may hinder the learning of more advanced mathematical concepts. The ability to represent small quantities is one of the most foundational numeracy skills; children learn to name small quantities before they learn larger number words (Piandtadosi et al., 2014) and in order to learn these labels, children must first be able to represent these quantities. As previously mentioned, research suggests that children’s representation of small sets of objects does not rely on language (Li et al., 2009; Feigenson et al., 2002; Feigenson & Carey, 2003). However, some DHH students’ struggles with mathematics may be traceable to early childhood delays in first language access, postponing the development of number concepts, including the ability to associate number words and/or signs with their corresponding quantities. Because many DHH children with hearing, non-signing parents do not receive much language input from their parents, either spoken or signed, this also limits opportunities for incidental exposure to linguistic and mathematical symbols, putting these children behind in numerical knowledge before even starting school (Pagliaro & Kritzer, 2010; Bandurski & Galkowski, 2004).

We have a great deal of evidence from typically-developing children, as well as adults from diverse linguistic backgrounds, that language is not involved in small quantity object tracking. However, in those cases, cognitive maturation and linguistic experience are confounded. Thus, it is not clear whether the foundational skill of representing small sets develops organically, and whether development of this skill would proceed normally even in the absence of typical language exposure or years of life experience. Non-human animals can track small quantities seemingly without language, but perhaps this ability is experience-expectant in humans (Greenough et al., 1987), so typical language experience may be necessary, as it seems to be necessary in so many other domains. Because typical human development expects language, such systems may get disrupted when language input is delayed. Language and maturation have not been decoupled in typical human development, so we must look to populations with atypical language experience, such as young DHH children who have variable language exposure and experiences. Since delayed access to a first language can have pervasive and long-lasting effects on language proficiency and neural organization, it is critical to test the effects of deprivation in initial language experiences on the development of small quantity object tracking, despite all previous evidence indicating that language experience does not affect object tracking. In sum, these considerations raise the question: does timing of first language access affect the ability to track small quantities? Our hypotheses are as follows:

H1. Language modality will not affect small quantity object tracking.

H2. Timing of first language access will not affect small quantity object tracking.

Our primary analysis investigates the effects on small quantity object tracking of language modality (spoken English vs. ASL) and the timing of first language access (early, i.e., from birth, vs. later, i.e., sometime after birth). Our exploratory follow-up analysis examines the relationship between children's small quantity object tracking and their knowledge of number words.

Methods

Participants

A total of 153 children, 57 typically hearing and 96 DHH, were recruited from educational programs throughout the United States (see Table 1). Their mean age was 5;2 years old (SD = 11.4 months, range: 3;1–7;5 years) and 57% were girls. Children with known or suspected additional disabilities were excluded. Signed informed consent was obtained from all caregivers and verbal assent was obtained from all participants prior to testing. We obtained a measure of socioeconomic status (SES) with the Barratt Simplified Measure of Social Status which uses parental educational levels and occupational prestige (Barratt, 2006). Possible SES scores ranged from 3 (e.g., the child had one parent who has less than a 7th-grade education and is not working outside the home) to 66 (e.g., the child had two parents with advanced degrees and high-prestige occupations). Participants were categorized into one of four groups based on their language experience (timing of first language exposure and language modality):

Early English: Typically-hearing children with hearing parents who began acquiring spoken English from birth

Early ASL: DHH children with at least one DHH signing parent who began acquiring ASL from birth

Later English: DHH children with hearing parents who began to acquire spoken English in early childhood via hearing technology (e.g., cochlear implant, hearing aid) and attended an oral program that emphasized listening/spoken language

Later ASL: DHH children with hearing parents who began to acquire ASL in an educational program that used ASL as the primary language of instruction

We recognize that these categories cannot perfectly capture every aspect of children's language experiences. However, we decided to use Language Timing as a binary variable (Early vs. Later) because we are confident that children in the Later Language groups had less cumulative exposure to language due to their limited access to language compared to children in the Early Language groups, who had full, uninterrupted access. Additionally, for children in the Later Language group, we decided to record 'age of first language exposure' as the age when the child received assistive hearing technology for children acquiring spoken English or the age when the child began attending school with a signing program for children acquiring ASL. While this measurement of first language access is not perfect and does not address the severity of children's deafness nor can it provide an accurate picture of when the child truly has accessible language input, it is important to note that all children in the Later Language group had limited language access to some degree. See Carrigan & Coppola (2020) for further discussion.

Table 1. Demographic information.

	Early English	Early ASL	Later English	Later ASL
Total Participants	57	27	41	28
Mean Age (years; months) (SD, range)	4;11 (0;9, 3;4–7;4)	5;4 (1;2, 3;5–7;4)	5;1 (0;10, 3;4–6;7)	5;9 (0;11, 3;1–7;5)
Mean SES* (SD, range)	54 (11, 8–66)	49 (16, 11–66)	50 (14, 3–66)	37 (18, 8–62)
w (% girls)	63% (36)	67% (18)	49% (20)	50% (14)
Mean Age of First Language Exposure (SD, range)	0	0	2;2 (1;4, 0;1–4;10)	3;6 (1;2, 1;6–6;3)

*Barratt Simplified Measure of Social Status (Barratt, 2006)

Materials

To measure small quantity object tracking we adapted the “Mr. Elephant” task created by Shusterman and colleagues (2017) who created it as an alternative to manual search tasks which are challenging to code and produce ambiguous search time outcomes. They designed the Mr. Elephant task so that the child could provide a clear, unambiguous answer, which facilitates connecting the child’s background to their likelihood of responding correctly.

Mr. Elephant was a custom-built wooden model made to look like the head of an elephant (Figure 1). The main part of the head was a hollow, wooden cube with a length, width, and height of 27 cm, painted dark blue. White eyes with black pupils were painted on the front, and green wooden ears slid into place on either side (Figure 1a). There was a cylindrical chute on the top of Mr. Elephant’s head and another chute that came through the nose (like a trunk). These two external chutes were connected by a tube inside of the box (Figure 1b). Small, yellow foam balls (“peanuts”) were placed inside the tube on the top of Mr. Elephant’s head and could be either trapped or released from Mr. Elephant’s trunk. A lever on the backside of Mr. Elephant controlled a small plastic door near the top of Mr. Elephant (indicated by the red arrow in Figure 1b). This lever trapped balls by sliding out to cover the chute. Another lever behind Mr. Elephant’s ear controlled a small plastic door near Mr. Elephant’s trunk. This lever released balls by displacing the plastic door, allowing balls to continue rolling out of Mr. Elephant’s trunk.

In addition to the setup of Mr. Elephant himself, two bowls were used to hold the balls. A small blue bowl, with a diameter of 6 cm and circumference of 48.5 cm, was used to catch balls coming out of Mr. Elephant's trunk.

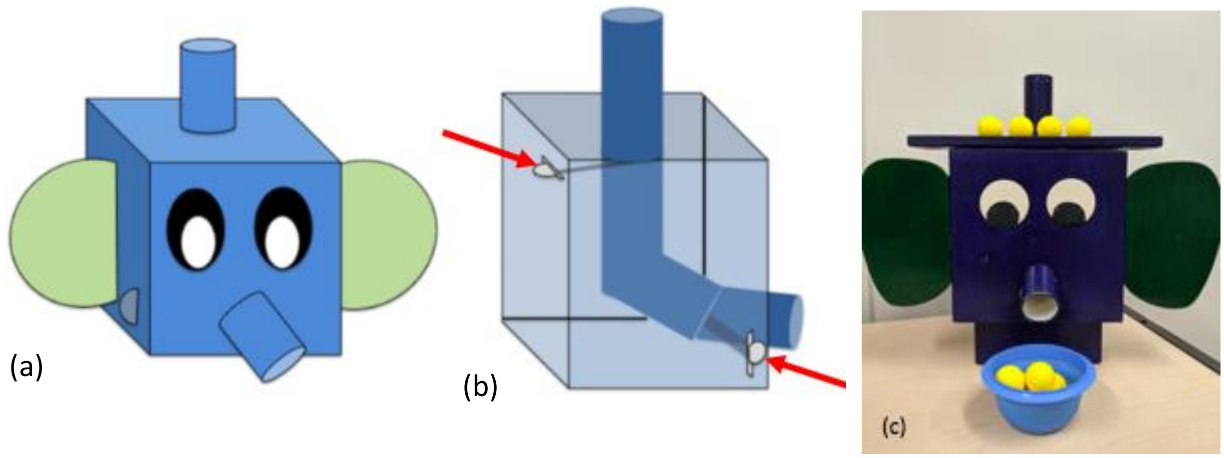

Figure 1. Schematic diagram and photo of Mr. Elephant (Shusterman et al., 2017).

Procedure

Parents filled out questionnaires regarding demographic information. For all behavioral tasks reported, each child was tested individually, in their preferred language (ASL or spoken English) by either a deaf, fluent ASL user or a native English speaker. The instructions were carefully developed to be comparable across the two languages by a team of deaf and hearing users of English and ASL. All interactions were video recorded.

During testing, the experimenter dropped N (2–7) balls into an elephant toy affectionately called Mr. Elephant; either N or N-1 balls exited via his "trunk". Children indicated whether any balls remained inside. One experimenter provided instructions to the child, while another (the 'facilitator') stood behind Mr. Elephant to operate the levers and add the balls when necessary. The child was seated in front of and facing Mr. Elephant, so they could see the balls being lined up across the top of Mr. Elephant's head, being placed into the tube on top of Mr. Elephant's head, and coming out of the trunk. The experimenter ensured the child was paying attention throughout this procedure and could not see the levers being operated by the facilitator.

The task was conducted in three phases: training, practice, and test trials. The aim of the task was to see if the child noticed if there was a change in the number of balls that went in and came out of Mr. Elephant, essentially if the child was able to accurately track the quantity of objects. In the training phase, the experimenter and facilitator introduced the Mr. Elephant model to the child and demonstrated how Mr. Elephant works: a ball that is dropped in will come out, but sometimes not all the balls would come out of the trunk. The facilitator operating Mr. Elephant first dropped a single ball into the chute on top of Mr. Elephant's head, and allowed it to be released. When the ball was released, the experimenter congratulated Mr. Elephant in the appropriate language for the child (e.g., "Good job!"). Then, the facilitator demonstrated a single ball being inserted, then getting "stuck." When the ball was stuck, the experimenter told the child that the ball was "stuck in the trunk" and that Mr. Elephant had to "sneeze" it out. The ball was released after the child helped Mr. Elephant sneeze, by either signing SNEEZE or saying "ah ah choo".

The practice phase consisted of two trials where a single ball was either stuck or released and the child was asked whether they should tell Mr. Elephant 'good job' (meaning there were no balls left inside Mr. Elephant's trunk) or 'help him sneeze' (meaning a ball was still stuck inside). The first trial was one in which the ball was dropped and immediately released. If the child responded to this trial indicating that they recognized all the balls that entered had exited Mr. Elephant (e.g., 'good job'), the experimenter agreed. However, if the child indicated that they thought another ball was still inside Mr. Elephant (e.g., 'help him sneeze'), the experimenter responded by telling the child that Mr. Elephant was 'all done'. For the second trial, the facilitator dropped and trapped one ball. Again, the child was asked whether they thought a ball was still inside Mr. Elephant. If the child responded with 'help him sneeze' or otherwise indicated that they knew a ball was still inside, the experimenter agreed, but if the child responded with ‘good job’ or indicated that they thought all the balls had exited, the experimenter responded by telling the child that there was a ball stuck in Mr. Elephant’s trunk and that they needed to ‘help him sneeze.’ If the child failed either practice trial, the experimenter and facilitator would repeat the practice trials until the child succeeded on each trial one time.

For the six test trials, the facilitator dropped and released the number of balls as indicated by the protocol sheet (see Table 1 in appendix for the test trials). For example, in the first trial, the facilitator dropped five balls, and released four of them, trapping one of them. After releasing the target number of balls, the experimenter asked the child the same question (e.g., should they tell Mr. Elephant ‘good job’ or ‘help him sneeze’?) and provided the same feedback as in the training phase. Correct answers received a ‘that’s right’ and incorrect answers were responded to by either ‘actually Mr. Elephant is all done’ or ‘we need to help Mr. Elephant sneeze,’ depending on the trial.

We were interested in small quantity tracking, so we entered into the analyses whether children succeeded on the two trials involving quantities 2 and 3 (2 in, 2 out; and 3 in, 2 out). Since here were only two small quantity trials, we were unable to distinguish between children who answered one trial successfully (50% correct) and children who answered no trials correctly (0% correct) as both performance patterns were not above chance. Therefore, we treated performance as a binary outcome: the child either got both trials correct or did not get both trials correct.

A total of 181 children participated in the Mr. Elephant task; 28 participants were excluded from the analyses presented here for one or more of the following reasons: (a) did not complete both small quantity trials, (b) equipment malfunction or experimenter error during the small quantity trials (e.g,. a ball got stuck on a trial where all balls were supposed to come out), or (c) did not understand the task, as noted by the experimenters or coders.

Results

A chi-squared test showed that the Early ASL and Early English groups did not significantly differ in their Mr. Elephant performance (X^2 (1, N = 84) = 0.243, p > 0.6), nor did the Later ASL and Later English groups (X^2 (1, N = 70) = 0.810, p > 0.3). We therefore collapsed the four groups into two groups based on language timing: Early Language and Later Language (regardless of modality). We ran a logistic regression including Timing, Modality, SES and Age as predictors of performance on the Mr. Elephant small quantity trials (i.e., 2 and 3 items) (Table 2). The logistic regression found that Timing (β = -0.95, *p* = 0.01) and SES (β = 0.029, *p* = 0.028) significantly predicted the likelihood of answering the small quantity trials correctly, while Modality and Age did not (see Figures 2 and 3). Children in the Later Language group were 0.39 times less likely to succeed on the task than children in the Early Language group. Additionally, for every 1 point increase in SES, children were 1.03 times more likely to succeed on the task. Models including an interaction between Timing and Modality or Timing and Age fit the data less well than the reported model.

Because SES was a significant predictor of Mr. Elephant performance, we used t-tests to compare SES scores between groups and found major disparities. In terms of Modality, the SES of the children in the English group (*M* = 52, *SD* = 12.6) was higher than that of the ASL group (*M* = 42, *SD* = 18.1), (*t*(79) = -3.24, *p* < 0.002). Similarly, with regard to Timing, children in the Early-exposed group (*M* = 52, *SD* = 13.3) had higher SES scores than the Later-exposed group (*M* = 44, *SD* = 16.8), (*t*(125) = 3.12, *p* = 0.002). A model with just SES, Age and Modality, (excluding Timing) fit the data less well than the reported model indicating that Timing explains variability in Mr. Elephant performance over and above any variability explained by SES.

	Success		
Predictors	*Odds Ratios*	*CI*	*p*
(Intercept)	0.09	0.01 – 1.27	0.082
Timing [Later]	0.39	0.19 – 0.79	**0.010**
SES	1.03	1.00 – 1.06	**0.028**
Modality [English]	1.07	0.49 – 2.33	0.857
Age	1.42	0.95 – 2.16	0.091
Observations	145		
R^2 Tjur	0.107		

Table 2. Logistic regression results. Timing of language exposure and SES were significant predictors of performance on the Mr. Elephant task.

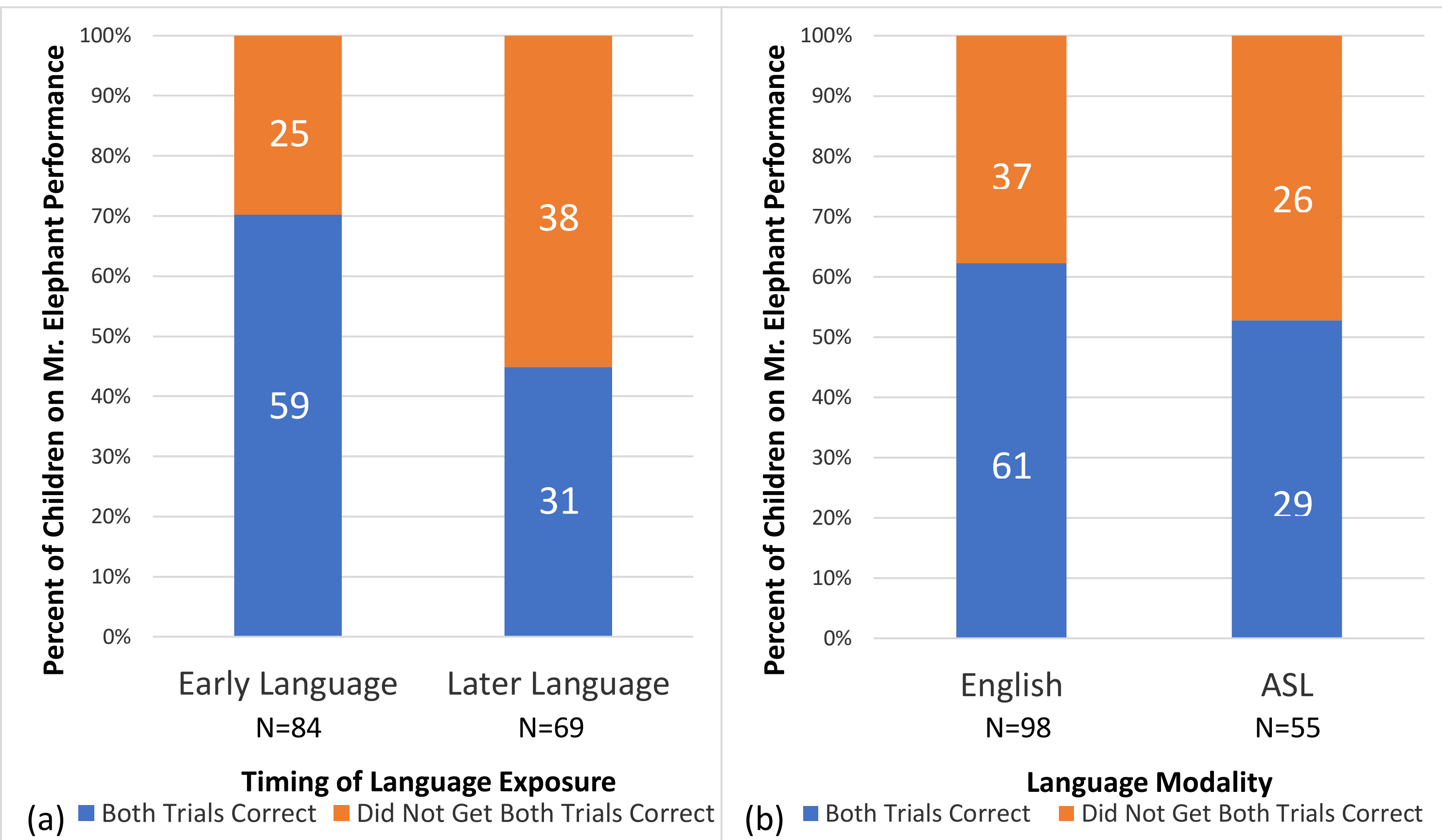

Figure 2. (a) Timing of language exposure is a significant predictor for performance on Mr. Elephant, but (b) modality of language is not. More children in the Early Language group succeeded on the Mr. Elephant trials compared to the Later Language group, whereas there was no significant difference between the English and ASL groups.

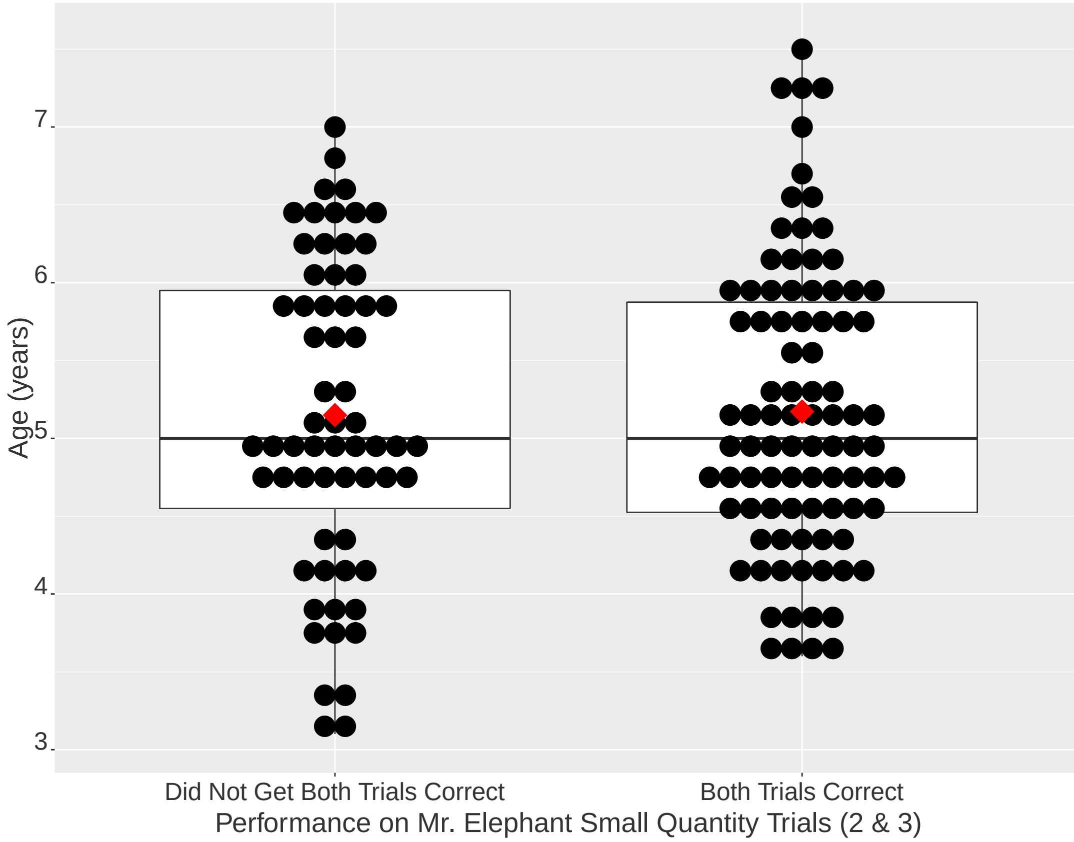

Figure 3. Age is not a significant predictor of performance on Mr. Elephant. The mean (red diamonds) and median ages (horizontal lines within the boxes) are equivalent between those who answered both trials correctly and those who did not.

Discussion

These findings show that the timing of access to a first language, but not the modality of language, affect children's ability to track small quantities. This finding is surprising and unexpected, since all previous literature suggests that the object tracking system and parallel individuation process is independent from language. The effect of Timing on performance on the Mr. Elephant small quantity trials indicates that language experience may affect small quantity object tracking, contrary to all previous evidence. Accordingly, our exploratory follow-up analysis further investigated what exactly it is about later exposure to language that may have influenced children's performance on the Mr. Elephant small quantity trials.

Exploratory Follow-Up Analysis

Given the surprising results of our primary analysis suggesting that small quantity object tracking does in some way depend on language, we wanted to see what exactly about language timing was directing this performance pattern. Therefore, we included two different language measures that were completed by participants the same day they did the Mr. Elephant task: (1) Highest Count, which records how high the child can correctly recite the count list (in English or ASL), and (2) Give-a-Number ('Give-N'), which assesses whether children know the exact quantities associated with specific number words/signs. Previous analyses from this dataset indicate that Timing predicts Give-N performance (Carrigan et al., in prep), so it is possible that differential knowledge of number word meanings for Early- and Later exposed children may explain why we found that Timing predicted performance on the Mr. E task. We decided to include Highest Count as another measure of number word knowledge that might precede Give-N proficiency; knowing the count list is useful when ascribing meanings to number words. To summarize, our questions in these follow-up analyses are: does knowing number words in a sequence (Highest Count) and/or knowing the meanings of number words (Give-N performance) affect DHH children's performance on small quantity object tracking (Mr. Elephant)?

Methods

Participants. We analyzed data from the same children who participated in the original analysis. Eight children (4 Early English, 1 Early ASL, 1 Later English, and 2 Later ASL) did not complete the Give-a-Number and Highest Count tasks in addition to the Mr. Elephant task. Of the remaining 145 participants, 53 were in the Early English group, 26 in the Early ASL group, 40 in the Later English group, and 26 in the Later ASL group.

Procedure

Give-a-Number

This task (Give-N) used one large bowl with a circumference of 76.5 cm and twenty rubber toy fish (5.5 x 5 cm). See Figure 4 for a picture of materials and task. The experimenter presented each child with the 20 plastic fish and placed the bowl on the table between them. The child was told a story in which the fish enjoy swimming with their friends in the “pond” but that not all of them can swim in the pond at the same time. On each trial, the experimenter asked the child to put **X** *(e.g., the target number of)* fish in the bowl. If the child spontaneously counted while generating the set, the experimenter looked away to avoid the possibility that the child would rely on the experimenter for cues.

After the child stopped putting fish in the bowl, the experimenter took the fish out of the bowl, lined them up 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**. If the child responded “Yes,” the experimenter asked “Can you count and make sure there are **X?**” The experimenter provided positive feedback regardless of the child’s accuracy in generating the set. Once the child finished the “count and make sure” procedure, the experimenter moved on to the next target value.

The test trials included all quantities 1 through 6, which were presented three times each in a fixed random order. If the child did not count the fish and instead placed multiple or all of the fish in the bowl continuously for all trials in the first two presentations of the quantities 1–6, they were classified as “grabbers”, and were not tested further.

A participant was considered to “know” a number if they provided a correct set size for that requested quantity on at least 2 out of 3 trials. We calculated a conservative measure of the highest number known for quantities 1–6 as the highest set size correctly produced two times with no more than one error on smaller quantities below. If a child initially received credit for knowing a given number (e.g., two), but subsequently gave that same N fish (2 fish) on requests for another quantity (like three, four, etc.), they ultimately did not receive credit for knowing that number.

Figure 4. Example of a participant completing the Give-a-Number task.

Highest Count

The elicited counting task followed a similar protocol to Sarnecka & Carey's (2008) sequence task that asked children to count to 10; here we asked children to count to 20 if they successfully counted to 10. We recorded the highest number reached without errors in either set (counting to 10 or counting to 20). The child's highest count was used if they counted more than once.

Results

Measures of children's Highest Count and Give-N performance were included in the analysis. A logistic regression model that included the Timing of language exposure, SES, Give-N and Highest Count, found that Timing (β = -0.82, p = 0.038) and Give-N (β = 0.64, p = 0.0025) were significant predictors of Mr. Elephant performance (Table 3). Children in the Later Language group were 0.44 times less likely to succeed on Mr. Elephant. For every successive Give-N quantity answered correctly, children were 1.89 times more likely to succeed on Mr. Elephant (see Figure 5). Note that the effect of SES found in the first model disappeared once

Give-N and Highest Count were added into the current model. Additionally, this model fit the data better than the first model. Other models including Modality and Age as additional predictors similarly found significant contributions of Timing of language exposure and Give-N, but fit less well than the reported model. An ANOVA likelihood ratio test showed no significant difference between models including or excluding Highest Count ($X^2(1) = 0.26$, $p > 0.6$), suggesting that Highest Count did not have any influence on Mr. Elephant performance. The reported model indicates that Give-N, along with Timing of language exposure, but not Highest Count, predicted performance on Mr. Elephant. Thus, simply being able to recite the number words in sequence did not influence small quantity object tracking, but understanding the meanings of number words as measured by Give-N may actually be important for small quantity object tracking. These measures are often discrepant: for example, one child in the Later ASL group was able to count to 20 when tested on Highest Count, but could only create accurate sets of fish up to 3 in the Give-N task. Being able to recite the count list correctly does not necessarily mean the child can ascribe meaning to each of the number words.

	Success		
Predictors	*Odds Ratios*	*CI*	*p*
(Intercept)	0.04	0.00 – 0.41	**0.010**
Timing [Later]	0.44	0.20 – 0.95	**0.038**
SES	1.02	0.99 – 1.04	0.164
Give_N	1.89	1.28 – 2.96	**0.003**
Highest_Count	0.98	0.89 – 1.07	0.614
Observations	137		
R^2 Tjur	0.163		

Table 3. Logistic regression results. Timing of language exposure and Give-N performance significantly predicted Mr. Elephant performance.

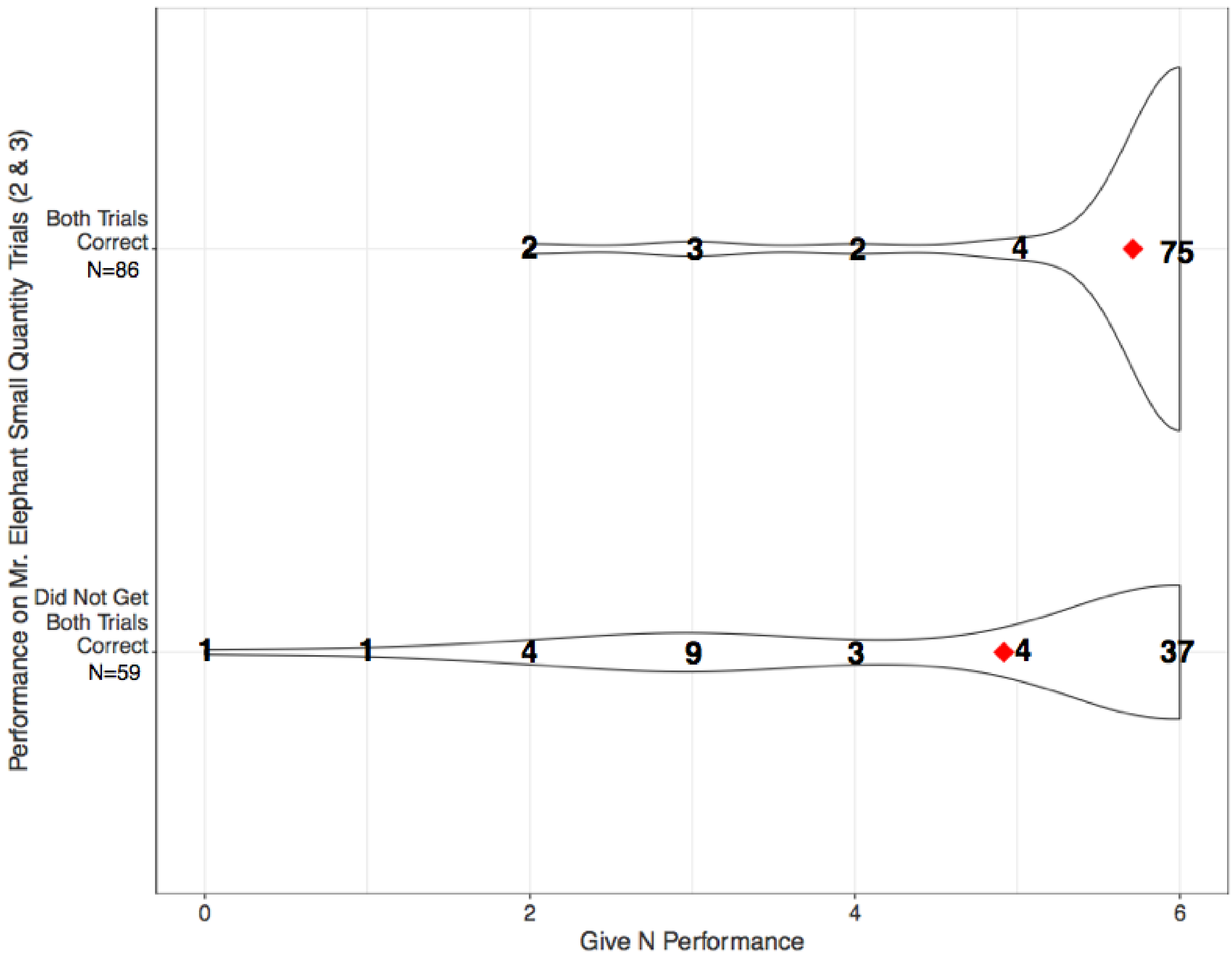

Figure 5. Give-N performance predicts Mr. Elephant performance; i.e., children who knew the meanings of more number words were more likely to succeed on the small object tracking task in Mr. Elephant. Means are represented by red diamonds. Numbers in parentheses represent the number of children who gave N as their highest trial (e.g., of the children who did not get both Mr. Elephant trials correct, 37 children were at ceiling and were able to correctly complete the Give-N trials all the way up to 6). Note that 112 (77%) children performed at ceiling for Give-N.

Discussion

These findings suggest that both the timing of language exposure and Give-N performance affect Mr. Elephant small quantity trials. Later access to language can have a negative impact on children's acquisition of the meanings of number words (Carrigan et al., in prep; Shusterman, Berkowitz & Lange, 2012), so timing of language exposure and Give-N are related, but any relation to small quantity object tracking has not previously been found. Thus, our finding that Give-N performance predicts Mr. Elephant performance is surprising. Previous research has found that small quantity object tracking does not depend on language (Carey, 2009), and yet the children in the present study who had a better understanding of number word meanings generally performed better on this object-tracking task with small sets. Therefore, language, specifically understanding the meanings of number words, is important for the Mr. Elephant task, a measure of small quantity object tracking.

General Discussion

This study produced unexpected findings that language experience, and factors specifically related to exposure to language that begins later in development, may actually play a role in children's small quantity object tracking. Our primary analysis found that the timing of first access to language predicted success on a small quantity object tracking task. Additionally, language modality (i.e., signed or spoken) had no effect on small quantity object tracking performance. These remarkable results prompted exploratory follow-up analyses, which found that, in addition to timing of language exposure, understanding the meaning of number words predicted success on the small quantity object tracking task. Furthermore, number word knowledge predicted success on the object tracking task to a better extent than count sequence knowledge. In light of these findings, it is necessary to revisit theories about the development of systems of number representation and the mechanisms involved in representing small exact sets.

It is important to point out that the Give-N trials only went up to 6, and 112 of the 145 participants (77%) included in the exploratory follow-up analyses performed at ceiling. The sheer number of children at ceiling for Give-N indicates that the task was fairly easy for most children. However, 37 of the children at ceiling on Give-N still did not succeed on the Mr. Elephant small quantity trials. These children should be able to accurately represent the quantities 2 and 3, so it is surprising that they did not succeed on the Mr. Elephant small quantity trials. This suggests that, even if knowing the meanings of number words does predict success on Mr. Elephant, it does not guarantee success. It may be that the children who performed at ceiling on Give-N but didn't do well on the Mr. Elephant task may differ in their Spontaneous Focusing on Numerosity (SFON), which refers to self-initiated focus of attention on exact quantity in sets of items or occurrences (Hannula & Lehtinen, 2005).

Researchers have found substantial individual differences in young children's SFON, as well as evidence that kindergarteners' SFON predicts later mathematical skills (Nanu et al., 2018; Bojorque et al., 2018; Hannula et al., 2010; Hannula-Sormunen & Lehtinen, 2015). In the current study, because children are not directed to count or explicitly told to attend to the number of "peanuts" in the Mr. Elephant task, children with lower SFON may not perform well, even if they do have good number knowledge, simply because they do not know or realize that they should attend to the exact quantities. Future research should consider adding an independent measure of SFON in order to address this possibility. It is also worth mentioning that parent-child interactions that involve numbers can improve and hone the child's SFON immediately after the interaction (Braham, Libertus & McCrink, 2018). DHH children with hearing parents (like those in the Later group in the present study) are already at risk of missing out on incidental number talk (Pagliaro & Kritzer, 2010; Bandurski & Galkowski, 2004), which may also affect children's SFON. No studies have yet been published on SFON in DHH children, but the use of number language in parent-child interactions could affect the development of SFON in this population, particularly DHH children with later language exposure.

While not included in any of the hypotheses, it was somewhat puzzling that children's age had no effect on their Mr. Elephant performance. Since Give-N performance improves with age and predicts Mr. Elephant performance, the finding that age did not predict Mr. Elephant performance was unexpected. This small quantity object tracking task may have been very simple for children with typical language experience at the age they were tested, so age would not be a factor in the Early Language group. Delayed language exposure, however, can have persistent and pervasive negative effects on many aspects of cognitive development, so for the children in the Later Language group, this Timing effect likely overshadowed any possible age or maturational pattern we might see with typical language experience.

Firstly, it is unclear if Mr. Elephant is a completely nonlinguistic task. Children were not prompted to count the balls, and since they only have to track two to three balls at a time, we assumed it was possible to succeed without counting. The language used in the task instructions was relatively simple, and was produced by fluent users with extensive experience working with children; however, it may have been challenging for children in the later-exposed groups to understand. Further, children were required to use language to respond, which could have affected their performance. Research with homesigners (deaf adults who have not had access to a linguistic community) has found that they struggle even in an experiential false belief task whose methodology does not rely on understanding a story (Gagne & Coppola, 2017). While the false belief task itself was minimally linguistic, participants were required to produce an explicit (non-linguistic) prediction (i.e., circling the picture of the item they thought the confederate would choose); this cognitive load may have prevented homesigners from demonstrating their knowledge. More broadly, it is plausible that requiring an explicit response on an otherwise non-linguistic task could be linked to language abilities, therefore putting language-delayed children at a disadvantage. Future research could look into using eye-gaze patterns or neuroimaging techniques, such as EEG, in order to eliminate language from a small quantity object tracking task altogether.

Another unresolved question is why adult homesigners who do not have access to linguistic input in their environment are able to track small quantities (Spaepen, 2008), but the children in the current study who had delayed or interrupted access to language had trouble with it. One reason could be that the adult homesigners have spent a lot more time interacting with the world and using numbers, whereas the children in the Later Language group had much less experience (at most seven years). Although the current study did not find an effect of age on performance in children between 3 and 7 years old, adults are better than children at attending to more objects (Trick, Jaspers-Fayer & Sethi, 2005). It should also be noted that while the adult homesigners performed well on some tasks, this was not the case when objects were not in continuous view, or were not objects but rather a series of knocks that they had to replicate. Under those conditions, the task became more challenging, even for the small sets (Spaepen et al., 2011). The objects in the current study were temporarily occluded for the brief moment they were inside Mr. Elephant, which may contribute to explaining this apparent discrepancy in performance.

When children must track objects that are temporarily hidden, working memory may be an important factor in performance. Both working memory and language are associated with many early mathematical skills (e.g., Purpura & Ganley, 2014). Research on children with specific language impairment show deficits in both language comprehension and working memory (e.g., Montgomery et al., 2010; Archibald & Gathercole, 2006), strengthening claims that working memory and language are related skills. Perhaps children with better working memory skills perform better on the Mr. Elephant task, helping them keep in mind how many balls entered and how many exited. Similarly, other executive functioning skills could have also influenced performance on the task. Indeed, later access to language has also been shown to negatively influence executive functioning abilities (Goodwin et al., under review; M. L. Hall et al., 2017; Dye & Hauser, 2014). Importantly, it may be difficult to extricate language timing from executive functioning. Nevertheless, an important next step would be to see if measures of executive functioning predict performance on Mr. Elephant.

Our first model found that, in addition to the Timing of exposure to language, SES also significantly predicted performance on Mr. Elephant; however, this effect disappeared in our second model which included Give-N and Highest Count. This finding parallels a result reported in Slusser et al. (2019), where Give-N fully mediated the relationship between parent education (a key component of family SES) and mathematical achievement one year later. In both accounts, the relationship between SES and a mathematical outcome was mediated by children's Give-N performance. SES has been linked to mathematics performance in a wide variety of research (e.g., Jordan & Levine, 2009) and when SES is controlled for, the amount of caregiver number talk predicts children's number word knowledge (Levine et al., 2010). Therefore, the results from our second model in which SES is no longer significant suggest that access to number talk may outweigh or mediate the effects of more distal factors like SES. Additionally, the groups had major disparities in SES; while possible scores ranged from 3 to 66, the Later ASL group had a mean SES of 36 while the Early English group had a mean SES of 54. While language modality was not a predictor of Mr. Elephant performance, children in the English group had a significantly higher mean SES than the children in the ASL group. Similarly for timing of language exposure, which was a significant predictor of Mr. Elephant performance, children in the Early-exposed group had higher mean SES than children in the Later-exposed group. Given these group differences, it may be difficult to completely disentangle SES from other variables in this study and future work should address this. Nevertheless, it does appear that children's language experiences, especially the timing of their first exposure to language, is most important.

Conclusion

Current theories and empirical work up to this point about the nature of humans' representations of numerical magnitude suggest that linguistic knowledge is not necessary to track small quantities of objects. These results, drawn from a relatively rare population who experience unusual variability in their language experiences, suggest that language experience and number word knowledge underlie the ability to track small quantities. More research is needed to investigate exactly how language may influence small quantity object tracking. Future research should explore completely nonlinguistic approaches to measuring object tracking skills and consider the roles of other cognitive skills such as executive functioning and SFON in explaining the relationship between language experience and object tracking.

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Appendix

Table 1. Mr. Elephant Trials. Small quantity trials analyzed are bolded.

	Practice Trial 1	*Practice Trial 2*	*Trial 1*	***Trial 2***	***Trial 3***	*Trial 4*	*Trial 5*	*Trial 6*
# ***of Balls IN***	1	1	5	**3**	**2**	6	4	7
# ***of Balls OUT***	1	0	4	**2**	**2**	6	4	6