Deaf children's number mapping skills: Later language exposure, not deafness, explains delays

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Theoretical Framework

Early mathematics skills consistently predict later academic and life outcomes (e.g., intelligence scores, academic motivation, attention, socioemotional skills, and SES; Duncan et al., 2007; Romano et al., 2010; Ritchie & Bates, 2013). Therefore, it is critical to identify why some children—for example, deaf and hard-of-hearing (D/HH) children—exhibit mathematical delays. Kritzer (2009) found that most preschool-aged D/HH children performed below average on the Test of Early Mathematics Ability, exhibiting delays before formal schooling. Such early delays may have a significant negative impact on D/HH individuals' academic achievement and employment. In 2017, D/HH individuals experienced a bachelor's degree gap of 15.2% (Garberoglio et al., 2019a). Garberoglio and colleagues (2019b) also found that educational attainment mediates the employment gap of 22.5% between D/HH and typically hearing individuals, suggesting that increasing D/HH people's academic outcomes by enhancing their early mathematics skills may narrow this gap.

Developing effective mathematical pedagogy and interventions requires a comprehensive and systematic approach to identify the underlying reason(s) for D/HH children's struggles with mathematics. Gottardis et al.'s (2015) meta-analysis of 23 studies concluded that D/HH children overwhelmingly exhibit poorer mathematical performance than typically hearing children. They also note that the studies' failure to examine D/HH children's language experiences may miss this critical contributing factor to the disparity.

Still missing, however, are examinations of the *timing* of language exposure on D/HH children's mathematics skills; this is especially important to consider since this population experiences extremely variable language input. Ninety-five percent of D/HH children are born to typically hearing parents (Mitchell & Karchmer, 2004). As a result, the vast majority of D/HH children experience delayed and/or reduced access to language. The lack of adequate language input results in detrimental and pervasive cognitive outcomes (Figueras, Edwards & Langdon, 2008; Henner et al., 2016; Hall, 2017; Botting et al., 2017; Jones et al., 2020).

Many studies demonstrate that language plays an important role in the number development of typically hearing children (Klibanoff et al., 2006; Levine et al., 2010; Negen & Sarnecka, 2012; Praet et al., 2013; Vukovic & Nesaux, 2013) and children with specific language impairments (Mainela-Arnold et al., 2011; Durkin et al., 2013). Recent work shows that language abilities also predict mathematical performance in D/HH children (Kelly & Gustad, 2007; Edwards et al., 2013; Madalena et al., 2020). A controlled study evaluating the impact of language modality and the timing of language exposure on D/HH children's number knowledge found that exposure to language from birth (in either modality) is critical to their understanding of number (Authors, in preparation). *Thus, valid scientific research must consider language experience rather than assume differences in performance are a result of deafness alone. Put simply, more research needs to examine whether the variability in D/HH's language experiences leads to their lower mathematical performance.*

Mapping is one foundational skill that has not been studied in D/HH children. Mapping, the ability to translate among number representations, e.g., Arabic numerals ("2"), number words (*"two"*) and dot arrays ("●●"), has been studied by Benoit and colleagues (2013), Hurst and colleagues (2017) and Authors (under review). Mapping abilities predict later academic success for typically hearing children (Fig1; Mundy & Gilmore, 2009; Brankaer, Ghesquiere, & DeSmedt, 2014; Göbel, Watson, Lervåg, & Hulme, 2014). Children, therefore, must be able to easily map among number representations before being confronted with more advanced arithmetic. Understanding which factors affect D/HH children's mapping skills (e.g., language experience) is essential to ensure that D/HH children achieve automatic and fluent processing of number representations and can benefit from formal mathematics instruction.

Objective

To understand the relationship between language experience and mapping skills, the current study evaluated the ability of four-and-a-half to nine-year-old children to understand the numerical equivalence of signed or spoken number words, Arabic numerals, and dot arrays. We compared the mapping performance of children learning American Sign Language (ASL) or spoken English as well as the timing of language exposure, specifically, when they gained significant access to language input. Children who were exposed to language from birth (Early-exposed) were compared with children whose language exposure began later in development (Later-exposed). The finding that delayed exposure to language negatively affects D/HH children's ability to produce sets of specific sizes (Authors, in preparation) leads us to expect that language will have a downstream effect on later mathematical skills, such as mapping. Thus, we hypothesized that the timing of children's language exposure, and not the modality of language, would negatively influence their mapping performance.

Methodology and Materials

One hundred nighty children (99 females) ages 4;6-9;11 (years; months) were predominantly recruited from schools for the deaf and elementary schools across the United States (Table 1). Children were placed into four groups (Early-ASL, Early-English, Later-ASL, Later-English) according to their modality of language (spoken English vs. ASL) and the timing of their language exposure (Early vs. Later). Early-exposed children were exposed to language from birth from their parents (children in the Early-ASL group had at least one deaf signing parent). In contrast, Later-exposed children were exposed to language later in development, with high variability in the quality of their language input. The age of exposure for the Later-English children was the age they began using their first hearing device; for Later-ASL children it was the age they entered a signing program.

Children mapped quantities 1-9 across three categories of set size: small (for quantities 1-3), medium (4-5), and large (6-9) between 1) Arabic Numeral and Signed/Spoken number word; 2) Dot Array and Arabic Numeral, and 3) Dot Array and Signed/Spoken number word (referred to as 'mapping pairs'). Using a laptop computer game, we administered fifty-one trials in a fixed random order that displayed the target value in one representational format and had them select the item that matched in quantity from an array of four possibilities in a different representational format (Fig2). To minimize the impact of language in delivering task instructions, children watched a video of a sample child successfully completing a trial, then were told it was their turn.

Results

We examined whether the timing of language exposure (Early vs. Later) and/or language modality (ASL vs. spoken English) affected children's mapping skills (measured by overall proportion correct). We ran a Tobit model (appropriate for proportion data) and included age, SES, set size, and mapping pair as predictors because they have been shown to predict children's mapping performance (Authors, under review), and also because including them improved model fit. Due to ceiling effects among the oldest children, we restricted our analysis to children ages 4;6 to 7;11 (n=135) (Fig3).

The type of language a child used (signed or spoken) did not predict children's mapping performance (i.e., across all mapping pairs) (β=0.00, p=0.92). Children who used ASL (M=0.84) performed equivalently to English speakers (M=0.87) (Fig4a; Tables 2 and 3). Early-exposed children (M=0.90), however, had significantly better overall mapping skills than Later-exposed (M=0.82, β=0.022, p<0.001) (Fig4b; Tables 2 and 3).

There was a significant interaction between modality and timing (β=0.18, p<0.001; Fig5; Tables 2 and 3). All children Early-exposed performed similarly well (ASL: M=0.90 and English: M=0.90; Wilcoxon: W=521, p=0.82). The interaction stemmed from children in the Later-English group (M=0.85) scoring higher than those in the Later-ASL group (M=0.79); however, this difference was not significant (W=518, p=0.20). The interaction can be attributed to the significantly later age of first exposure to language (in months) for the Later-ASL group (M=51) relative to the Later-English group (M=20) (W=1630, p<0.001); Fig6).

Discussion

The 8- and 9-year-old participants' performance at ceiling on this task aligns with the literature (Authors, under review). By this age, children have achieved mapping fluency, and can easily translate among all three number representations. Although some 8- and 9-year-old D/HH children performed at or near ceiling on mapping tasks, early struggles with mapping abilities may compromise later mathematical skills that depend on them (e.g., arithmetic fluency). As we expected, children learning ASL and English showed similar mapping performance: language modality does not matter. Rather, *our results indicate that being exposed to language later and/or having reduced access to language underlies D/HH children's lower mapping performance.* The age of first language exposure in our study is significantly earlier for children with hearing aids and/or cochlear implants[1] (Later-English group) compared to those entering signing programs (Later-ASL group). D/HH children can receive hearing aids from birth and cochlear implants at 12 months, although earlier implantations do occur (Miyamoto et al., 2017). While nothing specifically prevents D/HH children from beginning to acquire ASL at these early ages, this rarely happens for the majority of children who have hearing parents for reasons that are beyond the scope of this abstract. Interviewing parents of children with cochlear implants, Mauldin (2019) found that many clinics encourage parents to continue with spoken language acquisition exclusively (even when children are not able to communicate) and that using sign language was viewed as a "failure." It is therefore common for D/HH children to only enter a signing program once they have "failed" with a spoken language approach. This consequent difference in the age of first language exposure between the two Later groups leads to the observed difference in their mapping performance and reinforces the importance of early access to language. Placing the blame of "failure" on D/HH individuals instead of on the system perpetuates D/HH's underrepresentation (Cawthon & Garberoglio, 2017). As Gottardis et al. (2015) suggested and this work supports, more work that considers language experience when assessing D/HH children's mathematics skills is necessary.

[1] Many D/HH children still experience language delays despite using CIs (Hall et al., 2017; Carrigan & Coppola, 2020), therefore, the age at which they first receive a hearing assistive device is not a perfect proxy for their initial language exposure. Identifying reliable methods of measuring first language exposure remains a significant problem (Hall, 2020).

Significance

Deafness itself, nor specific hearing levels (Nunes & Moreno, 1998), does not explain the lower mathematics skills observed in D/HH children; this work demonstrates that the timing of language exposure affects D/HH children's ability to automatically map among number representations. The traditional approach to assessing the mathematical development of D/HH children would group them together based on hearing level and compare them to typically hearing children. In this study, we made a concerted effort to recruit D/HH children who, like typically hearing children, began learning their home language at birth. However, children who would be categorized in the Early-ASL group represent a tiny minority (~5%) of all D/HH children (Mitchell & Karchmer, 2004). Indeed, simply comparing the groups in our study who represent the vast majority of D/HH children (i.e., the Later-ASL and Later-English groups) with typically hearing children would suggest the following (erroneous) conclusion: D/HH children's (*Mdn*=0.90) mapping skills were significantly worse than typically hearing children's skills (*Mdn*=0.94) (Wilcoxon: *W*=1787, *p*=0.03; Fig7). Here we have demonstrated that an analytic approach grouping children only by hearing status overlooks the critical role of early access to language on mapping abilities and shows that generalizing about D/HH children based on hearing level is not appropriate.

Instead, we have shown that absent, delayed, or degraded linguistic input has negative consequences for children's mapping skills, which are an essential foundation for formal mathematics education. Identifying and ameliorating the root causes (e.g., delayed language) of D/HH children's relatively poorer mathematics skills is critical. More broadly, improving D/HH children's mathematical performance may narrow existing educational and employment gaps. It is therefore imperative for clinicians and educators to ensure that D/HH children have early access to language (in any modality).

Tables and Figures

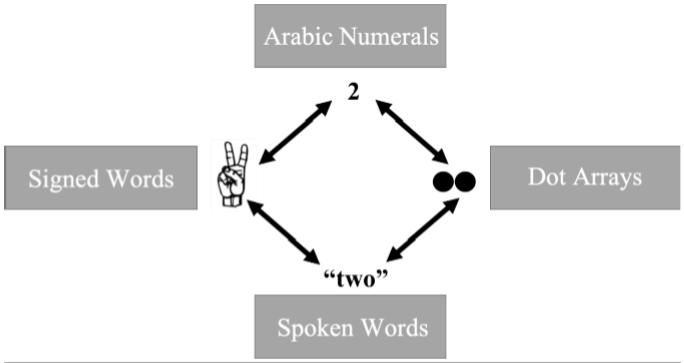

Fig1. Mapping among number representations.

	Sex *Female* *Male*	**Age (years)** *M (SD)* *Range*	**SES (3-66)** *M (SD)* *Range*	**Age of First Language Exposure (months)** *M (SD)* *Range*	**Children's Hearing Status**	**Parental Hearing Status** *(at least 1 parent)*	**School's Predominant Language Use**
Early English (n=48)	25 (52%) 23 (48%)	6;11 (1;4) 4;10-9;8	56.4 (12.3) 17-66	0 (0) 0-0	Hearing	Hearing	English
Early ASL (n=46)	27 (59%) 19 (41%)	7;6 (1;6) 5;2-9;11	43.8 (14.7) 3-62	0 (0) 0-0	D/HH	D/HH	ASL
Later English (n=46)	26 (57%) 20 (43%)	6;5 (1;4) 4;6-9;10	48.2 (13.2) 3-66	20 (15) 2-56	D/HH	Hearing	English
Later ASL (n=50)	21 (42%) 29 (58%)	7;4 (1;5) 5;1-9;10	42.4 (16.0) 3-63.5	51 (23) 3-103	D/HH	Hearing	ASL

Table 1. Demographics. SES was calculated according to the Barratt Simplified Measure of Social Status (BSMSS; Barratt, 2006).

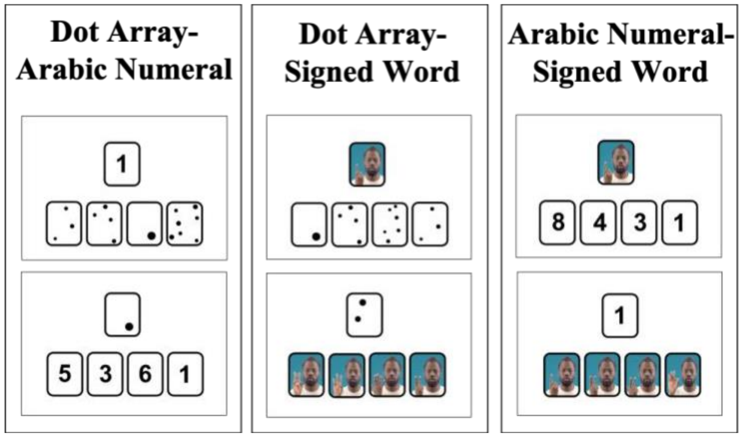

Fig2. Mapping Task: ASL version. The photo stills shown here, labeled "Signed Word," were actually videos. To maximize comparability, the English version featured videos of a woman saying the number words.

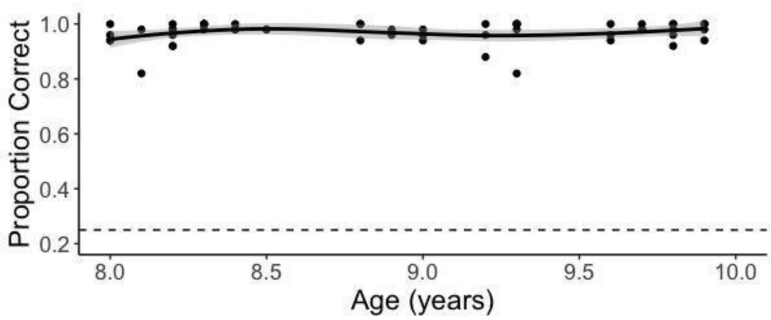

Fig3. Eight to nine-year-old's overall mapping performance. The dotted horizontal line indicates chance performance (0.25) and the solid line is a LOESS curve. Including children of all ages in the Tobit model resulted in a Hauck-Donner effect (causing a high p-value and loss of power) for age, meaning parameter estimates for age were too close to a boundary. In this case, 35% of children 8 to 9-years-old performed at ceiling, causing the age estimate to approach the upper limit of 1.

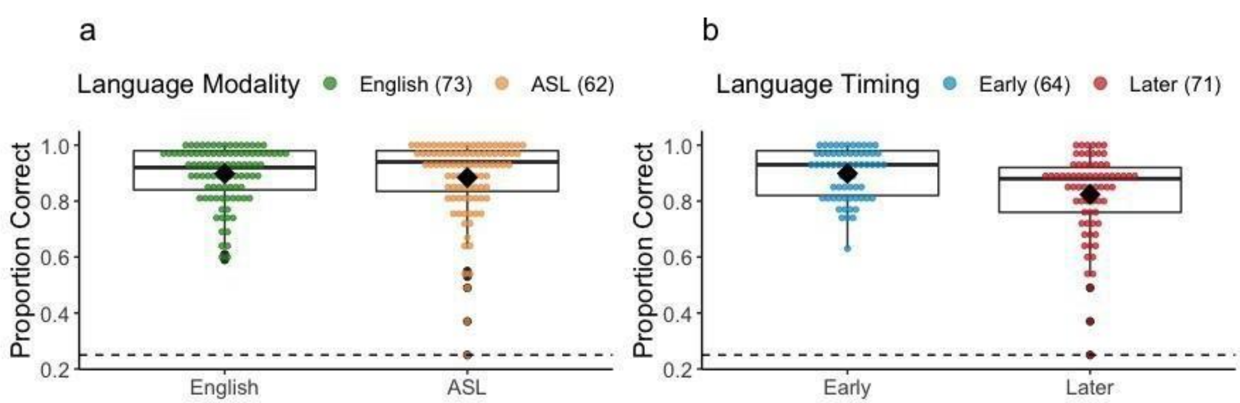

Fig4. Language experience and mapping performance. Four-and-a-half to 7-year-olds' mapping performance (proportion correct) by language modality and language timing. The dotted horizontal lines indicate chance performance (0.25). The medians are represented by the solid lines, means are represented by black triangles and each circle represents a child.

Reference groups: Small and Numeral-Word				
Predictors	*Estimates*	*Standard Error*	*t-statistic*	*p-value*
Intercept 1	0.57	0.12	4.83	**<0.001**
Intercept 2	-1.00	0.03	-32.86	**<0.001**
Age	0.15	0.02	9.08	**<0.001**
SES	0.00	0.00	2.16	**0.030**
Modality (English)	0.00	0.04	0.10	0.921
Timing (Later)	-0.22	0.04	-5.79	**<0.001**
Medium	-0.20	0.03	-5.99	**<0.001**
Large	-0.38	0.03	-11.73	**<0.001**
Quantity-Numeral	-0.24	0.03	-7.12	**<0.001**
Quantity-Word	-0.33	0.03	-10.17	**<0.001**
Modality (English) x Timing (Later)	0.18	0.05	3.53	**<0.001**
Observations	1215		R^2	0.25

Table 2. Tobit model with small and numeral-word as reference groups.

Reference groups: Medium and Quantity-Word				
Predictors	*Estimates*	*Standard Error*	*t-statistic*	*p-value*
Intercept 1	0.04	0.12	0.32	0.748
Intercept 2	-1.00	0.03	-32.86	**<0.001**
Age	0.15	0.02	9.08	**<0.001**
SES	0.00	0.00	2.16	**0.030**
Modality (English)	0.00	0.04	0.10	0.921
Timing (Later)	-0.22	0.04	-5.79	**<0.001**
Small	0.20	0.03	5.99	**<0.001**
Large	-0.18	0.03	-6.16	**<0.001**
Numeral-Word	0.33	0.03	10.17	**<0.001**
Quantity-Numeral	0.10	0.03	3.28	**0.001**
Modality (English) x Timing (Later)	0.18	0.05	3.53	**<0.001**
Observations	1215		R^2	0.25

Table 3. Tobit model with medium and quantity-word as reference groups.

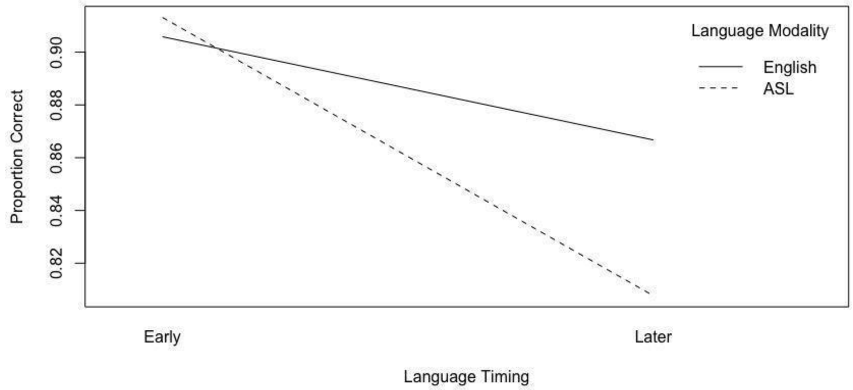

Fig5. Interaction between timing and modality.

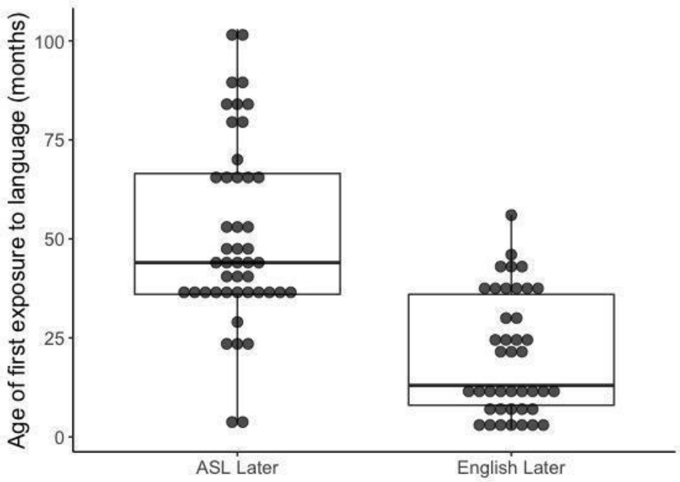

Fig6. Age of first language exposure (later groups). Age of first language exposure for Later-English and Later-ASL were calculated based on when children first received their hearing device and entered a signing program, respectively. The medians are represented by the solid lines and each circle represents a child.

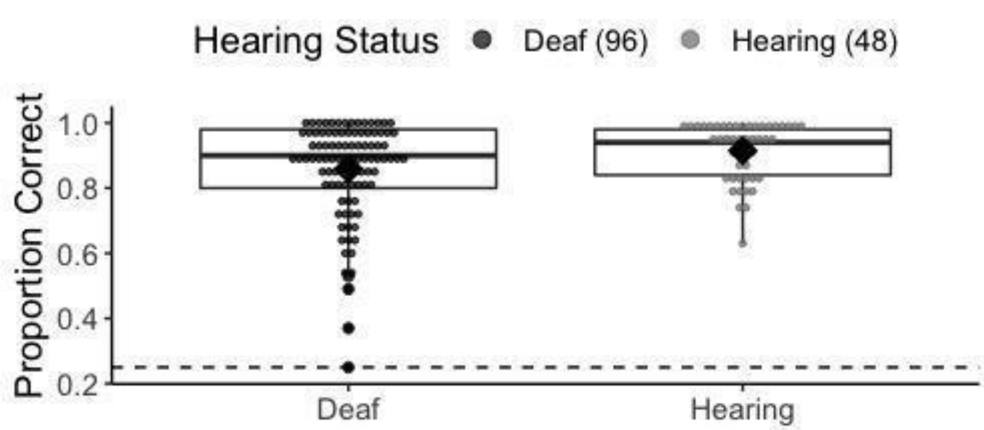

Fig7. D/HH children compared to typically hearing children's mapping performance. The dotted horizontal line indicates chance performance (0.25). The medians are represented by the solid lines, means are represented by black triangles and each circle represents a child.

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