

Language not auditory experience is related to parent-reported executive functioning in preschool-aged deaf and hard-of-hearing children

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Abstract

Much research has found disrupted executive functioning (EF) in deaf and hard-of-hearing (DHH) children; while some theories emphasize the role of auditory deprivation, others posit delayed language experience as the primary cause. This study investigated the role of language and auditory experience in parent-reported EF for 123 preschool-aged children ($M_{\text{age}} = 60.1$ months, 53.7% female, 84.6% White). Comparisons between DHH and typically hearing children exposed to language from birth (spoken or signed) showed no significant differences in EF despite drastic differences in auditory input. Linear models demonstrated that earlier language exposure predicted better EF ($\beta = .061-.341$), while earlier auditory exposure did not. Few participants exhibited clinically significant executive dysfunction. Results support theories positing that language, not auditory experience, scaffolds EF development.

Parents of deaf and hard-of-hearing (DHH) children often face difficult decisions about how to provide accessible language for their children. For most parents of children with severe to profound hearing levels, their DHH infant is the first deaf individual they have encountered and they have no experience communicating with DHH people. In addition, many DHH children do not have sufficient access to their parents' spoken language for typical language development to unfold without intervention. Because the vast majority of parents of DHH children are themselves hearing (Mitchell & Karchmer, 2004), they

often do not know a language that would be fully accessible for their child, that is, a sign language. Hearing parents are typically guided toward medical technology and spoken language-only interventions (Mauldin, 2016, pp. 158, 161), with bimodal-bilingual approaches including sign language a rarity (Clark et al., 2020).

Research indicates that the challenges surrounding language access for DHH children have consequences for cognitive domains outside of language, such as executive functioning (EF). EF refers to behaviors that allow an individual to overcome more automatic or established responses to achieve a goal (e.g., Garon et al., 2008). Much research has demonstrated the importance of EF to school readiness and achievement in childhood (e.g., Shaul & Schwartz, 2014), as well as to adult health

Abbreviations: ASL, American Sign Language; BRIEF-P, Behavior Rating Inventory of Executive Function—Preschool Version; DHH, deaf and hard-of-hearing; EF, executive functioning; GEC, Global Executive Composite; SES, socioeconomic status.

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outcomes, socioeconomic status (SES), and criminality (e.g., Moffit et al., 2011).

While myriad studies have established DHH children's increased risk for reduced or even clinically significant impairments in EF skills (Botting et al., 2017; Hintermair, 2013; Jones et al., 2019; Kronenberger et al., 2014; Oberg & Lukomski, 2011), the exact cause remains controversial. There has recently been much debate about the influence of spoken language and auditory input compared to signed languages that are perceived visually on the development of DHH children's EF skills. For instance, one model emphasizes the role of auditory deprivation on executive dysfunction in DHH children (e.g., Kronenberger & Pisoni, 2020; we will refer to this as the "auditory scaffolding model"). Conversely, other researchers have demonstrated that deaf children who have full access to a sign language from birth do not exhibit the same deficits in EF skills as deaf children who use spoken language, even when these native-signing children have little to no auditory experience (Hall et al., 2018; Marshall et al., 2015). Thus, these researchers argue that early language input, in either modality, is more important than early auditory input per se for the development of typical EF skills (here called the "language scaffolding model"). Determining which model better explains DHH children's EF development is important because each leads to differing clinical recommendations (i.e., ensuring early auditory input vs. providing access to early language input, regardless of modality).

The addition of new evidence from native-signing deaf children in different countries is compelling, but to date few studies have investigated EF development in this population (e.g., Hall et al., 2018; Marshall et al., 2015). Furthermore, most research has focused on school-aged children, making it unclear exactly when group differences might emerge. Beer et al. (2014) demonstrated EF deficits in preschool-aged children with cochlear implants who used spoken English, but EF development in signing preschoolers remains unexplored. The current study investigated the development of EF skills in preschool- and school-aged DHH children whose access to spoken or signed language began either from birth or at a point later in development.

What is EF?

Executive functioning is an umbrella term that refers to several interrelated processes concerning the control and monitoring of behavior and attention to achieve a goal (e.g., Blair, 2016). EF is commonly subdivided into working memory, inhibition, and shifting (e.g., Garon et al., 2008). Working memory reflects an individual's capacity to hold information and retrieve it when an additional cognitive load is present. A typical measure is the backward digit span task, in which participants repeat numbers back to the experimenter in the

reverse order of presentation. Inhibition is the ability to inhibit prepotent responses that are incongruent with a particular goal; a common measure is the Stroop Color and Word Test, in which participants must say the color of ink that a color term is printed in rather than reading the word itself (e.g., saying "blue" when presented with the word "red" written in blue ink). The shifting subcomponent of EF is the ability to adapt to new rules, often measured using a card sorting task for which a child must first sort by shape and then switch to sorting by color.

While these examples measure children's behavior, several rating-scale measures of EF exist, with some researchers reporting significant relations between performance and rating-scale measures (e.g., Garon et al., 2016), while others do not (e.g., McAuley et al., 2010). Still, each format offers advantages and disadvantages: behavioral tasks avoid possible rater biases, while rating scales can be more ecologically valid in that they measure EF during daily tasks rather than in artificial laboratory settings. Overall, behavioral and rating-scale measures provide complementary information about a child's EF skills (Isquith et al., 2013).

EF and language

A large body of research connects the development of EF and language in various typically hearing populations. In neurotypical children, language and EF are often highly correlated (e.g., Müller et al., 2009). Some authors have found that EF predicts language learning and development (e.g., Weiland et al., 2014), others have found that language predicts EF skills (e.g., Fuhs & Day, 2011), while still others have found bidirectional relations (e.g., Slot & von Suchodoletz, 2018). Significant relations have also been noted in neurodiverse populations, including Developmental Language Disorder (e.g., Pauls & Archibald, 2016; Wittke et al., 2013), Attention-Deficit/Hyperactivity Disorder (e.g., Sciberras et al., 2014), and Autism Spectrum Condition (e.g., Akbar et al., 2013).

Language and EF skills are often correlated in DHH children, with these children at risk of deficits in both areas (e.g., Figueras et al., 2008; Kronenberger et al., 2014; Mitchell & Quittner, 1996; Surowiecki et al., 2002). Some researchers have found that language skills influence EF skills in DHH children (Barker et al., 2009; Marshall et al., 2015), while others have found the reverse (Kronenberger et al., 2020). Sometimes group EF differences between DHH and typically hearing participants are no longer significant when language abilities are controlled (e.g., Beer et al., 2014).

But why is there such a close relation between EF and language in all of these populations? One possibility is that both language and EF are processed in similar prefrontal cortex brain regions and thus develop in tandem.

For instance, activation in Broca's area is observed in both working memory and language tasks (e.g., Garon et al., 2008). But there are additional reasons to expect EF to influence language, and vice versa. For instance, part of language learning requires children to direct and sustain their attention to the language input (e.g., when using situational context to learn the meaning of words). Children also must inhibit their own productions to engage in turn-taking and successful conversations and monitor their production to determine whether their message was adequately conveyed and correctly interpreted. For DHH children, EF skills may also compensate for underspecified phonological and semantic representations due to degraded auditory input (Kronenberger & Pisoni, 2020).

On the other hand, language is important for many EF skills. For example, when children are learning to self-regulate, they are taught to label their feelings, to count from one to ten to control their anger, and to verbally communicate their needs (e.g., Diamond & Lee, 2011). Similarly, toddlers with lower verbal skills have more frequent temper tantrums, presumably because they cannot adequately express their needs and desires (e.g., Manning et al., 2019). Furthermore, using language or internal dialogue can facilitate children's performance in working memory, shifting and inhibition

tasks (e.g., Alarcón-Rubio et al., 2014; Müller et al., 2009).

Contrary to Kronenberger and Pisoni's (2020) characterization of "language-focused approaches," no current theories emphasizing the importance of language in EF development posit that language is the sole predictor of EF. Rather, they argue that language is necessary but not sufficient to support typical EF development (e.g., Hall, 2020). Studies that emphasize the role of language in the development of EF in DHH children explicitly acknowledge the complex interplay of biological, psychological, and social factors in development by accounting for background factors such as age, gender, and SES (e.g., Hall et al., 2018, Table 1). Furthermore, language itself is an interpersonal communication tool used to navigate relationships and transfer knowledge; when children cannot understand or produce language, social interactions (including the language-based EF scaffolding described above) and intergenerational learning are invariably disrupted (Morgan & Dye, 2020). Understanding the contributions of early language experience relative to other factors is critical to developing a holistic picture of EF development, especially as this understanding influences evidence-based clinical recommendations to families with DHH children.

TABLE 1 Participant demographics

	Typically hearing (<i>N</i> = 46)	Early ASL (<i>N</i> = 26)	Later English (<i>N</i> = 23)	Later ASL (<i>N</i> = 28)
Age (months)				
<i>M</i> (<i>SD</i>)	54.7 (10.9)	60.8 (14.4)	60.7 (10.9)	68.0 (14.6)
Median [min, max]	54.5 [37, 85]	57.0 [41, 91]	60.0 [37, 78]	71.5 [37, 90]
SES				
<i>M</i> (<i>SD</i>)	55.6 (8.83)	48.2 (16.8)	48.8 (14.1)	42.7 (17.4)
Median [min, max]	56.0 [22, 66]	56.5 [11, 66]	51.0 [8, 66]	49.0 [9, 62]
Sex				
Female	24 (52.2%)	16 (61.5%)	13 (56.5%)	13 (46.4%)
Male	22 (47.8%)	10 (38.5%)	10 (43.5%)	15 (53.6%)
Race				
Asian	0 (0%)	0 (0%)	0 (0%)	3 (10.7%)
Black or African American	0 (0%)	0 (0%)	1 (4.3%)	0 (0%)
White	43 (93.5%)	24 (92.3%)	18 (78.3%)	19 (67.9%)
More than one	3 (6.5%)	1 (3.8%)	3 (13.0%)	3 (10.7%)
Other/missing	0 (0%)	1 (3.8%)	1 (4.3%)	3 (10.7%)
Ethnicity				
Hispanic	3 (6.5%)	0 (0%)	2 (8.7%)	5 (17.9%)
Non-Hispanic	42 (91.3%)	18 (69.2%)	17 (73.9%)	20 (71.4%)
Prefer not to answer	0 (0%)	1 (3.8%)	0 (0%)	0 (0%)
Missing	1 (2.2%)	7 (26.9%)	4 (17.4%)	3 (10.7%)

Note: SES was based on the Barratt Simplified Measure of Social Status; possible scores range from 3 to 66.

Abbreviations: ASL, American Sign Language; SES, socioeconomic status.

EF and auditory input

The most recent version of the auditory scaffolding model (Kronenberger & Pisoni, 2020) adopts a biopsychosocial systems framework, which incorporates a variety of causal interactions from the biological, psychological, and social levels. While most researchers would acknowledge all these as important in EF development, this theory uniquely posits that auditory input specifically contributes to the development of the brain connectome and thus EF skills. These authors hold that disturbances in connections between the auditory cortex and the frontal cortex (which mediates EF) can cause significant EF deficits, with variations in outcome dependent on the age of onset of deafness, the length of auditory deprivation, and individual variations in neuroplasticity, as well as other psycho-social compensatory mechanisms, such as school-based EF interventions. Furthermore, this research group emphasizes the role of auditory input over other sensory modalities in providing sequential stimulation, thus hypothesizing that auditory input is crucial to the typical development of temporal processing, sequential memory, and sustained attention. Importantly, the auditory scaffolding hypothesis predicts that severe-to-profoundly deaf children who experience little to no auditory input would experience a negative impact on the development of EF skills, accounting for other factors. Thus, the current study and previous research, that has included DHH children with little auditory experience, are important test cases for this hypothesis.

While space precludes an exhaustive review, we will briefly discuss two of the most consequential results that Kronenberger and Pisoni (2020) present in support of their theory. First, individuals with musical training tend to perform better on some types of EF tasks (e.g., Slevc et al., 2016). While Kronenberger and Pisoni argue that this supports a unique role for auditory input in the development of EF, the authors of these studies have generally not interpreted their results in this manner. Furthermore, differences in auditory experiences specifically are unlikely to be the causal mechanism underlying this relation given that musical training and performance involves many EF-supporting practices that are also present in other extracurricular activities which have been shown to improve EF skills, but which do not primarily involve auditory stimuli, such as martial arts practice (e.g., Diamond & Lee, 2011). Second, a recent study on visual habituation in deaf infants found that deaf infants took longer to habituate to visual stimuli and had fewer look-aways than typically hearing infants (Monroy et al., 2019). Additionally, infants with lower spoken-English skills prior to cochlear implantation exhibited longer times to habituation. These authors interpreted these results as an inefficiency in information processing due to reduced auditory input,

which may ultimately negatively affect additional cognitive skills, such as EF. An alternative interpretation is that the behavior of the deaf infants reflects adaptation to using visual information in different ways than hearing infants (e.g., for language: Brooks et al., 2020). Thus, these results could indicate resilience rather than a deficit in processing speed for deaf infants (for similar arguments in other domains, see, for example, Dye & Hauser, 2014). Moreover, the study design precludes comparing the amount of information extracted by infants in both groups; if deaf infants were extracting more information from the visual stimuli, they would be expected to take longer to habituate. While these results may indicate that reduced auditory input causes changes in processing of visual sensory input, the findings may have no implications for the relation between auditory input and broader cognitive functioning.

Further evidence for the role of auditory input in the EF development of DHH children is primarily drawn from studies of deaf children with cochlear implants who use spoken language. These children typically experience some period of auditory deprivation before they are identified as DHH and receive treatment and they also exhibit deficits in EF skills. However, language and auditory experience are confounded in these individuals, and it is thus impossible to disentangle their effects (e.g., Hall, 2020).

To appropriately evaluate the auditory scaffolding model, we must also consider the development of EF in children with limited or no auditory access who do have early exposure to language, that is, profoundly deaf children who use no assistive hearing technology but who are exposed to sign language from birth. While this group can be difficult to recruit because less than 10% of deaf children are born to deaf, signing parents (Mitchell & Karchmer, 2004) and perhaps also because of skepticism within the Deaf community of cochlear implants and researchers' intentions (Mitchiner & Sass-Lehrer, 2011), at least two research groups have found that native-signing DHH children do not exhibit the same deficits in EF as children later exposed to spoken language through cochlear implants (Hall et al., 2018; Marshall et al., 2015). Although the evidence is currently limited, this population seems to demonstrate that EF skills (and other cognitive skills, such as visual sequencing; Terhune-Cotter et al., 2021) can develop typically in the absence of auditory input as long as early language input is accessible.

The current study

This study investigated parent-reported EF as measured by the Behavior Rating Inventory of Executive Function—Preschool Version (BRIEF-P; Gioia et al., 2003) in typically hearing and DHH children. To address the relative contributions of language *and* auditory

input on the development of EF, we studied children who experienced varying degrees of access to both language and auditory input (measured by parent report). This allowed us to dissociate the influence of auditory stimulation from that of language input, and to ask the following questions:

Question 1: Do DHH children with access to sign language but not auditory input from birth exhibit EF skills comparable to their typically hearing peers?

Question 2: Do age of auditory and language exposure significantly predict EF?

Question 3: Do children with later, and likely degraded access to auditory and/or language input exhibit clinically significant deficits in EF relative to typically hearing peers?

We addressed the first question by directly comparing EF in typically hearing children learning spoken English to that of children who are severe-to-profoundly deaf who also began learning their first language, American Sign Language (ASL), at home from birth. We expected similar scores between these two groups if early access to language is enough to scaffold typical development of EF; group differences in favor of typically hearing participants would indicate that auditory input is also integral. The second question was addressed using linear models to evaluate the contribution of age of first auditory and language exposure on later EF in all participants. If both age of language and auditory access were significantly related to EF, this would indicate that early auditory input is necessary for typical EF development. The third question was evaluated by comparing the proportions of DHH and typically hearing participants scoring within the clinically significant range on the BRIEF-P to determine whether DHH participants are disproportionately represented among children who exhibited significant deficits in EF (i.e., relative risk ratios). This question addressed the level of severity of any observed differences in EF skills across different subgroups of participants. All analyses were confirmatory in nature as we aimed to test an existing theory about the development of EF.

METHOD

Participants

The data in this study were drawn from a larger project which investigated relations between language experience, mathematical abilities, and other cognitive skills using numerous performance tasks and parent-reported measures. The overall project recruited a total of 404 participants between the ages of 3 and 9 years old: 124 children had typical hearing and 280 were deaf or hard-of-hearing. Children with confirmed or suspected additional disabilities were not included in this study.

Participants were recruited from 35 locations across the United States between 2016 and 2020.

The current study included a subset of 123 children between the ages of 37 and 91 months and for whom parents returned a completed BRIEF-P form. Participant information is summarized in Table 1, with all information based on parent report. The Early ASL group includes all participants who are severe-to-profoundly deaf and who acquired ASL from birth via at least one deaf, signing parent. All the DHH children attended specialized programs for DHH children. The Later ASL and Later English group includes DHH participants who had hearing parents and attended programs emphasizing ASL or spoken English, respectively. All spoken language programs for DHH children were private, while ASL programs were both public and private. Children in both the Early and Later ASL groups attended the same signing school programs. In each program, all children 3- to 7-years old were invited to participate. Most of the DHH schools included preschool-aged children. For younger typically hearing children not yet in school, we also tested at our laboratories, local libraries, and in families' homes. We use the term "later" to indicate that the children did not have full access to their respective language from birth, due to later and potentially incomplete access to spoken English via hearing technology or delayed exposure to ASL.

Table 1 provides demographic information for all participants. While group differences for age were generally not significant, Dunn's test of multiple comparisons indicated that the Later ASL group was significantly older than the Typically Hearing group ($Z = 4.08, p < .001$). SES was based on Barratt's (2006) Simplified Measure of Social Status, which considers parental educational attainment and occupational prestige, but not income. Lower SES scores indicate lower levels of educational attainment and occupational prestige. We included this measure because SES has been found to explain a small, but significant, amount of variance on the BRIEF-P (e.g., Gioia et al., 2003); specifically, parents with lower educational levels tend to report more EF difficulties. Most group differences for SES were not significant, but Dunn's test of multiple comparisons indicated that the Later ASL group had significantly lower SES than the Typically Hearing group ($Z = -3.31, p = .006$).

Several measures of language and auditory experience are presented in Table 2. First, information about the type of hearing device is presented, with "Other" indicating anything other than a hearing aid or cochlear implant, including bone conduction implants. Information about the bilateral or unilateral use of these devices is generally unavailable for the participants. Detailed information about participants' hearing levels was missing for many participants; thus, they were only categorized as (1) typically hearing, (2) hard-of-hearing, and (3) deaf. Participants with known unilateral hearing loss were excluded.

TABLE 2 DHH participants' auditory and language experiences

	Typically hearing (<i>N</i> = 46)	Early ASL (<i>N</i> = 26)	Later English (<i>N</i> = 23)	Later ASL (<i>N</i> = 28)
Pre-device hearing level				
Typically hearing	46 (100%)	0 (0%)	0 (0%)	0 (0%)
Deaf	0 (0%)	15 (57.7%)	13 (56.5%)	21 (75.0%)
Hard of hearing	0 (0%)	7 (26.9%)	9 (39.1%)	5 (17.9%)
Missing	0 (0%)	4 (15.4%)	1 (4.3%)	2 (7.1%)
Type of hearing device				
Hearing aid	0 (0%)	11 (42.3%)	11 (47.8%)	12 (42.9%)
Cochlear implant	0 (0%)	0 (0%)	9 (39.1%)	8 (28.6%)
Hearing aid and cochlear implant	0 (0%)	0 (0%)	2 (8.7%)	1 (3.6%)
Other	0 (0%)	1 (3.8%)	1 (4.3%)	0 (0%)
None	46 (100%)	14 (53.8%)	0 (0%)	7 (25.0%)
Age of first auditory exposure (months) ^a				
<i>M</i> (<i>SD</i>)	0 (0)	49.0 (24.9)	21.2 (16.2)	38.6 (26.5)
Median [min, max]	0 [0, 0]	52.5 [1, 91]	16.0 [0.5, 58]	36.0 [3, 90]
Missing	0 (0%)	8 (30.8%)	0 (0%)	5 (17.9%)
Age of first language exposure (months)				
<i>M</i> (<i>SD</i>)	0 (0)	0 (0)	21.2 (16.2)	42.0 (13.2)
Median [min, max]	0 [0, 0]	0 [0, 0]	16.0 [0.5, 58]	36.5 [18, 76]
Missing	0 (0%)	0 (0%)	0 (0%)	2 (7.1%)

Abbreviations: ASL, American Sign Language; DHH, deaf and hard-of-hearing.

^aParticipants' current age was used for DHH children who did not use a hearing device.

The age of auditory exposure was zero (i.e., birth) for all typically hearing participants. For all other DHH participants, age of auditory exposure was based on parent-reported age of first hearing device use. In Table 2 and for all statistical modeling, the age of auditory exposure for severe-to-profoundly deaf children who used no hearing devices was considered to be the child's current age, indicating that they had not yet had significant auditory access that might have affected their EF skills. Specific ages of auditory access were missing for 13 children, 6 from the Early ASL group, and 8 in the Later ASL group. The Typically Hearing group had significantly earlier age of auditory exposure than all three DHH groups (Typically Hearing vs. Early ASL: $Z = 7.64, p < .001$; Typically Hearing vs. Later English: $Z = 5.53, p < .001$; Typically Hearing vs. Later ASL: $Z = 7.22, p < .001$). Later English participants did not significantly differ in age of auditory exposure from Early ASL ($Z = 2.26, p = .07$); or Later ASL: ($Z = 1.46, p = .29$). Early and Later ASL groups did not differ in terms of their age of auditory exposure ($Z = 0.89, p = .37$).

Age of language exposure was birth, or zero, for typically hearing children and DHH children exposed to sign language from birth. For DHH children using spoken language (Later English), age of language exposure was the age at which they received their hearing device. For DHH children who used ASL and who had parents who did not primarily communicate with ASL (Later

ASL), the age of language exposure was the age at which the child entered a signing program. Specific age of language exposure information was missing for two participants from the Later ASL group. Later English and Later ASL groups both significantly differed from each early language group ($p < .001$). The Later ASL group did not significantly differ from the Later English group in age of language exposure ($Z = 1.84, p = .13$). Individual background information for all participants is available on the Open Science Foundation website (<https://osf.io/phym2>).

Materials

Executive functioning was measured via parent report using the 63-item BRIEF-P (Gioia et al., 2003). The BRIEF-P is internally consistent (Cronbach's alphas .80–.97), has high test–retest stability ($r = .78–.90$), and construct validity (Gioia et al., 2003, pp. 47–65). To complete the BRIEF-P, parents indicate how frequently a behavior has been a problem for their child during the past 6 months (never, sometimes, or often). The form takes approximately 10–15 min to complete, and the assessment includes reference norms for children from the ages of 2 to 5 years, 11 months.

Due to a clerical error, 29 participants aged 6–7.5 years old were mistakenly administered the preschool version

TABLE 3 Means, standard deviations and *t*-test results of BRIEF-P raw scores for the children who received language exposure (in any modality) from birth

	Typically hearing (<i>n</i> = 46)	Early ASL (<i>n</i> = 26)	Welch's <i>t</i> -test results	
	<i>M</i> (<i>SD</i>)	<i>M</i> (<i>SD</i>)	<i>t</i> (<i>df</i>)	<i>p</i>
Global Executive Composite	87.8 (18.7)	89.5 (16.1)	-.40 (58.7)	.69
Inhibition	22.8 (5.9)	24.0 (6.1)	-.81 (51.1)	.42
Shift	13.0 (3.1)	13.5 (3.1)	-.57 (51.8)	.57
Emotional Control	15.0 (3.7)	14.7 (3.0)	.31 (60.4)	.76
Working Memory	22.7 (6.6)	23.1 (4.8)	-.29 (65.5)	.77
Plan/Organize	14.3 (3.4)	14.2 (3.0)	.14 (57.1)	.89

Abbreviations: ASL, American Sign Language; BRIEF-P, Behavior Rating Inventory of Executive Function—Preschool Version.

of this rating scale rather than the version normed on older children (the BRIEF). Because the BRIEF-P was based on the original BRIEF, there is much overlap between the two forms. Differences primarily consist of removal of the Organization and Monitor subscales, as well as modification of some items to be more appropriate for younger children (e.g., substituting “play area” for “school” for use with children who do not attend school; Gioia et al., 2003, p. 38). For analyses that included participants outside of the normed age range, only raw scores were considered. All results are based on the BRIEF-P version of this rating scale.

The BRIEF-P includes five subscales (Inhibit, Shift, Emotional Control, Working Memory, and Plan/Organize), three index scales (Inhibitory Self-Control, Flexibility, and Emergent Metacognition), and one overall summary scale (Global Executive Composite [GEC]). To limit the number of statistical models and to focus on individual EF components, the three index scales were not included in our analyses and will not be discussed further. The Inhibit subscale measures self-regulation of behavior and is assessed with statements such as *Acts wilder or sillier than others in groups [birthday parties, recess]*. The Emotional Control subscale similarly measures self-regulation, but focuses on emotion and consists of statements such as *Overreacts to small problems*. The Shift subscale measures a child's behavioral flexibility and includes statements such as *Becomes upset with new situations*. The Working Memory subscale measures a child's ability to hold information in mind for later use in goal-directed behaviors (e.g., *When given two things to do, only remembers the first*). The Plan/Organize subscale measures a child's ability to plan and implement their goal-directed behaviors (e.g., *When instructed to clean up, puts things away in a disorganized, random way*). Finally, the GEC includes all five subscales and thus can be considered a summary of EF skills, although if stark differences are present across subscales, the GEC is less informative.

Behavior Rating Inventory of Executive Function—Preschool Version norms are separated based on the child's sex, age, and assessor (parent or teacher). All

forms in the current study were completed by parents. The mean standard score (*T*-score) for all subscales and composite scales is 50, with a standard deviation of 10. Higher scores indicate worse EF skills, with a score of 65, or 1.5 *SDs* above the mean, considered significantly elevated. The BRIEF-P also includes two validity measures: the Inconsistency and Negativity scales. The Inconsistency Scale compares consistency of responses for two similar items; we excluded two forms that scored in the Inconsistent range. The second validity measure, the Negativity Scale, determines whether a respondent answered selected items in an unusually negative way. We included forms which scored in the elevated range (*n* = 3) because, based on previous research, we expected some DHH children to exhibit problems with EF and thus these responses may indicate true dysfunction.

Procedure

BRIEF-P forms, which include instructions, were sent home with children when behavioral data was collected at participating schools; forms were distributed directly to parents when data collection was conducted in participants' homes. Parents were encouraged to contact the research team with any questions. All returned forms were scored according to the instructions in the manual.

RESULTS

Recall that our research questions all broadly address how language and auditory exposure affect parent-reported EF. We begin by directly comparing the EF skills of children with access to spoken language from birth via typical hearing to those of severe-to-profoundly deaf children exposed to a sign language from birth. We then present a model for the BRIEF-P composite scale and each subscale that characterizes the contributions of age of auditory and language exposure, as well as other relevant background characteristics. We used BRIEF-P raw scores for these first two analyses to include the

largest number of participants as some participants were outside of the range of the BRIEF-P norms. Finally, we compare relative risk ratios for clinically significant standard scores on the BRIEF-P for the subset of participants under age 6 years (i.e., within the BRIEF-P norms age range). We address each of our research questions individually below. All analyses were run in R and full scripts used are available at https://github.com/emlini/SLaM_BRIEF_analyses.

Question 1: Do DHH children with access to sign language but not auditory input from birth exhibit EF skills comparable to their typically hearing peers?

We used Welch's *t*-tests to compare raw scores for the Typically Hearing and Early ASL groups because the participant groups had unequal variances and sample sizes. Table 3 provides the means and standard deviations of raw scores for the GEC and each individual BRIEF-P subscale and summarizes the *t*-test results. None of these group comparisons were statistically significant or approached significance. There is no evidence in our sample that children without typical auditory access, but who do have early accessible (sign) language exposure, exhibit differences in EF when compared to typically hearing children.

Question 2: Do age of auditory and language exposure significantly predict EF?

We then used linear models to determine how age of auditory and language exposure (in months) related to EF scores. These models included 109 participants due to missing age of auditory and/or language exposure for 14 participants (see Table S1 for demographic information for this subsample). BRIEF-P standard scores are divided by sex and age, but raw scores, as used in these analyses, do not factor in these variables. Thus, the background variables of sex and chronological age were included as additional predictor variables in all models. SES is also correlated with EF scores on the BRIEF-P (Gioia et al., 2003), so it was included as an additional predictor in our modeling.

Model results are presented in Table 4. Because age of language exposure and age of auditory exposure were significantly correlated, we tried adding these two variables to the model in different orders to determine whether one variable better explained the variability in BRIEF-P scores (e.g., Model A: model with demographics only, add age of auditory exposure first; then add age of language exposure; Model B: model with demographics only, add age of language exposure first; then add age of auditory exposure). Regardless of whether it was added before or after age of language exposure, age of

auditory exposure did not significantly predict BRIEF-P scores on the GEC, nor on any of the subscales, and its addition did not significantly improve model fit.

Socioeconomic status was a significant predictor for all BRIEF-P subscales except Working Memory, with higher SES related to lower, or better, EF scores. Sex and chronological age did not significantly predict any BRIEF-P scores. Age of language exposure significantly predicted the GEC and all subscale scores except for Inhibition and Emotional Control. We also ran separate models in which we replaced age of auditory exposure with length of auditory experience (time since first hearing device use), hearing status (typical, hard-of-hearing, or deaf), or language modality (English, ASL; see Tables S2–S8 for all model results). None of these additional variables were significant predictors of EF skills and their inclusion did not improve model fit over a model with demographic variables and age of language exposure. It was not possible to directly compare the model with hearing status, age of language exposure, and demographic variables to the model with only age of language exposure and demographics because we were missing hearing status information for six participants—three Early ASL, two Later ASL, and one Later English. However, hearing status was never a significant predictor of any BRIEF composite score or subscale, and for some subscales, its addition resulted in a model that was no longer a good fit for the data.

Question 3: Do children with later, and likely degraded access to auditory and/or language input exhibit clinically significant deficits in EF relative to typically hearing peers?

To address our third research question, participants were categorized into four groups based on their degree and timing of access to language input and the language they predominantly use as described in the Participants section above. The Early English group includes all typically hearing children. Standard scores were available for the subset of 98 participants under 6 years of age (see Table S8 for demographic characteristics of this subsample). The full distribution of standard scores is presented in Figure 1, with the mean of 50 and the clinical cutoff of 65 marked with horizontal dashed and dotted lines, respectively. As is apparent in this figure, the vast majority of participants scored below the clinical cutoff, with significant overlap across all four participant groups.

The remaining analyses categorized all standard scores as clinically significant (≥ 65) or not (< 65). Note that prior literature with DHH children (Beer et al., 2014; Hall et al., 2018; Kronenberger et al., 2014) used a cutoff of 60, resulting in more children showing elevated risk. Table 5 shows the percentage of children in each group that fell within the clinically significant range on the composite scale and each BRIEF-P subscale, as well as the relative risk ratios

TABLE 4 BRIEF-P raw score linear regression results

	BRIEF-P subscale					
	Global Executive Composite β (SE)	Inhibition β (SE)	Shift β (SE)	Emotional Control β (SE)	Working Memory β (SE)	Plan/Organize β (SE)
SES	-.354 (0.138)*	-.095 (0.045)*	-.065 (0.026)*	-.086 (0.031)**	-.046 (0.044)	-.063 (0.026)*
Sex (male)	-1.707 (3.579)	.880 (1.156)	-.917 (0.683)	-.742 (0.799)	-.612 (1.142)	-.316 (0.680)
Age (months)	-.029 (0.159)	.041 (0.052)	-.025 (0.030)	-.007 (0.036)	-.009 (0.051)	-.028 (0.030)
Age of exposure to language (months)	.341 (0.112)**	.072 (0.036) [†]	.061 (0.021)**	.032 (0.025)	.111 (0.036)**	.065 (0.021)**
Age of auditory exposure (months)	-.085 (0.082)	-.023 (0.026)	-.003 (0.016)	-.014 (0.018)	-.025 (0.026)	-.020 (0.015)
Constant	109.309 (11.246)**	24.485 (3.633)**	18.426 (2.145)**	20.205 (2.510)**	25.930 (3.587)**	19.263 (2.137)**
Observations	109	109	109	109	109	109
R^2	.170	.120	.168	.104	.118	.155
Adjusted R^2	.130	.077	.128	.060	.075	.114
Residual SE ($df = 119$)	18.311	5.915	3.493	4.086	5.841	3.479
F statistic ($df = 5; 119$)	4.226**	2.811*	4.162**	2.379*	2.761*	3.786**

Note: Bolding indicates statistically significant predictors.

Abbreviations: BRIEF-P, Behavior Rating Inventory of Executive Function—Preschool Version; SES, socioeconomic status.

[†] $p < .10$.

* $p < .05$; ** $p < .01$.

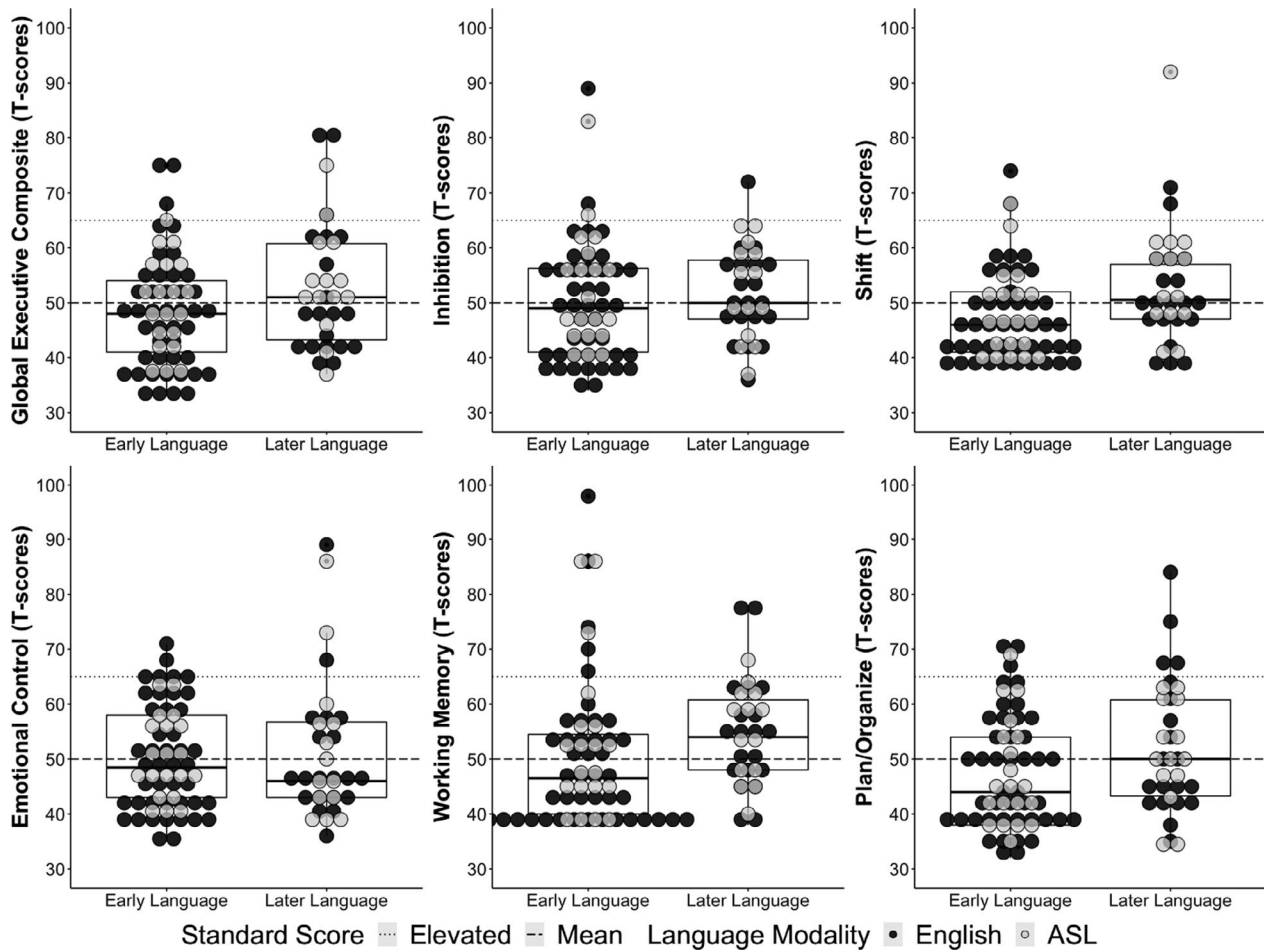


FIGURE 1 BRIEF-P standard scores. *Note:* Scores are presented by language timing group (Early vs. Later) and language (English, black vs. ASL, grey) for each individual executive functioning subscale and the Global Executive Composite. Each dot represents one child; dashed lines show the mean and the dotted lines show the clinical threshold (65). ASL, American Sign Language; BRIEF-P, Behavior Rating Inventory of Executive Function—Preschool Version

TABLE 5 Relative risk of clinically significant scores (T -score ≥ 65) in DHH participants with respect to typically hearing participants

	Percent clinically significant scores (number)				Relative risk [95% confidence interval]		
	Typically hearing ($n = 44$)	Early ASL ($n = 20$)	Later English ($n = 20$)	Later ASL ($n = 14$)	Early ASL	Later English	Later ASL
Global Executive Composite	7% (3)	5% (1)	15% (3)	14% (2)	0.56 [0.06, 5.08]	1.69 [0.37, 7.64]	1.61 [0.30, 8.67]
Inhibition	5% (2)	10% (2)	5% (1)	0% (0)	1.50 [0.23, 9.90]	0.75 [0.07, 7.80]	n/a ^a
Shift	5% (2)	5% (1)	10% (2)	7% (1)	0.75 [0.07, 7.80]	1.50 [0.23, 9.90]	1.07 [0.10, 10.95]
Emotional Control	7% (3)	0% (0)	10% (2)	14% (2)	n/a ^a	1.13 [0.20, 6.22]	1.61 [0.30, 8.67]
Working Memory	11% (5)	20% (3)	10% (2)	7% (1)	1.13 [0.30, 4.25]	0.75 [0.16, 3.54]	0.54 [0.07, 4.21]
Plan/Organize	7% (3)	5% (1)	20% (4)	0% (0)	0.56 [0.06, 5.08]	2.25 [0.55, 9.13]	n/a ^a

Note: A risk ratio for which the 95% confidence interval *did not* include 1 would be considered a statistically significant result; none of the DHH groups were significantly more likely than typically hearing participants to have clinically elevated scores on any subscale or on the composite scale.

Abbreviations: ASL, American Sign Language; DHH, deaf and hard-of-hearing.

^aCannot calculate risk ratio or confidence interval because no children within the comparison group scored within the clinically significant range on this subscale.

for the two groups of DHH participants compared to the typically hearing participants. This was calculated by dividing the percentage of children in each DHH group who had a *T*-score at or above 65 by the percentage of children in the Typically Hearing group who scored in the same range (we used the *riskratio.small()* function in the R “epitools” package, which adjusts for small sample size). A risk ratio of one would indicate that DHH participants were as likely as typically hearing participants to have *T*-scores at or above 65 (i.e., that there was no difference between the groups). Numbers below one mean that the DHH participants were less likely to score in the clinically significant range and numbers above one mean that they were more likely. The relative risk ratio for the Early ASL group on the Emotional Control subscale was not calculable because no children in the Early ASL group scored within the clinical range. A 95% confidence interval was used to determine whether the observed relative risk ratios were significantly different from those expected by chance ($p < .05$): all confidence intervals contained 1, indicating that the typically hearing group and the DHH groups did not significantly differ in their risk of executive dysfunction.

DISCUSSION

Our overarching research question was whether auditory input is necessary for typical EF development; both the auditory scaffolding and language scaffolding models predict that language experience is an important factor in the development of EF. We will address our three specific research questions individually below.

Question 1: Do DHH children with access to sign language but not auditory input from birth exhibit EF skills comparable to their typically hearing peers?

We found no significant differences when we compared the two groups of children with early access to language (i.e., typically hearing children learning spoken language and severe-to-profoundly deaf children learning ASL from birth). These results conflict with those of Beer et al. (2014), who found that DHH children who use spoken language exhibit differences in EF as compared to typically hearing peers by preschool age. Yet in Beer et al.’s study, language and auditory experience were confounded because all participants used spoken language. Our results suggest that deafness itself does not hinder EF development and that previous results demonstrating EF differences between deaf and hearing children were likely driven by deaf participants’ lack of early language exposure.

Some authors have speculated that expectations may be different for deaf children of deaf parents, leading to

typical parent-reported EF skills despite the presence of true difficulties in this domain (e.g., Kronenberger & Pisoni, 2020). If this were the case, underlying differences might not be apparent when using parent-reported measures of EF, but should instead be observable on behavioral measures that are not influenced by the cultural expectations of individual parents. While we cannot directly address this issue with our data, Hall et al. (2018) found that similar parent-reported EF results between these two groups could not be due to parental bias because children who also completed behavioral tasks showed the same performance patterns as reflected in the parent-reported measure.

Question 2: Do age of auditory and language exposure significantly predict EF?

When we considered parent-reported EF skills for all our participants, results were again consistent with the theory that language, not auditory input, scaffolds the development of EF. Age of auditory exposure did not significantly predict EF skills for any of the BRIEF-P subscales or for the composite, regardless of the order in which the predictors were entered into the model, but age of language exposure was a significant predictor for the Shift, Working Memory, and Plan/Organize subscales, as well as for the overall composite. Children with later exposure to language generally had worse EF skills as indicated by an increase in raw scores on all but the Inhibition and Emotional Control BRIEF-P subscales. It is not clear why age of language exposure did not predict scores on the Inhibition or Emotional Control subscales; perhaps these aspects of EF are less dependent on language than shifting, working memory, and planning/organization. It is also possible that the DHH participants in this study had received interventions focused on controlling emotions and inhibiting unwanted behaviors.

Our statistical modeling included additional background variables that have been shown to affect EF. SES was a significant predictor of raw scores for all but Working Memory, with higher SES predicting better parent-reported EF skills, a finding generally consistent with previous behavioral research that has found SES to be important in the development of EF skills (Gioia et al., 2003), although previous studies have found that these results typically hold across all EF subdomains. In contrast with some previous research, sex did not significantly predict scores in any of the EF domains in our dataset. BRIEF-P norm development found a small but significant difference in parents’ ratings of boys and girls, specifically on the Inhibit subscale (Gioia et al., 2003). Our sample may not have been large enough to detect such small differences. Similarly, small but statistically significant differences were found in the BRIEF-P norming sample based on chronological age, with younger children receiving slightly higher ratings

(Gioia et al., 2003), while chronological age was not a significant predictor for any of our models. Our sample size may not have been large enough to detect such small differences. Alternatively, it may be that the age variable in the BRIEF-P norming sample is in fact capturing not just chronological age, but also “amount of experience with language.” In typically developing populations like those included in the BRIEF-P norming sample, these variables are not usually separable. However, in our sample of DHH participants, the two can be teased apart. Our findings indicate that age of exposure to language may be more important to the development of EF than chronological age.

Some readers might take issue with the way we characterized the degree of auditory deprivation using a measure of “age of auditory exposure.” This measure combines information about a child’s pre-device hearing levels with the age at which they first used a hearing device. This estimate is likely a reliable proxy for the age at which a child begins receiving regular auditory input at lower decibels, even if this input is somewhat degraded. But it may not be a good measure of the degree of access to auditory input that the participants were currently experiencing. For example, we did not have any information about participants’ hearing levels using their assistive devices. The context of data collection (e.g., in schools and in participants’ homes) did not allow us to administer reliable hearing tests. However, we ran additional models including the auditory factors of length of auditory exposure and hearing level, which were also not significantly related to any EF subscales. Other studies of EF in DHH children also have not found reliable correlations between EF skills and similar audiological variables, such as age at cochlear implantation or pre-implant hearing levels (e.g., Beer et al., 2014; Hintermair, 2013; Kronenberger et al., 2014). Furthermore, for those studies which have found EF to be correlated with an auditory factor, like the duration of CI use (e.g., Beer et al., 2014; Kronenberger et al., 2014), this factor is confounded with age of language exposure in the DHH participants, who all use spoken language only. Thus, the relations found between, for example, the duration of CI use and EF skills may actually be attributable to a later age of access to language.

Question 3: Do children with later, and likely degraded access to auditory and/or language input exhibit clinically significant deficits in EF relative to typically hearing peers?

Turning to our comparisons of standard scores on the BRIEF-P, few participants across all groups exhibited clinically significant deficits in EF skills. Risk ratio analyses showed that no DHH group was significantly more likely than the typically hearing

group to have clinically significant scores (T -score ≥ 65). Thus, although our linear models demonstrated that age of language exposure significantly predicted EF scores on most BRIEF-P subscales, the size of this effect did not result in apparent clinical differences across groups. This may have been due to insufficient power when participants were split into four smaller groups.

These results are consistent with the BRIEF-P findings for the preschool-aged sample in Kronenberger et al. (2014), although their school-aged DHH participants demonstrated increased risk of clinically significant EF scores on the BRIEF. The relative risk results for the Early ASL participants in our study are also largely consistent with those found by Hall et al. (2018). We found no differences between typically hearing and deaf, native-signing preschool-aged participants in the current study. Hall et al. (2018) found that school-aged deaf native signers had a higher risk of clinically significant scores for the Inhibit and Working Memory subscales when compared to the typically hearing participants in their sample, but not when compared to the BRIEF norms. Hall et al. (2018) explained their results by pointing out the unusually low standard scores on these subscales in the typically hearing participants in their sample. A similar trend is not obvious among the participants in our sample: roughly 7% of the typically hearing participants’ scores are expected to fall 1.5 SD s above the mean, and the actual observed percentages are relatively close to those expected by chance (see Table 5). Unusually low standard scores could result from participant selection bias: highly educated, upper-SES parents may be more likely to participate in research and have been shown to be less likely to report EF problems on measures such as the BRIEF-P (Gioia et al., 2003). Although participant groups may be broadly matched on SES, there are clear differences in educational and occupational opportunities between deaf and hearing parents that could contribute to such results (Garberoglio et al., 2019). Another possibility is that differences in parent-reported EF between deaf and hearing parents may not emerge until school age, the age of the participants in Hall et al. (2018).

It is important to note that Kronenberger et al. (2014) and Hall et al. (2018) used a cutoff standard score of 60 to calculate risk ratios. In contrast, we used the threshold set by the creators of the assessment (i.e., 65: Gioia et al., 2003). When we re-ran the risk ratios for DHH groups using a cutoff score of 60, we found only that the Later ASL group was at significantly increased risk of clinically elevated scores relative to typically hearing participants on the Working Memory subscale (see Table S9). This could be due to a later average age of language exposure for the Later ASL group (though this difference was not significant when compared to the Later English group). Critically, in support of the language scaffolding

model, DHH children with early access to ASL were not at increased risk of having clinically elevated scores even with this lower cutoff.

Limitations and implications

One limitation of the current study is that our analyses did not include a measure of language abilities. This is an important consideration because variation in language abilities is observed even in typically hearing children and this variation has been related to EF, as discussed in the Introduction. This omission is due to the difficulty in comparing skills across different languages in different modalities, especially for a language such as ASL, for which few reliable standardized assessments for children in this age range exist. Yet even though our variable “age of language exposure” did not measure participants’ receptive or expressive language skills, this variable was a significant predictor for four out of six BRIEF-P scales, suggesting that the effects are robust. Consistent with these results, the DHH children acquiring spoken English in the larger sample from the same study scored, on average, 11.5 raw points lower than typically hearing children on the Peabody Picture Vocabulary Test (Carrigan & Coppola, 2020).

A second limitation is one that nearly all research in this area suffers from: our measure of EF, the BRIEF-P, is not a language-neutral assessment (e.g., Redmond et al., 2019). This can be seen clearly on BRIEF-P items like *When given two things to do, only remembers the first*. Children with limited vocabularies and grammatical impairments will likely struggle more with verbal directions than those with advanced language skills, making adequate language comprehension a prerequisite for this measure of working memory. Yet, this problem of disentangling language skills from EF measures also plagues behavioral research in this field. For example, even as researchers develop nonverbal tasks using stimuli that are less easily labeled (e.g., using a series of spatial locations rather than numbers in a working memory task), and/or do not require verbal responses (e.g., pointing at rather than repeating a sequence in either spoken or signed language), participants may nevertheless employ language-based rehearsal strategies. It is also not clear how ecologically valid such behavioral tasks are. So, while it is important to design more language-neutral tasks, imperfect rating-scale measures such as the BRIEF-P can still help inform us about children’s everyday functioning during daily tasks that often do rely on underlying language skills.

Despite these limitations, the current study is unique in that it included a systematic comparison of language and auditory experience across both language modality (sign vs. speech) and the developmental timing of exposure. By including a diverse range of participants, we were able to disentangle the contributions, or lack

thereof, of language and auditory experience. Using these types of models can be a powerful analytic tool that helps ameliorate the challenges of recruiting matched samples—especially given the low incidence of deafness in the general population and likely underlying group differences on various background characteristics, such as SES. This study is also the first to include EF data from preschool-aged deaf, native-signing participants, which provides important insight into the developmental trajectory of EF in DHH children.

Our results have important implications for theories about the relation between auditory and language experience and EF, as well as clear recommendations for clinical practice. Here we showed that early access to language, even more than auditory input, supports the development of EF skills. In a recent chapter, Kronenberger and Pisoni (2020) updated their auditory scaffolding hypothesis to situate it within the well-established biopsychosocial perspective on development. The argument that multiple factors influence the development of EF is not novel and is entirely compatible with our findings. Any single study of the effects of different factors on EF development must, due to statistical and practical considerations, limit the number of factors assessed. In this work, we include demographic variables known to influence EF development and we directly compare auditory and language experience to highlight the relative contributions of each of these variables.

Our results also have implications for theories of the relation between language and EF development. Because DHH children often lack adequate early access to language, their overall language exposure and subsequent language abilities vary more than in typically hearing children, allowing for possible dissociations between language and EF. Results from linear models showed that age of language exposure significantly predicted raw scores on the BRIEF-P subscales of Shift, Working Memory, and Plan/Organize, but not Inhibition or Emotional Control. This could mean that inhibition and emotional control skills are less dependent on language than the other aspects of EF. Alternatively, it could be that interventions for the preschool-aged participants in the current study focused more on emotional and behavioral regulation than other EF skills, compensating for later language exposure on these subscales only. The current study did not collect information about EF interventions and cannot distinguish between these two possibilities.

Overall, our findings strongly indicate that we must ensure that deaf children have access to *language*, not just speech (Hall et al., 2019). In many cases, the best way to ensure this would be to take a bilingual approach that includes both a signed and spoken language (e.g., Clark et al., 2020). Although much research has found that earlier interventions with cochlear implants or hearing aids lead to better spoken language outcomes, age-appropriate language development does not occur for many DHH

children, even using modern hearing technologies (see, e.g., the range of spoken-language outcomes reported for children with cochlear implants in Dettman et al., 2016). In contrast, sign languages are acquired by deaf children with adequate language exposure along a similar timeline to that of hearing children acquiring spoken language (e.g., Lillo-Martin & Henner, 2021). Recent findings show that DHH infants whose hearing parents began signing with them in early infancy show vocabulary sizes comparable to those of DHH infants who had deaf signing parents (Caselli et al., 2021). Furthermore, research has also demonstrated that DHH children acquiring both a signed and spoken language from birth can achieve age-appropriate spoken language skills (Davidson et al., 2014), possibly even outperforming their monolingual DHH peers (Hassanzadeh, 2012). Moreover, adoption of sign language can signal a family's acceptance of their deaf or hard-of-hearing child and may have additional benefits for social and emotional health (Kushalnagar et al., 2020).

Overall, these findings underscore that DHH children learning signed language from birth, without significant auditory and/or spoken language input, can develop EF skills on par with their typically hearing peers. They also demonstrate the importance of decoupling auditory experience and language experience in research design and interpretation. These results strongly support the recommendation for providing sign language in addition to spoken language to ensure that the child has as much support as possible for the development of EF. Thus, clinicians should use their considerable influence to ensure that DHH children have access to language, in any modality, as early as possible (e.g., Hecht, 2020).

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SUPPORTING INFORMATION

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