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Development of visual sustained selective attention and response inhibition in deaf children

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Abstract

Studies of deaf and hard-of-hearing (henceforth, deaf) children tend to make comparisons with typically hearing children for the purpose of either identifying deficits to be remediated or understanding the impact of auditory deprivation on visual or domain general processing. Here, we eschew these clinical and theoretical aims, seeking instead to understand factors that explain variability in cognitive function within deaf children. A total of 108 bilingual deaf children ages 7–13 years who use both English and American Sign Language (ASL) participated in a longitudinal study of executive function (EF) development. We report longitudinal data from a visual continuous performance task that measured sustained selective attention and response inhibition. Results show that the impact of deafness on these processes is negligible, but that language skills have a positive relationship with both: better English abilities were associated with better selective sustained attention, and better ASL abilities with better response inhibition. The relationship between sustained selective attention and English abilities may reflect the cognitive demands of spoken language acquisition for deaf children, whereas better ASL abilities may promote an "inner voice," associated with improved response inhibition. The current study cannot conclusively demonstrate causality or directionality of effects. However, these data highlight the importance of studies that focus on atypical individuals, for whom the relationships between language and cognition may be different from those observed in typically developing populations.

Keywords Deafness · Selective attention · Development · Sign language · Inhibitory control

Deafness is associated with changes in visual functions (Bavelier et al., 2006) and precipitates changes which exemplify *cross-modal plasticity*, in which changes in one sensory system bring about changes in another (Bavelier & Neville, 2002). Studies of visual functions in *deaf adults* have indicated malleability in the spatial distribution of visual attention, realized as an enhanced ability to localize objects and detect motion in the visual periphery by deaf adults (see Bavelier et al., 2006; Bell et al., 2019; Pavani & Bottari, 2012, for reviews). The neural signature of the effect is elevated recruitment of multisensory (and possibly auditory) cortex in the right cerebral hemisphere (Bavelier et al., 2000; Bavelier et al., 2001; Fine et al., 2005; Finney et al., 2001; Finney et al., 2003; Seymour et al., 2017; Vachon et al., 2013). Studies of visual functions in deaf *children*, on the other hand, have primarily focused on temporal aspects of attention (Dye & Hauser, 2014; Hoffman et al., 2018; Horn et al., 2005; T. V. Mitchell, 1996; Quittner et al., 1994; L. B. Smith et al., 1998; Tharpe et al., 2002; Yucel & Derim, 2008). These latter studies have assessed how well the child can shift attention across objects appearing one after the other at the same location, as opposed to how well the child allocates attention over space.

Evidence for visual deficits, rather than enhancements, in deaf children has come from a range of tasks, supporting the argument that a lack of auditory experience affects the development of visual abilities. Here we focus on a subset of those tasks where visual attention is directed toward behaviorally relevant target sequences presented over a relatively long period of time, called continuous performance tests (CPTs), that ostensibly provide a measure of *sustained selective attention*. One of the first studies to examine sustained selective attention to temporal sequences in deaf children used a visual CPT in which a sequence of digits was

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presented without a break over an extended period of time (Quittner et al., 1994). Children were required to attend to the stream and indicate the occurrence of relatively rare target sequences by pushing a button every time they saw a 1 followed by a 9. In this study, typically hearing children were compared with two groups of 6- to 13-year-old profoundly deaf children who used either spoken English or Total Communication: those with conventional hearing aids, and those who had received a cochlear implant.[1] Hearing children outperformed both groups of deaf children in this study—they detected a greater proportion of the 1–9 target sequences, and made fewer incorrect responses to nontarget sequences. Deaf children who had been using a cochlear implant for longer demonstrated better performance than those who had been wearing their implants for less time, with this effect of length of device use not seen in deaf children using conventional hearing aids. A two-wave longitudinal follow-up study in the same paper looked at CPT performance 9 months and 18 months after receiving an implant. Users of cochlear implants demonstrated task performance improvements over time not seen in a control group of deaf children using conventional hearing aids. These data led the authors to conclude that audition was important for the development of visual sustained selective attention skills, and that prolonged use of a cochlear implant resulted in commensurate improvements in performance. A subsequent study by the same group recruited a larger number of deaf children from the same populations, again comparing hearing children to deaf children with cochlear implants and those who used conventional hearing aids (L. B. Smith et al., 1998). Once more, language modes were reported to be either spoken English or Total Communication. The same visual CPT was used, and the broad conclusions drawn were the same: deafness resulted in weaker visual sustained selective attention, and use of a cochlear implant led to greater improvement over time in deaf children than did use of conventional hearing aids. The larger sample size also allowed the authors to compare the performance of deaf children who use spoken language only with those who used Total Communication—no performance differences were observed. They were also able to compare nonimplanted deaf children who were implant candidates (and recruited through a clinic) with nonimplanted deaf children attending a residential school for the deaf—again, no performance differences were observed. While these studies were primarily interpreted in terms of sustained visual selective attention, the authors also noted that the fine temporal structure in the auditory signal provided by a cochlear implant might have imparted advantages in a task where extraction of visual temporal structure was beneficial.

Subsequently, a longitudinal study of deaf implanted children was reported that sought to determine the relationship between performance on this visual CPT and length of cochlear implant use (Horn et al., 2005). The study looked at data collected from prelingually, profoundly deaf children before they received their implant and then again every year after implantation for 3 years. While all of the deaf children performed below published norms for typically hearing children, longer use of the implant resulted in improved performance on the visual CPT. Some of these children used only spoken language, whereas others also used Signed Exact English. Another study suggested that earlier implantation (before age 4 years) leads to better sustained attention than later implantation (after age 4 years) in deaf children receiving auditory-verbal therapy (Yucel & Derim, 2008). Again, performance of deaf children—implanted either early or late—was inferior to that of typically hearing control children. Together, these latter two studies lead to the conclusion that visual deficits could be remediated by early and sustained restoration of auditory input via a cochlear implant. More recently, Hoffman et al. (2018) analyzed data from a visual CPT task administered to 106 deaf children with CIs (5 years after implantation) and 66 hearing control children. Again, the data revealed significantly poorer *d*-prime scores for the deaf children, indicative of visual sustained selective attention deficits. Hoffman et al. reported that there were no significant correlations between measures of rate of change in receptive and expressive oral language skills and the *d*-prime measure, although they noted that, as a group, the children with cochlear implants were significantly delayed in their oral language development compared with the hearing control children.

Across several studies of deaf children, therefore, there is evidence that they struggle to process visual stimuli when they are the targets in a continuous performance test. Some improvement is seen in the performance of all children between the ages of 6 and 13 years. However, this improvement is more marked for deaf children who have had access to sound provided with a cochlear implant, than in those deaf children who use conventional hearing aids. These patterns of data have been interpreted as supporting a role for audition in the shaping of visual processes—notably higher-level visual cognition. This has been made explicit in the *division-of-labor hypothesis*, first articulated in Quittner et al. (1994), where it was argued that sound is part of the "expected environment" and that its absence therefore results in a perturbation of epigenetic development resulting in atypical visual processing because sound and vision are "coupled systems"—an example of experience-expectant plasticity (Greenough et al., 1987). Subsequently, L. B. Smith et al. (1998) referred to the importance of environmental sounds

[1] Aided auditory thresholds were equivalent in the two deaf groups at around 40 dB HL.

in organizing visual attention, although they did not further develop this theoretical framework. Quittner et al. (2004) were the first to articulate the division-of-labor hypothesis in its current form. They posited that multimodal inputs were essential in facilitating the allocation of attention, noting that auditory inputs alert children to the need to redirect their visual attention. In Quittner et al. (2007), reiterated in Hoffman et al. (2018), the situation for deaf children was made more explicit, with the authors noting that monitoring the environment and focusing on a task within the same (visual) modality makes it difficult for deaf children to attend to and focus upon a task. Note that the division-of-labor hypothesis is ambivalent about whether this reflects a need for deaf children to spread their attention across their environment and the task at hand, or whether they need to rapidly orient and reorient attention continually between the environment and their current task. The hypothesis simply states that, for hearing children, the requirement to monitor the environment is off-loaded to the auditory system which is then responsible for engaging the visual system when needed. For deaf children, however, this division-of-labor is not possible, resulting in additional processing demands on the visual system and weaker performance on visual sustained selective attention tasks as a result.

The division-of-labor hypothesis is of theoretical importance because it suggests that multisensory integration processes feed back into unisensory processing, providing a mechanism whereby a lack of sensation in one modality can impact processing in another behaviorally and neurally distinct sensory modality. However, in yet another CPT study, Dye and Hauser (2014) recruited profoundly deaf children who acquired a natural signed language (American Sign Language) from infancy from their deaf parent(s). While the performance of these deaf children was slightly poorer than that of hearing controls, the difference was not statistically reliable. Indeed, the effect size for deafness was much smaller than those consistently reported in the CPT studies with deaf children reported above, suggesting that a lack of access to sound may not be entirely—if at all—responsible for the reported performance differences. Dye and Hauser (2014) proposed that delayed access to natural language may also play a role, and in later work the proposal that the effect could be traced back to dyadic communicative interactions in the first several months of life was entertained (Morgan & Dye, 2020). Importantly, all of the ASL signing children reported in Dye and Hauser (2014) had a hearing loss of 75 dB or greater in their better ear, and none had received a cochlear implant. Thus, there is *prima facie* evidence that the division-of-labor hypothesis does not hold for these children, all of whom had early natural language exposure.

Research with deaf children commonly reports both heightened inattention and an inability or inhibit responses (impulsivity) compared with hearing peers (Altshuler et al., 1976; Castellanos et al., 2018; Lesser & Easser, 1972; T. V. Mitchell & Quittner, 1996; Yucel & Derim, 2008). A measure of response inhibition can be derived from CPT tasks by measuring the number of (incorrect) responses to nontarget stimuli where a child responds to the first of a two-digit target sequence. Using this approach, previous studies have reported lower response inhibition in deaf children as compared with their hearing peers (Hoffman et al., 2018; Horn et al., 2005; T. V. Mitchell & Quittner, 1996; Quittner et al., 1994; Yucel & Derim, 2008). The interest in response inhibition in deaf children is not new. Harris (1978) cites Altshuler as stating "audition is somehow necessary for internalized control of rage" (Altshuler, 1971, p. 1525), a conclusion based upon several descriptive studies of deaf children. Harris (1978) goes on to note that it may actually be the corollaries of deafness, such as parental stress, nonoptimal rearing practices or poor manual communication skills, that results in any observed deficits in behavioral control.

Studies reporting depressed response inhibition in deaf children have been used to suggest that such impulsivity is directly associated with the loss of auditory access—deaf children are more distractible and less able to ignore irrelevant visual stimuli because they cannot hear (Quittner et al., 1994). However, research has also posited the importance of language ability in supporting the proper development of impulse control in deaf children, most often under the umbrella of *executive functioning*. Quittner et al. (1994) discusses this possibility in the context of children with cochlear implants who display improved performance on the CPT relative to deaf controls, positing that this may be due to their better [spoken] language skills. In support of this possibility, they describe earlier research which suggests that early communicative experiences support the development of behavioral control and response inhibition processes; those experiences are diminished for most deaf children with hearing parents, as observed in Harris (1978), because the child and parent do not share an accessible language. Horn et al. (2005) also reported that response inhibition was correlated with receptive spoken language scores: deaf children who had higher receptive spoken language were less likely to respond to nontarget stimuli (i.e., demonstrated better response inhibition). More recently, a study that measured the frequency of externalizing behaviors (aggression, rule breaking, damage to property) in deaf children with cochlear implants found that children with low speech perception and spoken-language receptive vocabulary had higher rates of externalizing behavior problems (Boerrigter et al., 2019). However, such studies still implicitly emphasize the importance of auditory access by emphasizing *spoken* language access, rather than considering avenues of language acquisition which do not rely on audition (e.g., signed languages).

Parasnis et al. (2003) reported elevated levels of impulsive responding in deaf college students on a continuous performance test called the Test of Variables of Attention (T.O.V.A.), characterized by increased anticipatory errors. Interestingly, Parasnis et al. argued that the pattern of errors they observed might not reflect elevated impulsivity, but rather be the result of decreased perceptual sensitivity to stimuli in the central visual field due to a reallocation of attentional resources across the visual field in deaf individuals (see Bavelier et al., 2006). While there is evidence for such a redistribution for spatial attention in college-aged students, it is not clear whether this is also seen in younger deaf children (see Codina et al., 2011; Dye et al., 2009). Most recently, Daza González et al. (2021) used modified versions of the Conners' Teacher Rating Scale–Revised (Conners, 1997), a Stroop measure, and the Attentional Network Test (Rueda et al., 2004) to examine attention and inhibitory control in 9–10-year-old deaf and hearing children. While finding elevated levels of inattention in their deaf sample, the authors did not find group differences in inhibitory control, suggesting that this was not a significant contributor to the observed inattention. Like Parasnis et al. (2003), Daza González and colleagues suggested that inattention may reflect an adaptive strategy employed by deaf children to monitor their peripheral environment using their intact visual modality. This may be interpreted as inattentive, although it actually reflects a wider (not weaker) attentional focus.

In summary, for these executive function measures (sustained attention, response inhibition), the literature reports evidence for differences in performance between deaf and hearing children. Where differences are found, the performance of deaf children is typically considered inferior to that of their hearing peers. Researchers who have taken a deficit-focused orientation to deafness attribute this to either (i) a perturbation of multisensory integration resulting from auditory deprivation that has negative consequences for unisensory visual processing, or (ii) a failure to engage in typical linguistic or communicative interactions during a critical period in development that negatively impacts executive functions such as sustained selective attention and inhibitory control. Yet others have suggested that these apparent deficits are actually the result of ecological adaptations to deafness, and that not taking a deaf-centric approach to understanding them fails to consider the ways in which deaf children interact with their world through intact visual and tactile modalities (see also Dye & Terhune-Cotter, 2021). For cognitive psychology to inform interventions for deaf children, it is important to develop a viable theoretical account of how sensory and linguistic development interact to impact the development of higher-level cognitive functions. First, however, it is important to establish the relative contributions of sensory and linguistic/communicative factors. That is not straightforward with deaf children: due to the reality that human languages are predominantly oral/aural, sensory function and linguistic/communicative environments are often confounded in this population.

In order to determine the relative contribution of auditory experience and language exposure to the development of visual sustained selective attention and response inhibition, it is necessary to first dissociate the two factors. Such dissociation is possible through a sample of children from a low-incidence population—deaf children exposed to a natural signed language early in childhood. Deaf children enrolled at bimodal-bilingual schools vary in terms of their age of first exposure to ASL and their ASL proficiency, as well as in the extent of their hearing loss. Thus, this population allows testing of hypotheses about the independent and interactive effects of early signed language exposure and skill and lack of access to sound on the development of executive functions assessed in the visual modality.

The first goal of the current study was to extend our recent cross-sectional work showing typical sustained visual selective attention in deaf children exposed to ASL from birth (Dye, 2014; Dye & Hauser, 2014). Very few deaf children are born into deaf families (R. E. Mitchell & Karchmer, 2004), so, here, we attempted to determine the developmental trajectory of temporal visual selective attention in a more heterogeneous sample of deaf children who use American Sign Language as a primary means of communication. This population possesses significant variability in age of exposure to ASL and concomitant proficiency (Gee & Mounty, 1991; Mayberry, 1993; Newport, 1990) as well as extent of hearing loss. Using a four-wave accelerated longitudinal design (Willett et al., 1998), cohorts of deaf children were followed over a period of 3 years. We predicted that both visual sustained selective attention, as indexed by sensitivity on a visual continuous performance test, and response inhibition, as indexed by commission errors on the same task, would improve with increasing age in this sample.

Our second goal was to test the division-of-labor hypothesis. We predicted that ASL ability—as measured by the ASL Receptive Skills Test (Enns et al., 2013) and the ASL Comprehension Test (Hauser et al., 2016) or spoken language ability—as indexed by the OWLS Listening Comprehension subscale (Carrow-Woolfolk, 2011)—would predict performance on our visual sustained selective attention and response inhibition measures, whereas measures of hearing loss would not do so. If our predictions are supported by our data, then this would indicate that visual sustained selective attention and response inhibition in this population are less influenced by multisensory integrative processing (as postulated by the division-of-labor hypothesis) and more influenced by factors related to sustained and early language exposure and its contingent sociocognitive benefits.

Table 1 Time intervals (in days) between data collection waves

Data-collection waves	Mean period between waves (days)	*SD* period between waves (days)
Wave 1–Wave 2	248	15
Wave 2–Wave 3	172	7
Wave 3–Wave 4	236	40

Methods

Design

In order to determine the developmental trajectory of visual sustained selective attention and response inhibition across the school-age years, we employed a *four-wave accelerated longitudinal design*. Such a planned missing design (Rhemtulla & Hancock, 2016) allows us to draw conclusions about developmental change rather than simply differences between age groups and provides a sufficient number of data points to constrain developmental functions while maximizing statistical power. All data were collected by a single researcher (the second author) who traveled to six data collection sites across the continental United States. The testing schedule and timing of the waves was therefore determined both by the goal of spreading collection times over a period of 2–3 years, and the logistics of travel and access to the data collection sites. Table 1 reports the mean time period between data collection waves.

Outcome variables were (i) a d' sensitivity measure used to assess visual sustained selective attention, and (ii) the number of commission errors used to assess response inhibition. These measures were obtained at all data waves where possible. We also collected data corresponding to a set of variables that were used to predict the intercepts and slopes of the developmental functions of the d' sensitivity and impulsivity error measures. These included variables related to American Sign Language (ASL Receptive Skills Test, ASL Comprehension Test, TOSCRF-2 Reading Fluency, Age of First Exposure to ASL), English (OWLS-II Listening Comprehension, TOSCRF-2 Reading Fluency, Length of Hearing Aid Use), and hearing loss (dB PTA HL in better ear). These predictor measures were time intensive, and logistical constraints prevented their collection at each wave. We therefore implemented a design change after wave one of data collection, and only collected these measures at the data collection wave closest to each individual's 10th birthday. This had the added benefit of providing language measures that could be entered as either standard scores or raw scores.

Statistical power

An a priori power calculation was performed to determine the statistical power for a proposed final sample size (after attrition) of 100 deaf children. The power calculation used an alpha level of 0.01 to account for multiple outcome and moderator variables. Power was computed for a moderation effect using a multiple linear regression design with repeated measures at four time points. Assuming that only 5% of the variance in the outcomes is accounted for by the moderator variables of interest, 50% is associated with age and 20% is associated with residual between-subjects error, this gave 80% power to detect an interaction effect (age by moderator) with an effect size $f^2 = 0.053$ (1.25% of the variance)—a small-to-moderate effect size (Cohen, 1988) corresponding to that observed in the first author's previous studies using these dependent measures.

Participants

An initial 108 deaf children were recruited into the study across four waves of data collection. These children all attended bimodal bilingual schools for the deaf in the United States where American Sign Language (ASL) and English were the languages of instruction. The inclusion criteria were that children should be aged between 7 and 12 years of age at entry to the study, have some degree of diagnosed hearing loss, and be receiving an education where ASL was the primary means of instruction. Exclusion criteria were limitations in arm/hand mobility, neurological disorder, and/or documented learning or intellectual disabilities.

A total of 80 children provide data in Wave 1, 96 in Wave 2, 103 in Wave 3, and 94 in Wave 4. Data for all four waves were provided by 67 children, with 29 providing three waves of data, 6 providing two waves of data, and another 6 providing just a single wave of data. Of these 108 children, 15 children were removed from the dataset due to a priori exclusion criteria: 6 children were excluded due to neurological conditions (seizures, depression, and/or a history of concussion) and another 9 because of disabilities in addition to deafness. Background data was not available for a further 4 children, leaving a final sample for analysis of 89 children.

Participants at Wave 1 had an age range of 7;1 to 11;9, and by Wave 4 the age range was 8;6 to 13;6. The total age range covered was therefore 7;1 through 13;6. Pure tone average hearing loss (PTA HL) was established via audiograms conducted by certified pediatric audiologists in the schools. The final sample of 89 deaf children had a mean PTA HL in the better ear of 82 dB HL (*SD* = 28 dB HL) with a minimum of 12 dB HL (in the "normal hearing" range) and a maximum of 120 dB HL (profound hearing loss). The self-identified gender of the students indicated 40 male, 48 female and one nonbinary student. Fifty-six

Table 2 Demographic characteristics and group-level outcomes for participants

Variable	Deaf bilingual children		
	All $N = 88$*	Deaf Family $N = 75$	Hearing Family $N = 10$
Outcome			
Visual sustained selective attention (*d'*)	3.7 (0.8), [1.2, 3.8, 4.9] $N = 303$	3.8 (0.7), [1.9, 3.8, 4.9] $N = 264$	3.1 (1.0), [1.2, 3.1, 4.9] $N = 32$
Response inhibition (number of commission errors)	1.6 (2.3), [0, 1, 16] $N = 303$	1.3 (1.9), [0, 1, 12] $N = 264$	3.4 (4.0), [0, 2.5, 16] $N = 32$
Characteristic			
Age (years)	10.3 (1.4), [7.1, 10.4, 13.5] $N = 309$	10.4 (1.5), [7.1, 10.6, 13.5] $N = 267$	9.7 (1.1), [7.6, 9.8, 12.0] $N = 34$
Parent-rated sign skill of child	3.8 (0.5	3.8 (0.5)	3.6 (0.5)
Age parent began signing (years)	6.1 (10.7)	4.8 (9.5)	21.2 (14.0)
Parent-rated sign skill of parent	3.5 (0.9)	3.7 (0.7)	2.0 (1.0)
Spoken English Listening Comprehension			
Age (years)	10.3 (0.8), [8.5, 10.3, 12.1]	10.4 (0.8), [8.5, 10.3, 12.1]	10.2 (1.0), [8.9, 10.4, 12.0]
Raw score	19.4 (23.0), [0, 11, 102]	18.5 (23.2), [0, 10.5, 102]	31.9 (21.2), [12, 26, 64]
Standard score	44.6 (13.4), [40, 40, 105]	44.6 (14.0), [40, 40, 105]	46.0 (10.5), [40, 40, 69]
ASL Comprehension Test			
Age (years)	10.3 (1.2), [7.9, 10.25, 12.6]	10.4 (1.2), [7.9, 10.5, 12.6]	9.7 (0.9), [8.2, 10.0, 11]
Raw score	21.5 (3.9), [10, 22, 28]	22.4 (3.0), [15, 23, 28]	14.7 (3.3), [10, 14.5, 20]
Standard score	68.2 (28.3), [-12.5, 70, 115]	75.4 (20.1), [32.5, 77.5, 115]	6.3 (14.0), [-12.5, 6.3, 25]
ASL Receptive Skills Test			
Age (years)	10.3 (0.8), [8.5, 10.3, 12.1]	10.4 (0.8), [8.5, 10.3, 12.1]	10.1 (1.0), [8.9, 10.1, 12.0]
Raw score	33.2 (3.0), [24, 33.5, 39]	33.6 (2.7), [26, 34, 39]	29.8 (3.2), [24, 30, 35]
Standard Score	105.0 (4.1), [90, 105, 113]	105.5 (3.6), [94, 105.5, 113]	101.4 (6.5), [90, 102, 113]
ASL Factor Score	0.0 (1.9), [-4.5, 0.1, 3.7]	0.4 (1.6), [-4.5, 0.4, 3.7]	-2.9 (0.7), [-4.0, -2.6, -1.9]
ENGLISH Factor Score	0.0 (17.0), [-15.7, -6.0, 57.6]	-0.7 (17.4), [-15.7, -7.0, 57.6]	8.7 (13.4), [-6.1, 5.7, 33.4]
Hearing loss in "better" ear (dB HL)	81.5 (28.5), [11.7, 93, 120]	83.0 (28.5), [11.7, 95, 120]	63.8 (27.9), [35, 53, 100]
Age First started to use ASL (years)	0.6 (1.4), [0, 0, 10]	0.3 (0.8), [0, 0, 5.5]	2.8 (2.9), [0, 2, 10]
White, *n* (%)	55 (63.2%)	49 (65.3%)	4 (40.0%)

Note. Values represent mean (*SD*) [minimum, median, maximum] unless otherwise stated. *N*s for outcomes and ages reflect the total number of measurement occasions (up to 4 per participant), not the number of participants. Parent-rated sign skill of child was provided by the parent who completed the language background questionnaire (Likert scale endpoints for sign skill were 1 = *know a little bit* and 4 = *sign great*). * including 3 with no deaf/hearing family information

children were White (62.9%), four were Black or African American (4.5%), 11 were Hispanic (12.4%), two were Asian (2.2%), 13 were multiracial (14.6%), and three did not indicate a racial identity (3.3%). Of the 89 children in the final sample, 15 had two hearing parents while 72 had at least one deaf parent (66 had two deaf parents); two did not have data on family deafness. Parents reported age of ASL acquisition and ASL skill for both themself and their child. Those self-reports indicated that for the 72 children with deaf parent(s), both child and parent learned ASL very early in life and the parent usually rated themself and their child as "signing great" (i.e., 4 on a 1–4 Likert scale). For the 15 children with two hearing parents, children learned ASL somewhat early in life, and had high signing skills as rated by their parents; parents learned ASL during adulthood and rated themselves as moderately skilled at ASL. Only two deaf children were scored below a 3 on the 1–4 Likert scale of sign skill by their parents, and in both cases parents were deaf: one parent rated themself as a fluent signer and the other parent had an ASL age of acquisition of 40 years and also rated themself a 1 on sign skill. Fourteen children's parents scored themselves below a 3 on sign skill, eight of them at the minimum score of 1; 10 of those parents were hearing. Six parents (and one child) reported being fluent in Spanish, two of which reported being *only* fluent in Spanish; one parent reported using Russian and Russian Sign Language in the home, and one parent reported using Swedish Sign Language. Mean self-reported ages of acquisition and ASL skills of parents and children in the study are reported in Table 2.

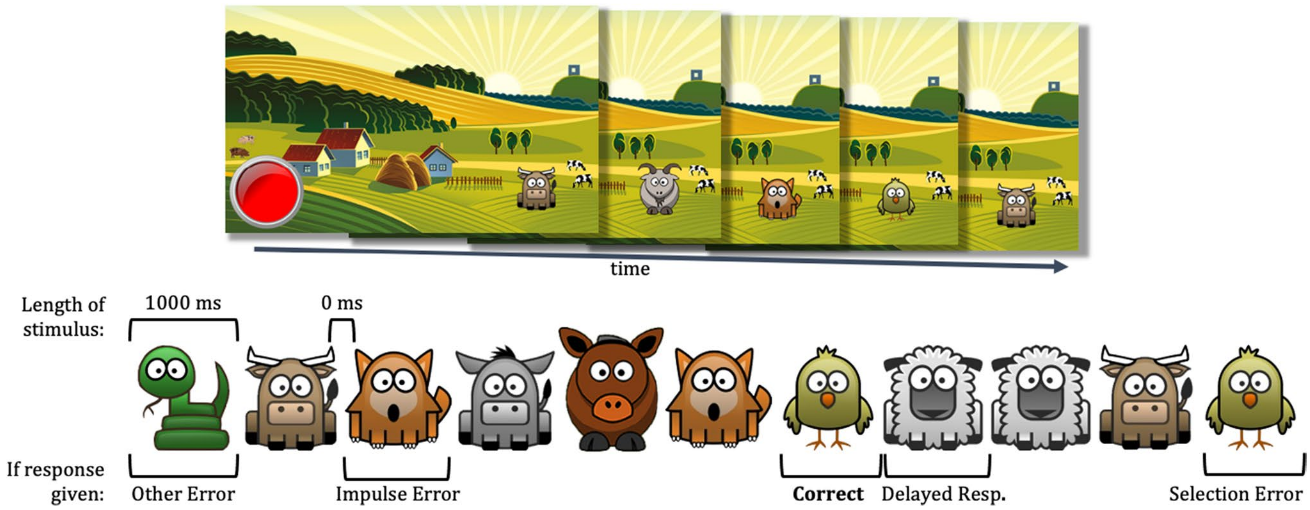

Fig. 1 A schematic of the continuous performance test design used in the current study. Children were presented with a farmyard scene and asked to help Farmer Brown look after his chicks. A sequence of 540 animals appeared in the lower right quadrant of the touchscreen at a rate of 1Hz with no ISI. Children were instructed to alert chicks by tapping the red button in the lower left every time they saw a fox followed by a chick in the sequence. Hits and false alarms were used to compute a *d*-prime sensitivity measure as an index of visual sustained selective attention, and impulse errors were counted to derive a measure of response inhibition

Only four of the children used cochlear implants (4.5%), with three of those children having bilateral implants. The mean age of first implantation was 3;2 (range: 2;0 to 4;0). A majority of the children did report using hearing aids (*N* = 61; 68.5%) but only 28 children indicated that they continued to use them on a regular basis (31.4%). Of those who had stopped using hearing aids, the mean age at which they stopped was 6;1 (*SD* = 2;5, range: 1;0 to 10;0).

Measures

Visual sustained selective attention and *response inhibition* were assessed using a CPT which consisted of a repeatable practice session (32 seconds) and a test session (9 minutes). The researcher encouraged the child to repeat the practice session if they struggled to master the task on their first try. In a cartoon farmhouse scene presented on a tablet, cartoon pictures of common animals appeared one at a time, in the same location near the lower right corner of the screen, at a rate of one animal per second. Children were instructed to respond by pressing a large on-screen image of a red "button" in the lower left corner each time a *fox–chick* sequence occurred. The instructions for this task motivated the children to select a *fox–chick* sequence on the premise of "saving" the chick from a hungry fox. The instructions first explained the task, then gave an example of a correct *fox–chick* sequence, an incorrect *cow–chick* sequence, and an incorrect *fox–snake* sequence, with the goal of clarifying that the only correct response was a *fox* followed by a *chick*. Instructions were given in English on the tablet with the accompanying animals displayed, and the researcher repeated the instructions in ASL and discussed the premise with the child to ensure that they understood the task. Practice sessions were repeated as necessary (which was no more than twice) before the experimental session began. The experimental session consisted of a single sequence of 540 animals with the target *fox–chick* subsequence occurring 48 times. Children were not told how long the session would last but were encouraged to be patient for the duration of the task. The task is shown pictorially in Fig. 1.

Visual sustained selective attention was operationalized as a sensitivity index (d'), which was calculated by subtracting the *z*-score of the false alarm rate—proportion of incorrect responses to a nontarget animal—from the *z*-score of the hit rate—proportion of correct responses to a target animal. *Response inhibition* was measured by counting the number of times that a child responded to a cue stimulus (a *fox*) without waiting to see if the target stimulus (a *chick*) would appear afterwards. A response to this stimulus is indicative that the child is attending to the stimulus stream but is unable to withhold a response. If the child responded to the *cow* in a *fox–cow* sequence, that would be categorized as an error but not used to compute their response inhibition score. There was a total of 96 *fox* stimuli in the task, meaning a possible maximum of 96 commission errors

Spoken English receptive skill was assessed using the OWLS-II Listening Comprehension Subscale (Carrow-Woolfolk, 1995). This test requires children to listen to a spoken sentence and then select which one of four pictures correctly corresponds to what they heard. Stimulus items assess a range of linguistic structures including lexical/semantic, syntactic, pragmatic, and supralinguistic. The researcher administering all tests was a Deaf white male who tested children at all of the different locations across the United States; a consistent live presentation of verbal stimuli was therefore not possible. Instead, a hearing colleague was filmed speaking each of the items. The items were presented as individual video files on a laptop. The laptop was positioned in front of the child, with the response book next to it, and the speaker was placed directly in front of the laptop. The child was prompted to pay attention to the laptop before each item was played; they were not allowed to touch the table or the speaker to feel the vibrations (a common request). After test completion, to minimize stereotype threat or associated negative feelings the child was reassured that their performance on this test was not critical. Standardized scores are reported in Table 2 but, because no deaf population norms exist for the test and the minimum standardized score of 40 obscures much of the variability in deaf scores, raw scores were used in all analyses.

American Sign Language (ASL) receptive skill was assessed using the ASL Receptive Skills Test (ASL-RST; Enns et al., 2013) and the ASL Comprehension Test (ASL-CT; Hauser et al., 2016). The ASL-RST comprises 42 multiple-choice items, in which the child watches an ASL sentence and selects one of four possible illustrations that they feel best matches the sentence. The ASL-CT comprises 30 multiple-choice items. Each item presents either an ASL sentence, for which the respondent selects the best match from four possible depictions, or a depiction, for which the respondent selects the best match from four possible ASL sentences; depictions are either a line illustration, a photo, or a video of a nonlinguistic event. While both tests measure ASL receptive skill, the ASL-RST was designed for use with children ages 3–12 years, whereas the ASL-CT was designed and validated with a sample of college-aged students (Allen & Enns, 2013; Hauser et al., 2016). The ASL-CT was added to the test battery to avoid a potential ceiling effect and capture higher-level variation in ASL receptive skill.

Written English processing was measured using the Test of Silent Contextualized Reading Fluency (TOSCRF-2; Hammill et al., 2014). This is a timed task that presents children with a series of sentences of increasing complexity. The words of each sentence are written in uppercase letters, and all spaces and punctuation are removed. The child is asked to segment each sentence into its constituent words using pencil lines to indicate word boundaries. A child's score is the number of words correctly segmented within the time limit, which is 1 minute for the practice session and 3 minutes for the experimental session.

Apparatus

The CPT was designed and administered using Paradigm (Perception Research Systems, http://www.paradigmexperiments.com), a software program for building and running experiments. It was administered on a GETAC F110 tablet computer running the Windows 7 operating system with an integrated 11.6-in. HD touchscreen (resolution 1,366 × 768 pixels; brightness 800 nits). Responses were recorded via the touchscreen. Spoken and signed language tests were administered using a Dell Latitude E7470 14-in. laptop connected via Bluetooth® to a Bose SoundLink Mini II stereo speaker.

Procedure

Upon recruitment of a child into the study, written informed consent was obtained from a parent or legal guardian; every child gave informed assent at the beginning of each testing session. Children were compensated with $10 for each half-hour of participation. Background information was obtained from the parents or legal guardians via a survey given online or in person; $20 was paid upon completion of this survey. The survey, which was given in both Spanish and English, included questions about language experience and demographic information, including household income, education level of the caregiver, and the language experience and deafness of family members.

The researcher collaborated with the schools' testing or administrative departments to test students on-site during the school day or after school, depending on the preferences of the school or parents. Tests were administered in ASL in a room free of distractions, with only the researcher, who was Deaf, and child present. A battery of attention, language, and cognition tests was given to each participant over two sessions, including, but not limited to, the tests reported here. Sessions were a maximum of one hour and separated by no less than a day and no more than two weeks. The first session consisted of attention and visual learning tasks, including the CPT task; the second session consisted of language and cognition measures. Measures were counterbalanced in all sessions, with the exception of the language assessments, which were given at the end of the session to avoid potential stereotype threat from administering tests of spoken and signed language to deaf children in a bilingual-bicultural environment.

Anonymized audiometric data were obtained from the schools' audiology departments with the parents' consent, as all the schools kept updated audiometric records of their students (usually from testing done "in house"). In cases for which audiometric data from multiple testing sessions were received, data from the most recent session were used. The pure tone average (PTA) in the "better" ear, defined as the one with the lower dbHL level, was used in the analyses. In the event that PTAs were not explicitly noted on the audiograms, they were calculated by averaging the dB HL ratings at 500 Hz, 1000 Hz, and 2000 Hz; if one or more of these

Table 3 Parameter values for observed variables entered into confirmatory factor analysis

Variable	*N*	Mean	Variance	Min, Max	Median
ASL-CT raw score	85	21.02	15.76	11, 28	22
ASL-RST raw score	86	32.85	11.18	24, 39	33
OWLS-II Listening Comprehension raw score	86	19.01	546.06	0, 102	10.5
TOSCRF-2 Reading Fluency raw score	83	71.16	642.42	25, 146	71
Age First Learned ASL	83	0.56	1.93	0, 10	0
Length of Hearing Aid Use	51	4.52	9.04	0, 10.75	4

values were not measurable due to profound hearing loss (denoted by NR on the audiogram), then only the observed values were averaged together. This therefore represents a conservative measure for those children with the most profound hearing losses.

Statistical analysis plan

The analysis plan involved using linear mixed models to determine age-related longitudinal change in visual sustained selective attention and response inhibition. Due to significant nonlinearity in longitudinal change for response inhibition, a post hoc decision to use generalized estimating equations models was made. We sought to determine the effect of language and auditory abilities on the outcome measures. An initial confirmatory factor analysis was used to derive English and ASL factor scores in order to (i) decrease the number of moderators entered into the statistical analyses and (ii) mitigate against measurement error given the opportunity to obtain these language measures just one time for most children. These two language factor scores and a measure of auditory ability (pure tone average hearing loss in the better ear derived from an audiogram) were then entered into the statistical analyses to explore their impact on the outcome measures and those of their interaction with a linear age term. A backward elimination algorithm was employed to select significant predictors, maintaining model hierarchy by keeping both parent terms if their interaction term was in the model.

Results

The aim of the study was to determine whether longitudinal change in visual sustained selective attention or response inhibition in deaf children was influenced by language and/or hearing loss. To that end, we collected several measures of language ability and factors known to be associated with language development in deaf children. We used these measures to conduct a confirmatory factor analysis with the goal of deriving latent factor scores to index ASL and English language ability.

Assessing language ability

For each participant in the dataset, scores on the relevant variables at the data collection wave closest to their 10th birthday were extracted. These variables were entered into a confirmatory factor analysis (Mplus 8.5; Muthén & Muthén, 2007) with ASL-RST raw score, ASL-CT raw score, TOSCRF-2 raw score, and Age First Learned ASL used to determine the ASL latent factor, and OWLS-II Listening Comprehension raw score, Length of Hearing Aid Use, and TOSCRF-2 Reading Fluency[2] raw score used to determine the ENGLISH latent factor. Parameter values for observed variables are shown in Table 3.

The initial model had an RMSEA of 0.000 with a 95% confidence interval of [0.000, 0.126], a CFI of 1.000, and an SRMR of 0.065. Modification indices indicated that associating TOSCRF-2 Reading Fluency with the ASL Receptive Skills test would significantly improve the model fit. After adding this term, the final model had an RMSEA of 0.000 and a 95% confidence interval of [0.000, 0.076], a CFI of 1.000, and an SRMR of 0.054. Model fit was considered to be acceptable and theoretically plausible. The model results are presented in Table 4 and shown in Fig. 2.

The latent factor scores for ASL and ENGLISH (reported in Table 2) were used as mediators in subsequent models. Each latent factor score had a mean of 0, with a standard deviation of 1.85 for ASL (range: −4.49 to 3.68) and a standard deviation of 16.09 for ENGLISH (range: −15.66 to 57.59) reflecting the higher degree of variability in English compared with ASL for this population of deaf children. Deaf children from deaf families had higher ASL scores (M = 0.40, SD = 1.64, N = 75) than deaf children from hearing families (M = −2.86, SD = 0.74, N = 10): BF_{10} = 366,584, 95% credible interval for the population effect size δ = [1.24, 2.70]. For the ENGLISH scores, deaf children

[2] TOSCRF-2 Reading Fluency raw scores were associated with both the ASL and ENGLISH latent factors in the CFA. This was a theoretically motivated decision given the known relationship between ASL fluency and English reading scores in deaf children (Holmer et al., 2016; McQuarrie & Parrila, 2014; Scott & Hoffmeister, 2017; Stone et al., 2015).

Table 4 Parameter estimates for confirmatory factor analysis

Parameter	Estimate	*SE*	Two-tailed *p* value
ASL by ASL Receptive Skills Test	1.000	0.000	—
ASL by ASL Comprehension Test	2.813	1.331	0.035
ASL by TOSCRF-2 Reading Fluency	5.098	1.603	0.001
ASL by Age First Learned ASL	−0.319	0.096	0.001
ENGLISH by OWLS-II Listening Comprehension	1.000	0.000	—
ENGLISH by TOSCRF-2 Reading Fluency	0.477	0.428	0.265
ENGLISH by Length of hearing aid use	0.054	0.050	0.284
ENGLISH with ASL	−4.149	4.375	0.343
TOSCRF-2 Reading Fluency with ASL Receptive Skills Test	17.242	9.392	0.066

from deaf families ($M = -0.69$, $SD = 17.36$, $N = 75$) showed a tendency to score lower than deaf children from hearing families ($M = 8.67$, $SD = 13.45$, $N = 10$), although there was insufficient evidence to distinguish the two groups on this factor: $BF_{10} = 0.91$, 95% credible interval for the population effect size $\delta = [-1.06, 0.13]$.

In order to check for differences in the language ability of deaf children from different racial categories, we compared White children with those who reported a non-White or mixed racial identity (henceforth, BIPOC). The BIPOC deaf children tended to have lower ASL scores ($M = -0.48$, $SD = 1.54$, $N = 33$) than did White deaf children ($M = 0.29$, $SD = 1.97$, $N = 55$), although the large degree of variability precluded any conclusions about the effect of racial identity on ASL scores: $BF_{10} = 1.14$, 95% credible interval for the population effect size $\delta = [-0.03, 0.80]$. The same pattern was observed for ENGLISH scores, with BIPOC deaf children ($M = -2.70$, $SD = 11.83$, $N = 33$) tending to score lower than white deaf children ($M = 1.62$, $SD = 19.37$, $N = 55$) but the data being inconclusive due to high variability: $BF_{10} = 0.41$, 95% credible interval for the population effect size $\delta = [-0.18, 0.63]$.

Sustained selective attention and impulsivity

Linear mixed models and generalized estimating equations models with Poisson distribution and log link were constructed, using compound symmetry covariance structure and independent working correlation structure for simplicity to facilitate convergence, for visual sustained selective attention and response inhibition errors, respectively. Main effects terms for age at time of test, ASL and ENGLISH factor scores, pure tone average hearing loss in the better ear, and interactions with age were considered. A backward elimination algorithm was employed to select significant predictors, maintaining model hierarchy by keeping both parent terms if their interaction term was in the model. SAS (Version 9.4; SAS institute, Cary, NC) was used for analysis. Individual growth curves are presented in Fig. 3.

For visual sustained selective attention, more hearing loss was associated with better visual sustained selective attention (beta = 0.004; 95% CI [−0.0007, 0.10]) when age at time of test (beta = 0.26; 95% CI [0.19, 0.32]) and ENGLISH (beta = 0.01; 95% CI [0.003, 0.02]) were in the model.

For response inhibition errors, better ASL knowledge was associated with fewer impulsive responses (beta = −0.12 for additive effect on the log(mean of impulsivity errors) or exp(beta) = 0.89 for multiplicative effect on the mean of impulsivity errors; 95% CI [−0.25, 0.01]) when age (beta = −0.23 or exp(beta) = 0.79; 95% CI [−0.36, −0.10]) was in the model. Modeling further, age was the only significant predictor for both outcomes with no substantial changes in effects from those reported above

Discussion

Our past research has demonstrated that deaf signing children and typically hearing children do not significantly differ on CPT performance (Dye & Hauser, 2014). Our concern here was to move beyond comparisons with typically hearing children and examine factors that might influence visual sustained selective attention and response inhibition within this population. Variability in the language abilities of deaf children provides an opportunity to explore how their higher-level cognition might be grounded in communicative and linguistic ability. While some theories have proposed that hearing loss itself—a lack of exposure to sound—can bring about deficits in this kind of processing (Smith et al., 1998), others have proposed that it is language ability that may drive cognitive function (see W. C. Hall, 2020; Morgan & Dye, 2020, for recent discussion, and Harris, 1978, for earlier formulations). To that end, we examined the effect of language ability (in ASL and English) and hearing loss

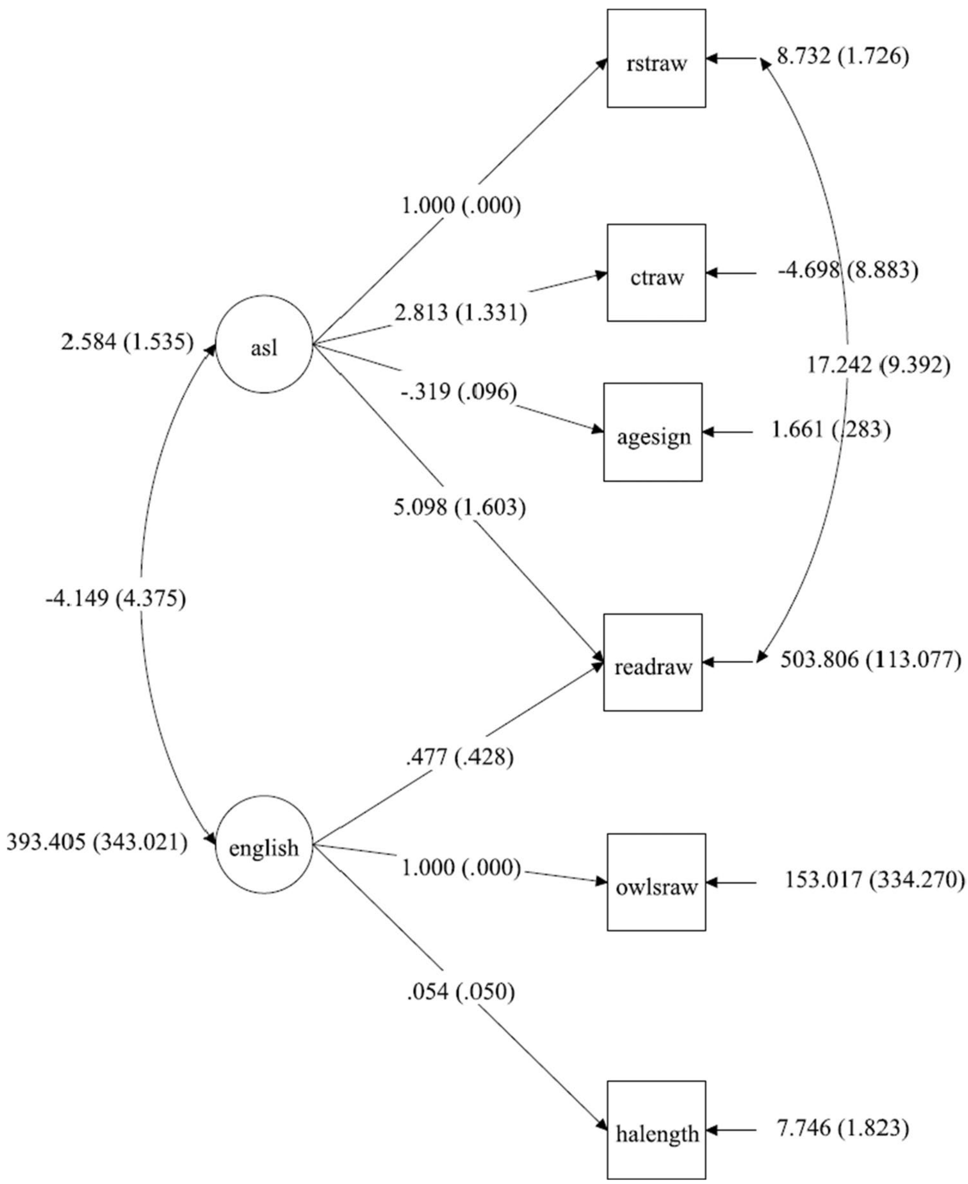

Fig. 2 A confirmatory factor analysis was used to derive latent factor scores measuring language ability in American Sign Language and English. Model fit was excellent and theoretically justified. Observed variable labels: `rstraw` (ASL Receptive Skills Test), `ctraw` (ASL Comprehension Test), `agesign` (Age First Started Using ASL), `readraw` (TOSCRF-2 Reading Fluency), `owlsraw` (OWLS-II Listening Comprehension), `halength` (length of hearing aid use). Using `readraw` to derive both ASL and English latent factors was an a priori modeling decision, whereas linking the covariances of `rstraw` and `readraw` was a post hoc decision motivated by modification indices

on the development of visual sustained selective attention and response inhibition as measured by a continuous performance test.

Confirmatory factor analysis was used to derive latent factor scores representing each deaf child's ability to comprehend ASL and English. The model fit indices for the CFA were good. Face validity of these latent constructs was supported by a comparison of the latent factor scores for deaf children born to deaf parents and those born to hearing parents. Deaf children born to deaf families had higher ASL scores, likely reflecting earlier and more consistent exposure to the language in this subpopulation. Meanwhile, deaf children from hearing and deaf families did not reliably differ in their English scores, despite lower levels of hearing loss in the children from hearing families (M = 64dB HL in "better" ear) compared with their peers from deaf families (M = 83dB HL in "better ear). There was a trend for BIPOC deaf students to have lower ASL and English scores than their white peers; however, these mean differences were accompanied by a large amount of within group variability. This trend should not be

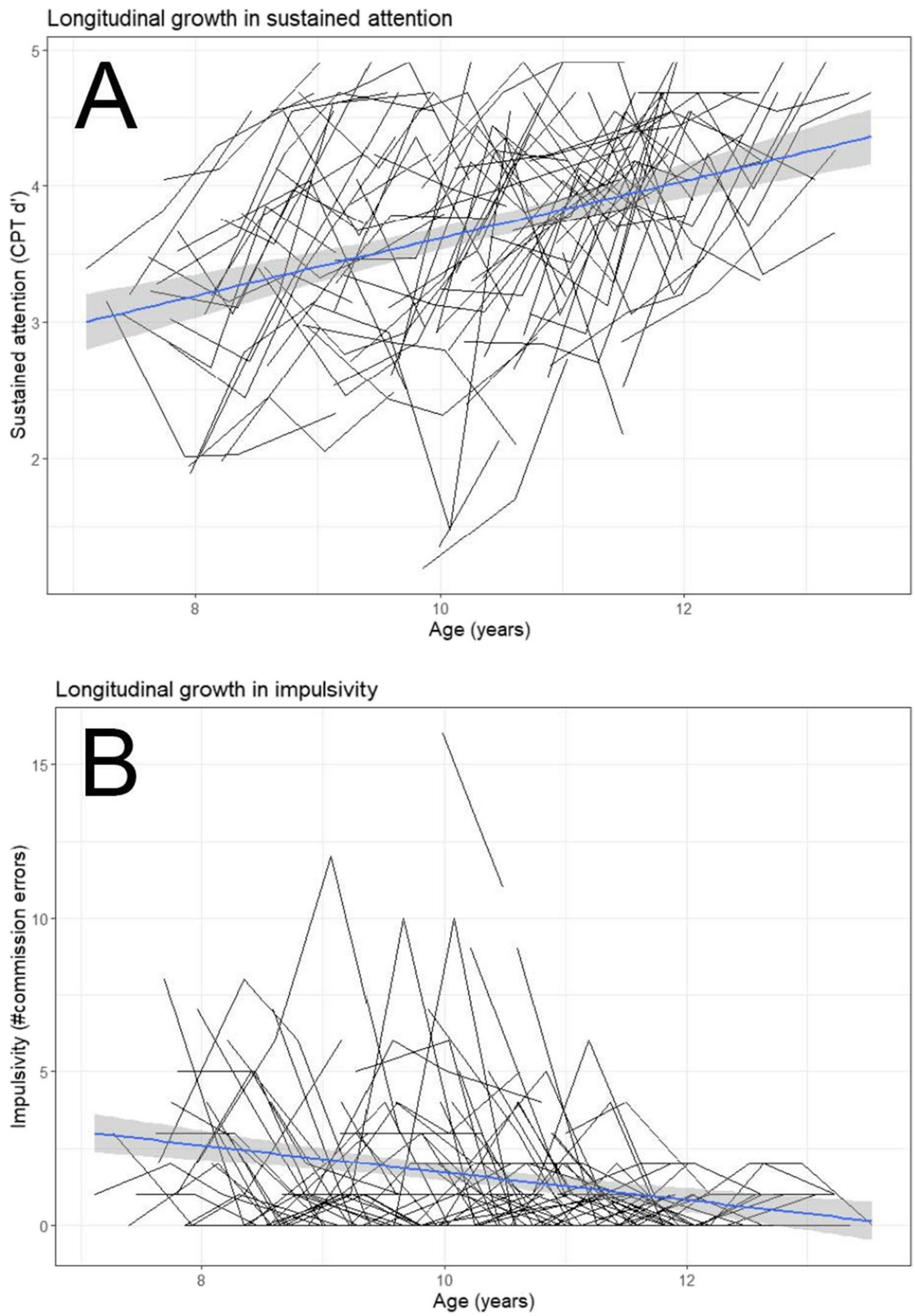

Fig. 3 Plots of longitudinal growth in (**a**) sustained attention, and (**b**) response inhibition based upon continuous performance data. Individual lines each represent one child sample over 2–4 waves. Blue lines represent mean linear growth as a function of age, with shaded gray regions denoting the 95% confidence interval for the slope. (Color figure online)

interpreted as a difference in language ability between BIPOC and White students. Instead, it is likely a consequence of our ASL and English assessments being biased towards White majority-dialect language users, and a failure on our part to accurately capture linguistic variation among BIPOC deaf students; such variation might have been either missed or penalized by our language assessments (see McCaskill et al., 2020, for a description of Black ASL and how it differs from White majority varieties of the language, and Taylor, 2022, for a recent treatment of cultural and social biases in K-12 assessment). Interestingly, covarying ASL receptive skills and English silent contextualized reading scores led to a much-improved model fit—this likely reflects the interdependence of ASL and English in the linguistic development of these DHH children.

Analysis of longitudinal measures of visual sustained selective attention and response inhibition across four waves of data collection revealed improvements in sustained selective attention and decreases in response inhibition errors as deaf children got older. Importantly, none of the factors in this study affected the growth components of these cognitive functions. Rather, they predicted overall performance levels, suggesting that any developmental influences occurred prior to the earliest age at which children participated in this study (i.e., 7 years of age). For visual sustained selective attention performance, both higher English scores and higher hearing losses predicted better performance. Meanwhile, the ASL scores predicted performance on response inhibition, with better ASL scores associated with decreased levels of impulsive responding across the age range tested.

Interpreting these findings in the context of accounts of language and cognitive performance in deaf children, we see a clear pattern in which English is associated with visual sustained selective attention and ASL is associated with inhibitory control. We have argued previously (Morgan & Dye, 2020) as have others (M. L. Hall et al., 2018) that a strong early communicative environment for young deaf children is essential for the development of executive functions more broadly, including visual sustained selective attention and response inhibition. This has been argued to stem from an appropriate development of intersubjectivity supported by early communication that provides a foundation for subsequent language development and internalization of behavior through an "inner voice" resulting in strong executive function (Morgan & Dye, 2020).

Interestingly, deaf children with more profound hearing losses displayed better visual sustained attention performance. This effect was not predicted: it runs counter to both the division-of-labor hypothesis, which predicts a negative relationship between hearing loss and visual sustained selective attention, and alternative hypotheses which predict a null relationship. In considering whether this effect has practical significance, it is important to note that the observed effect of hearing loss on sustained attention was quite small. The 95% confidence interval for the effect of a 29dB HL increase in hearing loss on sustained attention was between −0.0006 and 0.08 d' units, with a mean predicted value of 0.004 d' units. There is little theoretical basis to believe that *higher* hearing losses would result in *higher* visual sustained selective attention, beyond a simple visual compensation hypothesis. This, combined with the small size of the effect, suggests that the finding is of negligible clinical importance.

On the surface, the current data provide evidence in support of accounts that attribute the scaffolding of higher-level cognition in deaf children to language rather than hearing loss per se. However, the language experience of the deaf children in our study compels a more complex interpretation of the data. The mean age that the deaf children in our sample first started to use ASL was 0.6 years. Whilst there is some variation in the sample here, the median age for deaf children from deaf families was (perhaps unsurprisingly) 0 years and for those from hearing families it was 2 years of age. In addition, these children are enrolled in bilingual schools where ASL and written English are the primary languages of instruction. While the children have access to speech therapy (in spoken English) in their schools, it is not the primary language of instruction. For these children, ASL is learned first and provides the primary linguistic foundation for communication as well as learning written English later in development: spoken English is likely learned after ASL and certainly to a much lesser extent (if at all). This is clear from the language assessment data: performance on ASL assessments is high, whereas performance on spoken English assessments is largely near (but not at) floor. Thus, while it makes sense to consider the possibility that exposure to and acquisition of ASL is predictive of subsequent cognitive abilities—here, response inhibition—the same way of thinking with regard to the relationship between English and visual sustained selective attention may be mistaken. It is more likely that, rather than English supporting the development of visual sustained selective attention ability, such attention skills predict English in this population of deaf children. Therefore, it is also necessary to consider the role of higher-level cognition in supporting language acquisition in deaf children.

An alternative (speculative) account for the relationship between language and cognition in deaf children is one that takes into account both *temporal precedence* and the *acquisition process*. By temporal precedence, we refer to the age at which a language becomes accessible to a deaf child in a way that permits the mechanisms of language acquisition to act upon the linguistic input. For the deaf children under consideration here, their accessible and perceivable language is ASL, which is being acquired in the toddler and preschool years—even, for the most part, in those deaf children with hearing parents. ASL therefore has temporal precedence over English, which is often learned later in life and learned in a different way (i.e., predominantly in a written form). In addition, while ASL may be learned through exposure to the language during meaningful communicative interactions, much as how a hearing child might learn a spoken language, English is often also acquired through direct speech therapy, or by limited exposure at an age after the critical window for natural language acquisition. Moreover, deaf children's acquisition of spoken English does not necessarily precede or scaffold their learning of written English; a meta-analysis found that phonological awareness predicts only 11% of the variance in reading proficiency of deaf participants, as compared with

35% predicted by overall language ability (Mayberry et al., 2011). This is supported by recent evidence that skilled deaf readers may rely more on orthography, rather than phonology, in developing their neural representations of written English (Glezer et al., 2018). The acquisition process of both spoken and written English is therefore different in deaf children compared with hearing children, which necessitates consideration of the possibility that higher-level cognitive processes may predict English acquisition, rather than the other way around. Visual sustained selective attention may, therefore, be an important indicator of the skills required for a deaf child to learn English via instruction, rather than an outcome of successful English acquisition.

Although speculative, this is not a new proposal with respect to deaf children. Research by Kronenberger, Pisoni, and colleagues (Kronenberger, 2019; Kronenberger et al., 2020, G. Smith et al., 2019) has suggested that executive functions are an important predictor of spoken language development in deaf children with cochlear implants who are acquiring spoken language. However, that body of research has focused upon deaf children from hearing families who do not use a sign language such as ASL. As a result, suggestions for intervention have included executive function training as one way to improve spoken language outcomes (Kronenberger et al., 2011). The data from this study support the proposal that executive function skills such as visual sustained selective attention would improve spoken language outcomes in deaf children. However, as a result of work with deaf children who are primary users of a sign language, we propose that early sign language acquisition will (a) provide deaf children with a strong language foundation, averting the risk of negative outcomes associated with delayed or deficient acquisition of natural language (see W. C. Hall, 2017; Humphries et al., 2012; Murray et al., 2019), and (b) promote the acquisition of spoken language for those families who decide that this is an important outcome via promoting the development of executive function skills.

The crux of this proposal is that deaf children benefit from the temporal precedence offered by a natural sign language. That is, given that sign languages are perceivable by deaf children—with the exception of those who are low-vision or deaf-blind—and can be acquired without effort given appropriate input, they should be introduced to deaf children as early as possible. Hearing parents are able to provide input of sufficient quality to support sign language acquisition for their deaf child (Caselli et al., 2021) and programs exist in some countries and regions that provide families with access to Deaf professionals who can support families who choose this approach. This early acquisition of ASL is likely to promote healthy cognitive development, most notably the development of executive functions (such as response inhibition) and improve outcomes through the facilitation of communication between deaf infants and caregivers. In turn, the cognitive abilities promoted by early natural (signed) language acquisition will provide the cognitive basis for the acquisition of spoken language. There is a clear link established in the literature between early sign language acquisition and the successful acquisition of both spoken (Davidson et al., 2014; Giezen et al., 2014; Hassanzadeh, 2012) and written (Allen & Morere, 2020; Andrew et al., 2014; Stone et al., 2015) English. Unfortunately, currently the reverse practice is more common, with sign languages often only being introduced after a deaf child has struggled to acquire spoken language. The results of this approach have been labeled *language deprivation* (W. C. Hall et al., 2017) and, arguably, this has done significant harm to deaf communities around the globe. By studying the interplay between language and cognition in deaf children, cognitive psychology has the potential to inform alternative approaches to interventions that can maximize the linguistic, cognitive and social benefits for deaf children.

The study reported here used only one version of the Gordon Diagnostic CPT—the vigilance form—in an accelerated longitudinal design. Time constraints prevented the incorporation of other manipulations, such as presenting a single target or presenting distractors alongside the target stream, which would have allowed clearer identification of cognitive functions susceptible to variation in language ability. Future work should employ a more experimental approach rather than using a single form of a clinical diagnostic tool such as that employed here. We were also unable to obtain language assessment data at multiple waves, and the reported analyses are based upon language ability at around age 10 years. Deaf children, however, are likely to differ widely in their language growth trajectories. For some children, their performance at age 10 years may be asymptotic, whereas for others it may be part of a continuing growth in language development. Again, future work should establish growth trajectories for language acquisition alongside growth trajectories of executive functions. We also note that the characterization of commission errors as reflecting response inhibition (or impulsive responding) is open to interpretation—it could also be the case that working memory lapses result in temporary failure to engage an appropriate task set. Finally, a large number of the children in this study were born to deaf parents. While deaf parents also vary in their own language abilities and input provided to their children, deaf children exposed to ASL as infants by their deaf parents are often considered to be "high performers"; they also constitute only 5%–10% of the community of deaf people who use ASL (R. E. Mitchell & Karchmer, 2004). Recruitment of a larger number of deaf children from hearing families would increase the generalizability of research findings.

In conclusion, using a continuous performance test in an accelerated longitudinal design, we found evidence for a relationship between language abilities of deaf children assessed at age 10 years and their overall performance on measures of visual sustained selective visual attention and response inhibition. The pattern of results was not, however, straightforward in that spoken English abilities were associated with visual sustained selective attention and ASL proficiency was associated with response inhibition. In interpreting these patterns of data, we note that it is important to consider the language acquisition histories of deaf children, which are often atypical relative to those of hearing children. Making inferences about the role of audition in supporting cognition based upon comparisons between deaf and hearing children is fraught with difficulties in interpretation due to differences in language proficiency, language modality, and language acquisition histories. Overall, our results emphasize the importance of examining a child's language history and abilities, particularly as it relates to natural visual-gestural languages such as ASL, in exploring and discussing the etiology of observed cognitive differences between deaf and hearing children, rather than treating deaf children simply as hearing children who cannot hear.

Authors' contributions M.W.G.D. was responsible for conceiving of the study, obtaining funding, developing the methodology, and coding the experimental protocol. Participants were recruited and tested by B.T.C. Both M.W.G.D. and B.T.C. contributed to the data analysis and preparation of this manuscript.

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Declarations

Conflicts of interest The authors declare no conflicts of interest nor any competing interests.

Ethics approval This human subjects research was approved by the Institutional Review Board at Rochester Inst of Technology (FWA# 00000731, IRB# 00006623).

Consent to participate Informed written consent was obtained from parents or legal guardians of all children participating in this study. Informed assent was obtained from all children at each session of data collection.

Consent for publication Not applicable.

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Open practice statement All data and materials as well as the Mplus and SAS code and jamovi files used to conduct the analyses reported here are available online (https://osf.io/z9teg/files/). This study was not preregistered, but a copy of the grant proposal with proposed methods and analyses is available on the OSF repository.

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