Joint Action in Deaf and Hearing Toddlers: A Mobile Eye-Tracking Study

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Abstract

Infants experience the world through their actions with objects and their interactions with other people, especially their parents. Prior research has shown that school-age children with hearing loss experience poorer quality interactions with typically hearing parents, and difficulties in controlling their visual attention. In the current study, we used mobile eye-tracking to investigate parent-child interactions in toddlers with and without hearing loss. Parents and toddlers engaged in a goal-directed, interactive task that involved inserting coins into a slot and required joint coordination between the parent and the child. We examined the visual behaviors of the toddlers and the scaffolding behaviors of the parents. In contrast to previous work, preliminary findings reveal a pattern of potential similarities between deaf and hearing toddlers or their parents.

Keywords: dual mobile eye-tracking; parent-child interaction; joint action; visual attention; social-cognitive development

Introduction

Prelingual hearing loss has a profound impact on social, cognitive, and linguistic development. Not surprisingly, toddlers with hearing loss demonstrate delays in language skills, like speech perception and word learning (Houston & Miyamoto, 2010). However, studies have also shown that deaf[1] toddlers and children demonstrate poorly understood differences in cognitive skills such as visual working memory (Harris et al., 2013), visual habituation (Monroy et al., 2019), and visual statistical learning (Gremp et al., 2019) compared to their hearing peers.

These findings suggest that hearing loss has broad effects on social and cognitive development. However, despite the deep interest in identifying behaviors and cognitive skills that may predict language outcomes in children with hearing loss (Houston et al., 2012), to our knowledge no studies have focused on the domain of action in this population. The current study represents a first step towards filling this gap by investigating parent-child joint action in toddlers with and without hearing loss.

Toddlers' earliest experiences with the world are through their visual observations and motor actions (Hunnius & Bekkering, 2014). Certain motor skills may even be a prerequisite for language development (Iverson, 2010), as they create experiences that are relevant for communicative exchanges, as in parent-child play. Motor development also supports the development of action understanding, a precursor to advanced social-cognitive milestones such as theory of mind (von Hofsten & Rosander, 2018).

Two lines of evidence support the possibility that hearing loss early in life may affect motor experiences, particularly during parent-child interactions. A body of research has consistently demonstrated that hearing parents and their deaf infants (*Hd* dyads) behave differently compared with hearing children of hearing parents (*Hh* dyads). For instance, in a 1997 landmark longitudinal study, Meadow-Orlans and colleagues reported that deaf infants (at 12 and 18 months) demonstrated less compliance, and fewer reciprocal turn-taking and communicative exchanges with their hearing parents during parent-infant play than any other type of parent-infant dyad (critically, this study included hearing parents with hearing infants, deaf parents with hearing infants, deaf parents with deaf infants, and hearing parents with deaf infants). Although this study focused on expressive or emotional elements of parent-infant interactions, rather than specific motor behaviors or skills, it provides evidence that *Hd* dyads struggle to achieve smooth, coordinated interactions.

Deaf children also demonstrate consistent differences in general visual attention and joint attention with their parents during social interactions (Cejas et al., 2014; Dye & Hauser, 2014; Smith et al., 1998). Across a range of clinical and empirical studies, deaf children of both hearing and Deaf parents demonstrate differences in visual attention. In one of the few studies that focuses on deaf children of Deaf parents—who are exposed to natural language from birth and typically meet developmental milestones—Dye & Hauser (2014) found that younger deaf children (6-9-year-olds) demonstrated difficulties in maintaining selective attention in the presence of peripheral distractors. These findings suggest that auditory experiences play a role in the development of selective attention skills. More specifically, the need to reallocate visual attention to the periphery in the absence of hearing may disrupt this development. In the current study, we examined whether deaf and hearing toddlers demonstrate differences in their allocation of attention during a goal-directed, interactive task with their parents.

[1]In the current paper, we use the term *deaf* when referring to toddlers born with profound sensorineural hearing loss who have cochlear implants. Although they currently experience electronic sound through their implant, they are still considered deaf by most in the field. We adopt this term to highlight the fact that they were born with no useable acoustic hearing.

Parent behaviors also contribute to the different interaction patterns observed in *Hd* dyads. For instance, in the Meadow-Orlans study (1997), *Hd* mothers were rated as significantly less sensitive, flexible, consistent, and as showing less participation and positive affect than mothers from all other dyads. Over the past several decades, studies have examined the linguistic behaviors of parents and consistently found that hearing parents of deaf infants tend to be more directive, less responsive, and use simpler language than their counterparts (e.g., Chen et al., 2019; Fagan, Bergeson, & Morris, 2014). One explanation for this pattern of behavior is that *Hd* parents are adjusting to their child's language ability, which is likely delayed due to hearing loss.

Therefore, previous research has demonstrated consistent differences in the parent-child interactions between deaf children and their hearing parents. As highlighted earlier, this body of work has primarily examined the emotional and linguistic behaviors of parents, but little is known about the motor behaviors that take place during parent-child play and whether these are also affected by hearing loss.

The current study represents a first step in investigating parent-child joint action in *Hd* and *Hh* dyads, and is part of a larger, longitudinal project on joint action in infants and toddlers with hearing loss. Toddlers and their parents engaged in a joint, goal-directed task that required them to coordinate their actions to successfully drop coins into a toy piggybank. Inserting coins into a narrow slot demands hand-eye coordination and fine motor skill (in fact, it is an item on the Mullen Scales of Early Learning developmental assessment). In our study, we modified the task such that toddlers needed to jointly collaborate with their parent to achieve the goal of inserting the coins. Parents were instructed to interact with their child as they "normally would at home", which resulted in varying levels of parent engagement and scaffolding behaviors.

Here, we present analyses of toddlers' visual attention and parents' scaffolding behaviors during this joint task. First, we examined whether deaf toddlers demonstrate similar patterns of visual attention during the task, compared with their hearing peers. Based on evidence for poorer selective attention in deaf children, one prediction is that deaf toddlers spend less time attending to relevant locations—e.g., the goal location or the coin of interest—compared with hearing toddlers. Conversely, the interactive, goal-directed context of the task might elicit more attentive behaviors in deaf toddlers than the computer-based tasks typically used in prior studies.

Second, we examined the levels of scaffolding that parents provided during the motor task. Toddlers often found this task difficult at first and struggled to orient the coin correctly into the slot. Parents could help their child by providing visual cues, like pointing to the goal or tilting the piggybank towards them, or they could help the child by guiding their hand directly. Given the past evidence for more directive language in the parents of *Hd* dyads, we explored whether parents of deaf toddlers might demonstrate more scaffolding behaviors in the current study.

Our third question related to whether parent scaffolding modulated toddlers' visual attention in both deaf and hearing toddlers. Prior research has established that parent behaviors during parent-infant play modifies infant behavior (Chen et al., 2020; Suarez-Rivera, Smith, & Yu, 2019; Yu & Smith, 2017). For instance, Yu & Smith (2017) found that parents' actions with objects supports and extends infants' visual attention to those same objects. Though this study featured an unstructured play paradigm rather than a goal-directed, we predicted that parent intervention would affect children's attention. Due to the exploratory nature of this analysis, we did not have any a priori predictions about whether the effects of parent scaffolding on attention would differ between deaf and hearing toddlers.

Method

Participants

The sample consisted of 12 parent-toddler dyads that included six toddlers with hearing loss and six with normal hearing (Table 1). Deaf toddlers were diagnosed at birth with severe-to-profound bilateral sensorineural hearing loss (SNHL) and received cochlear implants before 18 months of age. At the time of testing, deaf toddlers had received approximately 6-12 months of useable hearing experience through their implant, and all were enrolled in speech-language therapy with the goal of attaining spoken language.

Each hearing toddler was matched in age (+/- 1 week) and gender to each deaf toddler. Hearing toddlers were born full-term and had no developmental diagnoses or history of chronic ear infections.

Table 1: Participant characteristics.

Toddler group	Mean (SD; range)
Deaf	
Age at Test	19.05 (3.71; 13.97-25.05)
Age at CI Activation	11.69 (1.88; 7.97-13.17)
Hearing	
Age at Test	19.17 (3.60; 14.27-24.89)

Procedure

Toddlers and parents were seated at a child-sized table across from one another. Both dyad members were fitted with head-mounted eye-trackers from Positive Science, LLC (Figure 1). Each eye-tracker has an infrared camera that records the right eye and a head camera that records the field of view. Two additional cameras recorded third-person views of the scene. All cameras recorded at 30Hz and were synchronized offline using ffmpeg (ffmpeg.org).

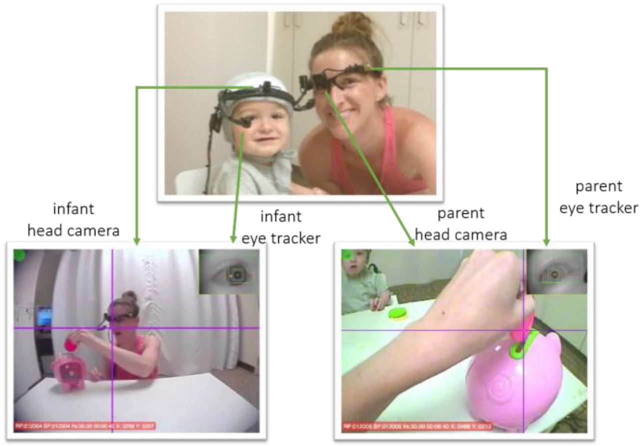

Figure 1: Eyetracking equipment and setup, showing examples frames in which the child is passing coins to his parent, who then places them into the piggybank slot. The crosshair indicates the estimated gaze target.

To calibrate the eye-trackers, a laser pointer was directed at nine unique locations on the tabletop to capture the toddler's attention. This phase was used for offline calibration using Yarbus software by marking the locations on the corresponding video frames when the eye was directed at the laser pointer.

Following calibration, dyads were presented with a toy piggybank that comes with ten colorful coins (Figure 1). In Round 1, the piggybank was placed before the child, and the coins were placed before the parent. Parents were instructed to hand the coins to the toddler one by one, so the toddler could then insert them into the piggybank. In Round 2, the items were switched so that the piggybank was placed before the parent and the coins before the toddler; it was the child's turn to pass coins to their parent who would then insert them into the piggybank. The objects were arranged such that the child could not complete the task alone; they needed to cooperate and coordinate their actions with their parents' to successfully insert the coins into the piggybank. There were 10 coins and therefore 10 trials per round, for 20 total trials per dyad). For the aims of the current study, we analyzed data from Round 1 only.

Data processing. After offline calibration, gaze direction was superimposed onto the head camera recording with a crosshair, yielding an additional recording of the calibrated gaze. All camera recordings were then exported into a series of single frames. Two independent coders used frames from the calibrated recording to determine, on every frame, whether the crosshair fell within one of four regions of interest (ROIs): the goal (the piggybank slot), the target coin, the parent's face, and the nontarget coins. The target coin was defined as the coin currently being brought to the piggybank and inserted into the slot; all other coins were defined as the 'nontarget' coins. Frames were excluded if the eye-tracker failed to capture the eye (e.g., the child knocked the camera out of place) or if the child was off-task (e.g., looking at the floor). Disagreements between coders that were longer than 10 frames (0.33s) were resolved via discussion with the first author; therefore, interrater reliability was 96%.

A third independent coder annotated every trial for the level of parent scaffolding during round one, when it was the child's job to insert the coins into the goal (Table 2). A trial was defined as the moment the first dyad member began reaching for the target coin, until the moment the coin was fully inserted into the piggybank.

Table 2: Levels of parent scaffolding.

Level	Definition
1.	**None**: child inserted coin into slot without help.
2.	**Some**: parent gestured to the goal to encourage the child or tilted the piggybank towards the child to make the task easier.
3.	**Lots**: parent physically helped the child through hand-over-hand guidance.
4.	**Complete**: the parent inserted the coin into the slot for the child.

Results

Gaze fixations to each ROI were converted into proportions by summing the total amount of time spent looking to each ROI (goal, target, face, nontarget) per trial, and dividing by the total length of the trial. Similarly, levels of parent scaffolding were converted into proportions by summing the total number of trials featuring each of the four levels and dividing by the total number of trials (10). Data processing was done in Matlab 2020a (Mathworks, Inc), and statistical analyses were done in R (R Core Team, 2019).

Visual Attention

Overall, infants were attentive during this task. On average, both groups spent over 70% of total time attending to one of the four ROIs of interest (Table 3). There was no significant difference in the overall proportion of looking time to the four ROIs, out of total interaction time, between groups, $t(10) = -.866$, $p = .407$. There were also no differences in mean gaze duration or the overall number fixations between groups (*ps* > 0.14).

Table 3: Descriptive Statistics.

	Deaf	Hearing
Visual Attention	Mean (*SD*)	Mean (*SD*)
Total looking (prop.)	0.70 (0.08)	0.76 (0.16)
Mean gaze duration (s)	1.35 (0.19)	1.29 (0.38)
Mean # Looks	19.04 (8.53)	12.71 (4.48)

Figure 2 shows the mean proportions of infant gaze to each ROI. A one-way ANOVA confirmed that gaze proportions differed significantly across ROIs, $F(3,104) = 62.57$, $p < .001$. Post-hoc comparisons using Tukey's Honest Significant Difference test revealed significant differences between all ROIs (all *ps* < .001) with one exception: there was no difference in gaze proportions between the face and nontarget ROIs. These findings confirm that toddlers attended significantly more to the goal than to any other ROI, and significantly more to the target coin than to either their parents' face or the nontarget coins.

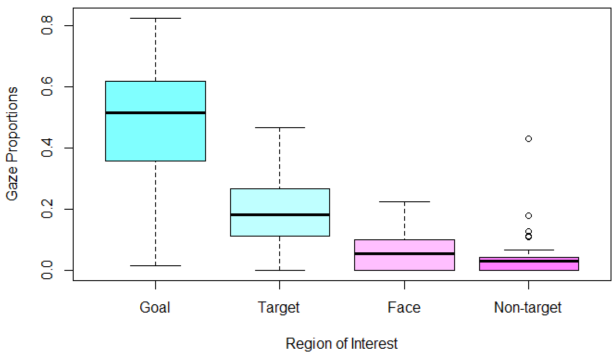

Figure 2: Gaze proportions to each ROI across all infants. Error bars represent 95% confidence intervals.

An ANOVA with gaze proportions as the dependent variable, ROI as a within-subjects factor and Group as a between-subjects factor revealed no roi*group interaction (p = .38), indicating that hearing status does not affect gaze distribution across the ROIs (Figure 3). Although hearing infants showed higher gaze proportions to the goal location, and deaf infants showed higher proportions to the non-target coins, these differences were not statistically significant.

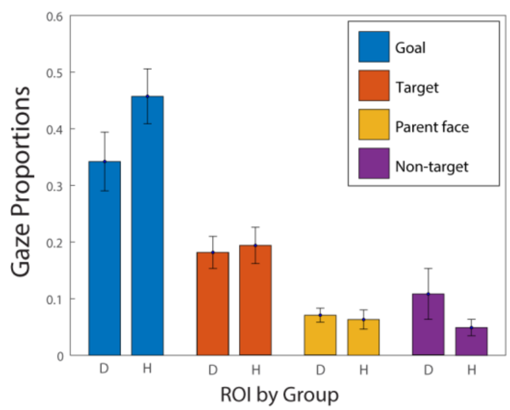

Figure 3: Gaze proportions to the four regions of interest, separated by group (deaf = D, hearing = H). Error bars represent the standard error of the mean.

Parent Scaffolding

Figure 4 depicts the levels of parent support for each toddler. A one-way ANOVA with mean number of trials as the dependent variable and levels of scaffolding as a within-subject factor revealed a significant effect of levels, $F(3,44) = 8.76$, p = .014. Across groups, toddlers completed most trials independently with no parent support (M = 4.58 trials per toddler), which was significantly more than the number trials taken over by parents (level 4, or 'complete' support; M = 0.67 trials). The number of trials in which parents provided 'some' support (M = 1.42 trials per toddler), and 'lots' of support (M = 2.08 trials) did not differ from other levels.

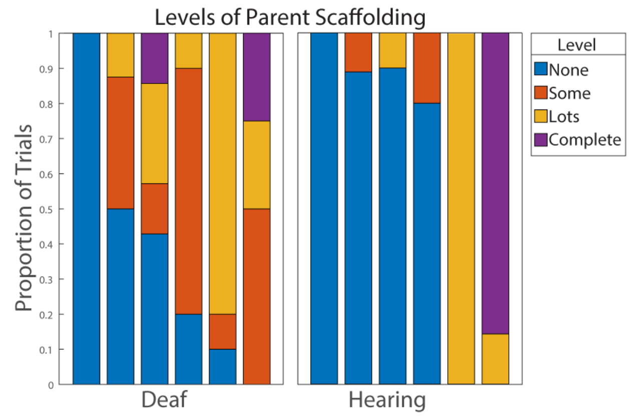

Figure 4: Proportions of levels of parent scaffolding for each toddler, separated by group.

An ANOVA with the mean number of trials as the dependent variable, Level as a within-subjects factor and Group as a between-subjects factor revealed no main effect of group, and no level*group interaction (ps > .74), indicating that levels of parent scaffolding does not differ significant between deaf and hearing toddlers.

To determine whether parents of deaf toddlers differed in the overall amount of scaffolding they provided, we conducted an independent-samples t-test on the mean proportion of trials containing any level of scaffolding; in other words, we collapsed across levels 2-4 and compared the proportion of trials between groups. This revealed no differences in overall amount of parent scaffolding between groups, $F(1,44) = .33$, p = .57. Thus, although the proportion of trials with some level of parents intervention was higher for the deaf toddlers (M = 0.63, SD =0.36) than the hearing toddlers (M = 0.40 trials, SD = 0.47), this difference was not statistically significant.

Does parent scaffolding modulate infant attention?

Our next question was whether attention to each ROI varied as a function of parent scaffolding (Figure 5), and whether this relationship differed between deaf and hearing groups. Because gaze proportions differed significantly across the four ROIS, we tested the effect of levels of parent scaffolding on gaze proportions by fitting a linear mixed-effect model to gaze proportions separately for each ROI, with Levels and Group as fixed effects and Participant as a random effect.

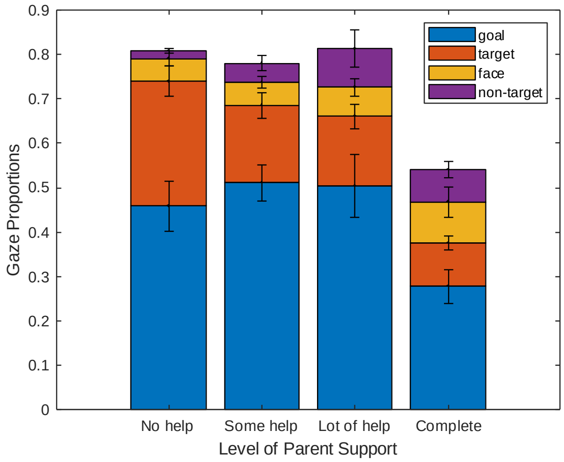

Figure 5: Stacked bars depict mean gaze proportions to the four ROIs per level of parent scaffolding, across groups. Error bars represent the standard error of the mean.

For the Goal ROI, the model revealed no main effects of level or group and no group*level interaction (*ps* > 0.40), indicating that parent scaffolding or hearing status did not modulate toddlers' attention to the goal.

For the Target ROI, there was a significant main effect of level, $\chi^2(3) = 8.63$, $p = .035$, revealing that attention to the target coin varied across levels of parent scaffolding. Proportion of looks to the target was highest when toddlers completed the trial independently ('None'; level 1), and progressively decreased as the level of scaffolding increased (Figure 6). This finding is not explained by a reallocation of attention to other ROIs: overall attention was lower during "complete" trials relative to all other trials (Figure 5). There was no main effect of group or group*level interaction (ps > 0.63), indicating that hearing status did not influence toddlers' gaze to the target coin.

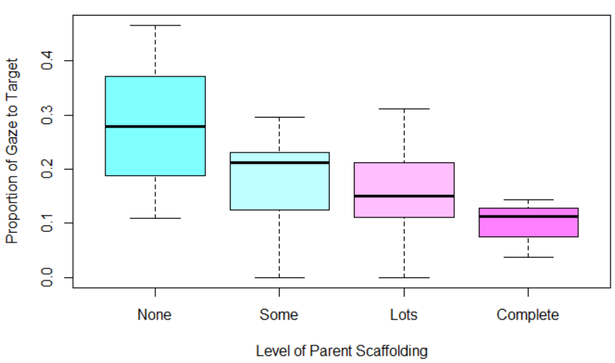

Figure 6: Boxplot showing gaze proportions to the target coin as a function of levels of parent scaffolding. Error bars represent 95% confidence intervals.

For the Face ROI, there was no main effect of level (p = 0.64), but there was significant group*level interaction $\chi^2(3) = 8.05$, $p = .045$. This interaction revealed a higher proportion of looks to the parents' face during Level 4 trials ('complete' help) in hearing toddlers compared with deaf toddlers ($M_{hearing} = 0.22$, $M_{deaf} = 0.03$).

Finally, analysis of the non-target ROI revealed no main effect of level (p = 0.42) but a highly significant group*level interaction ($\chi^2(3) = 33.79$, $p < .0001$). As with the face ROI, this interaction revealed that hearing toddlers spent more time looking at the non-target coins during trials in which parents provided "lots" of support (i.e., hand-over-hand guidance) compared with the deaf toddlers ($M_{hearing} = 0.20$, $M_{deaf} = 0.02$). However, given the low frequency of these trials, this finding should be interpreted with caution.

Discussion

The goal of the current study was to examine parent-child interactions during a goal-directed task in *Hd* (hearing parents with deaf toddlers) and *Hh* (hearing parents with hearing toddlers) dyads. Parents and their toddlers put coins together into a toy piggybank; specifically, parents handed coins to their child one-by-one and the child inserted them into the piggybank slot. We analyzed visual attention to task-relevant locations, parent scaffolding behaviors, and whether parent scaffolding modulated toddlers' attention.

Our main finding was that there were consistent similarities between *Hd* and *Hh* dyads in both the visual attention of the toddler and the scaffolding behavior of the parent. Across groups, toddlers demonstrated similar amounts of overall attention, length of gaze fixations, and distribution of gaze to task-relevant locations. They spent the largest proportion of the time looking at the goal (the slot), followed by the target coin, suggesting that toddlers were highly engaged with the task. Notably, toddlers spent a high proportion of time looking at relevant locations in the scene (above 70% of the time across groups). Toddlers also looked infrequently to their parents' faces, which is consistent with previous studies on parent-infant interactions using mobile eyetracking (Peters et al., 2020).

The similarities in visual behavior between deaf and hearing toddlers stands in contrast with previous research, which has documented poorer performance on sustained visual attention tasks in deaf school-age children (for a review, see Dye & Bavelier, 2010). Many of these studies employ standard computerized paradigms like the continuous performance task (CPT; e.g., Horn et al., 2005; Mitchell & Quittner, 1996; Quittner, Leibach, & Marciel, 2004; Smith et al., 1998) that typically require children to attend to a rapidly changing stream of stimuli like numbers. In the current study, visual attention was measured during an interactive, social task in much younger toddlers. One possibility is that active control and/or sensorimotor processes play a critical role in visual attention (Peters et al., 2020). Another possibility is that the differences previously observed in CPT tasks could be explained by a related cognitive process, like cognitive control. A third possibility is that these differences in visual behavior are not present early in infancy, but instead emerge later in development. This latter possibility raises questions about the underlying mechanisms that cause previously observed differences in visual attention in deaf children and is a critical question for follow-up work. Finally, it is important to highlight that all deaf toddlers in the current sample had worn cochlear implants for at least six months and were receiving speech-language therapy. It is likely that their hearing and language skills were developed enough to also benefit from their parents' verbal cues, another question for future work. It is possible that deaf toddlers without cochlear implants would not show such similarities with their hearing peers.

We also found no preliminary evidence for differences in parent scaffolding behaviors between parents of deaf and hearing toddlers. Though parents in *Hd* dyads showed more scaffolding behaviors than parents in *Hh* dyads, this difference did not reach significance. Nevertheless, this finding could be considered surprising in the context of previous research, which has found *Hd* parents to typically be less responsive and positively engaged in their interactions and more directive in their linguistic behaviors. One possibility is that this null finding is due to a small sample size, which we plan on increasing. An open question is whether parents also provide scaffolding through language; for example, by aligning utterances with toddlers' actions to encourage them or keep them focused on the task. An important next step will be to examine parents' speech and its effects on toddlers' behavior in the current task.

Finally, the third aim of the current study was to explore whether parents' scaffolding behaviors influenced toddlers' attention to task-relevant locations. We found that this was the case only for the target coin: attention to the coin had an inverse relationship with parent scaffolding, such that lower levels of scaffolding elicited a higher proportion of attention. One possibility is that parent intervention disrupts toddlers' attention to the target object they are trying to insert into the goal. This explanation is supported by the finding that overall attention was lower during the trials with the highest amount of parent intervention, and vice versa. An alternative possibility is the reverse: whenever their toddler demonstrates poorer attention, parents respond by providing more scaffolding to keep them engaged. However, attention to the goal location and to parents' faces was consistent across all levels of parent scaffolding, indicating attention to these locations was unaffected by parent intervention.

Interestingly, we found that hearing toddlers showed increased looks to their parent's face and to the non-target coins during trials with higher levels of parent scaffolding, but this pattern was not evident in the deaf toddlers. One speculation is that this pattern suggests more sensitivity in the parents of hearing toddlers, which would be supported by the literature. Whenever the toddlers are looking at the face or nontarget coins, instead of the goal or the target, parents provide more guidance. However, given that these conditions included fewer trials, we view this finding with caution.

In conclusion, the current study extends what we know about the parent-child interactions experienced by toddlers with hearing loss. Here, we have shown that deaf toddlers show largely similar patterns of visual attention while interacting with their parents, demonstrating an ability to focus to the task. Similarly, we also found comparable parent behaviors between groups, suggesting that the poorer parental responsivity observed in prior research may not be as pervasive as previously thought. Future work on this project will focus on analyzing the motor proficiency of toddlers, motor synchrony between parents and children, and linguistic behavior of parents.

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