Differences in Biological Motion Perception Associated With Hearing Status and Age of Signed Language Exposure

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This study investigates how American Sign Language (ASL) fluency and hearing status influence the perception of biological motion, using three point-light display (PLD) tasks. Prior research indicates that early exposure to ASL among deaf signers results in more rapid and effortless recognition of biological motion than hearing nonsigners, potentially due to the expertise in deciphering complex human movements or possibly due to neuroplasticity in deaf brains. However, it remains uncertain whether this advantage stems from signed language proficiency or the experience of being deaf. To explore this, we designed three PLD tasks involving viewing randomly moving dots, identifying a person from biological motion PLDs, and determining whether right-side up and inverted PLDs depict actions involving a ball. A diverse cohort of participants ($N = 224$) with varying ASL fluencies and hearing statuses completed the tasks online, providing us with reaction time and accuracy data. Our results demonstrate that earlier ASL exposure is associated with accuracy, especially on complex action identification tasks. Furthermore, we discovered robust evidence for a speed–accuracy trade-off in deaf participants, in which they performed more quickly but less accurately. The speed–accuracy trade-off was evident in the most difficult task, the action identification task. Further analysis of this deaf group revealed that earlier signed language acquisition led to higher accuracy in action identification task. We conclude that age of ASL exposure and hearing status both significantly contribute to variations in biological motion perception, with implications for understanding visual expertise and cognitive processing in both deaf and signing populations.

Public Significance Statement
Changes in brain function among people with sensory differences provide valuable insights into how experiences with one sense can change the functioning of other senses. There has been a long-standing curiosity about how using a signed language (like American Sign Language) might change visual perception abilities. In this study, we collected data about how quickly and accurately people can make sense of different types of movement. We found that while deaf people respond faster, their accuracy tends to be slightly lower than hearing people. We also found that people who learned American Sign Language earlier, both deaf and hearing, did better on the hardest task. Our work points to the importance of considering language modality and sensory diversity in understanding human perception and cognition.

Keywords: American Sign Language, biological motion perception, hearing status, age of acquisition, point-light display

In the 1920s, a deaf[1] lifeguard named LeRoy Colombo became famous for achieving a world record number of saves—estimated at 907 swimmers saved by his swift actions at the crowded beaches in Galveston, Texas. His extraordinary achievement could be explained by deaf lifeguards' higher "visual alertness" to their environments (Andrews, 2010). A century later, this supposition has come under the view of scientific research: In what ways might deaf people have enhanced visual abilities? Moreover, to what extent are those enhancements explained by their being deaf, as opposed to their expertise with signed languages? A critical factor in how LeRoy Jenkins saved so many drowning people may have been his sensitivity to biological motion, which is a crucial aspect of how we perceive others.

Biological motion perception is partially shaped by our prior experience with similar movements. Our visual systems display enhanced neural and cognitive abilities, such as improved memory and faster predictive processing, when processing human motion's familiar and fluid movements. For instance, expert dancers are especially attuned to complex dance movements (Amoruso et al., 2022; Cross et al., 2006). While previous research suggests that these enhanced visual abilities are primarily specific to within-domain actions, increasing evidence indicates that some people transfer their experience into different action domains. For example, deaf signed language users may apply their improved perception and understanding of signed language movements to their perceptions of everyday actions. This is not to suggest that deafness or other sensory disabilities lead to the development of suprahuman trade-offs of intact senses; rather, different skills may be strengthened due to the functional necessity of unique experiences and a modal underlying computational similarities. However, it remains unclear how deaf signers' visual abilities develop in this context. As research on deaf people is often coexistent with signed language users, it has been difficult to disentangle how deafness and signed language each may contribute to biological motion perception.

Deaf People's Visual Abilities

Deaf people exhibit marked and notable differences in their visual abilities. However, the precise nature and origins of these differences are not yet well understood. Cross-modal plasticity, a characteristic of sensory reorganization of neural processes in the brain, has been extensively studied through their unimodal sensory cortices (Alencar et al., 2019; Bavelier et al., 2006; Bavelier & Neville, 2002; Bosworth & Dobkins, 1999, 2002; Finney et al., 2001; H. J. Neville et al., 1983). This phenomenon refers to the functional adaptation of unimodal sensory cortices to modalities not typically associated with them in neurotypical populations. Studies of deaf human and animal models over the past half century show sensitivity in neural responses to sensory information beyond the scope of unimodal sensory perception. These findings suggest that the sensory and behavioral changes observed in the visual abilities of deaf people result from cross-modal neuroplasticity within the auditory cortex (Alencar et al., 2019; Bavelier et al., 2006; Bola et al., 2017; Bosworth & Dobkins, 1999, 2002; Corina et al., 2017; DeAndrea-Lazarus et al., 2022; Finney et al., 2001; Holmer et al., 2020; H. Neville & Bavelier, 2002; H. J. Neville et al., 1983). However, the specific ways in which cross-modal plasticity of sensory cortices in deaf people affects their low- and high-level visual processing remain unclear.

We know that deaf people exhibit a range of cognitive and neural enhancements in their visual system compared to hearing people, including in visuospatial attention, memory, and perception (Alencar et al., 2019; Bavelier et al., 2006; Benetti et al., 2021; Craig et al., 2022; Fine et al., 2005; Hauser, 2021; Quandt et al., 2021; Simon et al., 2020). For instance, researchers found that deaf participants showed significantly higher accuracy in motion detection and direction (Lomber et al., 2010, 2011; Shiell et al., 2014; Stevens & Neville, 2006). Deaf subjects also show enhanced perception of movement in the visual periphery, suggesting that they can better perceive motions across different visual pathways (Lomber et al., 2010; see Alencar et al., 2019 and Bavelier et al., 2006, for reviews on deaf vision). Those studies have suggested that the reuse of the auditory cortex in deaf people underlies the unique low-level visual abilities seen in deaf populations.

Compared to hearing people, deaf people exhibit unique behavioral and neural responses during low-level visual perception. However, we do not yet know if we can see similar effects in their higher level sensory cognition, such as biological motion perception. In deaf people, cross-modal neuroplasticity may also facilitate tactile and visual perception, which both play a role in including the perception of human movements (Karns et al., 2012; Meredith & Lomber, 2011; Simon et al., 2020; Villwock et al., 2022; for reviews, see Bavelier & Neville, 2002 and Cardin et al., 2020). For instance, recent studies examining deaf people's responses to point-light displays (PLDs) of signed language and complex movements suggest that their improved behavior responses in both signing and nonsigning deaf people may be from their sensory experience of being deaf (Lammert et al., 2023; Leannah et al., 2022; Quandt et al., 2021; Simon et al., 2020). However, the PLDs in the above studies have some methodological weaknesses, such as relying only on self-reported measures (Quandt et al., 2021), lacking a wide range of hearing statuses and language backgrounds (Lammert et al., 2023; Leannah et al., 2022; Quandt et al., 2021; Simon et al., 2020), or involving only simple types of motion perception (Lammert et al., 2023; Simon et al., 2020). These findings suggest how cross-modal neuroplasticity in deaf people could lead to a different engagement of sensorimotor processing for visual perception of human movements compared to hearing people (Quandt et al., 2021; Simon et al., 2020). However, the current characterization of deaf people's visual abilities leads to a question regarding how their higher level visual abilities could be changed.

Biological Motion Perception

The perception and interpretation of human movement is a crucial skill, known as biological motion perception, which has been long studied using PLDs (Johansson, 1973). PLDs are biological motion stimuli that are created from white dots attached to moving humans

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[1] We use little "d" deaf to represent the sensory and biological experience of being deaf as defined by current deaf studies scholars (Kusters et al., 2017). We opted for this definition instead of the commonly used binary of d/Deaf, where big "D" Deaf has been typically used in Western research literature on sociocultural formations of Deaf community, while the opposite binary has structured the little "d" deaf as a medical and pathologized view and experience of deafness. Since we are interested in how the rich sensory experience of being deaf changes perception, we used the new little "d" deaf that represents the sensory and lived experiences of a wide range of deaf people across different cultures and identities instead of the binary d/Deaf.

while removing other visual features such as form, outline, color, or texture (Johansson, 1973; Leannah et al., 2022; M. A. Pavlova, 2012; Quandt et al., 2021). Biological motion perception is an integral part of social and action perception, driving our ability to understand and predict others' actions based on our prior experiences with the actions. The underlying neural processing supporting biological motion perception involves a complex network of feedback simulation mechanisms through the sensorimotor cortices (Blake & Shiffrar, 2007; Blakemore & Decety, 2001; Calvo-Merino et al., 2005, 2006; Cannon et al., 2014; Cross et al., 2009, 2012; Gardner et al., 2015, 2017; Rizzolatti & Sinigaglia, 2016; Urgen et al., 2013). The common coding between multimodal sensory information about others' actions and the observer's representation of the same motor actions suggests an intertwining of the visual and motor systems (Quandt et al., 2012; Quandt & Marshall, 2014; Willis, 2023). The dynamic interactions between the two systems facilitate the perception of complex movements generated by other people (Blake & Shiffrar, 2007; Blakemore & Decety, 2001; Rizzolatti & Sinigaglia, 2016), further demonstrating that our experiences may shape our biological motion perception.

Given the proposed experience-dependent nature of biological motion perception, it is natural to wonder whether people with extensive experience with complex human movements exhibit quicker or more accurate responses when observing others in motion. For instance, with biological motion perception, people showed higher accuracy toward PLDs with coherent global human movement masked in noisy white dots motion compared to the dots with the same dynamic motion that are spatially scrambled (Grossman et al., 2004). Another PLD study showed that compared to 3-year-old children, 5-year-old children had higher recognition accuracy of human and animal PLDs' movement in different viewpoints, showing that biological motion perception in children becomes more accurate as they gain more experience with biological motion in their environment (M. Pavlova et al., 2001). Those studies show that people possess a heightened sensitivity to biological motion in their surroundings due to their experience with biological motion perception providing top–down modulation that allows humans to predict unfolding biological motions (Brinkman et al., 2014; Cross et al., 2012; Cruikshank et al., 2012; Hobson & Bishop, 2017; Pavlidou et al., 2014; Ulloa & Pineda, 2007; Urgen et al., 2013; Zarka et al., 2014). Specifically, our visual systems draw upon a range of enhanced neural and cognitive capacities, from better memory to faster simulation, when processing highly familiar biological motions, in contrast to nonbiological stimuli such as the random movement of scrambled PLDs or static images of PLDs. This effect of familiarity also extends into specific categories of action experience. For example, expert athletes such as professional dancers or those engaged in ball-related sports exhibit greater accuracy in predicting, perceiving, and comprehending human movements within their respective domains of expertise (Aglioti et al., 2008; Apšvalka et al., 2018; Chang et al., 2018; Y. H. Chen et al., 2020, 2022; Cross et al., 2006; Gao et al., 2023; Makris & Urgesi, 2015; Poulton, 1957; Romeas & Faubert, 2015; Wang et al., 2019; for a review, see Smith, 2016). Moreover, emerging evidence suggests that deaf people demonstrate faster and less effortful perception of PLDs than hearing nonsigners, suggesting that being deaf may lead to a similar expertise effect with biological motion perception. While most current biological motion perception research suggests that these enhanced visual capacities occur

in within-domain actions, some people, such as deaf signers or elite athletes, may be able to carry their experience into different action domains (Quandt et al., 2021; Romeas & Faubert, 2015; Simon et al., 2020). Extensive experience with certain types of movement (e.g., dance or signed language) could change people's biological motion processing.

This research demonstrates that experiential or developmental factors influence biological motion perception. For example, performance on biological motion tasks differs in older participants (Agnew et al., 2020), autistic people (Knight et al., 2022), and deaf signed language users (Quandt et al., 2021; Simon et al., 2020). Regarding the evidence for altered biological motion perception in deaf signers, a significant limitation of the research to date is the high overlap between being deaf and signed language experience, each of which may contribute to the effects observed in the literature so far. A deaf signer may show different biological motion perception due to neural reorganization due to being deaf. Alternatively, they may have developed an acute visual acuity for complex human movements due to their use of a signed language.

Sensory or Modality-Specific Language Experience(s)?

Signed language uses precise body, hand, finger, face, and eye movements to convey detailed linguistic information and create shared meaning (Emmorey, 2021; MacSweeney et al., 2008). Similarly, biological motion perception relies on extracting meaningful movement-related information to predict others' actions, intents, and desires (Caspers et al., 2010; Gardner et al., 2017; Hardwick et al., 2018; Molenberghs et al., 2012; Papitto et al., 2019; Rizzolatti & Sinigaglia, 2016). Theoretically, there could be a relationship between the mechanism involved in comprehending signed language movements and biological motion perception in sensorimotor cortices (Bosworth et al., 2019; Kubicek & Quandt, 2019; Lammert et al., 2023; Leonard et al., 2020; Quandt & Willis, 2021; Willis, 2023). Indeed, evidence suggests that learning a signed language can have modality-specific effects that potentially alter signers' perception (Bosworth et al., 2019; Emmorey, 2023; Quandt et al., 2021; Stoll & Dye, 2019). The visual and physical expertise acquired through signed language fluency could consequently impact the perception of biological motion in people who use signed language, regardless of their hearing status.

One possibility, based on prior findings on biological motion perception, is that signed language users' brains are automatically simulating biological motion and matching them with the incoming stream of sensory information, similar to what has been found during neuroimaging studies of biological motion perception (Cross et al., 2012, 2016; Gardner et al., 2015, 2017; Quandt et al., 2021). Other studies on deaf and hearing signers' visual attention found that knowing a signed language leads to enhanced peripheral visual processing of the inferior part of their visual field (Caselli et al., 2022; Stoll & Dye, 2019). This visual enhancement may arise from signers' fixations toward the face while perceiving the hand movements in their inferior peripheral visual field. This work demonstrates that learning a signed language changes visual processing for both signed and nonsigned movements. However, we do not know how signed language expertise generalizes toward an enhanced biological motion perception of other complex human movements, especially for deaf signers.

Thus far, the relationship between signed language expertise and biological motion perception is not clear, and the behavioral evidence supporting enhanced biological motion perception in signers, deaf or hearing, is mixed (Lammert et al., 2023; Leannah et al., 2022; Quandt et al., 2021; Simon et al., 2020). For instance, in a recent study using walking PLDs in a visually noisy environment, hearing signers were no different from hearing nonsigners (Lammert et al., 2023). However, the PLD walker stimuli may not fully reveal the extent of how signers' perception generalizes their experience with the complex, meaningful movements of signed languages to other types of nonsigning complex movements. Simply put, the commonly used PLDs of walkers may not be challenging enough to make deaf signers' enhanced biological motion perception apparent in the data.

The multifaceted effect of signed language and sensory experience on visual perception may explain some findings from Quandt et al.'s (2021) behavioral and electroencephalography results in identifying the PLDs of complex human movement. In this study, the behavioral results show that compared to hearing nonsigners, deaf signers self-reported less effort in identifying what kind of action is being shown in the PLD stimuli. In response to the same PLD stimuli in the electroencephalography study, we found that deaf American Sign Language (ASL) signers showed significantly earlier and more robust sensorimotor discrimination between coherent and scrambled PLDs. Across those behavioral and electroencephalography results, two questions emerged. Does the less effortful perception reported by deaf signers also appear in more objective measures, such as reaction time and accuracy? Moreover, is there an aspect of the sensory experience of being deaf and/or signed language experience that changes people's visual perception of random dot motion and/or coherent biological motions? For instance, deaf signers may use their enhanced sensory perception for low-level motion information to identify the PLDs' high-level biological motion and action information. Another possibility is that deaf signers may be able to recognize human movements better but not necessarily their meaning. Yet another explanation is that deaf signers can better utilize their action knowledge to modulate their top–down biological motion simulation for visual perception.

The Present Study

We designed a study to investigate the impact of ASL fluency and hearing status on biological motion perception. While recent evidence has suggested possible effects of being deaf or having signed language experience upon biological motion perception, the extent to which each factor may affect perception remains unclear. In addition, past work has examined these questions using relatively simple movement perception tasks, although the complexity of signed languages may particularly enhance the perception of similarly complex movements. To address these two goals, we designed three movement perception tasks completed online by 224 participants with varying ASL fluency and hearing statuses. We recruited participants from various ASL fluency levels, including a mixture of deaf, hearing, and hard-of-hearing (HoH) people. By performing bivariate and univariate analyses on these data, we aimed to isolate the relative contributions of various factors on the accuracy and reaction time in response to different motion detection tasks.

Method

To test our hypotheses, we created three sets of tasks and stimuli to examine the role of hearing status and signed language experience in biological motion perception. We ran this experiment through an online program to reach a broad sample of respondents varying by ASL fluency and hearing status.

Participants

From March 1, 2022, through July 8, 2022, we recruited participants via an online flier shared on social media, email lists, and word of mouth. Participants earned a gift card in exchange for their time. Three hundred participants completed the experimental task. Our preregistered data collection plan was to stop when we had 300 participants collected, with a make-up of roughly 100 hearing nonsigners with at least 50 hearing signers and 80 deaf signers. This plan is based on a power analysis of prior PLD studies that collected response time (RT) responses from participants. We also preregistered our exclusion criteria, excluding any responses that were given too fast or appeared for other reasons to be "bots" or fraudulent responses. We excluded 77 participants due to low-quality responses or technical difficulties. Thus, we included 224 participants (77 deaf, 20 HoH, and 128 hearing) in the final sample (see Table 1 and Figure 1). All demographics were self-reported via an online Qualtrics form. As evident in Figure 1, ASL Fluency was not evenly distributed between the three groups. The deaf group was strongly skewed toward higher levels of ASL fluency. While the hearing group had a sizable number of signers, a majority of hearing participants reported no ASL knowledge. Last, the HoH group was small and included only a few people at each ASL fluency level.

Table 1
Participant Demographics

Variable	Deaf	HoH	Hearing	$F(df)$	p	η^2
N	76	20	128			
Age; M (SD)	28.17 (9.5)	29.90 (9.0)	35.03 (11.4)	10.46(2, 221)	<.001	.086
Age of ASL acquisition[a]; M (SD)	7.34 (6.90)	11.88 (10.37)	16.68 (9.39)	20.46(2, 146)	<.001	.22
ASL fluency; M (SD)	4.56 (1.0)	3.05 (1.82)	1.59 (1.94)	75.55(2, 221)	<.001	.41

Note. This table reports the number of participants, the mean and standard deviation of their age, age of ASL acquisition, and their self-reported ASL fluency in each hearing status group: deaf, HoH, and hearing. *p* values represent the result of a one-way analysis of variance comparing the values across the three groups. HoH = hard-of-hearing; ASL = American Sign Language.
[a] Participants who reported no ASL knowledge had no age of acquisition.

Figure 1
Self-Reported ASL Fluency for Each Hearing Status Group
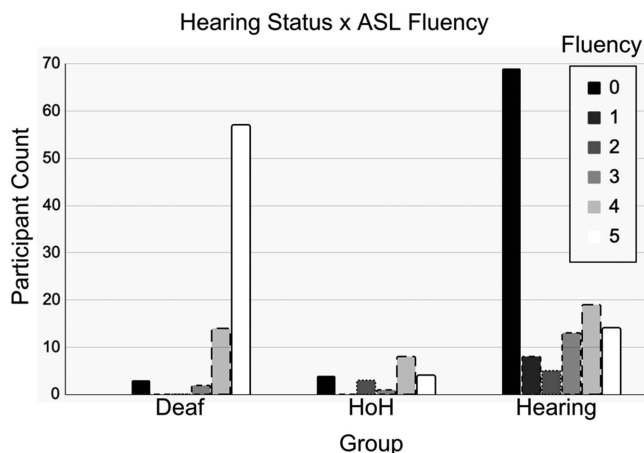
Note. Figure 1 shows the participant count of each hearing status group along with the count of self-reported ASL fluency levels in each group, from 0 (*I don't know any ASL*) to 5 (*fluent*). ASL = American Sign Language; HoH = hard-of-hearing.

The race and ethnicity of the participants were asked through a list that includes American Indian or Alaska Native ($N = 4$), Asian or Asian American ($N = 19$), Black or African American ($N = 19$), Hispanic, Latino, Latina, or Latinx ($N = 7$), Middle Eastern or North African ($N = 1$), Native Hawaiian or other Pacific Islander ($N = 0$), White ($N = 166$), prefer not to say ($N = 0$), and other with free text response ($N = 8$). Similarly, the gender of the participants were

asked with a list that includes male ($N = 100$), female ($N = 106$), nonbinary/third gender/not listed here ($N = 18$), and prefer not to say ($N = 0$).

Stimuli

### Random Dot Movement Stimuli

We created 36 random dot motion PLDs. These arrays were created at (https://codepen.io/vrsivananda/pen/MVXXOZ; Rajananda, 2017), a tool licensed under a free GNU license. There were 18 dots in each capture, with nine of the dots moving coherently in either a left or right direction. The other nine dots were moving randomly. Thus, we had 18 videos with mostly left movement and 18 with mostly right movement. The overall effect is that with some processing, a viewer can tell which direction half the dots are moving. Still, the random movement means that the direction is not always immediately obvious.

Person Perception and Action Identification Stimuli

We also created 18 coherent PLDs using 16 Vicon (Vicon Motion Systems Ltd., United Kingdom) cameras to create motion capture recordings. Each PLD was created by placing 18 markers on different body joints. For each recording, an actor performed one of six actions: jumping jacks, a high kick, an underarm throw, jogging, jumping rope, or a golf swing. We created each PLD by recording the motion information from three perspectives (see Figure 2): face forward (0°), oblique view (45°), and side view (90°), for a total of 18 action videos (three for each of the six actions). Each of these 18 videos was remade into a "scrambled control," in which the motion

Figure 2
Experimental Stimuli and Tasks
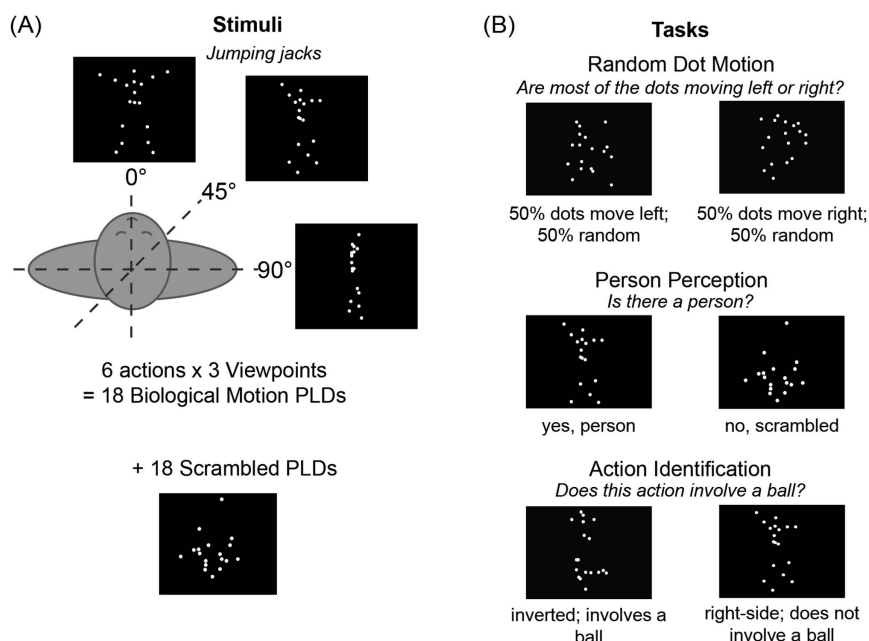
Note. (A) The biological motion PLDs were created by filming six actions, each from three different angles. (B) Three tasks were created which each used two types of stimuli. PLD = point-light display.

trajectories remained the same but the location of the dots differed. Thus, the scrambled PLDs retain some characteristics of biological motion but do not show coherent motion. These stimuli were the same as those used by Quandt et al., 2021. The videos are publicly available on the Open Science Framework at https://osf.io/yhtdr/.

Procedure

All participants completed an informed consent form approved by the Gallaudet University Institutional Review Board (IRB No. IRB-FY22-25). After providing informed consent, participants viewed and completed PLD tasks (see Table 2 and Figure 2) online. The PLD tasks were assembled using the PsychoPy software (Peirce et al., 2019) and hosted on the PsychoPy online platform Pavlovia.

Participants were told they would have only one opportunity to view each video. Before starting the experiment, participants completed practice trials for each task to become familiar with the instructions. The practice portion included eight video trials for each task, with a break between each set.

Tasks

Three types of stimuli were shown throughout the experiment as three separate tasks (random dot movement, person perception, or action identification; see Table 2 and Figure 2). Each task had 36 videos, totaling 108 videos. Participants were shown each of the 108 videos twice across six blocks for 216 trials in the entire experiment. Each block was one type of task, as described in the upcoming paragraphs. The six blocks were pseudorandomized, so participants did not complete the same task block twice in a row. Reaction time and accuracy for each trial were collected and included in the analysis.

There were two blocks of the random dot motion task, each with 36 videos per block. All of the videos were randomized within each block. The random dot motion task consisted of videos containing 18 moving white dots on a black background. Half of the videos contained dots that were mostly left-moving, and half contained mostly right-moving dots (see Stimuli section above for an in-depth description and link to publicly available videos). Participants had to identify whether most dots were moving right or left. They were asked to press one of two buttons on the keyboard to indicate whether the dots were moving left (F) or right (J).

Table 2
Study Tasks

Task type	Video stimuli
Random dot movement	36 videos • 18 "left" arrays • 18 "right" arrays
Person perception	36 videos • 18 action PLDs from three perspectives (0°, 45°, 90°) • 18 scrambled control PLDs
Action identification	36 videos • 18 action PLDs shown right-side up • 18 action PLDs shown upside down

Note. PLD = point-light display.

The person perception task had two blocks, each with 36 videos per block. Eighteen of the 36 videos depicted a person performing a specific movement in PLD, as described above (swinging a golf club, doing a high kick, jogging, jumping jacks, jumping rope, or tossing a ball). The six actions were each captured from three angles: 0°, 45°, and 90°. The remaining 18 videos acted as visual controls and contained scrambled versions of the previously mentioned six PLDs. The videos were shown randomly within each block. During the person identification block, participants had to identify whether a person was visible (e.g., they would answer person for the action videos and no person for the scrambled videos). They pressed one of two buttons on the keyboard adjacent to whether there was a person: No Person (F) or Person (J).

The action identification task had two blocks, each with 36 videos per block. Half of the videos were shown right-side up, while half were flipped upside down. Twelve videos showed actions involving a ball (e.g., underarm throw, golf swing), and 24 videos showed actions not involving a ball (e.g., jumping jacks, jogging). The videos were shown in randomized order within each block. During the action identification blocks, participants had to identify if the action shown required a ball, regardless of whether it was right-side up or upside down. They pressed one of two buttons on the keyboard adjacent to whether the action involved a ball: No Ball (F) or Ball (J).

After completing the experiment, participants responded to background questions. These included their current age, hearing status, age at which they acquired a signed language, frequency of ASL and other languages used during upbringing, current ASL usage, and self-assessment of receptive and expressive ASL skills. The fluency rating scales spanned from 0 (*I don't know any ASL*) to 5 (*fluent*). The scores for receptive and expressive skills were strongly correlated ($r = 0.93$, $p < .001$). Therefore, we used the ASL receptive scores as the sole measure of self-rated fluency in this study. We believe receptive skills are also a better fit for our research question, which is primarily concerning perceptual skills.

Data Processing and Analysis Approach

Data processing consisted of a series of descriptive statistics and modifications to remove outliers from the RT distribution so we could analyze the data. We excluded all RTs greater than three due to extreme outliers. We dropped participants whose average in any of the three tasks was lower than 60%, resulting in five participants being removed. The final sample was 224 participants, as described above.

Some of our predicted findings centered on comparisons between signers and nonsigners or between deaf early signers and hearing nonsigners. Thus, we computed new variables to assign group membership in the two groups. The signers group consisted of all participants (of any hearing status) who self-reported ASL receptive fluency of 3, 4, or 5 on the 1–5 scale. Signers represented 58% of the total sample, or $N = 132$. The nonsigners group consisted of all participants who self-reported an ASL receptive fluency of 0, 1, or 2 on the 5-point scale (41% of the total sample, $N = 92$). We opted for this cutoff because two was labeled as beginner on the scale, while three was labeled as intermediate. Thus, we determined that people reporting an ASL fluency of up to 2 were, at best, elementary users of the language and unlikely to know enough ASL to be considered proficient language users.

We defined the group of deaf early signers as all participants who identified as deaf and reported an AoA of under 6 years (15.6% of the sample, or $n = 35$; mean ASL fluency = 4.5, $SD = 1.3$). All deaf early signers had at least a fluency level of 4. Due to low N with the preregistered cutoff of deaf early signers having an age of acquisition (AoA) of <4, we expanded our group of deaf early signers to include AoAs under 6 years old. We defined hearing nonsigners as any participant who reported being hearing and had an ASL receptive fluency of 0, 1, or 2 (36% of the sample, or $n = 82$; mean ASL fluency = 0.22, $SD = .545$).

We preregistered predictions to help guide our data analysis. Our preregistered primary predictions were as follows:

1. AoA: Significantly slower RTs for action identification and random dot motion tasks with higher AoA.

2. Fluency: Significantly slower RTs for action identification and random dot motion are associated with lower ASL fluency.

3. Slower RTs for action identification and random dot motion for nonsigners than for signers.

4. Slower RTs for action identification and random dot motion for hearing nonsigners than for deaf early signers (who learned ASL before age 4).

5. No significant differences between any groups or on any independent measures on the person identification task.

Secondary predictions were as follows:

1. Performance will decrease on all measures with increasing age.

2. Gender will show no significant differences on any measures.

Then, we also included exploratory predictions of accuracy, which mirror the primary predictions of the RT variable.

Transparency and Openness

We reported how we determined our sample size, all data exclusions, all manipulations, and all measures in the study, and we followed the APA Style Guide Journal Article Reporting Standards (Kazak, 2018). The study's material, including stimuli, experimental presentation script, data, and analysis scripts, is available online (https://osf.io/yhtdr/). Data were analyzed using JASP, Version 0.18.1 (JASP Team, 2023). This study's design, hypotheses, and analysis were preregistered (https://aspredicted.org/blind.php?x=TCR_S7T).

Results

After preprocessing, we conducted a series of bivariate analyses with RT and accuracy. This analysis was followed by linear regressions used for the RT and accuracy analyses. The following analyses include the dependent variables of interest: accuracy on each task and overall accuracy (averaged across the three tasks) and RT on each task as well as overall RT (averaged across the

three tasks). The independent variables of interest included the following: AoA, which was continuous with missing data because nonsigners do not have an AoA; gender, which consisted of three categories; hearing status and task, which also both consisted of three categories; age, which was continuous; and ASL fluency, which was coded as zero through five.

Accuracy: Bivariate Analyses

We examined the association between accuracy and task using a repeated-measures analysis of variance (ANOVA). We used a Greenhouse–Geisser correction to account for violations of sphericity. Accuracy varied significantly between the three tasks, $F(1.82, 406.47) = 84.30$, $p < .001$, $\eta^2 = .274$. The overall accuracy for random dot motion was 91.6%, person perception was 96.3%, and action identification was 89.1%. Notably, post hoc tests revealed that all tasks differed significantly from one another.

To investigate the exploratory predictions regarding the relationship between AoA and accuracy in our data set, we conducted Kendall's tau-b correlations on accuracy with hearing status and age partialed out. With hearing status and age controlled for, AoA was negatively correlated with overall accuracy ($B = −.159$, $p = .004$, $Z = −.16$) and negatively correlated with accuracy on the action identification task ($B = −.176$, $p = .002$, $Z = −.18$). Thus, signers who learned ASL earlier had higher accuracy scores overall, and particularly on action identification.

Accuracy: Linear Regression

We conducted six linear regressions for accuracy. For each task (random dot motion, person perception, and action identification), we conducted one linear regression including the factor AoA, which naturally excluded all participants with no ASL experience (because they had no AoA), and one linear regression without the AoA factor, which included all participants.

Random Dot Motion

A linear regression analysis was conducted using JASP (JASP Team, 2023) to examine the relationship between age, AoA, hearing status, gender, ASL fluency, and accuracy on the random dot motion task. The model was nonsignificant, $R^2 = .084$, $F(10, 137) = 1.263$, $p = .258$, indicating that the regression equation did not explain a significant amount of the variance in accuracy. Running the same regression without the AoA variable (including all participants) also yielded no significant results, $R^2 = .058$, $F(11, 213) = 1.204$, $p = .286$.

Person Perception

A linear regression analysis examined the relationship between age, AoA, hearing status, gender, ASL fluency, and accuracy on the person perception task. The model was nonsignificant, $R^2 = .044$, $F(10, 137) = 0.638$, $p = .779$, indicating that the regression equation did not explain significant variance in accuracy. Running the same regression without the AoA variable (thus including all participants), the model was again not statistically significant, $R^2 = .032$, $F(11, 213) = .707$, $p = .717$.

Action Identification

A linear regression analysis examined the relationship between age, AoA, hearing status, gender, ASL fluency, and accuracy on the action identification task. The model was significant, $R^2 = .214$, $F(10, 137) = 3.731$, $p < .001$. As AoA increased (i.e., with a later exposure to ASL), accuracy on the action identification task was significantly lower ($\beta = -.003$, $SE \leq .001$, $p = .002$). Additionally, hearing status emerged as a significant predictor, in which deaf participants showed a lower accuracy than hearing participants ($\beta = .066$, $SE = .015$, $p < .001$). Running the same regression model without the AoA factor (thus including all participants), the model was significant, $R^2 = .138$, $F(10, 213) = 3.396$, $p < .001$. Again, older participants showed a lower accuracy ($\beta = -.002$, $SE < .001$, $p < .001$). Deaf participants had significantly lower accuracy in comparison to both HoH ($\beta = .041$, $SE = .02$, $p = .043$) and hearing participants ($\beta = .038$, $SE = .015$, $p = .012$).

To follow up on the finding of AoA predicting action identification accuracy, we reran the analysis, limited to only deaf participants who reported an AoA ($n = 76$, 34% of the total sample). Within the group of deaf participants, a later AoA was associated with lower accuracy ($\beta = -.004$, $SE = .001$, $p = .005$), even while controlling for age, sex, and self-reported ASL fluency.

Subgroup Analyses

Next, we compared accuracy for two specific groups of participants in line with our preregistered predictions: deaf early signers (hearing status = deaf and AoA < 6 years) and hearing nonsigners (hearing participants with ASL fluency < 3). We ran linear regressions on accuracy for all three tasks. There was no significant difference between RTs for the two groups when age was included as a covariate. Using a similar approach, we compared accuracy between two other subgroups in line with our preregistered predictions: signers (ASL fluency > 2) and nonsigners (ASL fluency < 3), regardless of hearing status. Again, a linear regression, including age and signing status, showed no significant differences in accuracy between signers and nonsigners.

Reaction Time: Bivariate Analyses

We conducted a repeated-measures ANOVA to compare RTs on the three tasks. Mauchly's test of sphericity indicated a violation of the sphericity assumption, so we used Greenhouse–Geisser corrections. The ANOVA revealed that RT varied significantly by task, $F(1.97, 431.85) = 475.99$, $p < .001$, $\eta^2 = .68$. Two of the post hoc tests (with a Bonferroni correction applied) were statistically significant at a $p = .001$ level, with responses to action identification, which has the highest mean RT ($M = 1,57$, $SD = .373$), being significantly slower than random dot motion ($M = 1.09$, $SD = .313$) or person perception ($M = 1.13$, $SD = .338$). The RT for person perception did not differ significantly from the RT for the random dot motion task.

We then ran Kendall's tau-b correlation between RT and AoA, which showed no significant correlation, $B = .07$, $p = .225$, $Z = .07$. We ran the same correlation with hearing status and age partialed out, and the correlation was still not significant.

Reaction Time: Linear Regression

Our analysis aimed to discern how hearing status and ASL experience influence performance across the three tasks. Consequently, we treated each task as a separate analytical unit. We employed two linear regression models for every task: one incorporating AoA and another excluding it. This dual-model approach was necessitated by the significant proportion of missing AoA data, particularly among hearing participants who lacked ASL proficiency and did not have an AoA value.

Random Dot Motion

First, we ran a linear regression on RT for the random dot motion task with a dependent variable of RT, with covariates age and AoA, and factors of hearing status, gender, and ASL fluency. The results indicated that the model was insignificant, $R^2 = .035$, $F(10, 137) = 1.540$, $p = .131$. We then ran the same linear regression without AoA; thus, all participants were included. The results indicated that the model explained a significant proportion of variance in random dot motion RT, $R^2 = .136$, $F(10, 213) = 3.357$, $p < .001$. Age and ASL fluency were both significant predictors of RT. Older participants were likely to be slower ($\beta = .007$, SE .002, $p < .001$). The model indicated that participants who reported an ASL fluency of 4 performed significantly worse than those with other fluency levels. However, upon examining our participant sample, we could not interpret this finding since there were so few participants who reported fluencies of 1, 2, or 3 on our 5-point scale (see Figure 1) against whom to compare those at fluency level 4. Given the unexpected nature of this finding, we present it without further interpretation.

Person Perception

Next, we ran a linear regression on RT for the person perception task with a dependent variable of RT, with covariates age and AoA, and factors of hearing status, gender, and ASL fluency. The results indicated that the model explained significant variance in person perception RT, $R^2 = .172$, $F(10, 137) = 2.847$, $p = .003$. Significant predictors included age, hearing status, and sex. Again, increased age predicted slower RTs ($\beta = .008$, $SE = .003$, $p = .013$). Hearing participants showed significantly slower RTs ($\beta = .208$, $SE = .07$, $p = .004$). We then ran the same linear regression, with the only difference being that no AoA was included; thus, all participants were included. The results indicated that the model explained a significant proportion of variance in person perception RT, $R^2 = .214$, $F(10, 213) = 5.806$, $p < .001$. Hearing participants had slower RTs than deaf participants once again ($\beta = .154$, $SE = .069$, $p = .026$). The effect of ASL fluency was nonlinear, with participants having a fluency level of 4 again showing a slower RT.

Action Identification

Next, we ran a linear regression on RT for the action identification task, with a dependent variable of RT, with covariates age and AoA, and factors of hearing status, gender, and ASL fluency. The results indicated that the model explained a significant proportion of variance in action identification RT, $R^2 = .199$, $F(10, 137) = 3.397$, $p < .001$. Hearing participants were again significantly slower than deaf participants ($\beta = .160$, $SE = .073$, $p = .03$). As before, age predicted RT ($\beta = .008$, $SE = .003$, $p = .008$). We then ran the same

linear regression, with the only difference being that no AoA was included; thus, all participants were included. The results indicated that the model explained a significant proportion of variance in action identification RT, $R^2 = .214$, $F(10, 213) = 5.806$, $p < .001$. Again, hearing participants responded more slowly than deaf participants ($\beta = .154$, $SE = .069$, $p = .026$). And again, older participants had slower RTs ($\beta = 011$, $SE = .002$, $p < .001$). Once again, the effect of ASL fluency appeared nonlinear, with the same finding for participants with fluency level 4.

Subgroup Analyses

Last, we compared RT for specific groups of participants in line with our preregistered predictions: deaf early signers (hearing status = deaf and AoA < 6 years) and hearing nonsigners (hearing participants with ASL fluency ≤ 3). We ran linear regressions on RTs for all three tasks, and when including age as a covariate, there was no significant difference between deaf early signers and hearing nonsigner RTs. Using a similar approach, we compared RT between two other subgroups in line with our preregistered predictions: signers (ASL fluency > 2) and nonsigners (ASL fluency < 3), regardless of hearing status. Again, a linear regression including age and signing status showed no significant differences between signers and nonsigners on RT.

### Exploratory Analyses of Speed–Accuracy Relationships

Upon examining the study results, it was apparent that the participants in the deaf group showed a markedly different relationship between RT and accuracy than hearing or HoH participants. For example, on the action identification task, deaf participants showed a nonsignificant positive relationship between RT and accuracy ($R = .081$, $p = .49$, $Z = .081$), indicating that as they replied slower, they replied more accurately (see Figure 3). In contrast, the other groups exhibited significant negative correlations between accuracy and RT for action identification. A faster response was associated with higher accuracy for hearing ($R = .081$, $p = .49$, $Z = .081$) and HoH ($R = -.233$, $p = .008$, $Z = -.238$) groups. The same analyses yielded no differences between groups for the other two tasks, on which all participants showed negative correlations with faster responses being more accurate, similar to the patterns for hearing and HoH groups on action identification. Thus, the unique speed–accuracy trade-off exhibited by deaf participants during action identification suggests a different mental computation occurs when deaf people encounter the most complex motion detection task.

We further explored this finding by calculating a new variable, the inverse efficiency score (IES), calculated by (task RT/task accuracy), so that each participant had one value for each task, indicating the overall performance based on both their speed and accuracy on each task. This metric is particularly helpful because it provides a clear picture of cognitive efficiency by combining both aspects into one measure. Lower IES values indicate better overall performance on the task: faster and more accurate responses, whereas higher IES scores reflect slower and less accurate responses.

We conducted an exploratory linear regression on the IES for the random dot motion task, including ASL fluency, sex, and hearing status as predictors and age as a covariate. The overall fit of the regression model was statistically significant, indicating that the predictors as a whole reliably distinguished between different IES scores, $F(10, 213) = 3.58$, $p < .001$, suggesting a meaningful association between ASL proficiency, among other factors, and the IES for the random dot motion task. Age predicted higher IES scores on the random dot motion task ($\beta = .01$, $SE = .003$, $p < .001$). Participants with an ASL fluency of 4 had significantly

Figure 3
Performance on Action Identification
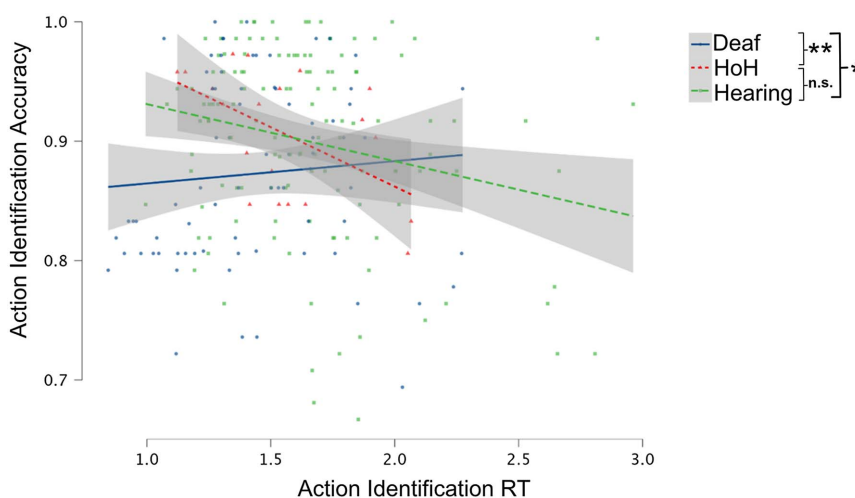
Note. The correlation between response time (RT) and accuracy on the action identification task for each group (deaf, hard-of-hearing [HoH], and hearing). Gray bands indicate 95% confidence intervals. n.s. = not significant. See the online article for the color version of this figure.
* $p < .05$.   ** $p < .01$.

higher IES scores than those with other scores ($\beta = .231$, $SE = .083$, $p = .006$).

Our next exploratory linear regression looked at the factors of ASL fluency, sex, hearing status, and age upon person perception IES scores. The model significantly explained the IES variability, $R^2 = .155$, $F(10, 213) = 3.91$, $p < .001$. Deaf participants demonstrated significantly lower IES scores than hearing participants, suggesting deaf people's more efficient cognitive processing during the person perception task ($\beta = .175$, $SE = .072$, $p < .016$). Once again, age positively predicted IES scores ($\beta = .01$, $SE = .002$, $p < .001$).

We conducted a linear regression looking at the factors of ASL fluency, sex, hearing status, and age upon the dependent variable of action identification IES scores. While the model as a whole significantly predicted IES scores, $R^2 = .206$, $F(10, 213) = 5.531$, $p < .001$, the only significant predictor was age ($\beta = .017$, $SE = .033$, $p < .001$), again showing that older participants performed less efficiently.

Discussion

In this study, we aimed to dissociate the effect of hearing status and signed language experience in biological motion perception of everyday complex human actions. The present study is an extension of a neuroscience study that examined the biological motion perception of deaf early signers compared to hearing nonsigners (Quandt et al., 2021). In the current work, we expanded the sensory and language diversity of our participant pool to include hearing signers and also deaf signers who acquired ASL later in their lives. By including a broad array of signed language experience and hearing status, we can gain unique insights into the interplay of signed language experience and the effects of hearing status. Our findings inform our understanding of the effect of cross-modal neuroplasticity in deaf people on biological motion perception and how knowing a signed language contributes to perception and cognition in signers, both hearing and deaf.

Our participants were presented with three tasks: random dot motion, person perception, and action identification. Each task requires the engagement of different aspects of perception, from low-level motion to biological motion perception and action understanding. In support of the notion that early signed language exposure may confer unique benefits to visual perception, we found that earlier ASL acquisition predicted higher accuracy on the most complex task of action identification. Interestingly, in a seemingly conflicting finding, being deaf was associated with lower accuracy on the same task. Further analysis of the deaf group found that earlier acquisition of ASL is associated with higher accuracy in action identification task, even when the sex, age, and self-reported ASL fluency were controlled for. These complex findings shed light on the intricate nature of how signed language experience and sensory diversity may each play a unique role in shaping people's perceptual systems and responses to visual stimuli. In the person perception task, deaf participants responded more efficiently than hearing participants, but at some cost to accuracy. Relatedly, exploratory analyses revealed that deaf participants displayed a unique speed–accuracy trade-off during the action identification task. Below, we will discuss the varying effects of signed language experience and hearing status on different types of motion perception.

Effects of Hearing Status

Our study addresses whether being deaf leads to faster and more accurate biological motion perception than hearing people. Our exploratory findings showed that our deaf group showed a distinctive speed–accuracy trade-off in the action identification task. Within this action identification task, we also found that within the deaf group, earlier age of acquisition of ASL significantly predicted higher accuracy in perceiving the type of action being shown. The deaf group also showed significantly faster RT and better IES scores in the person perception task, showing they are highly efficient at perceiving human movements.

On the other hand, with the frequently used task and stimuli in the study of deaf people's cross-modality plasticity (Alencar et al., 2019; Bosworth & Dobkins, 2002; Hauthal et al., 2013; Shiell et al., 2014), the random dot motion task, we found no significant difference based on hearing status, adding to the current literature showing either enhanced or no difference in behavioral response to random dot motion or other low-level motion stimuli. Our finding diverges from previous studies on perceptual expertise that found signing deaf participants are faster and more accurate when detecting small visual differences in motion, such as responding to dots moving in a particular direction (Hauthal et al., 2013) and other visual motion detection tasks (Shiell et al., 2014). Another study that investigated the effect of signed language experience and hearing status in spatial attention and motion discrimination tasks also found similar findings as our present study, with deaf signers showing overall no difference in thresholds and RT responses compared to hearing signing and nonsigning participants (Bosworth & Dobkins, 2002). Despite this developing understanding of the effects of cross-modal plasticity on behavioral responses, many neuroimaging studies of humans and animal models have shown that the deaf brain shows different patterns of neurophysiological responses to visual motion stimuli compared to the hearing brain. Through those different behavioral and neurophysiological findings on deaf people and animals' motion perception, we can cut through those studies to show what has been obvious to the deaf and signed language community over the past decades—that both lack or exposure of signed language as a deaf child has a long-lasting and measurable impact on their cognition and perception, such as math, spatial language, and second language processing (Karadöller et al., 2021; Lillo-Martin & Henner, 2021; Santos & Cordes, 2022; Skotara et al., 2012). Now, we turn to our findings regarding deaf signers' enhanced performance in person perception and action identification, which suggests that their brains may be more attuned to the meaningful movement of humans than more simple low-level visual motion stimuli.

Our results indicate that deaf individuals have a heightened ability to quickly perceive and respond to human movement. This is demonstrated by their significantly faster response times (RTs) in person perception tasks and greater efficiency, as indicated by lower IES, in action identification tasks compared to hearing participants. Our findings suggest that the attention of deaf individuals may be more acutely focused on both the meaning and the sensory aspects of human movements in their environment, potentially leading to quicker recognition of biological motion. This enhanced sensitivity could be an adaptive trait, considering that humans are a primary source of meaningful movements, including those involved in signed languages, physical actions, or signaling the presence of

someone entering a room. For deaf people, prioritizing rapid responses appears beneficial, even if it comes at the cost of accuracy.

Now, we discuss our findings that deaf people's biological motion perception of meaningful everyday actions is enhanced by early exposure to ASL. Overall, we found that on the most complex task of action identification, deaf participants were significantly faster and less accurate than hearing participants. On the surface, this effect could be the long-observed speed–accuracy trade-off that has been found in studies on expertise in perception, movement, and decision-making in various populations (Beilock et al., 2008; Chittka et al., 2009; Heitz & Schall, 2012; Henmon, 1911; Khalvati et al., 2021; Liu & Watanabe, 2012; MacKay, 1982; Penconek, 2022; for broad review of speed–accuracy trade-offs, see Bogacz et al., 2010 and Heitz, 2014), but the current findings regarding our deaf participants offer new insights on the effect of early signed language exposure. Our study's finding on the speed–accuracy trade-off reveals an experiential effect that has been long observed in signed language perception literature but not as frequently discussed in sensory perception and cross-modal plasticity research—that the effect of age of acquisition of a signed language as a deaf child has a measurable and long-lasting impact on their perception and cognition. Our findings suggest that deaf signers who learned ASL later in life are more likely to prioritize response speed at the cost of accuracy in the face of complex biological motion perception tasks. This suggests that early exposure to a signed language could play an important role in deaf children's cognitive development. However, the exact nature of the effect is a question for future studies.

The quicker and more efficient responses of deaf participants who acquired ASL early in life may stem from their superior perception of biological motion, enabling them to rapidly process complex and dynamic human movements and actions at the onset of stimuli. Our past work using a similar task (Quandt et al., 2021) revealed that deaf early signers show earlier and faster visual processing in the electrophysiological responses of their sensorimotor systems. This early perceptual advantage was evident even in tasks that did not require responding during the stimulus presentation. In the same study, we also found that deaf participants of a wide range of AoA reported that less effort was needed to identify the type of action in the PLDs. With the additional context provided by the present study, we can interpret the self-reported effort level with the addition of RT and accuracy measures, showing that deaf participants' reported effort level may reflect their efficiency in precepting meaningful human movements in their everyday environment. Our current work builds upon this to suggest that the ability of deaf people to extract meaningful information from complex human movement stimuli may enhance their predictive processing of human movement trajectories, allowing them to anticipate potential future actions more effectively.

Our finding shows that the age of signed language acquisition changes deaf people's biological motion perception, possibly due to the impact of language deprivation (W. C. Hall, 2017; W. C. Hall et al., 2017, 2019; Lillo-Martin & Henner, 2021). The effect of age acquisition of signed language has not been widely investigated in the current sensory perception and cross-modal plasticity literature (Alencar et al., 2019). One reason that the effect of AoA on deaf people's sensory perception has not been observed until now may stem from framing signed language experience as a binary question

where the person either knows a signed language or not (Alencar et al., 2019; Bosworth & Dobkins, 2002; Cardin et al., 2013; Fine et al., 2005). This binary question that focuses on deaf signers who have been exposed to signed language from a young age as an experimental design will have a difficult time in capturing the rich and nuanced experience of deaf people that may have an observable effect on their sensory perception. For instance, the developmental stages of biological motion perception in neural regions such as the inferior frontal gyrus may be extended into adolescence if the child does not receive sufficient social experience in early childhood (Nelson et al., 2007; Sheridan et al., 2022). Similarly, our findings could suggest that the lack of signed language exposure in early childhood (i.e., late AoA of a signed language) may impact deaf children's biological motion perception as deaf adults, as they may not receive enough human interaction input that allows for cross-modal reorganization of their brain, cognition, and perception.

This gradual effect of AoA on our deaf group's accuracy in action identification task supports the notion that we must investigate further how social deprivation and the subsequent impact on biological motion simulation and perception differs from the sensitive period of language, where insufficient access to language and communication has been described and discussed to drive the observed changes in language, cognitive, and socioemotional outcomes (Cheng et al., 2023; M. L. Hall, Hall & Caselli, 2019; Henner & Robinson, 2023; Koulidobrova & Pichler, 2021; Richardson et al., 2020). By better understanding the nuances of different developmental stages across the rich breadth of deaf experiences, we can more effectively understand how signed language knowledge changes how deaf people see complex human movements and the world around them. Next, we turn to another group of interest in our study: the signing participants of all hearing statuses.

Age of ASL Acquisition Effects

A critical variable in the studies with sign language users is the age at which a person first receives systemic exposure to the signed language. The effect of ASL knowledge on a person who is an early AoA signer, using ASL as a primary language since birth, is likely to be very different from the effect of ASL knowledge on someone who started learning in adulthood (Lillo-Martin & Henner, 2021). Our study revealed that early exposure to signed language (early AoA) enhances accuracy overall and specifically in action identification tasks, independent of hearing status. This supports our exploratory hypothesis. However, our primary hypothesis that early AoA would lead to faster reaction times in action identification and random dot motion tasks was not confirmed. Our results indicate that individuals exposed to signed language from a young age are particularly skilled at recognizing human actions in their visual field, even under difficult conditions, such as when our PLD stimuli were inverted. These findings suggest that early sign language exposure may confer advantages in complex visual perception, consistent with previous research on the broad cognitive benefits for signed language users in areas like motion, spatial, and action perception (Kubicek & Quandt, 2021; Quandt et al., 2021; Stoll & Dye, 2019). Furthermore, we found that an earlier AoA predicted higher action identification accuracy among deaf participants, highlighting that early signed language exposure significantly influences perception and cognition in deaf people.

We found that our primary hypotheses regarding the effect of signed language experience on RT on random dot motion and action identification tasks were not supported. We compared four measures of signed language experience: self-reported ASL fluency, deaf early signers compared to hearing nonsigners, signers compared to nonsigners. The hypotheses regarding measures of signed language experience were not supported. However, the exploratory hypothesis of the effect of the AoA on accuracy was supported. We found that earlier AoA in deaf, along with all hearing status groups, is significantly associated with higher accuracy in the action identification task. One unique aspect of our finding is that it generalizes perception outside of signed language movement into the perception of complex human movement. Generalization from signed language experience to complex human movement could be due to our signers' visual perception brain regions developing stronger connections between language and motion-processing brain networks, which could explain our present study's finding that knowing a signed language improves biological motion perception of everyday complex human movements (Banaszkiewicz et al., 2020; Cheng et al., 2023; Quandt et al., 2021). Below, we discuss how incorporating this finding into our understanding of the nature of signed languages and biological motion perception unveils signers' dynamic visual perception.

The early AoA signers' expertise in accurately identifying the PLDs of actions may come from one of the unique modality-specific aspects of observing signed language—viewing sustained, complex, and meaningful movements from start to end. Successful signed communication requires users to simultaneously process complex and dynamic combinations of manual, facial, and bodily movements occurring nonlinearly to successfully understand the meaning and language units from a rich multisensory visual input (Emmorey, 2021; MacSweeney et al., 2008). Signed languages contrast with spoken languages by providing a dynamic visual transitional movement from signers as soon as they start moving before the onset of signed words (Brozdowski & Emmorey, 2023; Emmorey et al., 2022; Willis, 2023). With this high level of visual attention toward human movement, signed words, and meaning in signers' day-to-day signed language interaction with other people, our signers' biological motion perception may be more able to rapidly simulate and weigh different possible complex movements and meanings during the perception of transitional movement toward the signed word and action. With this rich evidence of the importance of movement perception during signed language perception, the high level of expertise in complex biological motion processing could attune signers' visual perception to more efficient processing of complex visual motion with visual-spatiotemporal properties, such as the direction, position, and speed of complex human movements similar to that observed in signing humans (Bosworth et al., 2019). Our findings in this study further support the notion that the early acquisition of signed language facilitates the efficient perception and understanding of general nonsigned complex biological motion perception, such as our PLD stimuli of everyday actions.

We started this study with questions regarding the nature of deaf signers' visual perception: Do the changes come from hearing status or signed language experience? Might these changes manifest only in certain types of motion perception, and if so, which types of perception are affected? We show that the answer is that both hearing status and ASL experience confer changes to the accuracy and speed of responses. Our findings on the effects of earlier AoA in our action identification task suggest that the age of signed language exposure changes the signer's biological motion and sensory perception. However, it is not clear if this finding of the relationship between age of signed language acquisition and biological motion perception could be from language deprivation or the diverse sensory and social environments, both good and bad, that deaf people encounter (Henner & Robinson, 2023; Koulidobrova & Pichler, 2021; Nelson et al., 2007; Sheridan et al., 2022). Future research will need to investigate the developmental trajectories of deaf children's biological motion perception and how AoA effects of learning a signed language may impact the cross-modality plasticity of their auditory cortex.

Constraints on Generality, Limitations, and Future Directions

While our study recruited a large and diverse sample regarding ASL fluency and hearing status, generalizability may still be a concern. As seen in Figure 1, despite our efforts to recruit a broad sample of people with varied hearing status and ASL fluencies, we had little representation from deaf nonfluent signers and a modest sample of people reporting ASL fluency in the middle of the 0–5 range. These limitations constrained our analyses regarding ASL fluency, given the scarce data points for some ASL fluency scores. Thus, the variable of AoA was more informative for the present study, suggesting that future work also carefully considers asking participants about their ASL expertise using measurements that fully capture the nuanced language experiences of signers, both deaf and hearing (e.g., asking about fluency, age of exposure, and usage preferences).

In addition, certain details of our sample population were not included here. Our sample was composed of ASL users, and the extent to which these results apply to users of other signed languages remains unknown. Additionally, our study did not account for cultural, educational, and sociodemographic variables that may have influenced our results. Our analyses did not distinguish between left- and right-handed signers. It could be interesting to examine whether there are differences in the processing of biological motion depending on the handedness of the signers. Methodologically, using online tasks for data collection might have introduced some variability in participant performance due to differing environments, levels of distraction, and quality of hardware or internet connection when completing the tasks.

The present study reveals several associations between AoA, hearing status, and biological motion perception. However, it is important to underscore that these results are correlational, limiting our capacity to draw definitive causal inferences. One plausible interpretation of our findings is that engagement with signed language—due to the visual, spatial, and meaning complexity inherent in its structure—may enhance one's proficiency in detecting motion. Yet, an alternative interpretation must also be considered. Especially for hearing signers, it is conceivable that the relationship between ASL proficiency and enhanced biological motion perception is not one of cause and effect but instead a correlation rooted in individual variability in spatial skill and complex motion perception. Individuals who already possess superior skills in these areas may experience more success in signed language acquisition, thereby motivating continued ASL study. Consequently, while our findings contribute to the literature on language experience and perception,

further research is warranted to disentangle these relationships' precise nature and directionality.

Conclusion

Our research provides new and nuanced insights into the relationship between signed language acquisition, hearing status, and biological motion perception. By adopting an integrative approach and analyzing a diverse sample of deaf and hearing people with varying acquisition ages in ASL, we have teased apart the impacts of these variables on biological motion perception. Results suggest that hearing status and early signed language acquisition impact individuals' ability to perceive complex human actions and movements. More specifically, early acquisition of signed language was associated with better accuracy, and being deaf led to faster reaction times during the action identification task. This finding highlights the potential cognitive benefits derived from early and immersive interactions with a visually dynamic language like ASL, not just for deaf people but across the hearing spectrum. In line with other recent work showing that deaf people's systematic use of ASL serves as a protective factor in emotion expression, our results point to a possible protective effect of early ASL acquisition for biological motion perception. Indeed, our results suggest that early ASL acquisition is associated with more accurate action identification, and being deaf is associated with faster responses to motion stimuli. Taken together, these findings highlight the unique visual perception profiles of deaf lifelong signers.

Of particular interest, our findings also show that the effects of ASL, AoA, and hearing status varied across the three different tasks. This suggests that the visual and physical expertise acquired through early signed language exposure, alongside differences in hearing status, differentially impacts the perception of various types of motion, going beyond past work that has typically considered motion perception along a single dimension. Our research adds a fresh perspective to the literature on cross-modal plasticity in the face of sensory deprivation and the effects of language experience on perception. As such, it has potential implications for cognitive psychology, health and clinical outcomes, and education practices, particularly for those who are deaf or hard of hearing. By focusing on the potential strengths of signed language users and deaf people, this work underscores the importance of considering linguistic and sensory diversity in our understanding of human perception and cognition.

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