Deaf Signers Adapt Their Eye Gaze Behaviour When Processing an Unknown Sign Language

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Abstract

Sign languages are perceived visually and externalized using a signer's hands, face, and upper body. During sign language comprehension, deaf signers primarily focus their gaze on the face, while hearing non-signers attend more to the hands of a signer. Little is known about whether deaf signers adapt their gaze behaviour when processing unknown signs. Here, we report eye-tracking data from 15 deaf native signers of German Sign Language (DGS) and 15 hearing non-signers who were presented with videos in either DGS or an unknown sign language, all containing no linguistic mouth actions. Our data confirm that deaf signers generally fixate more on the face of a signer than hearing non-signers who attend to the hands in sign space. Moreover, only deaf signers increase their attention to the hands when processing video stimuli consisting of unknown signs compared to familiar signs, suggesting similar adjustment behaviours as observed in spoken languages.

Keywords: sign languages; visual attention; gaze behaviour; mouthings; mouth gestures; German Sign Language (DGS)

Introduction

We know that individuals processing spoken language adapt their gaze to aid comprehension in non-ideal listening situations (e.g., listening to a foreign language) but not whether there is equivalent behaviour in sign language processing. This matters because it tells us something about the flexibility of the language processing mechanisms and how these adapt to language in different modalities. Thus, the goal of the present study was to investigate how deaf signers adapt their gaze behaviour when faced with an unfamiliar sign language.

The world's different sign languages of deaf people are expressed and perceived in the visuo-spatial modality. Just like hearing people comprehending a spoken language, deaf signers focus their gaze on the face and, more specifically, the eyes of their interaction partner (Emmorey, Thompson & Colvin, 2008; Mastrantuono et al., 2017). One reason for this is that a lot of linguistic information in sign languages is conveyed via nonmanual markers in the face (Pendzich, 2020), Non-signers, on the other hand, have been observed to focus their gaze primarily on the hands of a signer when presented with sign language stimuli (Kubicek & Quandt, 2019). In both language modalities, speech and sign, the individuals usually focus on the eyes: But while the visual speech information in spoken language perception coming from the mouth of a speaker is in close proximity to the eyes, the language information in sign language perception comes from a

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potentially much larger range. The sign space usually ranges from anywhere on and above the head and face of a signer to the hips of a signer, and most commonly takes place somewhere about chest height (regarding the use of sign space see e.g., Emmorey et al., 2000). Since visual focus is on the eyes of a speaker or signer, this means that, while visual information in speech (mouth and lip movement) is mostly perceived in the central or paracentral vision, visual language information in sign is— in addition to the essential non-manual markings on the face (Pendzich, 2020)—also perceived in peripheral vision (from the head to the hips).

As a consequence, signers have been observed to have increased visual perception abilities in the periphery compared to non-signers. Moreover, they generally outperform hearing, non-signing individuals in tasks related to visuo-spatial and visuo-temporal processing: (Deaf) signers display increased spatial attention in the periphery (Bottari et al., 2011; Bavelier et al., 2000; Proksch & Bavelier, 2002), are more influenced by peripheral distraction (Chen at al., 2010), and have faster reaction times in peripheral detection tasks and show higher accuracy for such tasks (Codina et al., 2017). They show shorter reaction times for asynchrony in visual stimuli (Nava et al., 2008), and improved abilities in synchronized finger tapping (Iversen et al., 2015), but comparable visual temporal thresholds for the periphery and center to hearing non-signers (Heming & Brown, 2005), and poorer estimation of the duration of visual stimuli (Kowalska & Szelag, 2006).

While several studies have shown that deaf signers outperform hearing non-signers in a number of visual processing tasks, we know less about their visual language processing in non-ideal conditions. During normal language comprehension, signers have been observed to maintain eye contact like hearing non-signing adults do in spoken interactions (Emmorey et al., 2008). But while hearing non-signers show adjustments in their gaze behaviours under non-ideal listening conditions, we do not know how signers perform in language processing tasks in non-ideal conditions, e.g. of an unfamiliar sign language.

One study investigated deaf participants' gaze behaviour in (spoken) second language exposure: it was found that when confronted with an unfamiliar spoken language, while normal-hearing participants showed increased proportions of gaze to the mouth of the speaker, the deaf participants showed no such adjustment behaviour (Wang et al., 2020). Such adjustment behaviours to non-ideal listening conditions are commonly observed in hearing-speaking individuals' spoken language comprehension; If speech is presented at low volume (Lansing & McConkie, 2003), degraded (Sumby & Pollack, 1954), unclear or difficult to understand (Reisberg, Mclean & Goldfield, 1987; Vatikiotis-Bateson et al., 1998), hearing-speaking adults have been observed to look more at the mouth of a speaker than under unaltered conditions. Most relevant to the present study, there is evidence that adults in a second language learning environment show similar gaze behaviours, with higher proportions of looks to a speaker's mouth (Hirata & Kelly, 2010; Navarra & Soto-Faraco, 2007). Increased visual attention to the mouth of a speaker and away from the eyes of the speaker have been reported repeatedly in a number of different contexts and taken as indicators of increased recruitment of visual speech features to support auditory speech comprehension (Rennig et al., 2020).

Another study has investigated signers' gaze preferences in American Sign Language (ASL) when presented with isolated real signs, pseudo signs, real finger-spelled words, and pseudo finger-spelled words (Gappmayr & Lieberman, 2024). The authors found an effect of sign type as well as familiarity – seeing real ASL signs, signers showed a face preference, looking at pseudo signs and fingerspelled words both increased looks to the signer's hands.

While these studies show mixed results, to the best of our knowledge, no previous work has investigated whether and how signers adjust their gaze behaviour if confronted with stimuli of full sentences in a sign language unknown to them. Such knowledge is relevant to improve our understanding of the influence of modality-specific language experience on visual attention and to disentangle the mixed results of previous studies investigating signers' gaze preferences. Understanding how signers employ visual attention to navigate a familiar language in comparison to an unfamiliar language will deepen our understanding of the adaptability of the language processing mechanism and whether, and if so how, it adapts to difficult to comprehend input in the sign modality.

The aim of the current study was to investigate how deaf native signers distribute their gaze when confronted with an unknown sign language, in the absence of potentially informative mouth-actions (i.e. mouthings or mouth gestures). We compared the gaze preferences of native deaf signers to gaze preferences of hearing non-signers, who should not be able to differentiate between the two languages for two reasons: first, because they are unfamiliar with both sign languages, and second, because we ensured that the intensity of the movements across the two language conditions did not differ significantly. Specifically, we investigated, whether deaf native signers showed any adjustment behaviours in their gaze when confronted with an unknown language, as has been observed for hearing-speaking individuals confronted with an unknown spoken language.

We hypothesised (1) that deaf signers would, overall, fixate more on the face of a signer and less to the rest of the sign space than hearing non-signers, due to increased visual processing abilities, and (2) within the number of fixations to the face, we expected signers as well as non-signers to show a preference for the signer's eyes compared to the signer's mouth. Finally, (3) comparing the two language conditions, we expected no effect of language for the non-signers, as they should not be able to tell the languages apart. For the deaf signers, we expected an effect of language, as the absence of potentially-informative mouth actions should force them to seek further visual information about the unknown sign language in the sign space. Therefore, we expected signers to increase their fixations to the sign space in the unknown sign condition compared to their native sign language.

Methods

Participants

Participants were 15 adult deaf native signers (10 female, 5 male) and 15 adult hearing non-signers (9 female, 6 male). The signers had a mean age of 32.0 years (SD = 9.66), while the hearing non-signers had a mean age of 30.6 years (SD = 8.17). All signers reported German Sign Language (DGS) as their primary and preferred means for communication. All non-signers were native speakers of German. All deaf participants were born deaf (n = 14) or became deaf before the age of 2 years (n =1). The mean age of sign language acquisition was 0.93 years (SD = 2.02, whereas 12 participants acquired DGS from birth). All participants acquired DGS either from their parents (n = 11), in a preschool or school setting (n = 2), or from both, their parents and in school (n = 2).

Experimental Setup

The data presented here were collected as part of a larger project investigating the neural basis of syntactic processing in DGS (Trettenbrein et al., under review). Accordingly, eye-tracking data were collected using an EyeLink 1000 Plus eye-tracker (SR Research Ltd., Kanata, ON, Canada) mounted outside the scanner, measuring eye movements via a mirror inside the scanner, while participants underwent functional magnetic resonance imaging. Stimuli were presented using PsychoPy (version 2021.2.3; Peirce, 2008) and projected on a 1024 × 768 pixel screen visible via an eye-tracking compatible mirror projection system mounted on the head coil. The data, processing and analysis scripts for the current study are available here: https://osf.io/pv6ka/

Procedure

The experiment was split into two runs (each approximately 25 minutes long) with a break in between where participants left the scanner. Each participant received an individual, pseudo-randomized stimulus list for both runs, whereas the respective stimuli used were the same for all participants for the respective run. To avoid the influence of having participants perform an overt task during every trial, we employed a passive paradigm using relatively short sentences and lists of unconnected signs where participants had to constantly monitor the screen, yet only actively responded via button press during catch trials using filler items which occurred at random intervals.

Stimuli

In total, participants watched 240 video clips (including 64 fillers items not included in the analysis), edited and controlled for different psycholinguistic variables (Trettenbrein et al., 2021) as well as low-level motion properties (Trettenbrein & Zaccarella, 2021) to ensure consistency across conditions. The four experimental conditions were: (i) Signed sentences in DGS including pointing and agreement as markers of spatial syntax (condition: "DGS sentence"), (ii) lists of unconnected signs in DGS matched in length and visual complexity to the stimuli of the "DGS sentence" condition (condition: "DGS list"), (iii) sentences using signs from a sign language unknown to all deaf participants (UnkS) containing markers of spatial syntax (pointing and agreement) but devoid of lexicalized meaning (condition: "UnkS sentence"), and (iv) lists of unconnected signs also drawn from an unknown sign language not carrying any lexicalized meaning to the participants (condition: "UnkS list"). For the purpose of the current study, we were interested in the familiarity comparison and collapsed the sentence and list condition across each language condition. Filler and catch trials were not included in our analyses. Natural mouthings and mouth gestures as well as facial expressions were suppressed in all conditions and the signer instead maintained a neutral face with the exception of the non-manual marking of manual pointing and agreement locations in sign space using eye gaze (For further details about the stimuli see Trettenbrein et al., under review).

Regions of Interest

For each stimulus we created a flexible region of interest (ROI) for the gaze location, considering the movement within each video item. We identified four ROIs (Figure 1):

- Face (chin to forehead)
- Sign Space (body and hands, not face or head)
- Upper Face (nose to forehead)
- Lower Face (nose to chin)

The highest, lowest, leftmost and rightmost point of each ROI per item was identified using the motion tracking software MediaPipe (Google, n.d.). These minimum and maximum points then defined the ROIs' area for each individual item. A margin of 10 pixels was then drawn around each ROI. The ROIs *Upper Face* and *Lower Face* together form the ROI *Face*. The ROI *Sign Space* consists of all body and hand movements, excluding the face region. As a first step, we determined whether we could observe differences in gaze preferences in the two participant groups, deaf native signers and hearing non-signers. We compared the proportion of time spent by each participant group looking at (1) the ROIs *Face* vs. *Sign Space*, and (2) in a more fine-grained comparison within the ROI *Face*, we compared proportions of time spent looking at the ROIs *Upper Face* (nose to forehead) vs. *Lower Face* (nose to chin).

Motion Parameters

In addition to ROIs, we also extracted parameters of the intensity of motion of the signing for each item from the motion tracking software. We used these to control for equal amounts of motion within the two language conditions. We also used the motion parameters as a predictor in our statistical analysis to ensure that the differences in motion between the items did not influence the gaze behaviours of the participants.

Figure 1. Overview of our 4 Regions of Interest (ROIs): *Face* (green), *Sign Space* (red), *Upper Face* (yellow), *Lower Face* (blue). Each Region of Interest is defined flexible per presented item and covers the maximum of each ROIs extend per item.

Statistical Analysis

We compared the gaze preferences of the two participant groups, deaf signers and hearing non-signers, across all items divided by the different sign language conditions, DGS or UnkS.

First, we compared the two ROIs *Face* and *Sign Space*. We conducted two linear mixed effects models to assess the effect of participant group and language condition, as well as their potential interaction, on the fixations to the ROI *Face* and *Sign Space*. The models also included random effects for participants, session and item (fixations to the ROI (signer's *Face / Sign Space*) ~ participant group*language + motion parameter + (1 | Participant) + (1 | session) + (1 | item)).

Second, we drew a group comparison of the two participant groups in their gaze preferences to the ROIs *Upper Face* and *Lower Face*, when fixating to the *ROI Face*. As the ROIs *Upper Face* and *Lower Face* are mutually exclusive, we calculated a proportion of looking score. We conducted a linear mixed effects model to assess the effect of participant group and language, and their potential interaction, on this preference score. The models also included random effects for participants, session and items: (proportion of looking score (ROI *Upper Face* – ROI *Lower Face*) ~ participant group*language + motion parameter + (1 | Participant) + (1 | session) + (1 | item)).

Results

Gaze Preferences ROI Face vs. ROI Sign Space

Overall, hearing non-signers spent on average 25% (SD = 24.48%) of the time fixating on the signer's *Face* and 70% (SD = 26.27%) of the time fixating on the *Sign Space*, while deaf native signers spent on average 49% (SD = 33.97%) of the time fixating on the signer's *Face* and 46% (SD = 32.7%) of the time fixating on the *Sign Space*. For the comparison of the two participant groups, deaf signers and hearing non-signers, we found a significant effect for participant group on the proportion of fixations to the signer's *Face* (β=-24.33, SE=5.99, t= -4.06, p <.001) as well as for fixations on the *Sign Space* (β= 24.63, SE=5.48, t= 4.5, p<.001, Figure 2). Deaf signing participants looked more at the signer's face and less at the Sign Space than hearing non-signing participants.

We also found a significant effect for Sign Language (DGS or UnkS) on the proportion of fixations to the signer's *Face* (β= -4.03, SE=1.1, t= -3.66, p<.001) as well as for fixations on the Sign Space (β=4.45, SE=1.14, t=3.89, p<.001). We found an interaction between the two predictors Language and Participant Group for the proportion of fixations to the *Sign Space* (β=-3.14, SE=1.48, t=-2.12, p<.05), but not for the proportion of fixations to the signer's *Face* (β=2.57, SE=1.42, t=1.81, p=0.07). Deaf signers looked more to the ROI *Sign Space* and less to the ROI *Face* in the UnkS than in DGS, while hearing non-signers showed no effect of language condition. We found no effect of sign motion on the number of gaze fixations onto the signer's *Face* (β=2.23, SE=2.29, t=0.97, p =.33) or the *Sign Space* (β=3.44, SE=2.39, t=1.44, p=.15).

Both models fit the data well (ROI *Face*: AIC= 44088.71, BIC= 44146.92, R^2 (cond.) = 0.41, R^2 (marg.) = 0.13, ICC= 0.31, RMSE= 24.2; ROI *Sign Space*: AIC= 44489.47, BIC = 44547.67, R^2 (cond.) = 0.36, R^2 (marg.) = 0.13, ICC= 0.26, RMSE= 25.29).

Proportion of Looking Time: ROI Upper Face vs. ROI Lower Face

When fixating on the face, hearing non-signers spent on average 36% of the time fixating on the ROI *Upper Face* and, accordingly, 64% (SD = 38.21%) of the time fixating on the

ROI *Lower Face*, while deaf native signers spent on average 33% of the time fixating the ROI *Upper Face* and accordingly 67% (SD = 38.59%) of the time fixating the ROI *Lower Face*. We assessed the effects of participant group and language, and the potential interaction of both predictors on the fixations within the face, splitting these into the ROIs *Upper Face* and *Lower Face*. As the two ROI *Upper Face* and *Lower Face* are mutually exclusive, we have calculated a proportion of looking score.

We found no significant effect for either participant group (deaf signers or hearing non-signers, β= 12.63, SE=15.82, t=0.8, p=.43), language (DGS or UnkS, β=-4.03, SE=2.9, t=-1.39, p=.16, Figure 3), the interaction of participant group and language (β=1.1, SE=4.1, t=0.27, p=.79), nor for the motion parameter (β=8.87, SE=6.45, t=1.37, p=.17) on the proportion of fixations to the upper and lower of the signer. The model explained less of the variance than the models for ROI *Face* and ROI *Sign Space* (proportion of looking score model: AIC= 43635.46, BIC= 43691.88, R^2 (cond.) = 0.31, R^2 (marg.) = 0.008, ICC=0.31, RMSE= 63.7).

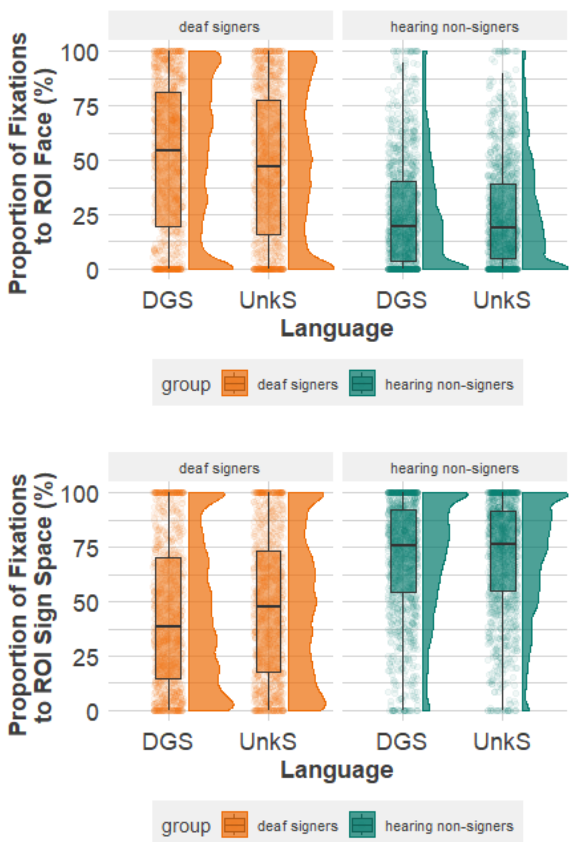

Figure 2. Fixation onto ROI *Face* (top) and ROI *Sign Space* (bottom) divided by participant group (orange: deaf signers and green: hearing non-signers) and Sign language (DGS: left, UnkS: right) in percent. Points represent raw data. Bean shows smoothed density curve illustrating the full distribution. Error bars show frequentist confidence intervals.

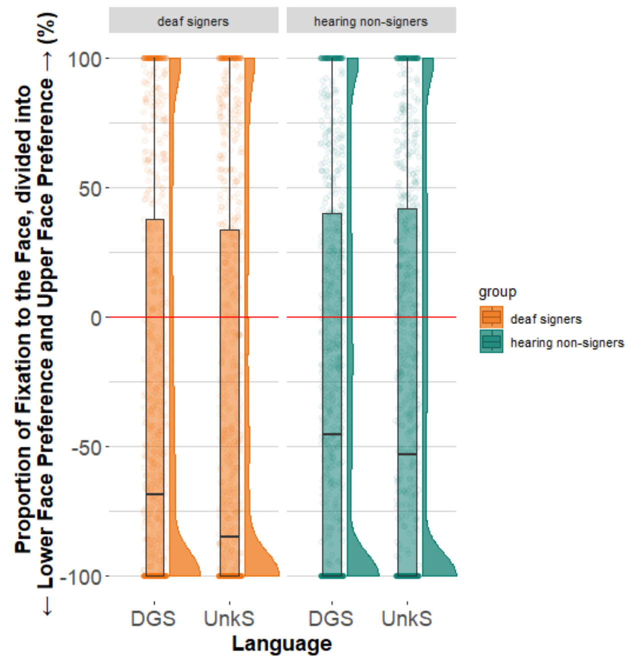

Figure 3. Proportion of Fixation onto the ROI *Face*, divided into fixations onto the ROI *Upper Face* and ROI *Lower Face*, displayed as a preference score. Negative values represent a *Lower Face* preference, positive values an *Upper Face* preference. Plot is divided by participant group (orange: deaf signers and green: hearing non-signers), and Sign Language (DGS: left, UnkS: right) in percent. Points represent raw data. Bean shows smoothed density curve illustrating the full distribution. Error bars show frequentist confidence intervals.

Discussion

Comparing deaf native signers' and hearing non-signers' visual attention during sign language processing, we report on two sets of results: First, we find differences between the participant groups in their overall gaze preferences. Second, within the group of deaf native signers, but not hearing non-signers, we find differences in gaze behaviour driven by sign language familiarity.

Overall, deaf native signers of DGS looked more to the *Face* of the signer than the *Sign Space* (hand movements not located on the head of the signer), while hearing non-signers looked more to the *Sign Space* than the *Face* of the signer. This is in line with previous findings for American Sign Language (ASL; see Emmorey et al., 2008; Gappmayr & Lieberman, 2024). Within the focus on the face, both groups directed more attention to the *Lower Face* of the signer than to the signer's *Upper Face*.

For hearing non-signers, the visual attention to the signers' *Lower Face* could be a result of them being presented with unfamiliar linguistic stimuli. This would be in line with previous studies that have observed such adjustment behaviors in non-ideal language perception tasks for spoken languages. For deaf signers, increased looks to the mouth, despite the absence of mouth actions, could be caused by the unnaturalness of the missing mouth actions However, increased attention to the mouth, could also emphasize the importance of mouthings and mouth gestures in DGS and other sign languages.

This could result in the mouth being the main focus of visual attention within a signer's face, even in the (for signers perceived as unnatural) absence of mouthings and mouth gestures. Future research is needed to determine whether the observed focus on the mouth is a natural feature of visual attention in sign languages or a result of our stimuli design, which excluded mouth actions and facial expressions. This could be studied by comparing gaze behaviors of participants presented with stimuli with and without natural facial expressions in the lower and upper face.

Comparing gaze behaviours for the stimuli in DGS and in the unknown sign condition, we find a significant effect of participant group and language, for both the gaze to the *Face* and the *Sign Space*. Deaf signers look overall more to the *Face* and less to the *Sign Space* than hearing non-signers. The main effect of language was moderated by an interaction between participant group and language for the *Sign Space*, but not for the ROI *Face*. Deaf signers employed more looks to the ROI *Sign Space* and fewer looks to the ROI *Face* in the unknown language condition than in the familiar language condition. Such an effect was absent in the hearing non-signers. Within the face fixations, comparing looks to *Upper Face* vs *Lower Face*, there was neither an effect of participant group, nor language, and there was also no interaction between the two.

Overall, the results support previous findings using other sign languages that show that deaf signers look overall more to the face of an interlocutor than to the sign space, and that deaf signers look more to the face than hearing non-signers. This suggests that signers indeed make use of their peripheral vision abilities during sign language processing, perceiving the manual signs in the peripheral field of view while centring their fixations onto the signer's face. Hearing non-signers, on the other hand, are unfamiliar with sign languages and focus more on the sign space, likely influenced by the higher amount of motion observed in the sign space than in the signer's face. For the deaf signers the face is likely the centre of focus for two reasons: the upper face serves a social function, providing eye contact, but also conveying emotions as well as linguistic non-manual information essential for sign language comprehension. The signer's lower face serves further linguistic purposes, providing important information, e.g. mouthings and mouth gestures.

Our findings of gaze adjustment behaviours are in line with previous findings in ASL, which also observed increased gaze to the sign space in pseudo signs and finger-spelled words compared to real signs and finger-spelled words (Gappmayr & Lieberman, 2024). The shift of increased looks to the signer's hands in the sign space away from the signer's face suggest an increased recruitment of central vision to support the processing of an unknown sign language. This parallels observation of adjustment behaviours in hearing non-signers' spoken language processing of, for example, a second language, who adjust to look more at the mouth in order to use visual speech cues to aid processing.

Given the increased peripheral vision recruitment in signers' sign language processing, our findings of adjustment behaviours raise questions regarding the interplay of visual attention and peripheral vision. Future research should further investigate the adjustment behaviour of deaf signers to unfamiliar sign languages. In particular, our study did not allow us to connect gaze movements time sensitive to movements in the video stimuli, which resulted in us having larger ROIs that included the movement during the whole video. Future studies should explore the temporal dynamics of the observed gaze effects in more fine-grained detail. This will allow to better understand when and under which circumstances signers and non-signers shift their gaze from one ROI to another. The current findings extend previous work on visual plasticity in deaf signers by demonstrating that their gaze behaviour is not only specialized for native sign language processing, but also flexibly adapts when confronted with an unfamiliar sign language. This suggests that deaf signers actively modulate central versus peripheral visual attention in response to linguistic uncertainty, like hearing speaking individuals do in spoken language processing under non-ideal conditions. Our results support findings on the dynamic nature of visual attention in language processing. The current study provides new insights into how deaf signers balance visual attention between manual and non-manual articulators when confronted with an unknown sign language These findings suggest that familiarity with the form of linguistic signals modulates visual attention also in deaf signers.

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