Detection of Extraneous Visual Signals Does Not Reveal the Syntactic Structure of German Sign Language (DGS)

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Abstract

Sentences are not just mere strings of words or signs but manifest a complex internal structure. Linguistic research has demonstrated that sign languages and spoken languages both exhibit hierarchical constituent structure which determines how individual elements in a sentence relate to each other. Here, we report the first adaptation of the psycholinguistic "click" paradigm, which aims to demonstrate the relevance of hierarchical constituent structure during auditory language processing, to the visuo-spatial modality of sign languages. We performed two independent online experiments: The main experiment with a group of 53 deaf signers using German Sign Language (DGS) as their primary means of communication and a control experiment with a group of 53 hearing non-signers. Both groups were shown videos of syntactically complex sentences in DGS. A white flash (mimicking the "click" in the auditory domain) to which participants had to respond could occur as an overlay to the video at different levels in the constituent structure. Our pre-registered inferential analyses yielded no effect for our syntactic manipulations, neither in the group of signers nor in the group of non-signers. Additional exploratory analyses suggest general effects of attention during the processing of communicative signals, as even the group of non-signers' behaviour was influenced by non-manual cues despite their lack of knowledge of DGS. We conclude that the simultaneous and time-shifted presence of different syntax-relevant cues (i.e., hands, mouthings, and non-manuals) makes the sign stream robust against disruption by extraneous visual signals and argue that non-signers attend to some non-manual cues due to their resemblance of communicative gestures.

Keywords: sign languages; syntax; constituent structure; hierarchy; non-manuals; sign language processing; psycholinguistics

Detection of Extraneous Visual Signals Does Not Reveal the Syntactic Structure of German Sign Language (DGS)

The ability to use grammatical rules to combine lexical items (i.e., words or signs) into phrases and sentences forms the core of the human capacity for language (Chomsky, 2017; Friederici et al., 2017; Lenneberg, 1969). Within a sentence individual phrases are hierarchically grouped into constituents, essentially groups of lexical items that behave as units (Everaert et al., 2015). For example, in the English sentence in (1) the lexical items *[the new and interesting book]* form a complex constituent, which can be focused (i.e., made more prominent by moving it to the front) in a so-called cleft-construction as in (2):

(1) *The girl reads the new and interesting book in the park.*

(2) *It is [the new and interesting book] that the girl reads __ in the park.*

This does not apply to the non-unit *[new and interesting book in]* which is why the construction in (3) is considered ungrammatical (conventionally indicated by an asterisk):

(3) **It is [new and interesting book in] that the girl reads the __ the park.*

The theoretical necessity of such groupings of lexical items into constituents for adequate descriptions of linguistic structures and their relations to each other was recognised early and by now is firmly established (Everaert et al., 2015; Graffi, 2001; Harris, 1946; Nida, 1948; Pike, 1943; Wells, 1947).

Research over the past decades has established that the grammatical structure of sign languages also relies on the hierarchical grouping of lexical items into constituents (Cecchetto, 2017; Kocab et al., 2023; Mathur & Rathmann, 2014; Sandler & Lillo-Martin, 2001, 2008; Tang & Lau, 2012). For example, in the German Sign Language (DGS) sentence in (4) only the complete constituent [BOOK NEW INTERESTING] can be topicalized (accompanied by a non-manual marker in the form of raised eyebrows glossed as "top") by moving it to the front as in (5).

(4) PARK GIRL IX_{3a} BOOK NEW INTERESTING READ

"The girl reads the new and interesting book in the park."

(5) ____________________________top
[[BOOK NEW] INTERESTING] PARK GIRL IX_{3a} __ READ

"It is the new and interesting book that the girl reads __ in the park."

This is not true for [BOOK NEW] as a sub-unit of the constituent which is embedded in the complex adjective phrase so that extraction results in (6) which is considered ungrammatical.

(6) ___________top
*[BOOK NEW] PARK GIRL IX_{3a} [__ INTERESTING] READ

"It is the new book that the girl reads and interesting in the park."

The basic principles upon which language-specific syntactic structures are created are therefore remarkably similar across modalities (i.e., speech and sign) which is why some researchers treat them as abstract and largely universal (Chomsky, 1995; Pfau et al., 2018; Sandler & Lillo-Martin, 2001, 2008).

Besides theoretical necessity in the study of linguistic competence independent of the modality of language use (Chomsky, 1965; van der Burght et al., 2023), the relevance of hierarchical constituent structure during language processing has so far primarily been studied using auditory and written language, starting off in the 60s of the past century with the so-called "click" paradigm. In this classic psycholinguistic paradigm, participants have to detect an extraneous auditory signal (i.e., a click) inserted into a stimulus (Ladefoged & Broadbent, 1960), a manipulation which was used to demonstrate that grammatical structure which is not present in the auditory signal itself affects language comprehension (Fodor & Bever, 1965). Variations of the paradigm have been employed to study the phonological, lexical and syntactic structure of spoken and written language (Foss & Lynch, 1969; Garrett et al., 1966; Holmes & Forster, 1970a, 1972; Kellas et al., 1988; Seitz & Weber, 1974), as well as music recognition (Berent & Perfetti, 1993) and artificial grammar learning (Franco et al., 2015; Gómez et al., 2011). Beyond the "click" paradigm, many studies in psycholinguistics (e.g., Bever, 1988; Miller, 1964; see Levelt, 1995 an overview) and neurolinguistics (Dehaene et al., 2022; Friederici et al., 2017; Hale et al., 2022; see Zaccarella & Trettenbrein, 2021 for an overview) have as of now demonstrated the pertinence of hierarchical constituent structure during auditory and written language processing.

In contrast to the extensively studied auditory and written domain, the role of hierarchical constituent structure during sign language processing remains poorly understood. Research over the past decades has demonstrated that sign languages as well as spoken and written languages are both primarily processed in the brain's left-hemispheric language network (Campbell et al., 2007; Emmorey, 2015; Trettenbrein, Papitto, et al., 2021). On the one hand, electroencephalographic studies with evoked potentials have shown that deaf signers' brains show sensitivity to grammatical violations similar to the evoked potentials known from studies of spoken and written language processing in hearing non-signers (Capek et al., 2009; Hänel-Faulhaber et al., 2014; Hosemann et al., 2018). On the other hand, functional magnetic resonance imaging studies aiming to identify the neural basis of syntactic processing and hierarchical structure in sign language so far have yielded conflicting results (Matchin et al., 2021; Moreno et al., 2018; for in-depth discussion see Trettenbrein et al., in press). Psycholinguistic work on sign languages took an interest in syntactic processing in sign language already early on (e.g., Grosjean & Lane, 1977; Klima et al., 1979), but then has often focused on lexical and semantic processing as well as modality-specific phenomena such as iconicity (Baus et al., 2013; Bosworth & Emmorey, 2010; Carreiras et al., 2008; Gutiérrez-Sigut & Baus, 2021; Thompson et al., 2009). To the best of our knowledge, no recent psycholinguistic studies have investigated hierarchy or constituent structure in sign languages.

The present study is the first to probe the relevance of hierarchical constituent structure during sign language comprehension by adapting the classical psycholinguistic "click" paradigm from the auditory-oral modality of spoken languages to the visuo-spatial modality of sign languages. Using short white flashes inserted into videos of DGS sentences as analogues to clicks in the auditory domain, we sought to determine whether deaf signers, like hearing speakers, automatically attribute constituent structure onto sequences of signs during sign language comprehension. We performed a pre-registered online experiment in which deaf signers watched videos of DGS sentences and had to respond to the white flashes, which could occur at different points in the constituent structure, as quickly as possible via button press. To rule out that observed effects are perceptual in nature we performed a second independent pre-registered online experiment using the same stimuli and experimental paradigm with a group of hearing non-signers as participants. We observed no effect of our syntactic manipulations in either experiment. Additional analyses revealed effects of topicalization and uncertainty for both groups. We discuss these findings by highlighting the simultaneous and time-shifted presence of syntax-relevant cues (i.e., hands, mouthings, and non-manuals) in the sign stream and argue that non-signers attend to some non-manual cues despite their lack of sign language knowledge, because they resemble communicative gestures (Hermann & Pendzich, 2018; Pendzich, 2020).

Materials and Methods

The experimental design, hypotheses, planned analyses, as well as stimulus materials were pre-registered independently at the Open Science Framework for both experiments. The full text of the pre-registration including stimulus materials for the main experiment with deaf signers can be found here: https://doi.org/10.17605/OSF.IO/N29AZ. The full text of the pre-registration for the control experiment with hearing non-signers can be found here: https://doi.org/10.17605/OSF.IO/9FR25.

Participants

Before the start of experiment, participants in both experiments gave informed consent via button press. All participants received monetary compensation for participating in the study, regardless of whether they successfully completed the respective experiment. Participants were recruited from institutional databases and by distributing advertisements at deaf clubs and organizations as well as on the internet. All procedures were approved by the local ethics committee at the University of Leipzig (as part of application 301/21-ek).

Main Experiment

A total of 80 deaf signers participated in the study, whereas the data from 53 of these participants (30 female, 21 male, 2 other; M age 34.11 years, SD = 12.25 years) met our pre-registered inclusion criteria and entered into the analysis. The vast majority of participants included in this sample reported that DGS was either their dominant or preferred mode of communication. On average, the self-reported age of sign-language acquisition was 1.52 years (SD = 3.37), with most participants reporting to have acquired DGS from their parents, family, and/or in a kindergarten or school setting. On a 7-point scale, participants on average rated their DGS skills as 6.64 (SD = 0.74). More than two thirds of our participants reported knowledge of an additional sign language other than DGS (e.g., American Sign Language [ASL], British Sign Language [BSL], and Polish Sign Language [PJM]) and/or International Sign (IS). Most participants were right-handed (N = 44), whereas five reported to be left-handed and four self-reported no clear dominance.

Control Experiment

A total of 71 hearing non-signers participated in the control experiment, 18 of which did not meet our pre-registered inclusion criteria and were excluded until the desired sample size of 53 (33 female, 22 male; M age 30.55 years, SD = 9.15 years) was reached, matched to the number of participants included of the sample of the main experiment. Except for one participant, all participants in this sample reported that German was their dominant and preferred mode of communication. All participants reported no knowledge of DGS and confirmed that they did not know more than ten signs in any sign language. Most participants were right-handed (N = 47), whereas six participants self-reported to be left-handed.

Stimuli

The paradigm for both experiments used short flashes inserted into videos of signed sentences as analogues to auditory clicks which, following Holmes & Forster (1970), could occur in the first or second half of a syntactically complex DGS sentence consisting of a main and a subordinate clause (Figure 1). The exact point in time when the flash occurred (indicated by using a "/") differed with regard to the syntactic structure of a sentence, so that a flash could occur either after a major break in the constituent structure separating two clauses, after a minor break, or not at a break as shown in (7)–(9) for the first and in (10)–(12) for the second half of the sentence.

(7) [NEXT MONTH WE HOLIDAY DRIVE CAN] / [OR WE FRIEND FAMILY TOGETHER HOUSE RENNOVATE]

"Next month we can go on vacation or we renovate the old house together with friends and family."

(8) [[IMAGINE] / [[CAR NEW] BIG]]] [IX$_1$ TWO BYCYCLE ONE SCOOTER LOAD]

"If the new car is big as I imagine, I can load it with two bikes and a scooter."

(9) [THREE FRIEND+++ LIKE [[FLAT / BIG] MOVE]]] [BUT WITHOUT PARENTS $_{3b}$SUPPORT$_{3a}$ IX$_{3a}$ RENT PAY $\overline{\text{CANNOT}}^{\text{neg}}$]

"The three friends would like to move into a big apartment, but without their parents supporting them they cannot pay the rent."

(10) [TODAY TRAVEL+GUIDE AND TRAVEL+GROUP WAIT STAND UNTIL

hn hs
CLOUDS DARK DISAPPEAR] / [REASON IX_{3pl} WET WISH NOT]

"Today the tour guide and the travel group wait until the dark clouds have disappeared because they do not want to get wet."

(11) [SPORTS+HALL INSIDE CHILD+++ BALL PLAY RELAXED MIX] [[OR TOGETEHR PRACTISE] / [FOR NEXT COMPETITION]]

"In the sports hall, the children casually play with the ball or practise together for the next competition"

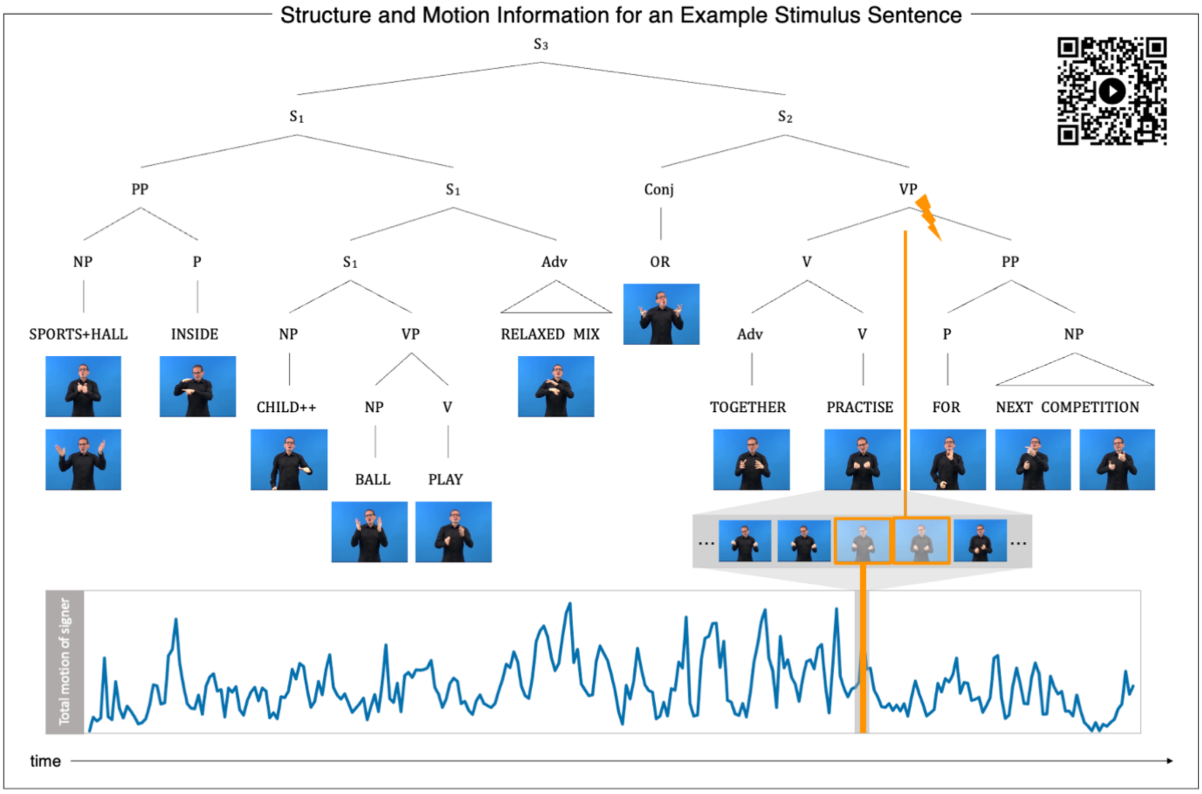
(12) [LAST WEEK MY BROTHER CAR TIRE FLAT] [BUT LORRY [FROM / ENGLAND] $HELP_{3a}$]

"Last week my brother had a flat car tire, but a truck driver from England helped him."

This yielded a 2x3 within-subject design with the factors *Position* (first vs. second half) and *Structure* (major vs. minor vs. no break). Such a design naturally balances out potential technical differences (e.g., operating system, web browser, etc.) amongst participants in online experiments (Bridges et al., 2020). In addition to the six experimental conditions, six additional filler items (14.29 %) in which no flash occurred were also included. The stimuli were designed with the aid of deaf informants and recorded in the professional filming facilities of the SignLab at the University of Göttingen by one of the authors who is a deaf native signer of DGS. To make the stimulus materials look as natural as possible, the signer produced mouthings and non-manuals spontaneously in the same manner as they would produce them in normal signed discourse (Pendzich, 2020; Trettenbrein, Pendzich, et al., 2021).

Figure 1

Structure and Motion Information of an Example Stimulus Sentence



Note. The top panel shows an example of structural description of the constituent structure of a DGS sentence in our stimulus set with the extraneous visual signal located at a minor break in the second half of the sentence (i.e., part of the condition "minor-second"; video: https://doi.org/10.6084/m9.figshare.22573105). Representative frames for each individual sign are provided at the terminal nodes of the tree together with English glosses. To illustrate: If this item had been part of the condition "major", then the extraneous signal would have occurred between the signs MIX and OR. If it had been part of the condition "no break" then the signal could, for example, have occurred between NEXT and COMPETITION. The abbreviations at the different nodes indicate different types of phrases (in order of occurrence in the diagram from left to right): Sentence (S), prepositional phrase (PP), noun phrase (NP), preposition (P), verb phrase (VP), verb (V), adverb (Adv), and conjunction (Conj). This DGS sentence roughly translates into English as *In the sports hall, the children casually play with* *the ball or practise together for the next competition.* The position in the diagram where the extraneous visual signal occurred is indicated by an orange flash. The smaller panel emerging from the position of the flash depicts individual frames in the video at this point in time and illustrates the two consecutive frames which were overlayed to achieve the visual manipulation. The bottom panel shows a plot of the total amount of motion of the signer occurring from frame to frame as determined by the analysis of data from body-pose estimation performed on the stimulus video clip. The orange bar indicates the position in the video where the flash occurred.

All clips were annotated following a pre-defined coding scheme that was based on the so-called long view of the sign (Jantunen, 2015), before flashes were inserted using a fully automated video-editing procedure (see file "add_clicks_to_stimuli.Rmd" in online resources). An initial set of annotations was created by one coder using ELAN (version 5.7-FX; Lausberg & Sloeties, 2009). A second coder then independently annotated 25 % of the stimulus items randomly drawn from the set. This revealed a very high overlap between the annotations by the different coders (Hedges' *g* for both the start and end of annotations: –0.02, 95% CI [–.02 –0.01]). Flashes were then inserted automatically using a custom-made procedure which read the ELAN annotations into R (version 4.0.4; R Core Team, 2019) and added a half-transparent white overlay to two consecutive frames (i.e., for a duration of 80 ms during playback) at the end of the annotation of the sign occurring immediately before the desired location of the flash in the constituent structure of the sentence. This procedure was designed to mimic the nature and placement of clicks used in the auditory study by Holmes and Forster (1970) as closely as possible in the visual domain.

To control our stimuli for a possible correlation between the manual and bodily motion of the signed sentences (e.g., articulatory pauses) and the probed constituent structure we used automated motion-tracking to quantify the movement of the signer in the videos

(Figure 1, bottom panel). We fit a body-pose model capturing the posture of the signer using OpenPose (version 1.7.1; Cao et al., 2019) to all stimulus clips and computed an index for the velocity of this model on a frame-to-frame basis using the OpenPoseR package (version 1.0.4; Trettenbrein & Zaccarella, 2021) in R. Based on the manual annotations of our stimuli, we then extracted the motion information for the duration of the annotations of all signs articulated immediately before a flash occurred. This indicated that the average motion of signs immediately before the occurrence of a flash (measured in arbitrary units) was very similar across conditions and did not differ systematically: major-first (M = 282.58, SD = 66.73), minor-first (M = 288.56, SD = 74.44), no break-first (M = 261.82, SD = 86.51), major-second (M = 305.18, SD = 101.27), minor-second (M = 332.36, SD = 181.07), and no break-second (M = 303.66, SD = 112.38).

Procedure

Both experiments were implemented in a fully-automated fashion in PsychoPy (version 2021.2.3; Peirce, 2008) and hosted on Pavlovia (Open Science Tools Ltd., https://pavlovia.org). Participants ran the respective experiment from home on their desktop computer or laptop in a web browser, following a pre-defined experimental flow (see folder “data_task_instructions” in online resources) that was designed to maximize the quality of the collected data (Kochari, 2019): After giving informed consent, participants filled in a basic demographic questionnaire. Next, they had to complete a short training session to practice the experimental task. In the main experiment with deaf signers, all instructions were given in DGS by means of pre-recorded videos. Participants were given the option to re-watch the instruction video and practice the task again, if necessary. In the control experiment with hearing non-signers, instructions were given in written German. In both experiments, the set of practice items was different from the set of items of the actual experiment. After completing the training session at least once, participants could progress to the actual experiment. When the experiment was completed (total duration: about 25–30 minutes), participants were automatically redirected to a secure server of the Max Planck Society to enter their payment information.

Every trial in both the main and control experiment had the same structure: Participants manually initiated a new trial by pressing the space bar with their dominant hand to ensure that their hand was already placed on the keyboard and in the correct location for giving a response. After a jittered pre-stimulus interval of 1.5–2 seconds, participants were presented with an item from one of the six conditions or a filler item. Once a flash occurred in a video, participants had to respond by pressing the space bar as quickly as possible. The presentation of the stimulus was followed by a jittered inter-stimulus interval of 1–1.5 seconds and the presentation of a binary comprehension question. In case of the main experiment, the question was presented in the form of a DGS video. Due to the lack of DGS knowledge of participants in the control experiment, the comprehension questions were replaced with questions about the possible content of the signed sentences presented in written German. In both experiments, participants had to respond by pressing either the "1" key (yes) or the "0" key (no). All items were presented in pseudo-randomized order different for every participant, created using the in-house randomization-software Conan (version 1.9; Nowagk, 1998) and selected using custom Python scripts.

Pre-Registered Analyses

Data cleaning and analysis for both experiments were performed in accordance with the respective pre-registered analysis plans.

Main Experiment

First, we excluded participants who did not complete the task, who wrongly reported the presence of a target (i.e., flash) in more than one third of the filler trials (2 out of 6), and whose overall accuracy in response to the comprehension question presented after the stimulus was < 75 % correct. Second, we removed all trials with an incorrect response to the comprehension question in order to make sure that only trials in which participants accurately processed the sentence entered into our analysis. Next, we removed trials in which (i) the response occurred before the flash, (ii) the response was given sooner than 180 ms (Fry, 1975) after the flash, and (iii) the response occurred later than the maximum duration of the signs immediately following the flash as automatically determined from annotation data (i.e., 1,520 ms). Lastly, due to the generally rather low number of trials caused by the need of a succinct experimental task we excluded data from all participants who did not reach a minimum of four trials per cell in the experimental design after the above exclusion criteria had been applied. This resulted in data from 53 out of a total of 80 deaf signers being included in the analyses.

Statistical analyses were performed by fitting a generalised linear mixed-effect model with a Gamma distribution to the raw reaction time (RT) data, using the lme4 package (version 1.1-33; Bates et al., 2015) in R. The fixed effect structure of our model included the factors *Structure* (“major” vs. “minor” vs. “no break”) and *Position* (“first” vs. “second” half) which respectively was treatment-coded with “major” as a reference level and sum-coded. Participants and items were included as random effects (Baayen et al., 2008). We started our analyses with a model that had a maximal random-effects structure including random intercepts and slopes for all fixed effects and their interactions for participants and items:

RTs ~ 1 + Structure*Position + (1+Structure*Position|Subject) + (1|Item)

We expected to observe RT differences according to the location of the flashes within the different constituent breaks. Specifically, we expected a main effect of *Structure*, with longer RTs for the “no break” condition compared to both “minor” and “major”, as well as a *Structure* × *Position* interaction, with longer RTs for the “no break” condition compared to both “minor” and “major” only in the first half of the sentence, similarly to the results of Holmes & Forster (1970).

Control Experiment

Participants were excluded from the analysis if they did not complete the experiment or reported to know DGS or indicated to be familiar with more than ten signs in any sign language. Moreover, we excluded data from participants who wrongly reported the presence of a target (i.e., flash) in more than one third of the filler trials (2 out of 6) and who did not reach a minimum of four trials per cell in the experimental design after the above exclusion criteria had been applied. Data collection was halted when the sample of participants meeting these criteria matched the size of the sample of the main experiment (N = 53).

The statistical analysis of the control experiment was identical to the analysis performed for the main experiment described above. Notice that the purpose of this control experiment was to ensure that there are no perceptual or other lower-level factors present in our stimulus videos that are related to our factor of interest (i.e. *Structure*). Due to the lack of sign language knowledge of the group of hearing non-signers participating in this control experiment, we expected to observe no RT differences according to the location of the flashes within the different constituent breaks. Specifically, we expected to observe no effect of *Structure*, with RTs not differing systematically across conditions, as well as no *Structure* × *Position* interaction.

Exploratory analyses

In addition to the pre-registered analyses described above we performed two independent additional exploratory analyses for both experiments: First, we adapted our inferential analysis by including *Topicalization* as an additional third factor into our experimental design. Second, we performed a re-analysis of our data within a Bayesian framework to quantify evidence for the null hypothesis.

Topicalization as Additional Factor

As described in the section "Stimuli" above, all items presented during the experiment were complex DGS sentences consisting of a main and a subordinate clause. In DGS, a part of a clause can be topicalized (i.e., made more prominent) by moving it to the front of the sentence (i.e., actually producing it before the main clause). In order to make the stimuli more varied and interesting for participants we had recorded two out of the six items per condition with a topicalized structure. Representative examples for the conditions "no break-first" and "major-second" are shown in (13) and (14) respectively.

(13) ___________________________top
[[YOUR / BIRD] COLOURFUL] IX_1 LIKE-TO-TAKE-CARE-OF __] [REASON MY CAT DIED IX_1 ALONE LIVE]

"Your colourful bird I like to take care of, because my cat died and I live alone."

(14) _________________________top
[RAIN+UMBRELLA NEW IX_3 GRANDMOTHER GRANDFATHER BUS __ ${}_{3b}$FORGET] / [BUT BACKPACK BLUE ${}_{3a}$TAKE${}_{3b}$]

"The new umbrella grandma and grandpa forgot on the bus, but they took the blue backpack with them."

As already mentioned above, the production of topicalized structures in DGS is accompanied by a non-manual marker (i.e., raised eyebrows) glossed as "top". We reasoned that the presence or absence of topicalization in some items could potentially have impacted responses to our stimuli in a manner that we originally had not considered.

Consequently, we included *Topicalization* as an additional factor in our experimental design and re-fit the respective models for both experiments with the following maximal random-effects structure:

RTs ~ 1 + Structure*Position*Topicalization + (1+Structure*Position|Subject) + (1|Item)

Because we had no a priori hypotheses about *Structure* for this additional exploratory analysis we re-coded the factor from treatment to sum coding so that any observed main effect would constitute an actual main effect and not just simple effect relative to the baseline when *Structure* was treatment-coded in the pre-registered analysis (Brehm & Alday, 2022). We expected that including *Topicalization* in our models should reveal whether the presence of the non-manual marker for topicalized structures indeed had effect on participants' responses, either by influencing the grammatical processing in the group of deaf signers in the main experiment or by affecting the way in which non-signers responded to the DGS videos in the control experiment.

Reanalysis in a Bayesian Framework

Due to the null result observed with our pre-registered analyses for both experiments, we sought to quantify the evidence for the null hypothesis by re-analysing both datasets within a Bayesian framework. Specifically, we computed a so-called Bayesian repeated measures analysis of variance (ANOVA) using the BayesFactor package (version 0.9.12) in R. That is, our model included *Structure* and *Position* as fixed effects and specified *Subject* as a random effect:

RTs ~ position*structure + subject

Because there were only two observations per cell in the experimental design for *Topicalization* we did not include it as a factor here. To meet the assumptions of ANOVA, RTs were log-transformed prior to the analysis as well as aggregated by condition and participant. Bayes factors were obtained via the bayesfactor() function which performs model comparisons as pre-specified in the BayesFactor package. We expected these analyses to confirm the absence of any effect of our experimental manipulations in either experiment.

Results

Pre-Registered Analyses

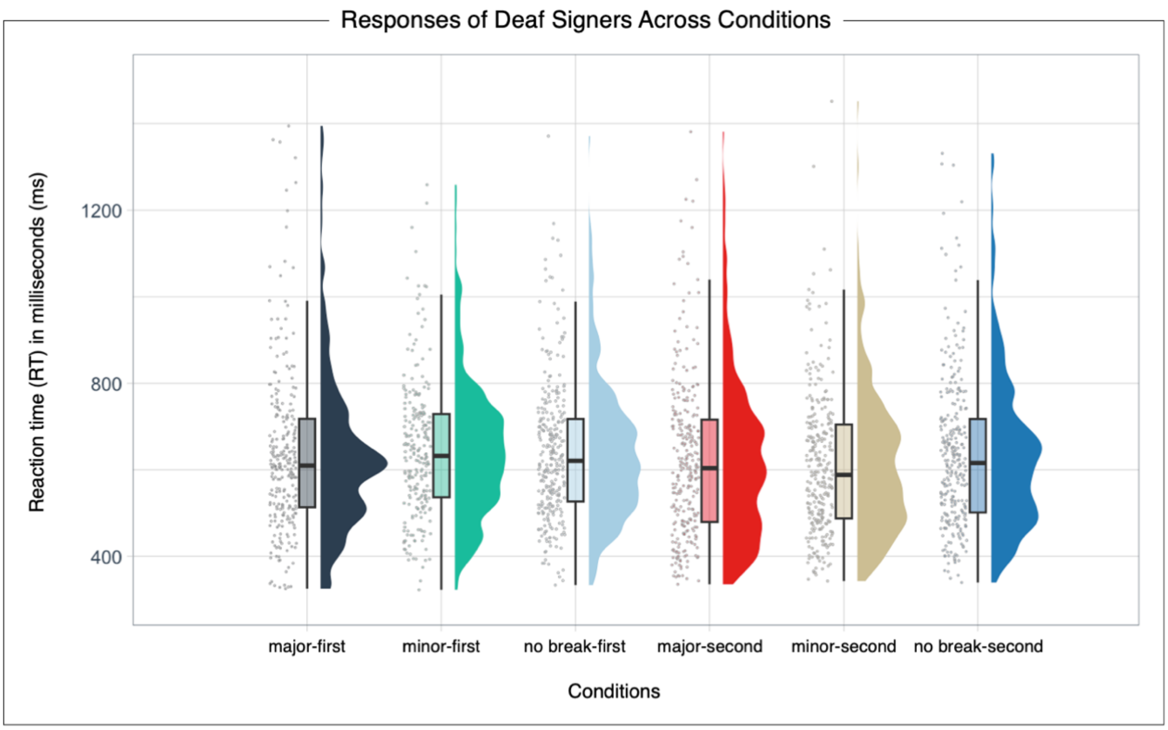
This section only reports the results of the pre-registered analyses for both experiments.

Main Experiment

The full pre-registered model converged yet, contrary to our hypothesis, neither the factor *Structure* nor *Position* could explain the variance observed. Results for the group of deaf signers are plotted in Figure 2. Details of the statistical analysis are provided as part of the Supplementary Materials in Appendix Table 1.

Figure 2

Main Experiment: Responses of Deaf Signers Across Conditions



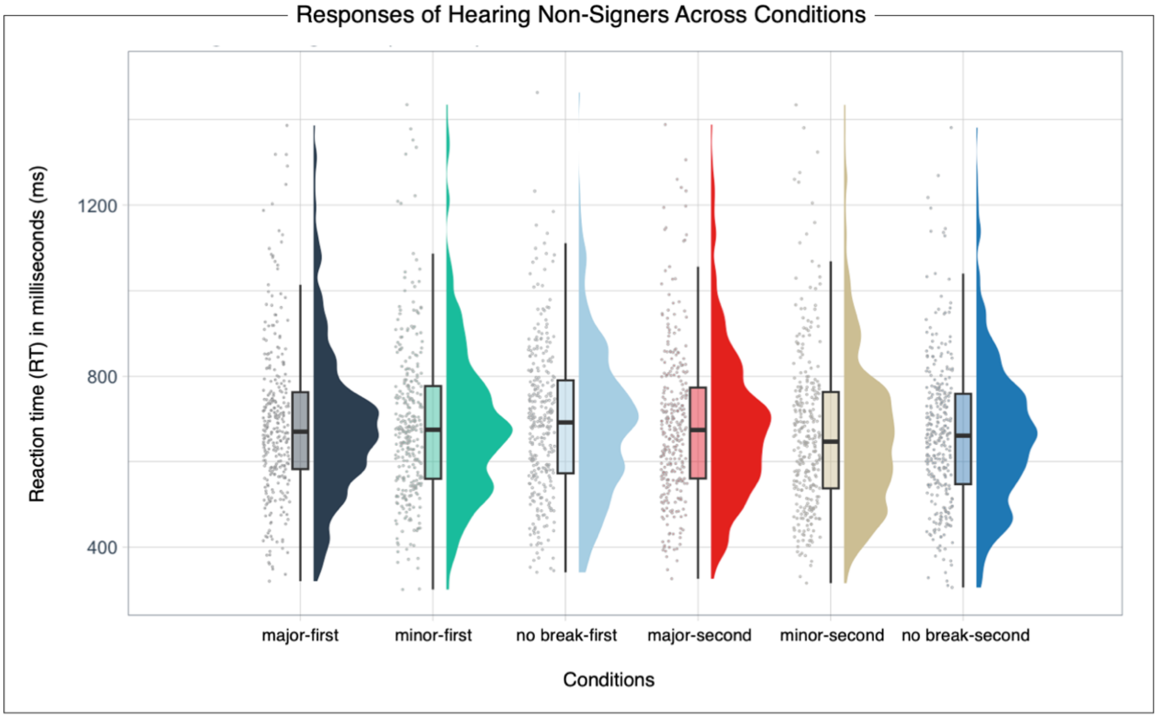
Note. Illustration of the results of the pre-registered analysis for the main experiment with deaf signers. Individual responses, their distribution, and means are plotted for all six experimental conditions resulting from the combination of the different levels of the factors *Structure* (major, minor, no break) and *Position* (i.e., first vs. second half of the video). From left to right: major-first, minor-first, no break-first, major-second, minor-second, and no break-second. Reaction times (RT) are given in milliseconds (ms). No statistically significant differences between conditions were observed (all p-values > 0.05).

Control Experiment

The full pre-registered model converged. In line with our hypotheses, we did not observe an effect of *Structure* and no *Structure* × *Position* interaction. Results for the group of hearing non-signers are plotted in Figure 3. Details of the statistical analysis are provided as part of the Supplementary Materials in Appendix Table 2.

Figure 3

Control Experiment: Responses of Hearing Non-Signers Across Conditions



Note. Illustration of the results of the pre-registered analysis for the control experiment with hearing non-signers. Individual responses, their distribution, and means are plotted for all six experimental conditions resulting from the combination of the different levels of the factors *Structure* (major, minor, no break) and *Position* (i.e., first vs. second half of the video). From left to right: major-first, minor-first, no break-first, major-second, minor-second, and no break-second. Reaction times (RT) are given in milliseconds (ms). No statistically significant differences between conditions were observed (all *p*-values > 0.05).

Exploratory Analyses

This section reports the results of the additional exploratory analyses which we performed for both experiments in order to better understand the observed null result obtained in our pre-registered analyses for the main experiment with deaf signers and how it can be set in relation to the data of the control experiment with hearing non-signers.

Topicalization as an Additional Factor

Re-fitting the full model including *Topicalization* as an additional factor in the fixed effects structure to our data from the main experiment with deaf signers revealed a main effect of *Topicalization* (Table 1). This suggests that participants were generally slower to respond to items with topicalization regardless of whether the click occurred within the topicalized structure. Moreover, we observed a *Structure* × *Position* × *Topicalization* interaction, indicating that participants were slower to respond in trials with topicalization when the click occurred in the first part of the sentence in the "minor" condition.

Table 1

Main Experiment: Generalised Linear Mixed Model Including Topicalization *as a Fixed Effect*

Fixed Effects	Estimate	SE	t	p
(Intercept)	6.431	0.038	171.113	0.000 ***
Structure1	0.006	0.015	0.414	0.679
Structure2	0.000	0.017	0.020	0.984
Position1	-0.018	0.011	-1.583	0.113
Topicalization1	0.020	0.009	2.370	0.018 *
Structure1:Position1	0.003	0.014	0.206	0.837

Structure2:Position1	0.001	0.014	0.047	0.962
Structure1:Topicalization1	-0.001	0.012	-0.092	0.927
Structure2:Topicalization1	0.008	0.012	0.687	0.492
Position1:Topicalization1	-0.010	0.009	-1.105	0.269
Structure1:Position1:Topicalization1	-0.021	0.012	-1.733	0.083
Structure2:Position1:Topicalization1	0.032	0.012	2.628	0.009 **

Note. Significance codes: *** < 0.001, ** < 0.01, * < 0.05

Similarly, re-fitting the full model including *Topicalization* as an additional factor to our data from the control experiment with hearing non-signers also revealed a main effect of *Topicalization* (Table 2). This indicates that hearing non-signers were generally also slower to respond to items with topicalization regardless of where the click occurred in the sentence. Moreover, we observed two *Structure* × *Position* × *Topicalization* interactions, indicating that hearing non-signers were still slower to respond to items with topicalization when the click occurred in the first part of the sentence (i.e., within the topicalized structure) and regardless of the location of the flash in the constituent structure.

Table 2

Control Experiment: Generalised Linear Mixed Model Including Topicalization *as a Fixed Effect*

Fixed Effects	Estimate	SE	t	p
(Intercept)	6.508	0.037	177.447	0.000 ***
Structure1	-0.004	0.015	-0.276	0.783
Structure2	-0.007	0.014	-0.501	0.616
Position1	-0.013	0.012	-1.139	0.255
Topicalization1	0.019	0.008	2.322	0.020 *

Structure1:Position1	-0.019	0.014	-1.314	0.189
Structure2:Position1	0.010	0.015	0.636	0.525
Structure1:Topicalization1	0.003	0.011	0.252	0.801
Structure2:Topicalization1	-0.014	0.011	-1.246	0.213
Position1:Topicalization1	0.002	0.008	0.202	0.840
Structure1:Position1:Topicalization1	-0.025	0.011	-2.173	0.030 *
Structure2:Position1:Topicalization1	0.032	0.011	2.802	0.005 **

Note. Significance codes: *** < 0.001, ** < 0.01, * < 0.05

Reanalysis in a Bayesian Framework

For the main experiment with deaf signers (see Table 3 for details), the Bayesian repeated-measures ANOVA indicated that our data provides strong evidence for an effect of *Position* (BF_{10} = 28.94), as well as strong evidence against an effect of *Structure* (BF_{01} = 0.078) and a *Structure* × *Position* interaction (BF_{01} = 0.06).

Table 3

Results of the Repeated-Measures ANOVA for the Main Experiment with Deaf Signers

	P(prior)	P(posterior)	Inclusion BF
Participant	1.000	1.000	
Position	0.600	0.980	28.940
Structure	0.600	0.100	0.078
Position:Structure	0.200	0.010	0.060

For the control experiment with hearing non-signers (Table 4), the Bayesian repeated measures ANOVA indicated that our data provides moderate evidence for an effect of Position (BF10 = 7.22), as well as strong evidence against an effect of *Structure* (BF_{01} = 0.052) and a *Structure* × *Position* interaction (BF_{01} = 0.057).

Table 4

Results of the Repeated-Measures ANOVA for the Control Experiment with Hearing Non-Signers

	P(prior)	P(posterior)	Inclusion BF
Participant	1.000	1.000	
Position	0.600	0.920	7.220
Structure	0.600	0.070	0.052
Position:Structure	0.200	0.010	0.057

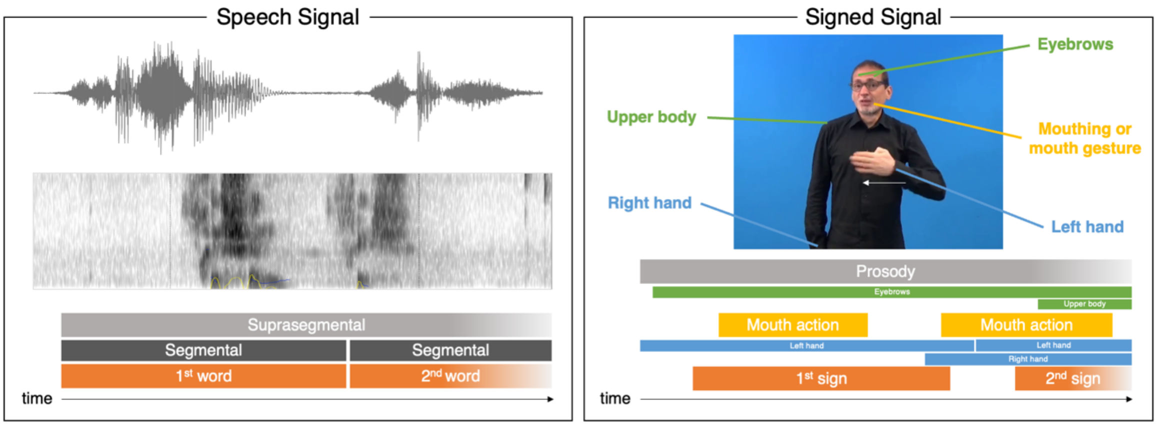
Discussion

In the present study, we set out to probe the relevance of hierarchical constituent structure during sign language processing, but did not observe any effect of our syntactic manipulation in the main experiment with deaf signers. We adapted the classical psycholinguistic “click” paradigm (Fodor & Bever, 1965; Garrett et al., 1966; Holmes & Forster, 1970, 1972) from the auditory-oral modality of spoken languages to the visuo-spatial modality of sign languages, by using short flashes inserted into videos of DGS sentences as visual analogues to auditory clicks, to reveal whether deaf signers automatically attribute constituent structure onto sequences of signs during sign language comprehension. The null finding of our pre-registered analysis for the main experiment indicates that the detection of extraneous visual signals does not reveal the syntactic structure of sign language, unlike similar studies with comparable tasks and operationalization conducted in the auditory-oral domain (Holmes & Forster, 1970). An additional exploratory re-analysis of the data in a Bayesian framework even revealed strong evidence against an effect of *Structure* in the experiment with deaf signers. In what follows, we will first discuss different explanations that can account for this null finding, before turning to the results of our exploratory analyses which raise questions about the processing of non-manual components in sign languages by signers and non-signers alike.

While our main experiment aimed to disrupt the processing or integration of syntax-relevant information in the signed signal, the complex simultaneous and time-shifted presence of syntax-relevant cues (i.e., hands, mouthings, and non-manual markers) may simply make the sign stream more robust against disruption by extraneous signals than the mostly strictly linear speech stream (Figure 4). To boost the importance of the sequential syntactic information provided by perceived word or signs, Holmes & Forster (1970) controlled their experiment for possible prosodic confounds similar to how our study attempted to do the same by using automated motion-tracking on our stimulus clips (see section “Stimuli” above). The parser is then assumed to build up syntactic structure by sequentially integrating incoming words or signs into the constituent structure during sentence comprehension based on expectations about the continuation of the sentence. Whereas we still concur that this, in principle, is a reasonable assumption, closer inspection of what syntax-relevant information is present at what time in the sign stream as opposed to the speech stream makes it clear that the signed signal is much richer (Meier, 2002) and, consequently, apparently less prone to disruption by extraneous signals. Indeed, the potential disruptive effect of the extraneous signal (i.e., “flash”) at exactly these points in time appears to have been readily compensated by the syntax-relevant information provided by the other articulators. Along these lines, it has also been argued that the nature of the major articulators of sign languages require longer transition phases between signs, whereas these transitions are likely already informative with regard to the next sign (Hosemann et al., 2013; Wienholz et al., 2023).

Figure 4

Syntax-Relevant Information Present in the Linguistic Signal Across Modalities



Note. A schematic depiction of the different properties of the auditory speech stream as opposed to the visual sign stream. The left panel shows the physical properties of the speech stream on top and depicts the different syntax-relevant information that can be imposed onto the representation of this signal at the bottom. Notice that the speech-stream is, for the most part, strictly sequential, with suprasegmental information being the only exception. The right panel shows a still from a video of a DGS sentence to (admittedly incompletely) depict the physical properties of the sign stream. Notice that the simultaneous and time-shifted presence of syntax-relevant information is the norm. That is, a mouthing (or mouth gesture) that may accompany a sign (colour-coded in yellow) does not extent for the same duration as the manual component (hand form, hand position, contact area, starting point, movement, and end point; colour-coded in blue). Notice that the boundary between a signs start and end point and transitory movements is blurry (Hosemann et al., 2013; Jantunen, 2015; Wienholz et al., 2023). Similarly, syntax-relevant non-manual cues such as raised eyebrows indicating topicalization or questions components or position and movement of the upper body (colour-coded in green) can extend over several signs (Pendzich, 2020; Steinbach, 2023).

In addition to the general many-to-one mapping specifically for syntax-relevant cues required during sign language comprehension, the canonical word order of DGS and other languages (signed and spoken) may impact the degree to which predictions of sequential elements constitute a cognitively useful strategy. That is, a central tenet of the paradigm by Holmes & Forster (1970) and, by extension, also our adaption of this paradigm to the visuo-spatial modality is that participants' responses to an extraneous signal will be influenced by what further elements the parser anticipates based on previously encountered elements (i.e., the parser projects an open node). While this is a reasonable assumption on the level of minor and major constituents, such predictive processing may simply not occur on the phrasal level (see Maran et al., 2022 for discussion), especially in languages where elements such as adjectives or adpositions usually follow the element that they modify (e.g., unlike in English or German, the adjective NEW follows the noun BOOK in DGS as shown in the example sentence in (4); see section "Introduction"). Accordingly, some trials of the within-phrase manipulation (i.e., the "no break" conditions) in our main experiment may have been affected by this (i.e., the parser does not project an open node after BOOK, instead the structure [BOOK NEW] is only built up if and when a postpositional element is encountered).

Despite our null finding in the present study, we believe that the linguistic evidence for hierarchical constituent structure in the sign languages of the world is compelling (Cecchetto, 2017; Kocab et al., 2023; Mathur & Rathmann, 2014; Sandler & Lillo-Martin, 2001, 2008; Tang & Lau, 2012). Accordingly, we caution readers not to interpret our failure to observe syntax-specific effects in this pre-registered study using a comprehension paradigm as evidence for a lack or the irrelevance of hierarchical constituent structure in the comprehension or production of DGS in general. Instead, against the background of the general state of research on constituent structure and hierarchy in language and, specifically, sign language, we believe that the greater robustness of the sign stream provides a reasonable explanation for the observed null result. At the same time, we believe that our findings and especially the methodological approach for creating stimuli developed for creating stimulus materials warrant further studies using different variations of the “click” paradigm (e.g., a version that does not rely on RTs during comprehension but instead increases the memory demands imposed on participants by requiring them to first encode and then decode the perceived sentences; Holmes & Forster, 1972).

To further explore the data collected, we performed two additional exploratory analyses which suggested that the presence of non-manual markers for topicalization in some items has a significant effect on the general responses to the “flashes” in both groups of participants, demonstrating that hearing non-signers attend to some non-manual cues of DGS (i.e., raised eyebrows marking topicalized structures) despite their lack of knowledge of the language. Interestingly, the main effect of *Topicalization* was not just present in the main as well as the control experiment but also showed the same directionality of the effect (i.e., signers and non-signers both were generally slower to respond to topicalized items, regardless of whether the “flash” occurred in the first or second half of the sentence). Moreover, hearing non-signers’ responses were especially inhibited when the non-manual marker was present at the beginning of stimuli presumably due to the overlap of this syntactic marker of DGS with non-manual gesture (Dohen & Lœvenbruck, 2009; Wierzbicka, 2000). Despite grammatical and lexical functions of non-manuals in the visual-spatial modality, both deaf signers and hearing non-signers also use non-manuals to express emotions, reactions, and attitudes (Pendzich, 2020). Specifically, Pendzich (2020) showed that raised eyebrows presented in isolation without a signed context are interpreted as an interrogative marker by deaf signers as well as hearing non-signers, pointing towards a possible gestural origin of this grammatical marker (Domaneschi et al., 2017; Janzen, 1999; Van Loon et al., 2014). Furthermore, this facial cue also showed a strong relation to scepticism for hearing non-signers (Pendzich, 2020).

The finding that signers and non-signers show similar effects for topicalized items despite the difference in their knowledge of DGS in combination with the observation that in both experiments participants were actually slower to respond when non-manual components in the form of raised eyebrows (i.e., topicalization markers) were present in the stimulus raises questions regarding the cognitive status of non-manuals. In the literature, two different views have been put forward: Some have considered non-manuals as direct surface realisation of syntax (Emmorey, 2002; Wilbur & Patschke, 1999), whereas others have argued that some aspects of the linguistic analysis of non-manuals may be achieved by other (not necessarily linguistic) cognitive systems (Atkinson et al., 2004), presumably in tandem with the language system. That is, signers are assumed to at least initially recruit additional cognitive resources (e.g., non-linguistic systems for processing facial gestures with a lexicalised meaning such as "top") but this information is then forwarded to the language system. Our data cannot resolve this question but they seem to indicate that the use of non-manual components indeed imposes additional processing demands regardless of participants' knowledge of DGS: Both experiments showed that participants were slower to respond when items included topicalization markers though only the group of deaf signers could have processed them as such lexicalised components.

Lastly, the Bayesian re-analysis of the data from both experiments confirmed the null result for our syntactic manipulation but, at the same time, also revealed evidence for an effect of position, thus indicating that the original effect of position observed by Holmes & Forster (1970) most likely is not linguistic in nature but instead reflects a general effect of attention. In the original paper that served as an inspiration for the present study, Holmes & Forster (1970) concluded that participants' slower responses to "clicks" occurring in the first half of the sentence as opposed to the second half reflected the decreased processing demands during the second half of the sentence because more linguistic information has already been encountered while the kind of new linguistic information that needs to be integrated becomes more predictable. Our adaptation of the paradigm to the visuo-spatial modality of sign language in combination with the data from the control experiment allow us reconsider this claim: If the response pattern described by Holmes and Forster was indeed only caused by increased cognitive demands during processing complex sentences, we should not have observed an effect of position in our control experiment with hearing non-signers who did not process the stimuli in a linguistic manner. In contrast, our Bayesian re-analysis showed an effect of *Position* in both experiments, though more pronounced for the main experiment with deaf signers. Hence, we argue that any observed effect of *Position* in this paradigm actually does not necessarily reflect decreased linguistic processing demands but indexes decreasing uncertainty as a trial progresses during the experiment.

Conclusion

While linguistic research has demonstrated that sentences exhibit a complex internal structure independent of modality (i.e., speech or sign) our set of pre-registered experiments adapting the classical psycholinguistic “click” paradigm to the visuo-spatial modality presented here failed to reveal the relevance of hierarchical constituent structure during sign language comprehension. Interestingly, additional exploratory analyses suggested that the behaviour of non-signers was systematically influenced by non-manual cues despite their lack of knowledge of DGS. The Bayesian re-analysis of the data from both experiments then revealed a general effect of uncertainty depending on whether the flash occurred in the first or second half of a video independent of participants’’ knowledge of DGS.

Against this background, we conclude that the simultaneous and time-shifted presence of different syntax-relevant cues (i.e., hands, mouthings, and non-manuals) makes the sign stream robust against disruption by extraneous visual signals. At the same time, our data indicate that non-signers without any knowledge of DGS nevertheless attend to the non-manual cue for topicalization (i.e., raised eyebrows) despite not comprehending its syntactic relevance, possibly because its form resembles a communicative gesture for interrogatives which has been grammaticalized in DGS (Pendzich, 2020). Future work should probe the constituent structure of sign languages using memory-based variations of the “click” paradigms similar to Holmes & Forster (1972). Similarly, it may prove fruitful to further develop paradigms aiming to dissociate the distribution, function, and processing of non-manual cues in signers and non-signers.

Author contributions (CRediT contributor roles taxonomy)

Patrick C. Trettenbrein: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing - review & editing; **Matteo Maran**: Conceptualization, Formal analysis, Methodology, Software, Validation, Visualization, Writing - review & editing; **Jan Pohl**: Data curation, Investigation, Methodology, Project administration, Software; **Thomas A. Finkbeiner**: Investigation, Methodology, Resources; **Emiliano Zaccarella**: Conceptualization, Methodology, Supervision; **Angela D. Friederici**: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing - review & editing; **Markus Steinbach**: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Visualization, Writing - review & editing; **Nina-Kristin Meister**: Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing

Data availability statement

All stimulus clips, task instructions for participants, data, and analysis scripts are publicly available from the Open Science Framework: https://doi.org/10.17605/OSF.IO/9BR3P.

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Online supplementary materials for "Detection of extraneous visual signal does not reveal the syntactic structure of sign language"

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Appendix Table 1

Main Experiment: Generalised Linear Mixed Model

Fixed Effects	Estimate	SE	t	p
(Intercept)	6.420	0.047	136.741	0.000 ***
Structure2	0.000	0.036	-0.007	0.994
Structure3	0.009	0.032	0.271	0.787
Position1	-0.014	0.024	-0.610	0.542
Structure2:Position1	-0.010	0.033	-0.310	0.756
Structure3:Position1	0.010	0.033	0.293	0.769

Note. Significance codes: *** < 0.001, ** < 0.01, * < 0.05

Appendix Table 2

Main Experiment: Generalised Linear Mixed Model

Fixed Effects	Estimate	SE	t	p
(Intercept)	6.508	0.043	150.633	0.000 ***
Structure2	-0.009	0.031	-0.299	0.765
Structure3	-0.012	0.033	-0.367	0.714
Position1	-0.002	0.023	-0.079	0.937
Structure2:Position1	-0.013	0.031	-0.425	0.671
Structure3:Position1	-0.023	0.030	-0.758	0.448

Note. Significance codes: *** < 0.001, ** < 0.01, * < 0.05