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EEG ANALYSIS BASED ON DYNAMIC VISUAL STIMULI: BEST PRACTICES IN THE ANALYSIS OF SIGN LANGUAGE DATA

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Abstract: *This paper reviews best practices for experimental design and analysis for sign language research using neurophysiological methods, such as electroencephalography (EEG) and other methods with high temporal resolution, as well as identifies methodological challenges in neurophysiological research on natural sign language processing. In particular, we outline the considerations for generating linguistically and physically well-controlled stimuli accounting for 1) the layering of manual and non-manual information at different timescales, 2) possible unknown linguistic and non-linguistic visual cues that can affect processing, 3) variability across linguistic stimuli, and 4) predictive processing. Two specific concerns with regard to the analysis and interpretation of observed event related potential (ERP) effects for dynamic stimuli are discussed in detail. First, we discuss the “trigger/effect assignment problem”, which describes the difficulty of determining the time point for calculating ERPs. This issue is related to the problem of determining the onset of a critical sign (i.e., stimulus onset time), and the lack of clarity as to how the border between lexical (sign) and transitional movement (motion trajectory between individual signs) should be defined. Second, we discuss possible differences in the dynamics within signing that might influence ERP patterns and should be controlled for when creating natural sign language material for ERP studies. In addition, we outline alternative approaches to EEG data analyses for natural signing stimuli, such as the timestamping of continuous EEG with trigger markers for each potentially relevant cue in dynamic stimuli. Throughout the discussion, we present empirical evidence for the need to account for dynamic, multi-channel, and multi-timescale visual signal that characterizes sign languages in order to ensure the ecological validity of neurophysiological research in sign languages.*

Keywords: *sign language, ERP methodology, simultaneity, dynamic visual stimuli*

1. INTRODUCTION

The neurophysiological investigation of sign language processing is of particular interest to both linguists and neuroscientists, because the unique conflation of the visual domain and language-pattern processing in signers provides unparalleled insights into the organisation of sensory and cognitive processing, as well as elucidates possible universal grammatical structures in human languages (Newmeyer, 2005). So far, a substantial proportion of studies on sign language processing have used structural imaging techniques and focused on the question of functional activation in the human brain during sign language processing. These studies revealed patterns of both the similarities and differences between signed and spoken language processing. For example, they showed that language in any modality recruits frontotemporal brain networks within the left hemisphere (cf. Emmorey, 2002; Malaia, Ranaweera, Wilbur, and Talavage, 2012), but sign language processing requires the unique involvement of the right hemisphere (Newman, Supalla, Hauser, Newport, and Bavelier, 2010a), as well as leads to an increase in inter-hemisphere connectivity (Malaia, Talavage, and Wilbur, 2014). However, high-resolution imaging techniques do not allow for further investigation of fine-grained temporal aspects of sign language processing. This aspect is of particular interest to researchers in the field of language science, since one of the main characteristics of language processing is that it proceeds extremely fast.

Sign languages use both manual (handshape, hand orientation, hand and arm movement) and non-manual channels (eyes, eyebrows, and mouth articulations; head, shoulders, and body positions) to communicate linguistic and paralinguistic (i.e., gestural communicational means used in emotional context) information/cues during communication. As defined for syllable structure in the manual portion of each sign, the handshape, hand orientation, and place of articulation are simultaneous/layered with the movement, unless the movement itself explicitly changes the handshape, orientation, or place of articulation (Brentari, 1998; Wilbur, 2011; Wilbur and Petersen, 1997; Malaia and Wilbur, 2020). Grammatical non-manual markings are layered on top of manual components, thus adding lexical, syntactic, and prosodic information (Wilbur, 2000). Due to the layering of manual and non-manual articulators in sign languages, several information channels end up being presented in parallel (e.g., Emmorey and Corina, 1990; Sandler and Lillo-Martin, 2006; Wilbur, 2000; Malaia, Borneman, and Wilbur, 2018). Therefore, the time component plays a critical role in sign language processing. To arrive at a better understanding of the mechanisms supporting language comprehension during the natural processing time course, a fine-grained analysis of the temporal aspects of sign language processing is required. Methods such as electroencephalography (EEG), which has excellent time resolution with respect to the measurement of ongoing brain activity, has become the method of choice for examining temporal dynamics within language processing (e.g., Bornkessel-Schlesewsky and Schlesewsky, 2009; Malaia, 2017) (for other articles on methodological overviews see e.g., Quer and Steinbach, 2019; Gutiérrez-Sigut and Baus, 2021; Malaia et al. (in press)).

There is a limited number of studies that have investigated the dynamics of natural sign language processing in sentence contexts using EEG. One of the earliest experiments was conducted by Kutas et al. (1987), who compared the processing of semantically anomalous sentences with that of semantically correct sentences during reading, listening, and sign language perception in American Sign Language (ASL). ASL sentences were presented to D/deaf[1] signers; the same structures were presented in spoken and written English to hearing non-signers. Kutas et al. (1987) observed an N400 effect for all three groups and concluded that this finding showed that the brain processes associated with the analysis of semantic anomalies were essentially equivalent during reading, listening, and the perception of ASL signs. Notably, the temporal parameters of the stimuli in the study were controlled by means of creating entirely artificial videos (one sign per second; each sign consisted of eight digitized frames for a total duration of 240 ms). This sign-by-sign presentation mode was used in subsequent work examining sign language processing by Neville et al. (1997) who noted that "between signs the subjects saw a still image of the signer" (Neville et al., 1997, p. 290). However, a sign-by-sign presentation mode is not a natural way of presenting stimulus material for sign languages. The processing of sentences presented sign-by-sign (or even as static pictures) does not tap into the same processing mechanisms when compared to the processing of sentences as naturally recorded sign language videos, because movement in the three-dimensional signing space and sign dynamics are essential parts of sign language structure (cf. Malaia, Borneman, and Wilbur, 2016; Malaia and Wilbur, 2019; Krebs, Strutzenberger, Wilbur, Malaia, Schwameder, and Roehm, 2021). Therefore, it is desirable to present signed sentences as naturally as possible in order to elicit natural sign language processing mechanisms.

In comparison to studies on spoken/written language sentence processing, there are relatively few published event related potential (ERP) studies that have used dynamic signed sentence stimuli (namely, Capek et al., 2009; Gutiérrez, Williams,

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[1] Per convention, *Deaf* with an upper-case D refers to deaf or hard of hearing people who define themselves as members of the sign language community. In contrast, *deaf* refers to the audiological status of an individual.

Grosvald, and Corina, 2012; Grosvald, Gutiérrez, Hafer, and Corina, 2012; Hänel-Faulhaber et al., 2014; Hosemann, Herrmann, Steinbach, Bornkessel-Schlesewsky, and Schlesewsky, 2013; Hosemann, 2015; Hosemann, Herrmann, Sennhenn-Reulen, Schlesewsky, and Steinbach, 2018; Hosemann, Mani, Herrmann, Steinbach, and Altvater-Mackensen, 2020; Krebs, Malaia, Wilbur, and Roehm, 2018, 2020, 2021; Wienholz et al., 2018). In one of the first natural signing studies, Capek et al. (2009) investigated the processing of semantic anomalies and verb agreement violations by Deaf signers in ASL. In spoken/written languages, these two types of violations (semantic vs. (morpho-)syntactic) lead to different ERP patterns, suggesting that different processing mechanisms are involved. These results were replicated using dynamic sign language data: while semantic anomalies reliably led to an N400 effect, verb agreement violation elicited two effects - a left anterior negativity (LAN), followed by a P600 effect. Hänel-Faulhaber et al. (2014) investigated the processing of semantic and morpho-syntactic (verb agreement) violations in German Sign Language (DGS) in Deaf signers and observed a pattern similar to that reported by Capek et al. (2009), namely an N400 effect for the semantic violation and a LAN-followed by a P600 effect for the verb agreement violation (but see also Hosemann (2015) and Hosemann et al. (2018) for an ERP study investigating verb agreement violations in DGS reporting different results).

In some of the studies using natural stimuli, the video material was cross-spliced, meaning that the video of the sentence portion preceding the critical word/sign was recorded separately, and then edited in such a way that it was identical among conditions; only the critical word/sign differed among the stimuli videos. This ‘full control’ method has been commonly used in investigations of auditory language processing (e.g., Darwin and Hukin, 2000; Freunberger and Nieuwland, 2016; Steinhauer, 2003; Malaia, Wilbur, and Weber-Fox, 2009). The rationale behind the ‘full control’ approach is that cross-splicing in auditory or video stimuli eliminates any differences in the material prior to the splice (due to coarticulation, prosody, etc.), which, in unaltered/non-spliced stimuli, may lead to processing differences before the critical sign appears (e.g., Grosvald et al., 2012; Gutiérrez et al., 2012). An example of this approach is provided in Grosvald et al. (2012), where signed sentences were presented with the critical sign appearing sentence-finally. For stimuli development, critical signs and associated sentential contexts were filmed separately, with each video beginning and ending with the signer’s hands in her lap. Each sentence context was then combined (in separate videos) with four critical sentence-final signs. Both of the source videos were trimmed to eliminate the unnecessary transitional movement towards the signer’s lap at the end of the video of the sentence context and the transitional movement from the signer’s lap at the beginning of the video of the critical sign.

Other approaches to control for undesirable “influence factors” within the sign language stimulus material have ranged from giving instructions to stimulus signers to avoid or minimize non-manual components (e.g., Hänel-Faulhaber et al., 2014; Hosemann et al., 2013; Hosemann, 2015) or to the presentation of stimulus material without the head of the signer being visible (Jednoróg et al., 2015).

From the historical perspective in EEG research, it is understandable that attempts will be made to fully control the stimuli to isolate the phenomena under investigation, but the use of ‘full control’ methods unavoidably alters multiple components of signed communication, from timing dynamics to its multi-channel nature. It is also likely to eliminate relevant cues used by signers during natural sign language processing. The attempts to create controlled stimulus material can lead to artificial constructions that are not informative with regard to natural sign language processing. The drastic nature of control methods, such as the removal of the head from the video in sentence presentation, is likely to lead to independent strong effects in EEG data, making any subsequent interpretation questionable.

However, the difficulty of integrating sign language research into the accepted neurophysiological paradigm for written language processing, which assumes full control of the symbolic stimuli, has led to a sparsity of research that used ecologically valid (i.e., fully dynamic and non-manipulated) stimuli. Sign language researchers, however, remain cognizant of the concerns resulting from the use of such controlled stimuli. For example, Moreno et al. (2018) specifically pointed out that, in their research, artificially constructed stimulus material might have caused a reduction in the activation of cortical language areas as compared to previous studies (e.g., Newman, Supalla, Hauser, Newport, and Bavelier, 2010a, 2010b; Newman, Supalla, Fernandez, Newport, and Bavelier, 2015). In this fMRI study on processing of French Sign Language (LSF), the material was spliced together because signs were recorded in isolation and the hands always returned to an intermediate resting position. Then the signs were strung together to form well-matched lists, phrases, or full-length sentences. Moreno et al. (2018) noted that “In such an artificial context, the loss of continuity, of prosodic cues, and of the facial cues which typically provide a global prosodic context for sign language (e.g., specifying whether the sentence is an affirmation or a question) could all explain the reduced amount of cortical activity.” (Moreno et al., 2018, p. 156).

As languages become better understood as multi-frequency information transfer systems (Blumenthal-Dramé and Malaia, 2019), it becomes crucial that non-manipulated stimuli and naturally valid material is used in sign language research to avoid the exclusion of potentially important processing cues, as well as to prevent an overly narrow interpretation of the results. However, although the use of natural dynamic visual stimulus materials is the most adequate approach to studying neural processing of sign languages, experimental designs with such dynamic stimuli encounters multiple challenges. In the following section, we provide detailed examples and discuss the following challenges: 1) the layering of manual and non-manual information from multiple articulators; 2) the identification of potentially relevant cues; 3) the variability of timing for cues within and between conditions, and 4) predictive processing in language.

2. CHALLENGES OF INVESTIGATING SIGN LANGUAGE PROCESSING

2.1 Layering of (non-)manual information

In sign languages, different articulators, either in the manual or non-manual domain, function independently from each other, albeit interactively, which allows signers to provide many pieces of information simultaneously. Thus, multiple channels in sign languages contribute mutually dependent and independent information components (Wilbur, 2000; see also Malaia et al. (2016) and Malaia et al. (2018) for quantitative analyses of information transmission by sign language articulators). To illustrate the layering of different sources of information, let us consider a sentence in Austrian Sign Language (ÖGS) (1)[2]:

y/n-q
puffed cheeks
(1) MAN BOOK GIVE$_2$[cl_2h C-hs]
Is the man giving you the heavy book?

Manual information may be layered in that the handshape of the sign GIVE can be chosen as a classifier handshape to express what kind of object is given, e.g., round, flat, thick, thin. Further, the non-manual marking for a yes-no question (‘y/n-q’, with the underline indicating the spreading/scope domain with respect to the manual signs) may be layered with an adverbial non-manual marking (‘puffed cheeks’, “with effort; for big/heavy things”). In addition, sign language structures may also be accompanied by non-linguistic gestural cues (not included in the example above). Due to the layering of these different information sources, sign languages show high levels of simultaneous complexity (Borneman, Malaia, and

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[2] Notation conventions: signs are glossed with small caps; non-manual markings are indicated by lines above the glosses (*y/n-q* indicates non-manual yes/no-question marking; *puffed cheeks* stands for the adverbial marking for “with effort, for big/heavy things”); the subscript *2* indicates a reference point within the signing space that refers to the second person referent; the classifier handshape accompanying the sign GIVE is denoted in squared brackets (*cl* indicates “classifier”; *2h* indicates that the sign is a two-handed sign; *C-hs* refers to the form of the handshape, which, in this case, is the C-handshape associated with the C in the manual alphabet).

Wilbur, 2018; Malaia et al., 2016), which makes it challenging to construct well-controlled (i.e., visually identical) stimulus material across conditions.

2.2 Identification of relevant cue(s)

Investigations in better-studied sign languages (e.g., ASL) have allowed for the circumscription of a number of manual/non-manual cues/markings with specific linguistic functions, e.g., negation or interrogation (Pfau and Quer, 2010; Sandler and Lillo-Martin, 2006; Wilbur, 2000, 2021; Quer, Pfau, and Herrmann, 2021). However, little is known about the relative contribution of these and other cues to online processing. Therefore, when attempting to create ecologically valid (i.e., naturally signed) stimuli accounting for all potential linguistic and paralinguistic cues becomes problematic. Attempts at 'fully controlled' stimuli (i.e., rigid manipulations of specific factors) carry with them the risk of eliminating important linguistic cues, while influencing linguistic processing in ways that makes it quite removed from natural online processing. An extreme example of such control is Jednoróg et al.'s (2015) work on Polish Sign Language (PJM), which presented signed sentence stimuli without the signer's head "to focus their [Deaf participants'] attention on the manual code" (Jednoróg et al., 2015, p. 193).

A potentially more subtle approach creating controlled, but ecologically valid stimuli relies on instructing signers participating in stimuli recording to minimise the use of non-manual cues in productions. Hosemann et al. (2013) specifically requested stimulus signers to minimise non-manual actions to avoid variations due to non-manual markings. Similarly, Hänel-Faulhaber et al. (2014) asked the stimulus signer to minimise affective and paralinguistic facial expressions, as well as body movements to minimise coarticulation and paralinguistic effects. While this approach is certainly preferable to manipulating the stimuli, both in terms of temporal dynamics and available visual content, it is important to note that intentional elimination of non-manual markings may lead to the elimination of potentially important cues that would normally be used by viewers during online processing. Non-manuals play a crucial role in sign languages, conferring both syntactic and semantic meaning, and native signers agree that natural signing inevitably includes face and body articulation.

Thus, complete control for specific manual and non-manual articulators during signing in a systematic way - to the degree that is expected, for example, in written language processing research - is extremely challenging. It appears preferable to investigate language processing in an environment that is as natural (ecologically valid) as possible, but this approach is in conflict with the paradigm of standard methods in ERP research, which requires multiple (30-40) repetitions of completely identical stimuli with millisecond-precision time-locking of each stimulus onset (e.g., Luck, 2014).

2.3 Variability within and between conditions

From the perspective of neural online processing of a sign language, little is known about the effects of subtle variability among manual or non-manual (linguistic as well as non-linguistic) cues in the stimuli. Differences between conditions, as well as non-homogeneity within conditions, may influence the time course and the strategy during sign language processing. For example, if specific manual/non-manual cues are systematically present in the stimuli in one condition, but absent in others.

Consider a situation in which a specific non-manual marking is a relevant cue for a particular sign language in a particular set of linguistic constructions. If we attempt to compare two experimental conditions that include this non-manual marking, each with a different likelihood/probability, the non-manual marking might not appear to be systematic or necessary overall, but could be an important probability-dependent cue for a specific processing strategy that could influence corresponding ERP effects. One such example would be the non-manual markings used for negation. In several sign languages, negation can be expressed by manual signs as well as different non-manual markings (often head shake, but also other non-manuals). Some non-manual markings used for negation are not obligatory and the likelihood of occurrence of these non-manual negative markers can vary. Indeed, there is evidence that some sign languages are more dependent on the presence of a manual negator (manual dominant), while others are more dependent on the presence of the non-manual dominant negator (Zeshan, 2006).

It is difficult to control for variability contributed by slight differences in non-manual markings or signs duration, because these cues may not be obvious even to the signer signing the stimuli, or may not appear consistent during the filming of the stimulus material. Research on linguistic characterisations of non-manual markers in a variety of sign languages is still ongoing, which means that natural signing is likely to contain markers whose purpose is not always clear. On the other hand, the intentional reduction of non-manual markers can lead to the creation of artificial stimulus materials, which interferes with the goal of studying ecologically valid sign language processing.

2.4 Predictive processing

The notion of *predictive processing* in human neuroscience encompasses a number of theories at various levels of representation: from information-theoretic models of the brain to brain network function (cf. Koster-Hale and Saxe, 2013). In general, predictive processing refers to the neural function by means of which the brain continually produces a model of the environment and updates it based on prediction errors (Clark, 2013; Walsh, McGovern, Clark, and O'Connell, 2020; Radošević, Malaia, and Milković, 2022).

Neural evidence for predictive processing is strongest in the areas of visual perception and linguistic processing (Malaia, Borneman, Krebs, and Wilbur, 2021). In visual processing, learning-based expectations about the visual environment have been shown to affect downstream visual processing as early as in 6-month old hearing infants (Emberson, Richards, and Aslin, 2015), supporting a hierarchical predictive feedback model (Rao and Ballard, 1999). In spoken language processing, contextual information, when quantified in terms of information-theoretic models as appropriate for narrowing predictions for upcoming signal at the phonological, morphological, semantic or syntactic levels, predicts processing cost across all levels of language description (Blumenthal-Dramé et al., 2017; Blumenthal-Dramé and Malaia, 2019; McConnell and Blumenthal-Dramé, 2019).

Linguistic metrics used to evaluate predictive processing and prediction error typically quantify the information load of an incoming stimulus in terms of how strongly it modifies the current model in the linear sequence of the unfolding linguistic signal. These metrics, including neighborhood density, word frequency, transitional probability (or cloze probability), surprisal, and entropy reduction, can only be computed based on substantial corpora. Among sign languages, such a corpus is currently available only for ASL (ASL-LEX, cf. Caselli, Sehyr, Cohen-Goldberg, and Emmorey, 2017; Sehyr, Caselli, Cohen-Goldberg, and Emmorey, 2021). A study comparing word frequency, phonological neighborhood density, and iconicity effects on ASL acquisition (Caselli and Pyers, 2017) indicated that all of these statistical metrics contributed to vocabulary expansion in children learning sign language.

Additional challenges that require careful consideration for EEG research on sign language are the layered and continuous nature of the physical signal (as outlined in section 2.1.). The signal in speech or written language is for the most part perceived sequentially. Sign language signal, on the other hand, is transmitted continuously and by multiple articulators, and thus different information is perceived simultaneously. Although coarticulation effects (i.e., overlapping of phonemes; the way a certain phoneme is articulated is influenced by physical properties of the following phoneme) are present in spoken languages as well, in this case, co-articulation only involves one information channel - the acoustic signal. Sign languages are produced by the manual and non-manual information channels, and therefore different manual and non-manual information is present in parallel. In addition, the transition between two lexical items is visible to the addressee in sign language perception, but it is not perceivable to the addressee during spoken language perception.

This means that, in sign languages, information critical for predictive processing (i.e., uncertainty reduction) may be contained in the transitional movement before the 'critical' sign is reached (e.g., Hosemann et al., 2013; Krebs et al., 2018; Krebs, Wilbur, Alday, and Roehm, 2019). In fact, in sign language research, transitional movements have been clearly shown to contribute early cues for predictive processing (Hosemann et al., 2013; Hosemann, 2015), both at the lexical and syntactic level (Brozdowski, 2018; ten Holt, van Doorn, de Ridder, Reinders, and Hendriks, 2009; Jantunen, 2010; Krebs et al., 2019). Moreover, while the relevance of transitions within sign language processing has been noted (Hosemann et al., 2013),[3] the question of whether the "transitional" movement is possibly part of the critical sign itself has not been adequately addressed (Green, 1984; Jantunen, 2010, 2015; ten Holt et al., 2009; see Krebs et al. (2019) for a more detailed discussion on sign onset and transitional movements).

Creating controlled stimulus material for studies in sign language processing, which is, by nature, a multi-channel, multi-scale, layered communication modality, while attempting to minimise the effect of linguistic and non-linguistic factors that are external to the research question is a trade-off between maintaining ecological validity of stimuli and keeping other factors to the minimum across experimental conditions.

3. CONSEQUENCES FOR THE INTERPRETATION OF ERPS

Having pointed out the challenges in creating linguistically valid stimulus material in sign language, we now turn to the question of appropriate interpretation of observed ERP effects for dynamic stimuli. In particular, we discuss two concerns that are a natural consequence of the challenges encountered in stimuli creation: 1) The "trigger/effect assignment" problem, and 2) the effect of dynamic differences between conditions on neurophysiological data.

3.1 The "trigger/effect assignment problem"

One of the consequences of simultaneous layering of information from multiple articulators in sign languages, and the lack of clarity as to which visual cues may be relevant for linguistic processing, is the question of onset-time assignment. For time-domain analysis, it is necessary to identify a specific time point as the onset of the EEG signal in order to calculate ERPs (frequency-domain analysis can, on the other hand, be more flexible, depending on the question being addressed – see section 4.2.).

Defining the onset (and offset) times of a sign within a sentence is a notoriously problematic issue for ERP research in sign language. Most phonological models of sign language define the onset of a sign as its "first hold" in space, i.e., the time point when the target handshape arrives at the target position from where the movement in sign will commence (for signs that include change of location movement), or at the target position at which the sign is articulated (for signs that do not contain path movement). This definition is based on the "hold-movement-hold" model (Liddell and Johnson, 1989). However, the assumption that the first hold of a sign is the critical phonological cue for defining the onset of a sign is somewhat problematic. First, "holds" of signs are better described as phonetic, similar to rhythmic holds in speech (cf. Wilbur, 1990). Second, not every sign indicates a clearly defined first hold (see Hanke, Matthes, Regen, and Worseck, 2012) – instead, sentence articulation is typically continuous and dynamic, such that only a path change following

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[3] "In addition to providing new evidence regarding the application of forward models during language comprehension, our results call for a new interpretation of transition phases in sign language. It is apparent from our data that the transition phase cannot be treated as a "meaningless" trajectory that serves to link two meaningful signs with one another, but that it rather carries a substantial amount of meaning itself. It must be stressed, however, that the present study only demonstrates that this information can induce a prediction error. It does not, conversely, show that the degree of information suffices to allow for sign recognition. Whether or not this is the case is an interesting question for future research. Based on the present findings and the assumption of a forward model, we would predict that the transition phase should allow for sign recognition at least under certain circumstances, namely when the combination of sentence context and trajectory provides enough information for recognition of the upcoming sign." (Hosemann et al., 2013, p. 2232)

handshape formation for sign onset can be identified within the filmed stimuli. Third, partial information for the upcoming lexical sign is often available during the preceding transitional movement (e.g., Jantunen, 2010; ten Holt et al., 2009).

In addition, the layering of non-manual and manual information complicates the process of determining to which cue(s) a specific ERP effect may be traced. For instance, while investigating the processing of word order variations in Austrian Sign Language (ÖGS), Krebs et al. (2018) reported that the onset of the observed ERP effect related to reanalysis might be time-bound to the following: 1) the transitional movement that indicates from which location in space the verb sign would begin its movement (i.e., the location with which the subject argument is associated), or 2) specific non-manual markings preceding/co-occurring with the transitional movement. Since many aspects of sign language grammar and sign language processing are poorly understood, determining which visual cues provide relevant information for processing is often impossible.

One approach used to assess the relationship between the stimulus and the observed ERPs in early work with dynamic sign language stimuli consisted of relying on ERPs identified in spoken language research (their latencies, topography and polarity) to make inferences about sign language processing. The concern with the broad application of this approach in early work was the lack of appropriate baseline grounded in sign language processing mechanisms.[4] Such an approach was adopted in Hosemann et al. (2013), who investigated the processing of sentences in German Sign Language (DGS) with expected vs. unexpected endings. Compared to control sentences, those with semantically unexpected endings (the target condition) demonstrated a pattern consisting of two effects - a negativity, followed by a positivity. The negative effect was interpreted as an instance of an N400. Operating on the assumption that the observed effect was identical to the N400 ERP observed in response to the semantic prediction violation in spoken language research, the researchers made inferences as to the cue that could evoke the observed effect. As a result, the transitional motion was identified as the trigger for ERP denoting violation of semantic prediction. This illustrates the potential for overgeneralization inherent in using the findings from a different modality in studies researching higher level cognitive processes.

While functional significance of transition phases is certainly important, the application of ERP latencies from other domains of research, such as spoken language processing or (non-linguistic) visual processing to sign language processing, is somewhat problematic. Signing and speech differ in modality, and therefore, in the associated anatomical processing regions that generate observed ERPs, e.g., in addition to the perisylvian language regions within the dominant (mostly left) hemisphere, sign language processing involves enhanced recruitment of the non-dominant (mostly right) hemisphere, as well as visual processing areas (Malaia, Ranaweera, Wilbur, and Talavage, 2012; Malaia et al., 2014; Malaia and Wilbur, 2010). Visual processing per se, on the other hand, does not include linguistic processing. Moreover, sign language stimuli differ quantitatively in substantive ways from everyday visual environments and gesture (Malaia et al., 2016; Borneman et al., 2018), and signers show differences in non-linguistic visual processing compared to non-signers (Bosworth, Wright, and Dobkins, 2019; Gurbuz et al., 2020a, b).

Processing of ERPs typically relies on an averaging procedure over multiple segments of continuous EEG data time-stamped with onsets of the stimuli in one category. However, individual words always differ in length (i.e., duration), frequency of occurrence in different types of corpora, typical age of acquisition, paradigm density, and likelihood probability of occurring in a specific syntactic structure (cf. Pulvermüller and Shtyrov, 2006; Blumenthal-Dramé et al., 2017). Depending on the unit of analysis (i.e., phoneme, word, syntactic structure), the standard approach in psycholinguistic research is to attempt to bal-

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[4] The differences between neural mechanisms of processing speech vs. sign language have been documented in detail since the early 2000s (e.g., Bavelier et al., 2008; Newman et al., 2010a).

ance averages of pertinent statistical parameters between conditions and to avoid obvious outliers within conditions. This is often not possible since appropriately annotated corpora, on the basis of which such psycholinguistic statistics are calculated, do not exist for most sign languages. As an additional complication, the length of transitional movements can differ depending on the places of articulation for each sign. If transition time between the pre-critical and the critical sign differs between individual sentences, it may affect the timeline of presentation for each subsequent sign in an additive manner. This variability can lead to temporal 'blurring' of the observed effects, especially when ERP waveforms are averaged for each condition. In the context of longer linguistic units, such as phrases and sentences, the issue is complicated by predictive processing, since it is impossible to evaluate whether an observed ERP effect might be elicited by the preceding context.

An alternative approach to evaluating the time course of sign language processing with respect to different cues is to timestamp continuous EEG signal with trigger markers for each potentially relevant cue in the dynamic stimuli (see below for a more detailed description). This procedure allows for a more fine-grained analysis of the temporal succession of ERP patterns; however, it does not provide the 'ground truth' – i.e., it does not allow for the conclusive determination of whether an observed ERP effect is the result of that specific cue (although a stronger, time-limited ERP pattern might serve as a probabilistic argument for cue relevance). A better understanding of the linguistic status of a variety of manual and non-manual cues, as well as unit-appropriate statistical data for each sign language extracted from corpora, would contribute to improving the interpretability of EEG data based on natural signing stimuli.

3.2 Example analysis

In the following, we will present examples illustrating how differences in timing, i.e., sign dynamics between two experimental conditions, may lead to artifacts during processing. The example uses data from a word order variations experiment (Subject-Object-Verb (SOV) compared to Object-Subject-Verb (OSV) orders) in Austrian Sign Language (ÖGS) (Krebs, 2017). Studies of analogous structures in a number of spoken languages have indicated that sentence-initial arguments with ambiguous syntactic function are preferentially interpreted as the subject of the clause (Malaia et al., 2009; Malaia, Wilbur, and Weber-Fox, 2012; Wang, Schlesewsky, Bickel, and Bornkessel-Schlesewsky, 2009). This phenomenon, termed subject preference, leads to reanalysis effects in response to object-first sentences (which, while grammatically correct, still evoke a 'garden-path' type effect). Behaviorally, reanalysis is reflected in lower acceptability ratings, as well as longer reaction times to non-subject-initial word orders (e.g., Bornkessel, McElree, Schlesewsky, and Friederici, 2004; Haupt, Schlesewsky, Roehm, Friederici, and Bornkessel-Schlesewsky, 2008), longer reading times (Schlesewsky, Fanselow, Kliegl, and Krems, 2000), increased regressions and longer fixations during reading (e.g., Kretzschmar, Bornkessel-Schlesewsky, Staub, Roehm, and Schlesewsky, 2012), as well as different ERP effects (see e.g., Bornkessel-Schlesewsky and Schlesewsky, 2009 for an overview).

Preverbal arguments in ÖGS sentences, which lack any form of case-marking, are referenced by index signs in the signing space in front of the signer (in the ÖGS stimulus material, the first argument is always referenced at the left side of the signer and the second argument at the right side in both SOV and OSV orders). After the arguments were referenced in space, either agreeing verbs or agreement markers (which accompany plain verbs that do not indicate verb agreement) can disambiguate the syntactic function of the arguments by means of a path movement from the location associated with the subject to the location associated with the object (and/or by facing of the palm/fingertips towards the object location). See Table 1 for a sentence example of an SOV and an OSV structure in ÖGS involving an agreeing verb.[5]

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[5] Notation conventions: Signs are glossed with small caps; IX = manual index sign; Subscripts indicate reference points within the signing space

Table 1. *Example for SOV and OSV orders in ÖGS*

SOV	OSV
GRANDCHILD IX$_{3a}$ GRANDMOTHER IX$_{3b\ 3a}$VISIT$_{3b}$ *The grandchild visits the grandmother.*	GRANDCHILD IX$_{3a}$ GRANDMOTHER IX$_{3b\ 3b}$VISIT$_{3a}$ *The grandmother visits the grandchild.*

An EEG analysis of critical verbs and agreement markers revealed the expected ERP effects for OSV compared to SOV sentences. In particular, it appeared that these reanalysis effects were triggered by the prior transitional movement of the index sign towards the verb sign or the agreement marker, and/or by non-manual markings co-occurring with the index hand which references the second argument NP.

An additional analysis, however, indicated unexpected ERP effects on the preverbal arguments which started before the onset of the sign (the onset was defined as the time point when the target handshape and the target location of the sign were established and the movement of the sign initiated).[6] As ÖGS has no known case-marking for arguments, this required careful investigation of the stimuli videos, to determine whether the stimulus material included any visual cues that might have led to these ERP effects. Stimulus sentence-videos were screened for a multitude of manual and non-manual parameters (brow raise, eye gaze directions, head tilt, head turn, body lean, body shifting, shoulders, the movement of the hand(s), pointer height and durations of index signs and argument NPs) by three researchers from two independent labs.[7] Inspections of the video material did not reveal any systematic (or unsystematic) (non-)manual markings that could result in ERP differences for preverbal arguments.

Where systematic differences did occur was the time course between the two experimental conditions. Compared to SOV, OSV sentences were signed faster – by a few milliseconds per

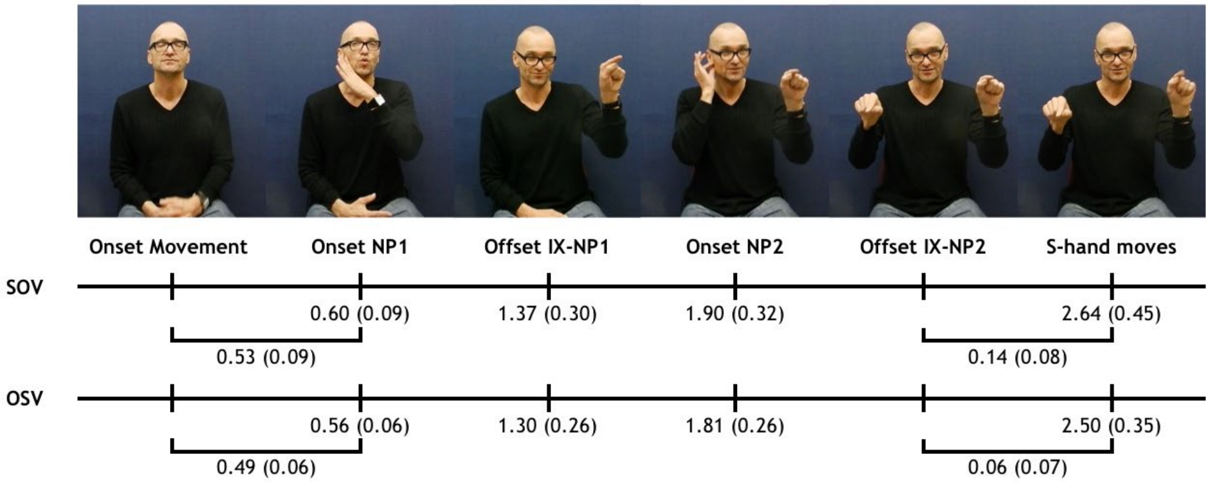

Figure 1. *Illustration of the differences in time course between SOV and OSV orders for the plain verb condition. Time points and durations are given in seconds. Standard deviations are presented in parentheses. All of the given values differ significantly for both conditions (SOV vs. OSV).*

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[6] For instance, when we considered the plain verbs with regard to the onset of the first argument, we observed an anterior-central distributed negative effect starting before the onset of the first argument (in the -200 to 150 ms time window) for OSV compared to SOV (a more detailed description of the results is presented in Krebs, 2017).

[7] We would like to thank Brandy Selleck Morris and Domenica Marchiafava from the Sign Language Linguistics Lab at Purdue University for their assistance with data analysis.

sign. This timing difference was found to be cumulative across multiple time points in the sentences (see Figure 1; Krebs, 2017). The differences would not be noticeable in the course of normal signing interactions – however, for ERP analysis, a cumulative difference of 40 ms (at the point of first argument onset), or 90 ms (at the point of second argument onset) is substantial – especially if it is consistent between conditions.

The difference in timing between conditions is quite interesting, since it could be linguistically relevant. It has been proposed (at least for ASL; cf. Wilbur, 1990; Wilbur and Schick, 1987) that transition phases preceding or following signs may be modulated for stress (prosodic marking). In ASL, stressed signs have a longer duration than non-stressed signs. Thereby, transitional movements are transformed in a way that they are perceived as partially belonging to the rhythm of the lexical sign (Wilbur, 1990; Wilbur and Schick, 1987).[8] Thus, one could speculate that OSV structures in ÖGS are prosodically marked (similar to topic-constructions in which the stress is on the first argument, e.g., Aarons, 1994, 1996; Liddell, 1980; Ni, 2014). On the other hand, the difference in timing between SOV and OSV orders could be an artifact of the stimulus filming procedure. In this case, the SOV sentences were filmed before the corresponding OSV sentences. Therefore, the timing difference could be the result of a simple habituation effect during production. The signer, who was already familiar with the sentence context, might have signed the OSV structures a little faster and used shorter transitions in OSV sentences.

If the timing differences were an artifact of signing order (habituation), reversing the order of production (signing OSV before SOV) would be expected to reverse the timing effect, while a randomised order would then eliminate the effect entirely. If, however, the timing differences were linguistically determined, signing order would not affect the dynamics of the sentence. A re-recording, with the same signer, of a subset of the stimuli sentences in reversed order, as well as in pseudo-randomised order, revealed the occurrence of habituation, rather than linguistic interpretation. Subsequent studies, for which the stimulus material was filmed in pseudo-randomised order, revealed no ERP effects prior to the disambiguation condition. For instance, in the ERP study on processing of word order variations in ÖGS, for which the stimulus material was filmed in pseudo-randomised order, the authors observed no ERP effects on (or before) the first argument (Krebs, 2017; Krebs et al., 2018).

However, linguistic factors also cause differences in timing between conditions. For example, an ERP study on topic-marked constructions in ÖGS (Krebs et al., 2020) revealed a systematic timing difference due to a pause after the topic was signed (there was no pause in sentences without topic marking). Interestingly, word order manipulations may also lead to timing differences. When the signer keeps the spatial referencing of the preverbal arguments constant among conditions (i.e., the first argument is always referenced at the left side of the signer and the second argument is always referenced at the right side of the signer independent of SOV or OSV word order), the signer has to produce a longer transitional movement towards the sentence-final agreeing verb sign for SOV orders, because it is necessary to move back to the position of the first argument to produce the path movement of the verb (which - in the regular case - would be indicated by a path movement from the location in space associated with the subject to the object position; see Figure 2). When compared to the OSV structures, this longer transitional movement towards the verb sign in SOV results in systematic, condition-dependent timing differences.

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[8] In particular, Wilbur and Schick (1987) reported that transitional movements preceding signs, which are usually short in duration, lax in production, and do not carry a beat as part of the rhythm, may be transformed into movements resembling lexical movements of signs by increasing their speed, tensing the hands during articulation, including non-manual behaviors during their production, and modifying the rhythm to reflect the presence of an additional movement.

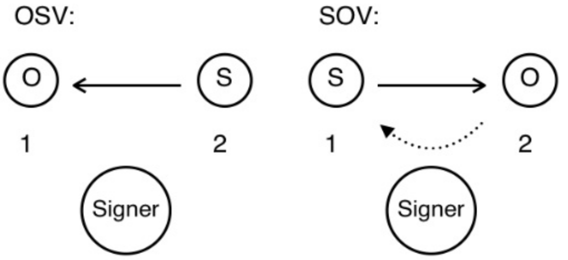

Figure 2. *Schematic illustration of the longer transitional movement towards the verb sign required in the SOV orders (see right picture) compared to OSV structures (see left picture). In both conditions, the signer referenced the first argument on her left side and the second argument on her right side (indicated by the numbers). In both conditions, the argument structure was expressed by a path movement from the subject (S) to the object (O) position (indicated by the continuous arrows). In OSV orders, this path movement was produced from the argument referenced second (S) towards the argument referenced first (O). In SOV orders, however, the signer had to move back from the position where the second argument (O) was referenced towards the first argument (S), resulting in a longer transitional movement towards the verb in SOV orders (indicated by the dotted arrow).* (reprinted with permission from Krebs et al. 2018)

These examples illustrate that ERP studies on sign languages need to take into account the visuo-spatial, multi-layered nature of signing modality, with both linguistic- and non-linguistic cue dynamics unfolding on millisecond scale. Time course differences between conditions need to be calculated and reported quantitatively, even when stimulus filming follows the best practice of recording in a pseudo-randomised order. In the case of latency shifts within the stimulus material, they need to be taken into account in interpretation of ERP effects. This can be facilitated by the comparison of latency differences in the stimulus material with the observed ERP component latencies. Very small timing differences within the stimulus material could be systematic and result in ERP latency differences that are statistically significant, although they are not necessarily interpretable. If the observed ERP effect is relatively strong (either in terms of amplitude or duration), and the difference in latency is very small, it is unlikely that the ERP effect is solely the product of a latency shift. For instance, in Krebs et al. (2020), the effect interpreted as reflecting reanalysis (time-locked to the instance when the transitional movement towards the disambiguating verb became visible) overlaps with time intervals in the stimuli for which systematic differences in timing were observed. Thus, the ERP effect measured between 200-400 ms cannot result solely from a 30-ms shift in latency.

4. ALTERNATIVE APPROACHES TO EEG DATA ANALYSIS FOR NATURAL SIGNING STIMULI

One crucial difference between speech and sign language is the amount of predictive information available in the transition between individual words/signs. In speech, relatively little information is contained in the transition between words that could provide information regarding the upcoming word, as evidenced by the fact that most phonological rules do not apply across word boundaries, except for those identified as fast speech phenomena. In signing, the transition between signs consists of hand articulator movement from the place of articulation and the end of one sign to the place of articulation that is appropriate for the onset of the next sign. Transitions in speech, then, can be relatively short, if not containing intentional pauses. Additionally, the change of position of speech articulators is for the most part not visible/audible to the addressee and cannot serve as a cue for predictive processing. In sign language, transitions provide plenty of information since all the articulators used for signing are constantly visible and indicative of upcoming articulation. Thus, transitional movements in sign language provide continuous input for predictive processing at multiple levels (phonological, lexical, and syntactic) by providing novel input that restricts the potential options for places of articulation, handshapes, and trajectories that are compatible with prior context. Since transitional movements are informative, they need to be included in ERP analyses (see also Hosemann et al., 2013; Hosemann, 2015), because otherwise early predictive processing effects might be eliminated in the baseline interval.

4.1 Inclusion of transitional movement in linguistic analysis

One approach that can help evaluate the relevance of transitional movement for online sign language processing is the inclusion of multiple potential onset triggers as timestamps in the stimuli: this allows for the evaluation and comparison of different stimulus onset times in post processing. This method was used, for example, in the study of Krebs et al. (2018), which investigated the processing of word order variations in ÖGS. ERPs were analysed separately for two different trigger markers: first, the point of handshape formation that was used for measuring ERPs in previous studies investigating sign language processing (e.g., Capek et al., 2009), and second, the point at which the transitional trajectory towards the disambiguating verb was visible (Figure 3; Krebs et al., 2018) (for a similar approach see also e.g., Hosemann, 2015; Hosemann et al., 2013, 2018, 2020; Krebs et al., 2020; Krebs, Malaia, Wilbur, and Roehm, 2021; Malaia, Krebs, Roehm, and Wilbur, 2020; Wienholz et al., 2018).

Figure 3. *Illustration of the two trigger markers, i.e., the time points at which ERPs were measured. The image on the left displays the trigger "Transition" and the image on the right displays the trigger "Handshape": shown for the two-handed verb sign* ÜBERFALLEN *"to attack someone" which has an internal movement. The trigger "Handshape" was identified when both hands showed the initial handshape.* (reprinted with permission from Krebs et al. 2018)

Krebs et al. (2018) observed a significant ERP effect only with respect to the trigger "Transition". The interpretation of this effect, however, required further behavioral investigation. A behavioral gating study reported in Krebs et al. (2019) confirmed that disambiguation was triggered by cues visible before the handshape of the verb is established (i.e., the manual transitional movement and/or co-occurring non-manuals). Thus, it became clear that disambiguation of syntactic structure was triggered by visual cues presented before the manual verb sign was visible. As a result, the ERP effect bound to the transition trigger was interpreted as that of syntactic reanalysis.

Note that the question of which component of the transitional movement might be informative for processing (i.e., the initial part of the transitional movement, such as when the hand changes its movement direction or orientation, or later parts of the transitional movement, such as when a handshape change or the handshape formation of the upcoming sign is visible) may depend on the linguistic role and length of the unit of investigation (sign vs. phrase vs. sentence), as well as on the experimental design of the study. For example, if the critical sign is embedded within a sentence, the syntactic structure preceding it would narrow down the range of possibilities for a grammatical sign in the sentence: then, the early portion of the motion (toward the place of articulation) might be sufficient for statistical prediction of the correct sign. If, on the other hand, the experimental design relies on a word list (e.g., lexical retrieval task), syntactic/pragmatic constraints would not affect processing and handshape disambiguation (in the later portion of transitional movement) might be more informative (and dependent on the handshape's/sign's neighborhood density).

Consider Figure 4, which provides a frame-by-frame illustration of the visual signal prior to the time points typically used to define sign onset and measuring ERPs (shown for two separate verb signs). The handshape of the upcoming sign might be predicted by signers before the time point when the target handshape of the sign is entirely established, as well as before the time point when the handshape of the sign reaches the location from where the movement of the sign begins. The examples illustrate signs produced in isolation. When signs are produced in the context of a sentence, transitional movement from one sign to the next is even more informative, since the preceding context further narrows down the type of sign (e.g., verb/noun) in the following syntactic position.

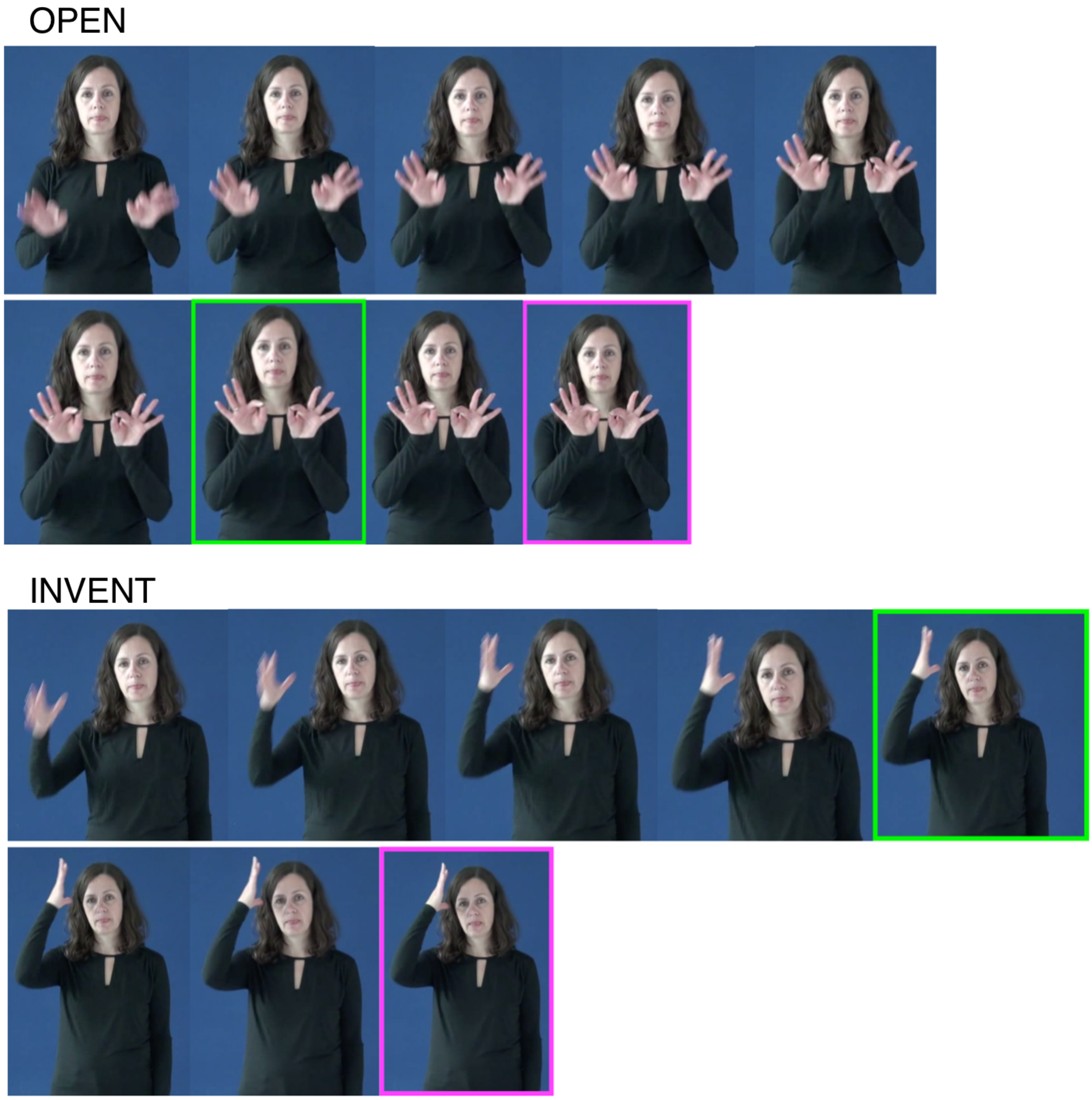

Figure 4. *Frame-by-frame illustration of the beginning of the ÖGS signs* OPEN *and* INVENT*. The signs are produced in isolation, i.e., there are no other signs preceding or following them. In both examples, the pictures illustrating the time points often used for defining sign onset and measuring ERPs are marked with coloured frames: The picture with the green frame illustrates the time point when the target handshape of the sign was fully established. The picture with the purple frame indicates the time point when the handshape reached the location from where the movement of the sign began. The handshape of the upcoming sign might be predictable by signers even before the time point when the target handshape of the sign has been fully established (picture with green frame) and therefore, also before the time point when the handshape reaches the location from where the movement of the sign begins (picture with purple frame).*

4.2 Frequency-domain analyses

Frequency-domain analyses in EEG focus less on the question of when specific responses happen, and more on the question of what frequency bands of neural activity are involved in the response. Time-frequency analyses can still be time-locked – for example, they can indicate suppression or enhancement of activity in specific frequency bands by means of event-related synchronisation (ERS) and desynchronisation (ERD) analyses (which do not, in fact, assess neural synchronisation, but simply calculate the power of the spectral response that is time-locked to the stimuli (cf. Hari and Puce, 2017)). These analyses are useful for hypothesis testing in fields of research where both the functions and sources of specific frequency responses are well-established, such as motor activity (mu rhythm of the sensorimotor cortex) and visual processing (posterior alpha rhythm).

The type of time-frequency analysis that is potentially useful for hypothesis testing in language research is entrainment tracking. Neural entrainment is a frequency-following response (or envelope tracking) to the rhythms of periodic external stimuli, especially in the auditory and visual domains. It is currently established that signal-based entrainment at a range of frequencies forms the basis of speech comprehension (Ding, Melloni, Zhang, Tian, and Poeppel, 2016; Riecke, Formisano, Sorger, Başkent, and Gaudrain, 2018). This type of research in sign language is complicated by the higher dimensionality of the visual signal: both spatial and temporal frequencies are present in the visual domain, and carrying out speech-like entrainment analysis would require dimensionality reduction of the stimulus signal in a way that would retain fidelity to the original signal in terms of its linguistic content.

One approach to carrying out stimulus-response analysis in the frequency domain in sign languages has been to rely on information-theoretic measures characterising dynamic visual signal, such as power-spectral density of optical flow (Borneman et al., 2018). Interestingly, quantitative analyses of EEG signal coherence with such measures consistently indicates high salience of low (under 4 Hz) frequencies to language comprehension (as measured by behavioral responses), which suggests reliance on predictive processing in sign language comprehension (Ford et al., 2021; Malaia et al., 2021; Borneman et al., 2021), despite high spatiotemporal frequencies inherent in sign language signal (Bosworth, Bartlett, and Dobkins, 2006; Bosworth et al., 2019). This indicates that online comprehension is likely driven by low-frequency (temporal and spatial) visual signal, and supported by predictive processing mechanisms grounded in sign language knowledge (see also Malaia, Ford, Borneman, Krebs, and Ames, 2021).

5. CONCLUSION

We have identified several challenges in using EEG in research for sign languages. These span from the challenges of creating well-controlled stimulus materials, unaffected by statistical frequency or habituation effects, to the interpretation of ERP components that are elicited by (informative) transitional movement between signs. We presented several examples of combining EEG and behavioral experiment sequences to evaluate whether observed ERP components represent neurocognitive correlates of linguistic processing, or stem from stimuli or analysis artifacts, especially with respect to the timing of visual cues, sign duration, and ERP latencies.

While complete control of statistical and temporal features of linguistic stimuli in sign language can undermine the ecological validity of neurocognitive processing, the interpretation of EEG effects needs to carefully consider multiple parameters of signed stimuli, both in terms of physical features likely to lead to sensory processing differences (contrast, size of the signer in the video during presentation, etc.), as well as potential linguistic cues available in the video (from non-manual features to transitional movement).

As more research in neurocognition of sign language leads to rapid gains in understanding of the grammar of sign languages and sign language processing, an open discussion on methodology used by the different research groups working on a variety of sign languages can lead to rapid progress in the field. The study of sign language processing can provide a unique window into human neurocomputational ability. The challenges in the field, however, are sufficiently different from those of spoken language, visual processing, or social neuroscience, to warrant collaborative work to establish best practices.

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Disclosure of interest

The authors report no conflicts of interest.

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