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Lexical prediction via forward models: N400 evidence from German Sign Language

Jana Hosemann[a], Annika Herrmann[a], Markus Steinbach[a], Ina Bornkessel-Schlesewsky[b], Matthias Schlesewsky[c,*]

[a] Department of German Philology, Georg-August-University Göttingen, Göttingen, Germany
[b] Department of Germanic Linguistics, University of Marburg, Marburg, Germany
[c] Department of English and Linguistics, Johannes Gutenberg University Mainz, Jakob-Welder-Weg 18, 55099 Mainz, Germany

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ABSTRACT

Models of language processing in the human brain often emphasize the prediction of upcoming input—for example in order to explain the rapidity of language understanding. However, the precise mechanisms of prediction are still poorly understood. Forward models, which draw upon the language production system to set up expectations during comprehension, provide a promising approach in this regard. Here, we present an event-related potential (ERP) study on German Sign Language (DGS) which tested the hypotheses of a forward model perspective on prediction. Sign languages involve relatively long transition phases between one sign and the next, which should be anticipated as part of a forward model-based prediction even though they are semantically empty. Native speakers of DGS watched videos of naturally signed DGS sentences which either ended with an expected or a (semantically) unexpected sign. Unexpected signs engendered a biphasic N400—late positivity pattern. Crucially, N400 onset preceded critical sign onset and was thus clearly elicited by properties of the transition phase. The comprehension system thereby clearly anticipated modality-specific information about the realization of the predicted semantic item. These results provide strong converging support for the application of forward models in language comprehension.

1. Introduction

The literature on the neurophysiology of language has recently seen a great deal of discussion with regard to the role of prediction in language processing. Thus, there is good evidence to suggest that the human language processing system anticipates individual words during the comprehension process. For example, DeLong, Urbach, and Kutas (2005) observed a modulation of the N400 event-related brain potential (ERP) when a determiner ("a" or "an") was incompatible with the predicted following noun (e.g. when "kite" was predicted as in "The day was breezy so the boy went outside to fly…", "an" versus "a" engendered an N400 effect). Findings such as these (for similar results, see Otten, Nieuwland, & van Berkum, 2007; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; Wicha, Moreno, & Kutas, 2004) provide strong converging support for the assumption that the language processing system actively engages in predictive processing of upcoming input, rather than relying primarily on bottom-up input information (for a framework describing the interplay between top-down prediction and bottom-up information, see Federmeier, 2007).

1.1. Modeling prediction in language processing

How should these predictive mechanisms be envisaged? Perhaps the most straightforward assumption in this regard is that prediction is implemented via lexical preactivation. In this view, the sentence (and discourse) context serves to preactivate expected (or lexically associated) upcoming words and the degree of a word′s preactivation determines the N400 amplitude. Such "lexical" accounts of the N400 have become dominant over the past few years, as they can derive the observation that the N400 does not straightforwardly mirror sentence plausibility (e.g. Lau, Phillips, & Poeppel, 2008; Brouwer, Fitz, & Hoeks, 2012; Stroud & Phillips, 2012). This is apparent, for example, in "semantic reversal anomalies" such as "The hearty meals were devouring…" (Kim & Osterhout, 2005)—i.e. implausible sentences in which the critical word has a high degree of lexical-semantic association to the preceding context and which do not engender an N400 effect in comparison to plausible controls in English and Dutch (e.g. Kuperberg, Sitnikova, Caplan, & Holcomb, 2003; Kolk, Chwilla, van Herten, & Oor, 2003; Kim & Osterhout, 2005; Hoeks, Stowe, &

* Corresponding author. Tel.: +49 6131 3923478; fax: +49 6131 3923836.
E-mail address: schlesew@uni-mainz.de (M. Schlesewsky).

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Doedens, 2004).[1] In spite of their inherent appeal, however, lexical models of this type do not provide a principled explanation for N400 amplitude modulations that are not due to spreading activation between lexical entries (for N400 effects based on discourse congruence independently of lexical association, see Camblin, Gordon, & Swaab, 2007). This raises the question of how more abstract levels of prediction might be implemented.

The assumption of forward models in language processing appears to provide a promising solution to this question. As proposed by Pickering and Garrod (2007), the language comprehension system may draw upon the language production system to emulate (i.e. set up a forward model of) the current input. The output of this model, i.e. the predicted word, can then be matched against the word actually encountered. In the neurophysiological domain, a similar view has been advocated by Federmeier (2007). She proposes that top-down, predictive mechanisms in language comprehension are achieved via a tight coupling between the comprehension and production systems and that this coupling takes place primarily within the left hemisphere. The right hemisphere, by contrast, processes the input in a more strongly stimulus-based (feed-forward) manner. Evidence for this view stems from ERP studies with visual half-field presentation techniques (for an overview, see Federmeier, 2007) and from correlations between production measures and predictive processing in comprehension (Federmeier, Kutas, & Schul, 2010). An interdependence between the N400 and production abilities has further been reported for commissurotomy patients (Kutas, Hillyard, & Gazzaniga, 1988).

It remains to be examined, however, how specific the information provided by such forward models is. The vast majority of previous electrophysiological studies on prediction in language comprehension have used segmented (typically word-by-word) visual presentation. Hence, to explain prediction under these conditions, a forward model would essentially only need to provide an activated lexical entry and, perhaps, a visual word form (for evidence in favor of prediction down to the orthographic level, see Dikker, Rabagliati, Farmer, & Pylkkänen, 2010; Dikker & Pylkkänen, 2011). In accordance with current neurobiological models of speech processing, however, forward models could also be expected to provide much more detailed information regarding the projected upcoming input. Rauschecker and Scott (2009), p. 722, for example, assume a "predictive motor signal" that "inform[s] the sensory system of motor articulations that are about to happen". In the present study, we tested the hypothesis that forward models in language processing go beyond the activation of lexical entries and, instead, provide modality-specific information regarding the expected sensory properties of the upcoming input. To this end, we capitalized upon the manual-visual modality of sign languages. Sign languages have modality-specific articulatory properties, which render them an ideal testing ground for examining the specificity of forward models in language processing. In the next subsection, we briefly introduce two properties that will be most relevant for our study.

1.2. *Predicting input in a sign language: Simultaneity and three-dimensionality*

Because of the specific properties of the manual-visual modality, sign languages differ from spoken languages in two respects: First, they are produced in a three-dimensional signing space and second, they can use different kinds of articulators simultaneously. These articulatory differences also affect the architecture of grammar. The three-dimensional signing space in front of the signer′s upper body is relevant for the production of lexical manual signs, which are constituted by the four basic phonological parameters handshape, orientation, location, and movement. A change of one parameter in any of the three spatial dimensions can cause a change in meaning (Stokoe, 1960; Padden & Perlmutter, 1987; Sandler, 1989; Brentari, 1998). (Note that orientation is not always treated as a fourth parameter but often subsumed together with handshape under the term "hand configuration" (Battison, 1978; Sandler & Lillo-Martin, 2006). We list them separately here because many sign languages show phonological minimal pairs for the two parameters. However, as the distinction between handshape and orientation is not relevant for our study, we also use the term "hand configuration" when the distinction between orientation and handshape is irrelevant for the purposes of the discussion.) For example, the minimal pair GIVE and VISIT in German sign language (DGS) only differs in the orientation of the palm: upwards (supine) versus inwards (neutral). In all other parameters, the two signs are completely identical. Additionally, sign languages allow for the use of multiple distinct articulators simultaneously (fingers, hands and arms for manual signs; and face, head, and upper part of the body for so-called non-manual components). This use of multiple articulators enables the simultaneous realization of lexical and grammatical information manually and non-manually (Wilbur, 2000; Pfau & Quer, 2010). On a sublexical level, for instance, all four phonological parameters are produced simultaneously to realize a lexical sign. While the hand is shaped in a certain form, palm and fingers are oriented into a certain direction, and hand and arm are positioned at a certain location before moving on a lexically (or grammatically) specified path. None of these parameters can be articulated independently from the others, as will be discussed in more detail in Section 1.4. The specific properties of the manual–visual modality thus enable sign languages to realize phonological parameters simultaneously.

Crucially for the purposes of the present study, a continuous signing stream must involve transitions between the phonological parameters of one sign and those of the following sign. This divides the signing stream into two kinds of phases: lexical signs and transition phases between signs. Interestingly, in sign languages, unlike in spoken languages, these transition phases between signs are rather long, due to the relatively massive articulators which have to move in space (Meier, 2002). Therefore, sign languages are an ideal object of study for time-sensitive experimental methods. In the present study, we examined ERP correlates of processing these transition phases in order to shed light on whether the language processing system sets up specific predictions regarding hand trajectories and change of hand configuration towards an expected sign. Under the assumption of a forward model that allows for the anticipation of modality-specific sensory properties of the linguistic input, we hypothesize that prediction error should already be measurable within the (non-lexical) transition phase (i.e. prior to the critical sign onset).

1.3. *Previous electrophysiological studies on sign language processing*

Event-related potential studies on the processing of natural signing have been very rare up to now. Kutas, Neville, and Holcomb (1987) were the first to show that N400 effects for semantic anomalies occur in written, spoken and signed contexts. This general modality independence was subsequently confirmed by further studies on lexical-semantic aspects of sign language processing in American Sign Language (Neville et al., 1997; Capek

[1] Note, however, that this may be a language-specific phenomenon, as other languages such as German, Chinese and Turkish do show N400 effects for semantic reversal anomalies (Bornkessel-Schlesewsky et al., 2011). In addition, recent results from English indicate that N400 effects for reversal anomalies can vary even within a language based on the experimental environment (Bourguignon, Drury, Valois, & Steinhauer, 2012).