Towards a Neuro-Cognitive Model of Human Sentence Processing

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Abstract. A formal sentence processing system is proposed which simulates different event-related potential (ERP) elicitation between sentences with and without unambiguous case marking. The electroencephalographical data are based on German subordinate clauses and Japanese sentences. As a formal framework we adopt Dynamic Syntax (Kempson et al. 2001), which enables incremental update of information by underspecifying tree information. This is augmented with default syntactic and semantic specifications which reflect shallow but efficient human sentence processing.

1 Introduction

Recent developments in non-invasive measurement of brain activities have paved the way for directly observing how linguistic information is processed in the human brain. However, no attempts have hitherto been made to model human sentence comprehension based on the data provided by those methods from a unified formal point of view. This paper proposes a parser which behaves in a similar manner to humans in eliciting different event-related potentials (ERPs) depending on whether NPs are unambiguously case marked or not. The crucial role therein is performed by syntactic underspecification in incremental processing, which is made possible by Dynamic Syntax (Kempson et al. 2001) adopted as our formal linguistic theory.

2 ERPs in Sentence Processing

ERPs, i.e. diverse kinds of electrophysiological response to stimuli, is known to reflect the higher human cognitive capacities. They are also acknowledged as a useful tool to investigate the process of language understanding in the human brain. The most typical ERPs associated with specific steps of processing are outlined below:

(i) An **early left-anterior negativity (ELAN)** is elicited approximately 150-200 ms after a critical word onset which is involved with a word category error.
(ii) A **left-anterior negativity (LAN)** is observed between 100-500 ms after presenting stimuli with morpho-syntactic errors.
(iii) An **N400** is a negativity which peaks about 400 ms after the word onset. This is typically ascribed to a failure to integrate a word meaning to the preceding context.
(iv) A **P600**, a late centro-parietal positivity occurring between 600-1000 ms, is associated with the integration of different types of information and completion of sentence processing.

Mainly based on these electrophysiological data, Friederici (1999, 2002) proposes a neuro-cognitive model of sentence understanding which is composed of three processing steps. An erroneous input sentence is considered to invoke an excessive processing load at at least one of these steps, giving rise to (an) ERP(s) explained in (i) to (iv) above.

Phase 1 (100-300 ms): The initial syntactic structure is built up based on the identification of word category. An error in this phase causes an ELAN.

Phase 2 (300-500 ms): Lexical-semantic and morpho-syntactic information is processed in parallel without interaction, leading to the assignment of thematic roles. The first subprocess, if overloaded with an erroneous input, elicits a LAN, the latter an N400.

Phase 3 (500-1000 ms): Lexical-semantic and morpho-syntactic information with other types of information is integrated to complete sentence processing. A failure during this phase engenders a P600.

Although this model has been designed to cover many aspects of human sentence processing as reflected by EEG data, the perspective of computational processing is completely missing. This, according to our view, in turn leaves our understanding about the functions of the ERPs still in a primitive stage.

3 Dynamic Syntax

Dynamic Syntax (Kempson et al. 2001, Cann et al. 2005) is a grammar formalism based on a modal logic of finite trees which attempts to account for typologically diverse linguistic data by incrementally building up partial trees in a way that reflects on-line processing. One of its marked features is syntactic underspecification, which resolves what has been a major difficulty in natural language processing—incremental parsing of sentences of head-final languages as words are input from left to right. Since in these languages the syntactic position of a word or phrase is often unknown while it is being processed on-line, it is temporarily left underspecified. Only after the head is read in, a full-fledged syntactic specification is produced. This mechanism, as mentioned above, provides a fundamental framework to process head-final languages such as Japanese from left to right. Furthermore, in combination with default specifications in syntax and semantics which are originally beyond the scope of the Dynamic Syntax formalism, we can simulate shallow and efficient sentence processing by humans in which later cancellation of defaults made on-line leads to excessive computation loads.

4 ERP Data in German and Japanese

Bornkessel et al. (2003) and Schlesewsky and Bornkessel (2004) observed different ERPs in the reanalysis of German head-final subordinate sentences with full morphological case marking and those with ambiguous case marking.

(1) a. dass der Mönch dem Bischof **folgt**
that the monk-NOM.SING the bishop-DAT.SING follow-SING
'that the monk follows the bishop'

b. dass der Mönch dem Bischof **gefällt**
that the monk-NOM.SING the bishop-DAT.SING please-SING
'that the bishop likes the monk'

(2) a. dass Maria Lehrerinnen
that Maria-NOM/DAT/ACC.SING female teacher-NOM/DAT/ACC.PLUR
folgt
follow-SING
'that Maria follows female teachers'

b. dass Maria Lehrerinnen
that Maria-NOM/DAT/ACC.SING female teacher-NOM/DAT/ACC.PLUR
gefällt
please-SING
'that female teachers like Maria'

(3) a. dass Maria Lehrerinnen
that Maria-NOM/DAT/ACC.SING female teacher-NOM/DAT/ACC.PLUR
folgt
follow-SING
'that Maria follows female teachers'

b. dass Maria Lehrerinnen
that Maria-NOM/DAT/ACC.SING female teacher-NOM/DAT/ACC.PLUR
folgen
follow-PLUR
'that female teachers follow Maria'

First, Bornkessel and the colleagues compared active verbs with an agentive subject like the one in (1a) and object-experiencer verbs denoting the dative object person experiencing something as in (1b), both sentences fully case-specified. They observed a remarkable ERP, an early parietal positivity P345, for object-experiencer verbs in contrast to active verbs. However, for sentences such as (2a) and (2b) in which proper name and plural NPs are ambiguous between nominative, dative, and accusative, they found no difference. Furthermore, in an experiment on subject-initial and object-initial structures in case-ambiguous sentences such as (3a) and (3b), an N400 was observed for object-initial sentences in contrast to subject-initial ones.

The results show that different incremental tree buildings are involved with case-specified and case-ambiguous trees: while unambiguously case-marked sentences are processed by fixing a syntactic tree step by step, ambiguous case NPs are left unspecified in terms of their syntactic positions until the verb is read in. It is also supposed that a sentence with insufficient information is interpreted temporarily by default, both in syntax and semantics. The NP *der Mönch* (the monk-NOM.SING) unambiguously marked as nominative in (1b) at first undergoes a thematic role interpretation as agent, which is canceled later by the object-experiencer verb demanding a less oblique thematic role (i.e., 'experiencer') for the dative than for the nominative NP. For sentences with ambiguous case markings (e.g., (2a,b)) no fixed tree is built before the verb, thus free from the need to reanalyze. Furthermore, while the first NP *Maria* in (3a,b) is at first not integrated into the whole tree, a temporary decision about their syntactic position as subject is made, which may later prove to be incompatible with the verb inflection.

An experiment to investigate whether a similar processing revision may be found in Japanese, a strict head-final language, has been carried out by Hirotani (2006). Sentences (4a-c) below all share the same sequence of NPs marked by the nominative, dative, and accusative case marker. They are only different in the predicates, which are active, passive, and causative forms, respectively.

(4) a. John-ga Mary-ni purezento-wo **atae-ta**.
John-NOM Mary-DAT present-ACC give-PAST
'John gave Mary a present.'

b. John-ga Mary-ni purezento-wo **atae-*rare*-ta**.
John-NOM Mary-DAT present-ACC give-PASSIVE-PAST
'John was given a present by Mary.'

c. John-ga Mary-ni purezento-wo **atae-*sase*-ta**.
John-NOM Mary-DAT present-ACC give-CAUSATIVE-PAST
'John made Mary give (somebody) a present.'

Hirotani observed a centro-parietal negativity 150-450 ms after the critical word onset for the predicates in (4b) and (4c) in contrast to that in (4a). In light of the fact that the obtained ERP component is similar to the N400 observed for the German sentences, it sets computer linguists a challenging task to give a unified formal account of the data from German and Japanese.

5 Sentence Processing Model based on Dynamic Syntax

5.1 Sentence Processing System

In order to account for the EEG observation cited in the previous section, we extend the Dynamic Syntax formalism by introducing reanalysis and default parsing. This is also a formal revision of Friederici's (1999, 2002) three-phase neuro-cognitive sentence comprehension model, except that we do not adopt a parallel semantic processing component *independent of syntax*, which is computationally implausible.

> Iterate the execution of Steps 1 and 2 for each word from left to right until the end of the sentence. Stop if there is no more word left and the representation obtained is appropriate as that for a sentence.
> **Step 1:** A word is identified from the lexicon based on the predicted word category and input.
> **Step 2:** (i) A new syntactic-semantic representation is formed based on the lexical information and grammatical rules by extending the representation built so far.
> (ii) For a word with insufficient morpho-syntactic information, its syntactic status is left underspecified. A default specification is assigned to the word, which is sanctioned as a final one when the word's head has been read in without causing any inconsistencies.
> (iii) To an NP or AdvP with a fixed syntactic position, a semantic role is assigned by default.

Steps 1 and 2 and the outermost level which completes sentence processing correspond to Phases 1, 2, and 3 in Friederici (1999, 2002), respectively. In executing these steps and level, if pieces of information do not match, processing is restarted back at the position where the cause of the mismatch arose. Both such backtracking and overwriting of default specifications discussed in the next section are assumed to overload the processing and engender each characteristic ERP.

5.2 Default Parsing

In this section, we investigate how the modified version of Dynamic Syntax can account for our ERP data.

Semantic role default processing

Figure 1 outlines the analysis of sentence (1a). (i) in the figure is the partial tree obtained by parsing the first input *der Mönch* (the monk-NOM.SING). The root node has a decoration $Tn(a)$ giving the location of the root node (the part of the tree embedding this subordinate clause is omitted), $?Ty(t)$ standing for the requirement that a type t be obtained as a result of sentence processing, and $\Diamond$, the pointer, representing that this node is being processed currently. The lower node has a LOFT-modality (Blackburn and Meyer-Viol 1994) followed by a tree node identifier $\langle\uparrow_0\rangle Tn(a)$ which together indicate that this is an argument node immediately below the root node. Fo presents a semantic value and Ty a logical type. Here they indicate a definite NP with type e, which is semantically treated as a kind of anaphora.

The formula after the slash '/' is an extension to the original Dynamic Syntax formalism which stands for default information assigned to the node. Here, the node, which represents the first NP in the sentence, is interpreted as having a thematic role Proto-Agent. Thus, in distinction from the original Dynamic Syntax version, we adopt a Davidsonian representation of case roles and by so doing strictly differentiate between the syntactic representation (i.e., the tree) and the semantic role representation (i.e., semantic role predicates). *know* is equivalent to the operator L in Konolige's (1988) Autoepistemic Logic, which allows default logic notations using operators. Default specifications are built up independently of the partial tree formation by Dynamic Syntax and interact with this only when the syntactic or semantic information of the whole tree is obtained. When they do, they are either added to the node decoration or simply neglected. Therefore, they do not affect the monotonicity in Dynamic Syntax tree building.

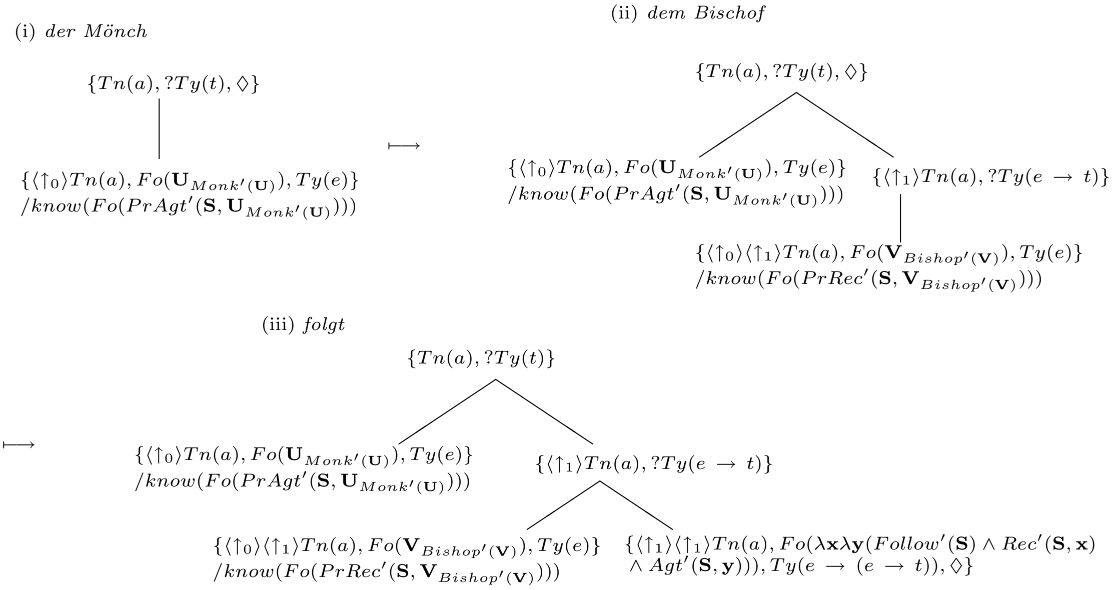

Fig. 1. Parsing of (1a) (*dass*) *der Mönch dem Bischof folgt*

(ii) is the partial tree resulting from extending (i) by the information of the input *dem Bischof* (the bishop-DAT.SING). A node for this constituent is added in the tree, intervened by a node which is the immediate head daughter to the root node. The indirect object node is specified to be the root's head daughter's argument daughter ($\langle\uparrow_0\rangle\langle\uparrow_1\rangle Tn(a)$), with a default constraint that it is a Proto-Recipient.

(iii) is the partial tree we get immediately after reading in the verb *folgt* (follow-3PERS.PRES.SING). A node for this word is newly made in the tree as sister to the indirect object.

By applying the β-reduction and type application rule two times, we have the following decorations to the root node:

(5) $Fo(Follow(\mathbf{S}) \wedge Recipient(\mathbf{S}, \mathbf{V}_{bishop(\mathbf{V})}) \wedge Agent(\mathbf{S}, \mathbf{U}_{monk(\mathbf{U})})), Ty(t)$

The first formula value above is compatible with the default specification for the root node which is obtained based on defaults on the subject and indirect object nodes:

(6) $know(Fo(Proto\text{-}Agent(\mathbf{S}, \mathbf{U}_{monk(\mathbf{U})}))) \wedge know(Fo(Proto\text{-}Recipient(\mathbf{S}, \mathbf{V}_{bishop(\mathbf{V})})))$.

This is so, since meaning postulates unify a Proto-Agent with an Agent and a Proto-Recipient with a Recipient.

By contrast, (1b) is distinct from (1a) in the semantic value (7a) associated with the verb *gefällt* (please-3PERS.PRES.SING). This gives rise to the formula (7b) attached to the root node:

(7) a. $Fo(\lambda\mathbf{x}\lambda\mathbf{y}(Please(\mathbf{S}) \wedge Experiencer(\mathbf{S}, \mathbf{x}) \wedge Patient(\mathbf{S}, \mathbf{y})))$
b. $Fo(Please(\mathbf{S}) \wedge Experiencer(\mathbf{S}, \mathbf{V}_{bishop(\mathbf{V})}) \wedge Patient(\mathbf{S}, \mathbf{U}_{monk(\mathbf{U})}))$.

(7b) is incompatible with (6) since, while in the former the indirect object NP *dem Bischof* (the bishop-DAT) is the semantically less oblique case Experiencer, (6) says that this NP has the more oblique case role Proto-Recipient. Note that an Experiencer can unify with a Proto-Agent. We assume that the cancellation of the default constraint demands excessive processing, causing the ERP.

Syntactic underspecification and defaults

The step-by-step processing of sentence (3b) is diagramed in Figure 2. The problem the processing of this sentence faces is that both the proper noun *Maria* and the indefinite plural noun *Lehrerinnen* (female teachers) are ambiguous between nominative, dative, and accusative. However, in distinction

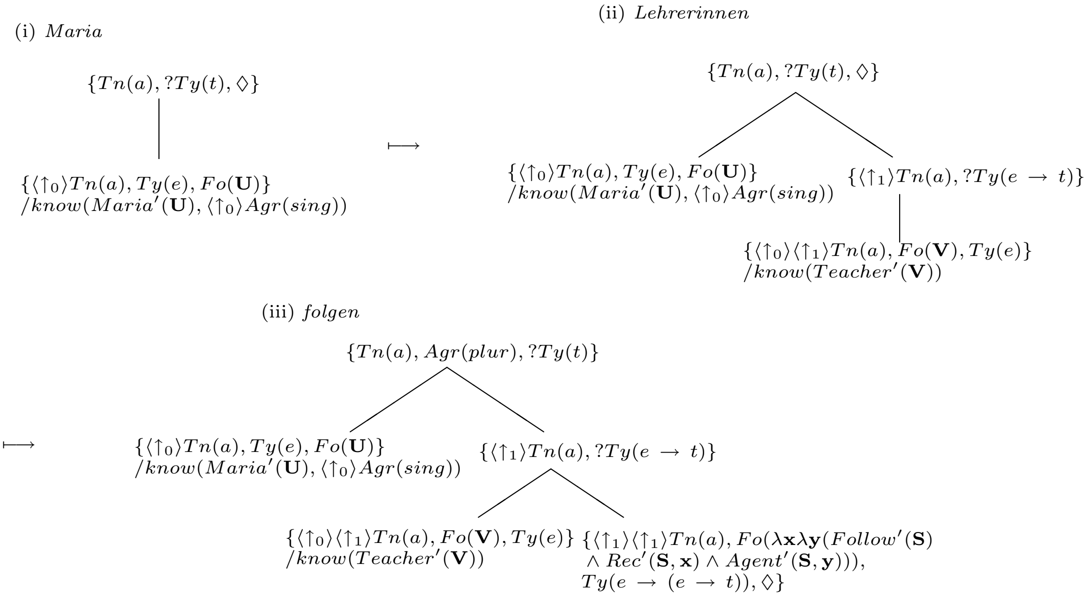

Fig. 2. Parsing of (3b) (*dass*) *Maria Lehrerinnen folgen*

from the first version of Dynamic Syntax (Kempson et al. 2001), the current version (Cann et al. 2005) does not allow more than two nodes remaining unfixed simultaneously, since otherwise the nodes will not be distinguished from each other. As a result, the seemingly natural solution of underspecifying multiple case NPs until reading in the verb is prohibited. Accordingly, we make a choice to specify the incompleteness of the tree indirectly: while the tree is processed incrementally in such a manner that it dominates subject and object nodes, the semantic value for each node is kept underspecified as a metavariable and is only specified as a default.

The semantic values of the two NPs are kept syntactically underpsecified in this manner (i) through (iii). At the same time, however, a dafault rule is applied to them based on the word order: the subject node is associated with the semantic value for *Maria* and the object node with that for female teachers. This is tantamount to say that the first NP is syntactically interpreted as subject and the second as object by default. Furthermore, the first NP is assigned a morpho-syntactic feature $Agreement(singular)$ by default, which should be put at the root node and is checked later with the one deriving from the verb. Note that this sentence does not undergo a default semantic role interpretation as (1a,b), since this kind of default is triggered by morphological case markings.

Step (iii) in the figure illustrates the parsing state immediately after the clause-final verb has been input. The last task in the sentence processing is to decide the semantic values for the subject and object nodes which remain underspecified. Usually, defaults take priority and are acknowledged as authentic node decorations at this last stage of processing. In this case, however, the default feature $Agreement(singular)$ is incompatible with the feature $Agreement(plural)$ which is imposed by the verb *folgen* (follow-PRES.PLUR). The defaults are canceled therefore, and the processing goes on to find an answer compatible with the agreement feature on the verb. The conclusion drawn is that this is a construction with a scrambled word order in which the first NP is the object and the second is the subject.

By contrast, the defaults turn out to be true in processing (3a), since the verb's inflectional form is singular and is compatible with the default agreement feature.

Sentence processing in Japanese

Now let us see whether the ERP data from sentences (4a-c) in Japanese can be given an account within the framework common to the German data. Hirotani (2006) interprets the ERP component (i.e., N400) as engendered by revision of thematic roles assigned to the initial two NPs. We, however, argue that there exist noticeable similarities between these data and those for (2a) and (3a,b).

In parsing these Japanese sentences, revision of syntactic trees is unavoidable.

(8) a. [NP$_{\mathrm{NOM}}$ [NP$_{\mathrm{DAT}}$ [NP$_{\mathrm{ACC}}$ (V)]]]
b. [NP$_{\mathrm{NOM}}$ [NP$_{\mathrm{DAT}}$ [[NP$_{\mathrm{ACC}}$ V] AuxV]]]

(8a) above schematically accounts for the syntactic structure assumed for the three NPs by default until the predicate is input. While this works for (4a), it turns out to be wrong for the other sentences, to which the construction in (8b) is reassigned as a result of reading in the predicate, the passive form in (4b) and the causative in (4c). As shown here, while only the nominative and dative NPs are subcategorized for by the auxiliary verb (i.e., *rare* or *sase*), the accusative NP directly combines with the main verb. Although details are omitted in this paper, the underspecification of syntactic information at the initial stages of sentence processing, which is complemented by defaults, and its later update can be formalized in a manner similar to that for (3a,b).

The similarities between the sentences in German and Japanese pointed above may give an explanation to the similarity between the two ERPs, the N400 observed for (3a–b) and the centro-parietal negativity for (4a)-(4b,c), which may lead to a formal, more generalized understanding about a repository of ERPs. This assumption, however, needs to be verified by further experiments.

6 Conclusion

We have shown that syntactic underspecification as formalized in Dynamic Syntax is essential in accounting for the difference in ERP elicitation in the human parsing of NPs with ambiguous and fully specified case markings. We also believe that formal syntacticians will benefit from brain activity data in capturing the processing by the real human parser, and have outlined an approach to this task.

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