Animacy Information in Human Sentence Processing: An Incremental Optimization of Interpretation Approach*

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Abstract. To formalize and analyze the role of animacy information in on-line sentence comprehension, results of several on-line studies are compared and analyzed according to a new model of incremental optimization of interpretation. This model makes use of violable ranked constraints. To analyze the use of animacy information a set of four constraints is needed, namely CASE, SELECTION, PRECEDENCE, and PROMINENCE. It is shown that the pattern of constraint violations of these four constraints provide sufficient information to reflect the on-line effects of language comprehension studies in which animacy information played a crucial role. More specifically, the evaluation of sentences in which either case information or animacy information in combination with the selection restrictions of the verb were used, showed that the model can account for the ambiguity resolution with both sorts of information. The model was also successfully applied to the on-line processing of a more complex object relative structure in English.

1 Introduction

The different sorts of information that become available incrementally during natural language comprehension are very diverse varying from morphosyntactic information (e.g. case marking, word order, number) to semantic/conceptual information (e.g. animacy, specificity). In contrast to the morphological marking of case and number, which incorporates both semantic and syntactic information, animacy is merely semantic (or conceptual) in nature. It plays a role of utmost importance in fulfilling the selectional criteria of the verb, and as such, it is quintessential for the incremental interpretation of a sentence.

To investigate the role of animacy information in sentence comprehension a newly developed model of incremental optimization of interpretation is used [1]. This model uses a set of ranked interpretive constraints that are violable on a

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word-by-word basis. These constraints are derived by analyzing characteristics of Dutch and English that are relevant to the processing of animacy information.

This paper presents a first attempt to map the patterns of constraint violations onto the on-line effects found in studies in which the use of animacy information was investigated. Thus, the model of incremental optimization of interpretation that is adapted in this paper can be shown to predict the kind of processes elicited on-line on the basis of the pattern of constraint violations. By applying this model that is based on principles of the time insensitive model of Optimality Theoretic Semantics [2] to on-line human sentence processing studies, we bridge the gap between theoretical linguistic models and natural language processing.

2 Four Constraints on Interpretation: Case, Precedence, Prominence, and Selection

In languages with a case system such as German, morphosyntactic information can be used to interpret the syntactic and semantic relations. In German, not only personal pronouns, but also articles and adjectives are overtly case marked. If a sentence starts with an accusative case marked NP, as is illustrated in (1), it will not only be identified as the object of the sentence, but it also triggers the expectation of a suitable subject and predicate. Thus case information helps to determine the interpretation.

Den Zaun hat der Junge zerbrochen.
[the fence]$_{\text{ACC.3SG}}$ has$_{\text{3SG}}$ [the boy]$_{\text{NOM.3SG}}$ broken (1)
"The fence, the boy broke."

There are, however, also languages with a poor case system such as Dutch and English. In these languages, case is only visible on pronouns. Hence, the eventual interpretation of many sentences is dependent on other sorts of information. Even in languages with poor case marking there are hardly any sentences that are difficult to interpret. In English, this is not all that surprising because of the strict word order that constrains the interpretation in such a way that the first argument in a main clause is almost always the subject of the sentence.[1] Because Dutch has a relatively free word order and no case marking on full noun phrases, many sentences are ambiguous. In these cases, in Dutch as well as in German, in which due to morphological poverty of certain phrases the same kind of ambiguities occur, the interpretation will be based on the strong preference for the canonical word order with its concomitant (subject precedes object) reading. This is also known as word order freezing (cf. [3], [4]). In a sentence such as in (2), there is a strong preference for interpreting the

[1] As can be seen in the English translation of example 1, it is possible that the object precedes the subject in English. This, however, can only be the case as a form of topicalisation.

first NP as the subject. In other words, in the absence of conflicting information, the preferred interpretation is one in which the subject precedes the object (cf. [5], [6], [7]).

De patiënt	heeft	de arts	bezocht.	
[the patient]$_{\text{SUBJ/OBJ}}$	has	[the doctor]$_{\text{SUBJ/OBJ}}$	visited	(2)
"The patient visited the doctor."				

Most experiments that found evidence for the subject before object preference dealt with sentences where the subject and the object both were animate used in combination with agentive transitive verbs. However, several off-line and on-line experiments in Dutch and English showed that besides case-marking and word order, animacy information is an important source of information for the comprehension process (cf. [8], [9], [10], [11]). For instance, McDonald [10] compared the validity of three cues (word order, noun animacy and case inflection on pronouns) in choosing the controller (agent) of transitive sentences and relative clauses. Experiments in which subjects had to assign the agent role after listening to the sentence showed that, in Dutch, animacy was a better cue than word order, whereas, in English, the reverse was the case. MacWhinney, Bates and Kliegl [12] found that in German, too, animacy was a better cue than word order. Hence, there seems to be coherence between word order freedom and the role of animacy information in sentence processing in different languages.

Where word order preferences might help to identify the subject of a sentence, animacy information provides us with information about the potential control over the action expressed by the verb, as well as the prominence relation between the arguments. That is, given the fact that for many verbs it is the subject (which in most sentences is the first argument of the sentence) that is in control of the action, it is expected that given an animate and inanimate NP in a sentence, it is more likely that the animate NP is the subject and the inanimate NP is the object of the sentence. In other words, the first argument outranks the second argument in control or prominence, thus in most cases, in animacy. Note, however that in sentence processing the information becomes available incrementally. Therefore, the animacy of a possible second NP is not yet available at the moment the first NP is being processed. Moreover, it might be unclear whether a transitive or intransitive verb comes in. If animacy information of the initial NP is used as soon as it becomes available it cannot be used in relation to the animacy of the other argument(s). What can be taken into account is whether the argument that is being processed is animate and is potentially in control and prominent.

As we have seen in example 1, it is very well possible that word order preference is not followed. This also holds for the expectation of the prominence relationship between the arguments and the control characteristics of the subject. Although not as common as an animate subject, it is not only possible that the subject of a sentence is inanimate, it might also be that given an animate and inanimate NP, the inanimate NP has to be the subject of the sentence and the animate NP the object. It is the verb that imposes these selection restrictions

onto the arguments, as is illustrated in (3a) a,b. Verbs such as *please* take an experiencer (animate) object, while verbs as *like* take an experiencer (animate) subject.

The holiday pleased the boy. (3a)

The boy liked the holiday. (3b)

So far, four possible constraints that play an important role in language processing follow from the above discussion. The first constraint is based on morphological case-marking, the second on a general preference of word order, whereas the other two constraints are more directly related to the role of animacy information. In (4) the self-explanatory constraint CASE is defined.

CASE: the subject is nominative case marked, the object is accusative case marked (4)

In (5) the word order constraint PRECEDENCE is defined which is based on a strong preference for the subject-before-object word order. If this constraint is satisfied, it leads directly to the interpretation in which the subject precedes the object.

PRECEDENCE: the subject (linearly) precedes the object (5)

Note that PRECEDENCE, as it is formulated above, can be considered an instantiation of a linearity constraint as proposed within the framework of Property Grammars [13]. However, the use of constraints in Property Grammars (PG) radically differs from our use of constraints. In PG constraints are used to encode syntactic information and although constraint evaluation takes place on the basis of grammatical as well as ungrammatical inputs, a grammatical input should not violate any constraints. In our Optimality Theoretic model of interpretation, the input is the form (being it grammatical or not) and the output (that is built up incrementally) is the (optimal) interpretation of that form. The constraints are potentially conflicting, which is one of the basic characteristics of Optimality Theory [14], and as a consequence optimal outputs often violate numerous constraints (in order to satisfy stronger ones).

The third constraint, PROMINENCE, concerns the potential control characteristics of the subject and the prominence relationship between the subject and the object. Prominence can be measured along different scales, such as animacy, specificity, or (pronominal) person (cf.[15], [16], [3]). As it is defined in (1), it is expected that the subject of a sentence has potential control over the action expressed in the sentence. Additionally, we assume that in case of a transitive relationship the subject outranks the object in PROMINENCE. In terms of animacy, it is expected that the subject is animate, and when a second argument is present, the constraint is clearly satisfied if the object is inanimate.

PROMINENCE:

the subject is animate and thus has potential control; (6a)

the subject outranks the object in prominence (6b)

The fourth constraint is called SELECTION and reflects the inherent semantic relation between the verb and the subject or the object. This constraint plays a crucial role in interpretation if a verb always selects an inanimate NP as the object or an animate NP as the subject.

SELECTION: syntactic functions are assigned to the arguments fulfilling the selectional restrictions of the verb (7)

At this point, note that in sentence 3a where the initial NP is the inanimate subject, the word order constraint PRECEDENCE is satisfied, but PROMINENCE is violated. This violation of PROMINENCE is directly related to the satisfaction of SELECTION. In sentence 1 on the other hand, PRECEDENCE is violated, but PROMINENCE is satisfied. Here, the satisfaction of PROMINENCE goes hand in hand with the satisfaction of CASE. The interplay of the different constraints will be further explained in the following section.

3 The Model of Incremental Optimization of Interpretation of Animacy Information

In this section, the constraints will be ranked so that they can be used in the model of incremental optimization of interpretation. The ranking of the constraints is established by principles taken from the theoretical perspective of Optimality Theory (cf. [14] and Optimality Theoretic Semantics (cf. [2]).

As already pointed out above, within the framework of Optimality Theory constraints are violable rules that are potentially conflicting. These constraints are reflections of linguistic regularities. A constraint is never violated without any reason, but only in order to satisfy another, stronger constraint. This basic characteristic of Optimality Theory (OT) originates from its predecessor, Harmonic Grammar, a linguistic theory that uses the connectionist well-formedness measure Harmony to model linguistic well-formedness [11].

As the name of our model indicates, we assume that during human sentence processing, the optimal interpretation of a sentence (form) is being built up incrementally. Hence, we assume the process of optimization itself to be incremental. Optimality Theoretic Semantics [2] gives a straightforward tool for analyzing processing in this way. OT semantics [2] take as a point of departure free generation of interpretations in combination with the parallel evaluation of violable constraints. The integration of pragmatic, semantic, and syntactic information in a system of ranked constraints is proposed to correctly derive the optimal interpretations for inputs that contain utterances, i.e., forms in context. Thus, in OT semantics, the direction of optimization is from form to meaning, that is, it is optimization from the hearer's point of view. To use this approach for our purpose of analyzing experimental results of processing requires an incremental approach to optimization. That is, the process of optimization of interpretation proceeds while the information comes in word-by-word, or constituent-by-constituent.

Before incremental optimization of interpretation can be used to analyze the role of animacy information in sentence processing the four relevant constraints that were defined above, have to be ranked. We determine the ranking by examining the optimal output interpretation in case of a conflict between constraints. Such a situation was illustrated in example 3a in which an inanimate NP is interpreted as the subject of the sentence. This indicates that SELECTION must outrank PROMINENCE, since the optimal reading will be an animate object reading, despite the fact that this leads to an inevitable violation of PROMINENCE. If the animate object precedes the inanimate subject, there is not only a conflict between SELECTION and PROMINENCE, but also between SELECTION and PRECEDENCE. This is illustrated by the Dutch example in (8).

De jongen beviel de vakantie.
the boy pleased the holiday (8)
"The holiday pleased the boy"

The optimal reading for the sentence in (8) is the one in which the initial NP is the object of the sentence. Thus, PRECEDENCE is violated to satisfy SELECTION; hence SELECTION not only outranks PROMINENCE, but also PRECEDENCE. This leaves us with the issue of ranking PRECEDENCE and PROMINENCE. Because of much processing evidence that in case of ambiguity, a sentence-initial NP is interpreted as the subject even if it is inanimate, we assume that PRECEDENCE outranks PROMINENCE. Finally, we assume that CASE is the strongest of the four constraints. This can be derived from the fact that we obtain a sometimes pragmatically odd yet optimal interpretation when SELECTION must be violated in order to satisfy CASE, as in a German sentence such as *Der Zaun hat den Jungen zerbrochen* glossed as 'the fence$_{NOM}$has the boy$_{ACC}$ broken'. In this sentence, despite the fact that transitive *break* normally selects an animate subject, the inanimate NP *der Zaun* 'the fence' is interpreted as the subject because of its nominative case. That is, the sentence can only mean that the fence broke the boy (see [17] for more evidence on the important role of case in human sentence processing). In (9) the ranking of the four constraints is given.

CASE >> SELECTION >> PRECEDENCE >> PROMINENCE (9)

4 Applying Incremental Optimization of Interpretation to the On-line Use of Animacy in Dutch Sentence Comprehension

Having established the ranking of the constraints, incremental optimization of interpretation can be used to evaluate word-by-word sentences used in on-line studies in which animacy information was manipulated. We will apply incremental optimization to three reading studies in which event related brain potentials

(ERPs) were measured. ERPs are small changes in spontaneous activity of the brain that occur in response to certain sensory events. Because of the multidimensionality of the signal, differences in the effects are related to differences in the nature of the involved processes. ERP patterns ("components") are characterisable in terms of polarity (negative vs positive), topography (at which electrode site an effect is visible), latency (the time at which the effect is visible relative to the onset of a critical stimulus), and amplitude (the "strength" of the effect)(cf.[18], [19]). These characteristics as well as the high temporal resolution of ERP measures make these studies extremely suitable as test cases for the application of incremental optimization of interpretation.[2]

In the first two studies animacy information is used to resolve subject-object ambiguities in Dutch, as was reported by Lamers [8], [20]. Additionally, object relative clauses taken from a study of Weckerly and Kutas [21] will be evaluated.

Lamers [8], [20] investigated sentences such as given in 10, 11, and 12 in two ERP studies.

De oude vrouw in the straat verzorgde hij ...
The old woman in the street took-care-of he ... (10)
"He took care of the old woman in the street ..."

Het oude park in the straat verzorgde hij ...
The old park in the street took-care-of he ... (11)
"He took care of the old park in the street ..."

De oude vrouw in the straat verzorgde hem ...
The old woman in the street took-care-of him ... (12)
"The old woman in the street took care of him ..."

Notice that sentence 11 is disambiguated by the animacy information of the initial NP because of the selection restrictions of the verb. That is, the verb selects an animate subject and as a consequence, when the verb comes in, the sentence-initial NP can (no longer) be interpreted as the subject of the sentence. The sentences in 10 and 12 are clearly disambiguated at the time the case-marked pronoun is encountered (which is unambiguously nominative in 10 and accusative in 12). Lamers reports early and late positivities at the verb for sentence 11 starting with the inanimate NP in comparison to sentence 10 as well as at the nominative case marked pronoun in sentence 10 in comparison to the accusative case marked pronoun in 12, as can be seen in Figure 1[3]. The effects were interpreted as structure building problems, possibly involving reassignment of syntactic functions and thematic roles. Strikingly, the effects are

[2] For a similar application of incremental optimization of interpretation to the processing of sentences in which the distinguishability of two arguments used in a transitive relation was addressed, the reader is referred to de Hoop and Lamers [1].

[3] For a complete overview of the results the reader is referred to Lamers [8], [20].

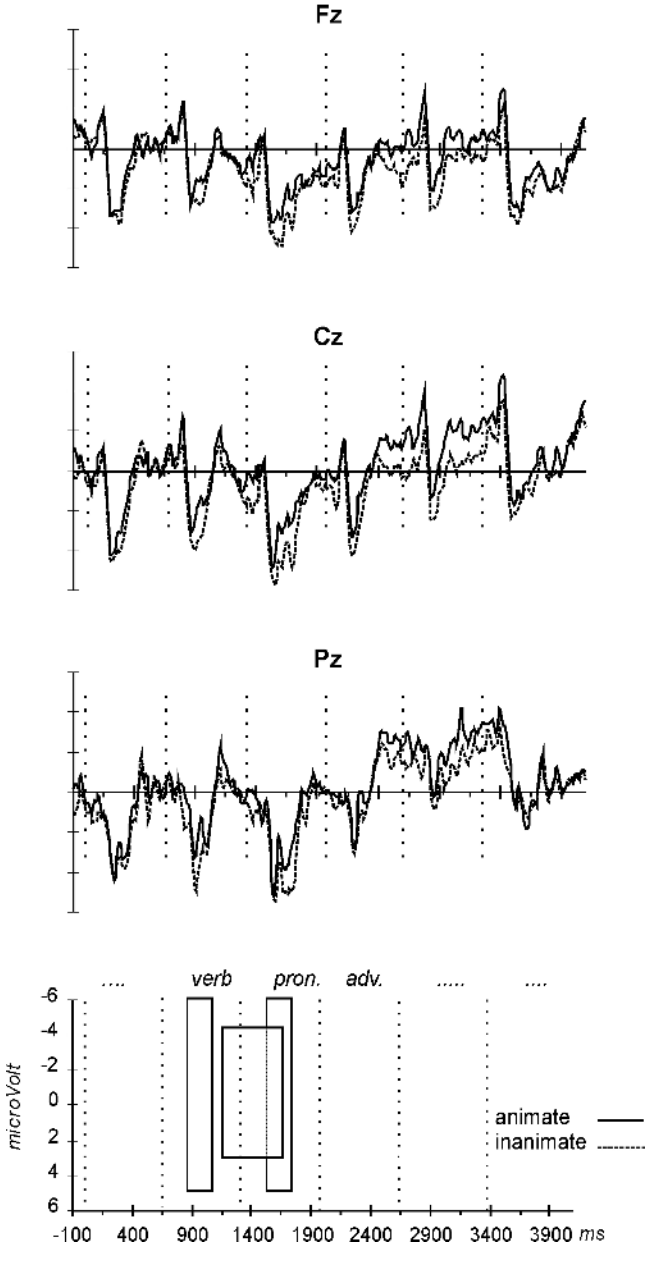

Fig. 1. Average ERP waveforms of sentences starting with an animate and inanimate NP at the three midline electrode sites (Fz, Cz, and Pz). The time frame starts 100 ms before the onset of the word preceding the verb, with a baseline 100 ms before the onset of this word; positive is plotted down. The rectangles indicate the time windows in which significant differences on the midline electrodes were found at the verb and the pronoun between sentences starting with an animate and inanimate NP

Table 1. An overview of the pattern of violations of CASE, SELECTION (SEL), PRECEDENCE (PREC), and PROMINENCE (PROM) for the sentences from the examples 10 and 11 up to the verb. In this table as in all the following tables an ✓ indicates that at this word the optimal interpretation satisfies the constraint, whereas an * indicates a violation of the constraint; Pos.=positivity; grey columns indicate the point in the sentence in which ERP differences were reported

	De oude vrouw...	verzorgde...	Het oude park...	verzorgde...
CASE				
SEL		✓		✓
PREC	✓	✓	✓	*
PROM	✓	✓	✓	✓
ERP				early,late Pos.

similar although different sorts of information are used for disambiguation (the verbal selection criteria and the case-marking of the pronouns, respectively). We claim that this similarity can be explained within the incremental optimization model. The evaluation of these sentences against the set of constraints will show that the pattern of constraint violations is the same in the two different contexts. These patterns of constraint violations are illustrated in Tables 1 and 2. In contrast to tableaux normally used to present constraint satisfaction patterns in Optimality Theory, in this paper a table shows only the pattern of constraint violations of **the optimal interpretation at time t**[4]. In the left panel of Table 1 a schematic overview is given of the constraint violations pattern of the **optimal interpretation** of the incoming words of sentence 10. In the right panel the evaluation of the object-initial sentence 11 is given. As can be seen, PROMINENCE is violated as soon as the initial inanimate NP becomes available in order to satisfy the higher ranked constraint PRECEDENCE. In that stage, the optimal interpretation is the subject-before-object reading. Up to the verb SELECTION cannot play a role in the parsing process, since no relevant information is available. At the verb, it becomes clear that the subject has to be animate. Hence, the optimal interpretation of the initial inanimate NP changes from subject to object. As a consequence, PRECEDENCE is violated, but PROMINENCE is satisfied. It is at this point in the sentence that Lamers found the significant ERP effects (early and late positivities) for sentence 11 compared to 10 (Table 1).

Table 2 is a schematic overview of the constraint violations patterns of the crucial words of sentences 12 (left panel) and 10(right panel). The ERP effect that is illustrated was found at the moment the case marked pronoun was encountered. Let us now compare the pattern of constraint violations found at

[4] Obviously, what is the optimal interpretation may vary through time. For example, the optimal interpretation of the sentence in 12 will be the subject-initial interpretation **until** the verb comes in. Then the optimal interpretation switches to the object-initial interpretation, due to the fact that Selection is ranked above Precedence.

Table 2. An overview of the pattern of violations of CASE, SELECTION(SEL), PRECEDENCE (PREC), and PROMINENCE (PROM) for the sentences 12 and 10 until the disambiguating case-marked pronoun

	De oude vrouw...	verzorgde	hem	De oude vrouw...	verzorgde	hij
CASE			✓			✓
SEL		✓	✓		✓	✓
PREC	✓	✓	✓	✓	✓	*
PROM	✓	✓	✓	✓	✓	✓
ERP						early,late Pos.

the nominative case marked pronoun to the pattern observed at the verb of the sentence starting with the inanimate NP (Table 1 versus Table 2). At the nominative case marked pronoun information becomes available such that the object-initial interpretation overrules the subject-initial interpretation, which was optimal until that point. At that time, PRECEDENCE must be violated (the object precedes the subject), whereas PROMINENCE is still satisfied, given that a pronoun is more prominent in a discourse prominence hierarchy than a full NP (cf. [16], [15], [3]). The resulting pattern is basically the same pattern as the one created at the verb of the inanimate condition 11. Thus, the similarity of the constraint violation patterns indeed reflects the similarity in ERP effects reported in the on-line studies. This indicates that the four constraints of the incremental optimization of interpretation model successfully capture the role of animacy information in subject-object ambiguity resolution in Dutch.

5 Extension of the Approach to English

Although English has a strict word order, relative clauses can either be subject initial or object initial. Weckerly and Kutas [21] investigated the influence of the animacy on the processing of object relative clauses with a local structural ambiguity. The sentences used in this study differed in the word order of an animate and inanimate NP, as exemplified in (13) and (14)

The novelist that the movie inspired praised the director ... (13)

The movie that the novelist praised inspired the director ... (14)

In the initial NP, the subject of the main clause is either animate (as in (13)) or inanimate (as in (14). Hence, there is already a difference in the pattern of constraint violations at the first argument, as is illustrated in Table 3. Since it concerns a violation of the lower ranked constraint in order to satisfy PRECEDENCE, it is not expected that this violation pattern will lead to strong on-line effects. Nevertheless, Weckerly and Kutas do report an enhanced negative shift for the sentence with an initial inanimate NP, indicating that the processing of an initial inanimate NP is more costly than an animate NP.

At the word *that* it is clear that a relative clause has to be processed, although it is not yet known whether it concerns a subject or an object relative clause. Since *that*refers to the initial NP, the pattern of constraint violations is the same as was found at the previous word.

As soon as the determiner comes in, it becomes obvious that an object relative clause is being processed (because the incoming NP must be the subject of the relative clause). We assume that at this point in the sentence the comprehension process is mainly concerned with integrating incoming information in the relative clause, while the main clause information is stored in verbal working memory. Thus, focusing at the relative clause, at *that* PRECEDENCE is violated in both sentences. Because both sentences have the same structure, this violation will not be reflected in the ERP-waveform. If, however, a comparison would have been possible between subject relative clauses and object relative clauses we expect this violation to be reflected as an early and late positivity corroborating the findings of Lamers [8], [20]. Since subject relative sentences were not part of the study of Weckerly and Kutas [21], such a comparison is unfortunately not possible.

In sentence (13) the object refers to an animate NP, and thus PROMINENCE is violated (Table 3, upper panel). In (14) the object is inanimate and thus, it is still very well possible that the incoming subject of the relative clause outranks the object in prominence and control. Since there is a difference in the pattern of constraint violations between the two sentences, differences in ERP waveforms are expected. However, at the determiner of the incoming subject of the relative clause, no differences in ERP-waveforms were reported. This might be due to the fact that a determiner is a high frequent closed class word, which has to be followed by the semantically more important noun, the subject of the relative clause.

In sentence (13) the subject of the relative clause is inanimate. Consequently, PROMINENCE is violated. In (14), however, the subject is animate and outranks the inanimate object in prominence. The comparison of the two ERP waveforms

Table 3. An overview of the pattern of violations of SELECTION(SEL), PRECEDENCE (PREC), and PROMINENCE (PROM) for the sentences 13 in the upper panel, and 14 in the lower panel. The constraint CASE is omitted because it plays no role here; Neg.=negative; LAN=left anterior negativity

	The	novelist	that	the	movie	inspired	praised...
SEL						✓	✓
PREC	✓	✓	✓	*	*	*	✓
PROM	✓	✓	✓	*	*	*	✓
ERP					N400	late Pos.	LAN,late Pos.

	The	movie	that	the	novelist	praised	inspired...
SEL						✓	✓
PREC	✓	✓	✓	*	*	*	✓
PROM	✓	*	*	✓	✓	✓	*
ERP		Neg.shift	Neg.shift				

showed an N400 for the inanimate NP.[5] Weckerly and Kutas explain this N400 in terms of the violation of the expectancy of an animate noun. Since animacy is clearly involved in the violation of PROMINENCE, the explanation of Weckerly and Kutas corresponds with the constraint violation pattern (in accordance with the claims made in [1]).

The subject of the relative clause is followed by the verb. In sentence (13) the verb *inspire* comes in, which selects an animate object. Hence, SELECTION is satisfied at the cost of a violation ofPROMINENCE. *Praise*, in (14), can only be used in sentences with an animate subject, and thus SELECTION and PROMINENCE can both be satisfied. A late positivity (P600) was found at the verb that violates SELECTION. Weckerly and Kutas argue that this positivity is caused by more difficult processing probably involving problems in thematic role assignment. This explanation corroborates our discussion above that the so-called experiencer verbs assigning the role of experiencer to the (necessarily animate) object of the sentence, and not the more frequently used roles of theme or patient (cf. [8]) inherently combine the satisfaction of SELECTION with a violation of PROMINENCE.

More puzzling is the ERP-effects found at the verb of the main clause. As can be seen in Table 3, ERP-effects are found at the verb that does not cause any constraint violation. This contrasts with the correspondence between ERP-effects and constraint violations in every other word position of the sentences. A possible explanation for this discrepancy between the incremental optimization of interpretation analysis and the ERP-effects might be that the complexity of the structures at issue in this study is not accounted for by just the three constraints used for our present purposes. The constraints that were used in the model of incremental optimization are directly derived from rules and mechanisms of the language faculty. It would be highly unlikely to assume that the effects found in the ERP-waveforms are only reflections of language specific processes. As a matter of fact, Weckerly and Kutas explain the finding of a left anterior negativity in terms of differences in memory load caused by the difficulties of the preceding object relative clause with the inanimate subject. A similar reasoning is given for the late positivity, which is interpreted as a reflection of the complexity of the object relative clause. Further research is necessary to determine whether the pattern of constraint violations, such as the one found for the sentences with an inanimate subject (Table 3, upper panel) is an indication for high demands on working memory and general processing complexity.

Nevertheless, we think that finding a correspondence between constraint violations and ERP-effects on almost every word position indicates that the model of incremental optimization of interpretation can also successfully be used for the analysis of the human processing of complex structures.

[5] The N400 is normally taken as an indication of problems in the comprehension process of semantic information, possibly including ease of lexical access and lexical/discourse integration processes (cf. [18], [19]).

6 Conclusion

If an argument is processed, animacy information becomes available. In this paper we have shown that a newly developed model of incremental optimization of interpretation can analyze the role of animacy information in language comprehension. In this model four violable constraints were defined, namely Case, Selection, Precedence, and Prominence. By applying the constraints incrementally in a word-by-word fashion, patterns of constraint violations come about that largely correspond to the differences in ERP waveforms found in the relevant ERP studies.

We conclude that the incremental optimization model provides a useful tool in psycholinguistic research that bridges the gap between theoretical linguistic models and natural language processing.

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