Yet Another Sentence Processing Model *
– Processing Based on Working Memory, Activation, and Well-formedness –

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1 Introduction

In the theoritical syntactic literature, hierarchical structures have played a central role in accounting for various phenomena. However, that does not mean that linear order has no role to play. Given that sentences are processed from left to right, it would be natural that linear order plays some role in making (un)acceptability judgments. In this paper, we will deal with certain phenomena that could only be explained in terms of word order. This paper reports our ongoing attempt to construct a formalized model which is based on the notion of working memory and activation value, and demonstrate how our model successfulluy accounts for the data in question. In this paper, first we summarize the kinds of linear order effects to be accounted for by our model, and point out that they could not be accounted for in structural terms. Secondly we illustrate the observational generalizations in processing terms, propose a formalized sentence processing model, and discuss a relation between our model and (un)acceptabilities. Then, we demonstrate how our model accounts for the data in question uniformly, mention some remaining problems and concludes the paper.

2 Problem for Syntactic Analysis

Kaplan and Bresnan (1982) pointed out the contrast in (1a-b), which is a problem for a movement-based analysis of topicalization.

(1) a. [That he was sick], we talk about for days.

b.*We talk about [that he was sick] for days.

c. cf. We talk about [the fact [that he was sick]] for days.

The solution proposed in the LFG literature (Kaplan and Zaenen 1989; Bresnan 2000; Falk 2001) is based on the LFG assumption that complement selection is stated in terms of grammatical function (GF), instead of part of speech (POS).

However, such LFG accounts fail to extended to the contrasts in the following coordination examples.

(2) a. John was thinking about [his girlfriend].

b.*John was thinking about [that he was stupid].

c. John was thinking about [his girlfriend] and [that he was stupid].

d.*John was thinking about [that he was stupid] and [his girlfriend].

(3) a. Ken agreed with, but John denied, that Mike was wrong.

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b.*John denied, but Ken agreed with that Mike was wrong.

Also, the order of conjuncts in (3) alters the (un)acceptability status. This leads us to assume that it would be plausible to model a theory of acceptability based on linear order. Through these examples, we can observe one generalization, which we call "The Linear Order Effect"[1] :

(4) **The Linear Order Effect**:
The syntactic requirement the head imposes on an argument is effective only to the extent that the argument is "sufficiently close" to the head in linear order.

It might be possible to propose a non-linear-order-based account for the contrast in (1), as has been done by Kaplan and Bresnan (1982) and Kaplan and Zaenan (1989), but non-linear-order-based accounts for (2) and (3) are absolutely inconceivable. Moreover, non-linear-order-based accounts are absolutely impossible for examples like (5):

(5) a.?Ken was thinking about, (pause) that he was stupid

b. Ken was thinking about, by the way, that he was stupid.

The observation is that the insertion of a pause improves the acceptability (5a), while the insertion of *by the way* makes the sentence fully acceptable (5b).

Based on this observation, we propose a memory-based account [2].

(6) **Memory-based Sentence Processing Model** (General Idea):
The syntactic information is deactivated on the following conditions:
condition (i): when the parser assumes that the predicate-argument structure has been constructed by the parser
condition (ii): as the processing time increased or overt phrase is inserted

Condition (i) states that the syntactic information is fully deactivated when the semantic content is assumed to have been obtained. Likewise, condition (ii) states that the syntactic information is gradually deactivated by the passage of time. Note that the degree of deactivation is not the same degree of deactivation due to condition (i) differs from that due to condition (ii). This difference is motivated by the assumption that the syntactic information is necessary only for constructing the predicate-argument structure. On the other hand, deactivation due to the passage of time is an unpreferable but unavoidable consequence of the limited capacity of working memory. Also, this model is based on the assumption that syntactic information is needed only to obtain the semantic content, and that the capacity of working memory is severely limited. These lead us naturally to expect that syntactic information is deactivated rapidly from working memory as soon as it has played the role of constructing the semantic content.

As stated, this model is not formalized yet. Our next task is to formalize it so that we would be able to implement it on a computer, if one wishes. It is this task that we turn to in the next section. Now, let us formalize our memory-based model.

3 Formalization

The activation value is represented as a natural number and we define a counter *av* which calculate the activation value. *av* takes two arguments; If variables are typed, the type declaration of $av(X, \mathrm{CAT})$ is:

(7) If $X = av(X, \mathrm{CAT})$, then $X \in \mathbb{N}$

X is a node and "CAT" is a syntactic catogory label of X. We illustrate a tree annotated by activation values in fig.1.

Let n be the number of the possible parsings at a given point ($av(X, \mathrm{CAT})_1$ ... $av(X, \mathrm{CAT})_n$), and T be the sum of the activation values of $av(X, \mathrm{CAT})_i$.

(8) $T = \sum_{i=1}^{n} av(X, \mathrm{CAT})_i$

Then T is a constant.

Also, we assume that the amount of activation values at a given point "T" is equal or greater than 0 and equal or less than 1.

[1]A similar generalization has already been pointed out by Moosally (1998) and Sadock (1988). However, they have not formulated a non-stipulatory account. Also note that their observations are limited to coordination examples and therefore do not cover the contrast in (1).

[2]This idea is based on the discussion in Takahashi and Ishikawa (2004) and Takahashi and Yoshimoto (2006)

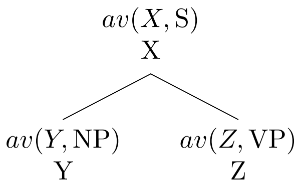

Figure 1: A tree annotated with activation values for "S → NP VP"

(9) $0 \leq T \leq 1$

Let the cannonical category label is CAT_k, other possible label is CAT_i, and the fouthcoming category is CAT_j, then the activation value of node Z is as follows [3]:

(10) $$av(Z, \mathrm{CAT}_j) = av(Z, \mathrm{CAT}_k) + \sum_{i=1}^{n} av(Z, \mathrm{CAT}_i)$$
$(j = k, k \neq i)$

Also, the activation value of the encountered category which is different with predicted one is:

(11) $$av(Z, \mathrm{CAT}_j) = 1 - \sum_{i=1}^{n} av(Z, \mathrm{CAT}_i) \quad (i \neq j)$$

Note that $av(Z, \mathrm{CAT}_i)$ in (11) represents all the predicted values by the parser.

We have proposed that there are two conditions of deactivation of syntactic information is regulated by two distinct conditions (i) and (ii) in (6). This means that the amount and manner of deactivation differs depending on whether it is caused by (i) or (ii). Furthermore, among those cases where (ii) causes deactivation, we also want to distinguish cases where there is only a silence and cases where there is an overt lingusitic expression.

Thus, we define three deactivation functions. The argument of each function is an activation value. These functions are applied while $av(X, \mathrm{CAT}) > 0$.

(12) a. f: applied when the predicate-argument structure is assumed to have been obtained

b. g: applied by the passage of time

c. h: applied when overt phrases are inserted

These functions are defined as follows:

(13) a. $f =_{\text{def.}} \lambda X.\mathtt{id}(X)\ av(X, \mathrm{CAT}) = 0$

b. $g =_{\text{def.}} \lambda X.\mathtt{id}(X)\ av(X, \mathrm{CAT}) = av(X, \mathrm{CAT}) - a$

c. $h =_{\text{def.}} \lambda X.\mathtt{id}(X)\ av(X, \mathrm{CAT}) = av(X, \mathrm{CAT}) - b$

Let c be the time the application of g takes and t be the amount of time that has passed since the node in question has been constructed. Then the the amount of deactivation caused by the iterative application of g is:

(14) $$\text{cycle} =_{\text{def.}} \frac{t}{c}$$

The number of cycle is treated as the coefficient of a in function g. Let $av_0(X, \mathrm{CAT})$ be the activation value of the category lable of a node when it has just been constructed. Then, when n cycles has passed since the construction, given that no other overt linguistic expression has been encountered, the activation value $av_n(X, \mathrm{CAT})$ in question has now become:

(15) $$av_n(X, \mathrm{CAT}) = av_0(X, \mathrm{CAT}) - na$$

We determine the value of the constants in (13) through psycholinguistic experiments and linear regression analysis of the results.

When the each activation value of possible parsings predicted on a look-ahead basis is deactivated by the application of functions in (12), since the amount of values of predicted categories is decreased to less than 1, then the activation values of all other categories are averaged and equally raised:

[3] We assume that the activation value transfer is in proportion to the degree of the garden path effects.

(16) $av(Z, \mathrm{CAT}_m) = \dfrac{1 - \sum_{i=1}^{n} av(Z, \mathrm{CAT}_i)}{m}$
where m is the number of categories.

4 Activation Values and the (Un)acceptabilities

In this section we relate the notion of activation value to the (un)acceptable status of a sentence.

First, let the maximum activation value is 1 and minimum activation value is 0, namely:

(17) $\forall X, Y[0 \leq av(X, Y) \leq 1]$

If the look-ahead construction and overtly expressed construction contradict each other, it results in unacceptability usually. Then we define a function $\mathtt{wf}_1$ as in (19), which takes in a node and returns its well-formedness, and which obeys (18) (irrespective of the well-formedness of its daugheters; see the definition of $\mathtt{wf}_2$ below); the well-formedness is a real number.

(18) $0 \leq \mathtt{wf}_1(Z) \leq 1$

We assume that all the category labels are linearly ordered (for technical convenience) and assigned an integer.

(19) $\mathtt{wf}_1(Z) =_{\mathrm{def.}} av(Z, \mathrm{CAT}_i)$

We distinguish well-formedness values from activation values since we assume that the former is necessary for gaining the whole well-formedness of phrases and that is not changed once the value is obtained while , the former is changed by the conditions in (6).

(19) gives the well-formedness of each node, putting aside the effects of the well- formedness of its daughters. Next we assume another function $\mathtt{wf}_2$, which takes in a node and returns its well-formedness as determined by the well-formedness of its daughters. This function is defined as:

(20) $\mathtt{wf}_2(Z) =_{\mathrm{def.}} \Pi \mathtt{wf}_1(Z_i)$
where Z_i refers to each daughter of Z

That is, the mother's well-formedness is the product of the well-formedness of its daughters. Finally we define yet another function wf (without a subscript), which takes in a node and returns its well-formedness as determined by *both* its category label specifications *and* the well-formedness of its daughters:

(21) $\mathtt{wf}(Z) =_{\mathrm{def.}} \mathtt{wf}_1(Z) \times \mathtt{wf}_2(Z)$

If there is no other "label" clash in the sentence, $\mathtt{wf}(Z)$ will be "carried over" to the topmost S node, which we equate with the degree of acceptability of the whole sentence.

5 Demonstrations

5.1 Topicalization

In our memory-based model, (1b) is predicted to be unacceptable for the reason outlined in the end of last section. On the other hand, (1a) is predicted to be acceptable since the "CP" label of the topicalized phrase has been so deactivated, ($av(X, \mathrm{CP})$ has become 0, if X is the node dominating the topicalized phrase) when the parser encounters *about*, which requires its label to be "NP" ($av(X, \mathrm{NP} = 1)$). Then:

$$
\begin{aligned}
\mathtt{wf}_1(X) &= av(X, \mathrm{CP}) \\
&= 1 - 0 \\
&= 1 \\
\mathtt{wf}_2(Y) &= \mathtt{wf}_1(Y_1) \times \mathtt{wf}_1(Y_2) \\
&= \mathtt{wf}_1(Y_1) \times \mathtt{wf}_1(X) \\
&= 1 \cdot 1 \\
&= 1 \\
\mathtt{wf}(Y) &= 1
\end{aligned}
$$

This value is carried over to S. The degree of acceptability is so high in our model that (5a) is predicted to be acceptable.

Note that the semantic constraints are fully imposed on the topicalized phrase because the semantic content is not deactivated from working memory.

5.2 Complement Coordination

We assume that, when dealing with a constituent coordination structure with two conjuncts, the human parser initially constructs a structure containing only the first conjunct before reading the conjunction (*and*) and after that, it combines with the second conjunct; the structure is subsequently modified into a coordinate structure when the conjunction and the second conjunct are encountered. This assumption is experimentally supported by Sturt and Lombardo (2005).

With this assumption in hand, the pattern in (2) can be explained as follows.

Upon encountering *about*, the parser constructs its complement X with the label "NP" ($av(X, \text{NP})$ =1). Since $av(X, \text{NP}) = 0$ at this point, subsequent coordination of the NP conjunct with the forthcoming CP does not cause a label clash. Thus the sentence is predicted to be acceptable.

5.3 Insertion

In our model, the partially or completely acceptable status of (5a-b) are due to the presence of a time interval between the head and the complement (the pause in (5a)) or the inserted adjunct in (5b). The difference between (5a) and (5b) is the difference between the deactivation values; in (5a), the deactivation value is "$\frac{t}{c}a$" while the degree of deactivation value of the "NP" label in (5b) is "$\frac{t}{c}a + b$". Thus, the acceptability status of (5b) is better than (5a).

5.4 RNR

In our model the Right Node Raising examples (3a-b) are accounted for as follows. In (3a), *about* and the "raised" phrase *that Mike was wrong* are adjacent, while in (3b) they are not. In our model, the constraints imposed by the head *with* are loosened or deactivated by the application of the function g while processing the second conjunct. Moreover, since the second conjunct is an overt linguistic expression, h is also applied. Hence we have:

$$av_i(X, \text{NP}) = av_0(X, \text{NP}) - \frac{t}{c} \cdot (a + b)$$

where $av_i(X, \text{NP})$ is the av value when the parser encounters the *that*-clause and $av_0(X, \text{NP})$ is the av value immediately after *with* is encountered. This is not high enough value to cause a label clash with a non-NP label of the "raised" phrase, and hence (3a) is correctly predicted to be acceptable, in contrast to (3b), where the "NP" specification due to the lexical requirement of *with* is active enough when the "CP" specification of the "raised" phrase, resulting in label clash.[4]

6 Conclusion

We have observed certain phenomena that could not be accounted for in structural terms and argued for an observational generalization in terms of linear-order. We formulated the generalization as a memory-based model by defining the activation value, deactivation function, and the relation between the acceptability degrees and the activation values. Also, we reconsidered and succeeded in accounting for the data which are difficult for grammar-based account in terms of this formalized model. We think this model is intuitively natural for human sentence processing.

We leave it to future work (i) to extend the coverage of the present model, and (ii) to extend the model so that it will also account for various degrees of garden path effects exhibited by various sentences (in various contexts).

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[4] In the present model the number of the intervening overt expressions has no effect; all that count is whether some overt lingusitic expression or other intervenes. This is against our intuition, and we intend to remedy this defect in the future development of our model.

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