A Theory of Processing Difficulty Based on Syntactic Prediction

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Recent work on sentence processing suggests that comprehenders make predictions while they process language: not only do they integrate new words incrementally with previous input, put they also anticipate upcoming linguistic material (Kamide et al., 2003). However, there are currently no formal models that model the process of making and verifying syntactic predictions. (A possible exception is Hale's 2001 surprisal model.)

Here, we propose a model of syntactic processing difficulty based on the explicit prediction of syntactic categories. The model is word-by-word incremental and assumes that fully connected syntactic structures are built. Alternative structures for ambiguous input are processed in parallel, with a search beam to capture memory limitations. The assumptions of the proposed model are:

- At each word, a set E of syntactic expectations e is generated; an expectation is an incomplete syntactic structure that denotes categories needed to build a grammatical sentence from the current input.
- Expectations are held in memory in parallel, and have a probability $P(e)$.
- Each structure has a timestamp t corresponding to when it was first predicted, or last activated.
- Processing difficulty is incurred either when expectations become incompatible with the current input (this bears similarities to analyses changing ranks as in (Jurafsky, 1996)), or when successful integration takes place.

We can then formalize the processing difficulty D_w at word w as:

$$D_w \propto \sum_{e \in E_i} f\left(\frac{1}{P(e)}\right) + \sum_{e \in E_d} f(P(e)) \tag{1}$$

Here, E_d is the set of syntactic expectations that are incompatible with w and are discarded, and E_i is the set of successful integrations at w. Furthermore, f is a decay function based on time stamp t.

To implement this model, we use tree-adjoining grammars (TAG). This facilitates modeling syntactic predictions, as TAG explicitly distinguishes arguments (predicted) from modifiers (not predicted), and makes it possible to maintain fully connected structures for incremental processing (Mazzei et al., 2007). The proposed theory can account for:

- locality effects (Gibson, 1998): the more dependents are integrated (E_i), the more processing cost is incurred, subject to a distance-based decay function f
- anti-locality effects (Konieczny, 2000): the more expectations are discarded (E_d), the more processing cost in incurred

- digging-in effects (Tabor and Hutchins, 2004): discarding expectations that have been maintained longer is more costly (decay function f)
- prediction (Kamide et al., 2003): syntactic categories are predicted explicitly as part of the formalism
- ambiguity resolution and garden paths: accounted for by probabilistically ranked parallelism as proposed by Jurafsky (1996).

As an example, consider "Mary loves Peter" (see (1)–(4)). We assume an initial expectation of a sentence (S↓). When processing "Mary", the lexicon entry is looked up, and the category is type-raised since it cannot be connected to S directly. The verb is integrated by merging the left context with the lexicon entry, i.e., predicted categories (with ↓) are matched against instantiated categories (without ↓). Finally, "Peter" is integrated.

The proposed model is attractive because it incorporates cognitive concepts such as memory limitations and decay and potentially accounts for a wide range of empirical phenomena.

Appendix

(1) lexicon: (NP Mary); (NP Peter); (S (NP↓) (VP (V loves) (NP↓)))

(2) type-raised "Mary": (S↓ (NP Mary) (VP↓))

(3) structure for "Mary loves": (S (NP Mary) (VP (V loves) (NP↓)))

(4) final parse: (S (NP Mary) (VP (V loves) (NP Peter)))

References

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