Computational Psycholinguistics day 3: Surprisal-based sentence processing

Class notes

July 13, 2007

1 Background

Previous usage of predictability-based measures of sentence comprehension difficulty:

- Empirical observations that *Cloze* probability (Taylor, 1953) affects reading times (Ehrlich and Rayner, 1981) and event-related potentials (ERPs; Kutas and Hillyard, 1980, 1984)

My brother came inside to...	chat? eat? play? rest?
The children went outside to...	chat? eat? play? rest?

- Use of root mean-squared (RMS) word-prediction error to evaluate neural-net learning of natural language sentences (Elman, 1990, 1991; Christiansen and Chater, 1999; MacDonald and Christiansen, 2002; Rohde, 2003)
- Predictability is implicated in mathematical models of word reading, but usually on an absolute probability scale (Reichle et al., 1998; Engbert et al., 2005; see McDonald et al., 2005 for an exception)

2 Hale 2001

Proposals:

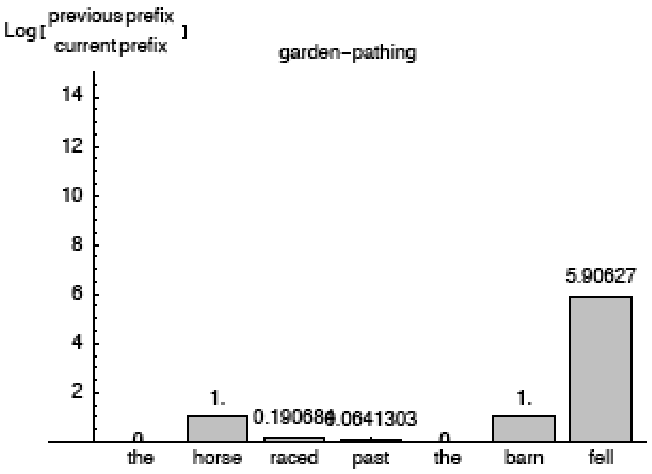
1. Probabilistic context-free grammars (PCFGs) are a good model of how human sentence comprehension works.
2. A probabilistic Earley parser is a good model of online *eager* sentence comprehension for PCFGs

3. The cognitive effort associated with a word in a sentence can be measured by the word's negative log conditional probability:

$$log\frac{1}{P(w_i|w_{1\cdots i-1})}$$

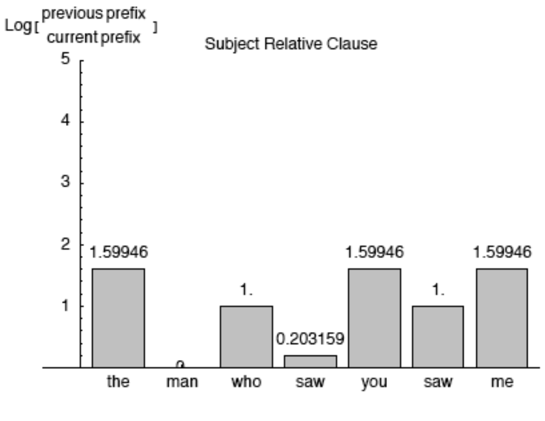
Results from this proposal:

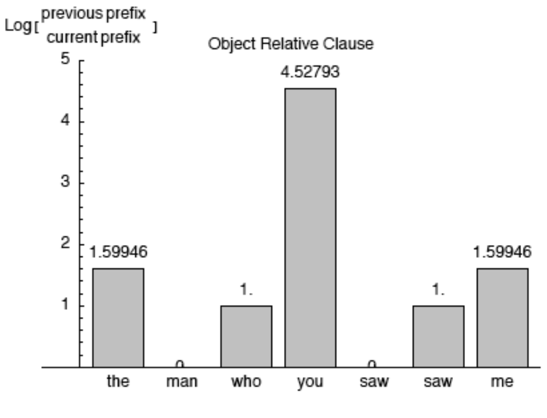
1. Garden path sentences: *the horse raced past the barn fell*



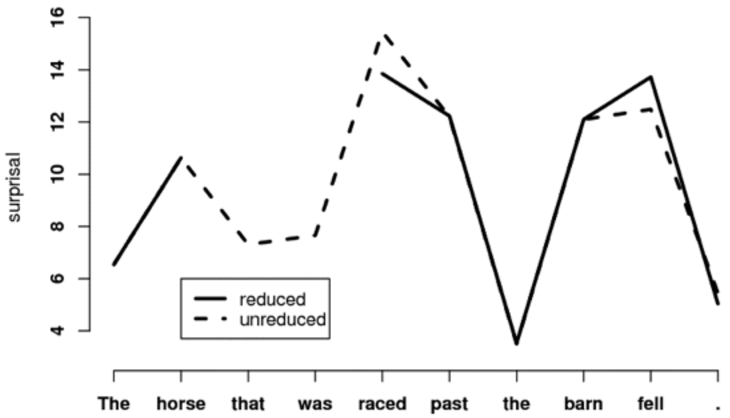
2. Subject/object RC ambiguities: one of the best-established processing asymmetries is the English subject/object RC asymmetry:

   The reporter who attacked the senator $<^{easier}$
   The reporter who the senator attacked





Caveat: these results are with a tiny, mostly hand-crafted grammar. Example using the entire Brown corpus:



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A different derivation of surprisal:

1. Let the probability distribution over *complete structures* T (e.g., context-free trees) given a string prefix $w_{1 \cdots i}$ be denoted as $P_i(T)$.
2. The *relative entropy*, or *Kullback-Leibler divergence* (Cover and Thomas, 1991), $D(q||p)$ between two probability distributions is
   - a natural (though asymmetric) measure of probabilistic distance;
   - can be thought of as the penalty incurred for using the distribution p to encode the finer-grained distribution q.
3. It turns out that the relative entropy between distributions before and after a word w is equivalent to the surprisal of w:

$$D(P_{k+1}||P_k) = \log \frac{1}{P_k(w_{k+1})}$$

4. If we think of probabilistic distance as the amount of work involved in reranking the candidate set T, then surprisal is also a measure of reranking work.

Results:

1. Constrained syntactic contexts.

   German verb-final clauses (Konieczny, 2000):

(1) a. Er hat den Abgeordneten begleitet, und ...
He has the delegate escorted, and ...
"He escorted the delegate, and ..."

b. Er hat den Abgeordneten ans Rednerpult begleitet, und ...
He has the delegate to_the lectern escorted, and ...
“He escorted the delegate to the lectern, and ...”

c. Er hat den Abgeordneten an das große Rednerpult begleitet, und ...
He has the delegate to the big lectern escorted, and ...
“He escorted the delegate to the large lectern, and ...”

	Average RT (ms)	Surprisal	DLT prediction
no PP	514	15.99	faster
short PP	477	15.41	slower
long PP	463	15.35	slower

2. Verb identity versus verb location (Jaeger et al., 2005):

(2) a. The player [that the coach met **at 8 o’clock**] bought the house...

b. The player [that the coach met *by the river* **at 8 o’clock**] bought the house...

c. The player [that the coach met NEAR THE GYM *by the river* **at 8 o’clock**] bought the house...

	Number of PPs intervening between embedded and matrix verb		
	1 PP	2 PPs	3 PPs
DLT prediction	Easier	Harder	Hardest
Surprisal	13.87	13.54	13.40
Mean Reading Time (ms)	510 ± 34	410 ± 21	394 ± 16

3. Facilitative ambiguity:

(3) (Traxler et al., 1998)

a. The daughter$_i$ of the colonel$_j$ who shot herself$_{i/*j}$ on the balcony had been very depressed.

b. The daughter$_i$ of the colonel$_j$ who shot himself$_{*i/j}$ on the balcony had been very depressed.

c. The son$_i$ of the colonel$_j$ who shot himself$_{i/j}$ on the balcony had been very depressed.

The ambiguous form can derive probability mass from both attachments; the unambiguous form can only derive mass from one attachment.

4 Other developments

- Other views of surprisal

  - Smith (2006) has shown that surprisal can be derived as a highly general optimization of a time/resource tradeoff, assuming only a *scale-free property* (that the cost of a unit U can be derived as the sum of the costs of the subunits $u_{1 \cdots n}$ that make it up)
  - This works because joint events are characterized by products of probabilities, and the log of a product is the sum of logs

- Surprisal and sentence production:
  - With some extra (empiricially testable) assumptions, surprisal can lead to the idea of *uniform information density* (UID)
  - Under UID, optimal communication involves smoothing out the surprisal profile of an utterance

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