On hallucinated garden paths

Roger Levy
UC San Diego
Department of Linguistics
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Incrementality and Rationality

- Online sentence comprehension is hard
- But lots of information sources can be usefully brought to bear to help with the task
- Therefore, it would be rational for people to use all the information available, whenever possible
- This is what incrementality is
- We have lots of evidence that people do this often

“Put the apple on the towel in the box.” (Tanenhaus et al., 1995)
Garden-pathing in incremental parsing

- *Garden-path* sentence a consequence of incrementality
- Classically: preferred global analysis ≠ prefix’s preferred analysis

\[
\text{The horse raced past the barn fell}
\]

- Some recent examples don’t match this definition
  - Tabor et al. (2004): garden-paths on *continuous substrings*

\[
\text{The coach smiled at the player tossed the frisbee}
\]

- Today: *garden-paths on discontinuous-substring prefixes*
Probabilistic grammars give good model of rational incrementality and garden-pathing (Jurafsky, 1996; Crocker & Brants, 2000; Hale, 2001; Levy, 2008).

(McRae et al., 1998)
Grammar ↔ Input-recognition modularity? II

- But implicit modularity assumption: decisions made during *input recognition* aren’t subject to later revision

- Caveat: It’s clear that prior context can affect the recognition process for newly perceived words…

  He swept the *flour*...
  The baker needed more *flour*...

  (Slattery, JEP:HPP)

- …but in most models, *outcome* of input recognition is categorical

Misperceived more often as *floor*
Grammar ↔ Input-recognition modularity? III

- This partition between input-level and sentence level analysis could be real (Fodor, 1983)
- Or, it could be a practical modeling simplification
- In a system utilizing all available information, sensory uncertainty should be included in grammatical inferences
- Levy (2008, EMNLP) modeled how this could look, using a noisy channel model
  - Goal of comprehension: infer sentence \( w \) and structure \( T \)
  - Comprehender perceives noisy sensory inputs \( I \)
  - \( I \) is integrated with grammatical/world (“prior”) knowledge \( G \) for inferences about sentence form and structure

\[
P_G(w|I) \propto \sum_T P(I|T, w) P(w|T) P(T)
\]

- Average over \( w \)  
- Knowledge of noise processes  
- Prior knowledge \( G \)
Uncertain-input model: two predictions

- **Prediction 1:** if current input would be more likely if previous input were *slightly different*, comprehenders should question their beliefs about the past.

  
  
  The coach smiled at the player *tossed* the frisbee 

  toward

- Supported by Levy, Bicknell, Slattery, & Rayner (2009, *PNAS*): readers’ eye movements regress from *tossed*.

- **Prediction 2:** expectations about future input may sometimes reflect what previous input *might have been*.

  - i.e. comprehenders may enter a *hallucinated garden path*.

- Investigated in the current experiments.
Hallucinated garden paths

- Traditional “NP/Z” garden-path sentence:
  *While Mary mended the sock fell off her lap.*

- Generally assumed to be eliminated by appropriate comma:
  *While Mary mended, the sock fell off her lap.*

  - Fodor 2002: “With a comma after mended, there would be no syntactic garden path left to be studied.”

- But consider the following sentence:
  *While the clouds crackled, above the glider soared a magnificent eagle.*

  - Comprised of an initial intransitive subordinate clause…
  - …and then a main clause with locative inversion.
    *(c.f. a magnificent eagle soared above the glider)*

  - Crucially, the main clause’s initial PP would make a great dependent of the subordinate verb…
  - …but doing that *would require the comma to be ignored.*

- Inferences through …*glider* should thus involve a tradeoff between perceptual input and prior expectations
Inferences as probabilistic paths through the sentence:

- Perceptual cost of ignoring the comma
- Unlikeliness of main-clause continuation after comma
- Likeliness of postverbal continuation without comma

These inferences together make *soared* very surprising!

\[
P(w_i|\text{Context}) = \sum_{\text{Path}} P(w_i|\text{Path, Context})P(\text{Path}|\text{Context})
\]
Hallucinated garden paths: Experiment 1

• Two properties come together to create the “hallucinated garden path”
  1. Subordinate clause into which the main-clause inverted phrase would fit well (*here, absence of clause-final PP*)
  2. Main clause with locative inversion

• Experimental design: cross (1) and (2)

While the clouds crackled, above the glider soared a magnificent eagle.
While the clouds crackled, the glider soared above a magnificent eagle.
While the clouds crackled in the distance, above the glider soared a magnificent eagle.
While the clouds crackled in the distance, the glider soared above a magnificent eagle.

• The phrase *in the distance* fulfills a similar thematic role as *above the glider for crackled*
• Should reduce hallucinated garden-path effect
• We predict an interaction on reading times at soared
• Methodology: word-by-word self-paced reading
• Readers aren’t allowed to backtrack

So the comma is visually *gone* by the time the inverted main clause appears

Simple test of whether beliefs about previous input can be revised: do reading times soar at *soared*?

Experiment details:
• 40 participants, 24 items, 62 fillers
• Each trial followed by a yes/no question (with feedback)
Results: whole sentence reading times

Processing boggle occurs exactly where predicted (Interaction p<0.05)

While the clouds crackled, above the glider soared above a magnificent eagle.
RT distribution at main verb *soared*

- Readers get *really* confused!
- This manifests itself in many very long RTs at the disambiguation of the hallucinated garden-path
Expt 1: question-answering accuracy

- Comprehension questions also answered least accurately in the no-PP, inverted condition.
- Significant interaction ($p<0.05$)
Experiment 1: summary

• We find highly localized reading-time evidence of a *hallucinated garden path* disambiguation effect

• Global sentence-comprehension data support the online reading-time results

• Garden path is over a *discontinuous* substring of the input

• We might call this *deletion-overriding*
  • Comprehender pursues inferences available only if some part of the input is treated as *absent*
While the clouds crackled, above the glider soared above a magnificent eagle.

Hallucinated garden paths: Experiment 2

- Possible objection to Experiment 1: spillover?

Processing boggle might really be starting here… …but only manifest itself in RTs here
Hallucinated garden paths: Experiment 2

- Address this possibility by putting more neutral material (an RC) in between hallucinated GP onset and resolution

While the clouds crackled, above the glider soared a magnificent eagle.
While the clouds crackled, the glider soared above a magnificent eagle.
While the clouds crackled, above the glider that was flying low soared a magnificent eagle.
While the clouds crackled, the glider that was flying low soared above a magnificent eagle.

- Design crosses inversion with length of hallucinated GP

- The hallucinated garden-path hypothesis predicts:
  - Small (or no) differences on RTs inside the RC
  - a main effect on reading times at soared

- Experimental details:
  - 56 participants, 24 items, 80 fillers
  - Each trial followed by a yes/no question (with feedback)
Experiment 2: RT results

- **Surprise:** *soared* RTs highest in short inverted condition!
- **But we do** get our clear main effect one word later

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**Experiment 2: RT results**

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**Interaction:** *p* < 0.01

**Main effect:** *p* < 0.001
Experiment 2: RC RTs unfolded

- There really is complete neutralization of RT differences across inversion condition inside the pre-disambiguation RC
Expt 2: question-answering accuracy

- Significant main effects of inversion and of length
- Interaction statistically insignificant (despite superficial appearances)
Recent work has explored possible consequences of rational language comprehension under uncertain input.

**Substitution overriding** \((at \rightarrow as)\) previously demonstrated.

Here I demonstrate **deletion overriding** \((, \rightarrow \emptyset)\).

Deletion overriding can lead to *hallucinated garden paths*.

Tendency for GP hallucination trades off between:
- **Prior expectations** from grammatical & world knowledge.
- Fidelity to sensory input (likelihood in a model of noise).

Online comprehension as **rational probabilistic inference**.

Open questions:
- Can we also find **insertion overriding**? **Swap overriding**?
- What factors determine comprehenders’ priors and noise models?
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Beautifully lit garden path
http://home-biba.blogspot.com/
2009/10/away-with-fairies.html

No Title (Photogram of two hands and garden path)
Sue Ford, c. 1970