Interaction between local coherence and garden path effects supports a nonlinear dynamical model of sentence processing.

Roeland Hancock & Whitney Tabor, University of Connecticut

Predictive sentence processing models that incorporate both lexical and syntactic expectations [2,4] have treated these as additive sources of information, yet experimental data have provided support for interacting syntactic and lexical expectations [1]. Three classes of incremental parsing models—additive surprisal, noisy-channel, and self-organizing—make distinctive predictions in the case of local coherence following syntactic ambiguity. We present simulation results from a self-organizing nonlinear dynamical model (Self-Organized Sentence Processing ; SOSP [5–7]) which predicts speeded reading time when local coherence coincides with garden path disambiguation, and we present experimental data in support of this prediction.

We examined incremental lexical and syntactic effects by manipulating local coherence in a 2 $\times$ 2 design that fully crosses local coherence (LC) and garden pathing (GP) (see items 1a-1d).

1a (+GP +LC) The division encamped near the fierce *battle was fought* by the brigade.
1b (+GP -LC) The division encamped near the fierce *battle was pestered* by the brigade.
1c (-GP +LC) The division that was encamped near the fierce *battle was fought* by the brigade.
1d (-GP -LC) The division that was encamped near the fierce *battle was pestered* by the brigade.

In (1a), the critical disambiguating region *was fought* occurs within a locally lexically coherent fragment *battle was fought*, with low trigram surprisal. In (1b), the corresponding context has high trigram surprisal. Comparison with the unambiguous controls (1c, 1d) isolate locally coherent lexical and syntactic effects, and highlight conflicting predictions from three classes of models.

Additive surprisal models predict that both garden path and locally coherent structures can influence parsing, but that they do so independently. Noisy-channel models predict garden path effects and they sometimes predict local coherence effects if there is a locally coherent structure with high probability and a low-cost edit that can license it [3]. Here, however, the most plausible low-cost edit (”and” after ”battle”) does not produce an interaction with garden pathing in our materials. In SOSP (Table 1), processor state $\mathbf{x}$ is governed by a potential function called “Harmony” ($H(\mathbf{x})$). Each harmony peak corresponds to a stable configuration of bonds (fully grammatical structure, suboptimal structure that is a coherent tree, or an ill-formed mix of partially completed trees). SOSP uniquely predicts that the local coherence effect and the garden path effect will interact because strong bottom-up formation of fully grammatical structures in the unreduced examples (1c and 1d) dwarfs the potential of local coherence, but weaker bottom-up induction of an ill-formed mix of trees due to the garden path in 1a and 1b causes the difference between the locally coherent and nonlocally coherent structures to manifest as an effect. Such interactions are a hallmark property of nonlinear dynamical systems, where parameter changes can cause categorical change (bifurcation).

58 participants read 40 experimental items and 40 fillers in a web-based centered-window self-paced reading task. Log-transformed reading times were residualized for word length, position, and frequency. Linear mixed effects analysis at the critical region (Figure 1b) showed significantly longer reading times for garden path sentences overall ($t = 2.4, p = .02$) and an interaction with local coherence effects ($t = 2.1, p = .04, BF_{H1} = 4.9$), with shorter reading times for locally coherent (1a) than locally incoherent (1b) garden path sentences. These results confirm the distinctive prediction of the SOSP model, supporting the view that local coherence effects arise from bottom-up dynamics in the parser.

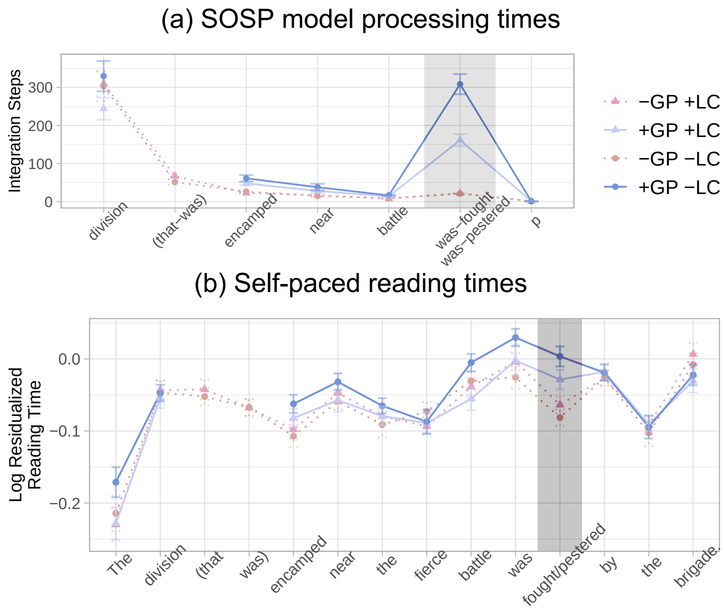

Figure 1: **(a)** SOSP predicts a garden path $\times$ coherence interaction at the disambiguating verb (shaded). Processing time is measured in Euler integration steps to convergence at each word. **(b)** Self-paced reading data confirm this prediction.

A structure's harmony = product of bond harmonies (each reflecting degree of clash)	$h_i = \prod_{l \in bonds} \left(1 - \frac{dist(\mathbf{f}_{l,daughter},\, \mathbf{f}_{l,mother})}{nfeat}\right)$
Radial basis functions define peaks at each structural locus, $\mathbf{c}_i$. γ is peak width.	$\phi_i(\mathbf{x}) = \exp\left(-\frac{(\mathbf{x}-\mathbf{c}_i)^\top(\mathbf{x}-\mathbf{c}_i)}{\gamma}\right)$
In addition to peaks for individual structures, there are peaks at the averages of future possible structures for initial substrings.	$\mathbf{c}_j = \frac{1}{\sum_i w_i} \sum_i w_i \mathbf{c}_i$ for $\mathbf{c}_i$ a destination from partial parse j, $w_i = h_i p_i$, p_i = probability in PCFG for grammatical parsing
The global harmony at any point is the height on the flank of the locally dominant peak.	$H(\mathbf{x}) = \max_{i \in 1 \ldots n} h_i \phi_i(\mathbf{x})$
Competitive bond formation and feature specification is noisy hill-climbing on the landscape.	$\frac{d\mathbf{x}}{dt} = \nabla_{\mathbf{x}} H(\mathbf{x}) + \eta$

Table 1: SOSP dynamics.

References: **[1]** K Christianson et al., Cogn Psychol 42, 368–407 (2001). **[2]** MW Crocker et al., J Psycholinguist Res 29, 647–669 (2000). **[3]** R Levy, EMNLP, 234–243 (2008). **[4]** J Mitchell et al., ACL, 196–206 (2010). **[5]** G Smith et al., Cogn Psychol 124 (2021). **[6]** G Smith et al., ICCM, 138–143 (2018) **[7]** W Tabor et al., AMLaP (2020).