Dependency trees guide real-time comprehension in naturalistic reading

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Background: A central question in psycholinguistics is how grammatical structures contribute to real-time sentence comprehension. Recent evidence from at-a-glance reading suggests the presence of a “tree-spotting” mechanism, whereby participants match words to syntactic trees during real-time processing (Fallon & Pylkkänen, 2024). However, much less is known about the format of the “tree” and the strength of its influence. Theories including Derivational Theory of Complexity, Good Enough Parsing (Ferreira et al., 2002) and shallow parsing (Sanford & Sturt, 2002) have attempted to reconcile syntactic theory with real-time parsing strategies, albeit with differing levels of success. The current study, however, proposes that the syntactic tree in dependency grammar could may function as a guiding mechanism in real-time reading comprehension, given its success in aligning with brain responses (e.g. Weissbart & Martin, 2024). Building on this hypothesis, the study further investigates the relative weight of sentence structural properties in comparison to other factors influencing comprehension.

Aims & Methodology: The study has two primary objectives. First, it seeks to test whether there’s an observable preference in fixating on words central to dependency tree building, reflected by eye movement transition probabilities. Second, it assess the weight of the influence from syntactic factors in comparison with other factors in guiding the eye movement scanpath. To achieve this, we used an openly available ZuCo dataset (Hollenstein et al., 2018). It comprises simultaneous eye-tracking and EEG recordings of 12 native English participants (5 females; mean age = 37.5 years; SD = 10.3 years; all right-handed) during reading. The hypotheses are as follows: (1) words central to tree-building (those associated with larger parsing depths) will show higher between-word transitional probabilities in actual eye movement sequences compared to original word sequences, and (2) structural properties of a sentence (e.g., parsing depth) will better explain scanpath deviations compared to other factors.

Analysis & Results: To test the first hypothesis, we used the Stanford parser to analyze sentence structure and categorized words as either heads or non-heads based on their parsing depth. Our results revealed that head-to-head transitions in the observed eye movement sequences were significantly more frequent than in the original word sequences ($p < .05$). This suggests a preference for matching words to a dependency grammar-based tree structure during real-time parsing. To assess the strength of this syntactic influence, we constructed a Bayesian network to examine the relative contribution of various factors to deviations in scanpaths from the original word order. The scanpath deviation was measured by edit distance, calculated via the Needleman–Wunsch algorithm. Two structure-related factors, which were derived from previous research (Lu, 2010), i.e. maximum depth and the number of clauses, were used here. Additionally, we considered two more factors identified in the E-Z Reader model (Reichle et al., 2003), which highlights the role of familiarity, surprisal in guiding eye movements. Surprisal is extracted from GPT2. Given that these five variables are highly interdependent (Figure 1(a)), we employed Bayesian networks to model the causal relationships among them. Using the hill-climbing algorithm, we learned a network structure that closely matched our initial hypotheses about the variable relationships. To assess the relative importance of each factor in explaining scanpath deviations, we applied two metrics: (1) mutual information and (2) edge strength. For both metrics, the structural variable of maximum depth outweighed all other factors in guiding eye movements (see Figure 1(b), Table 1).

Conclusion: Combined, the evidence supports the dependency trees as a possible candidate to connect together formal grammar theories and real-time parsing strategies. Also, given the strength of maximum depths in guiding eye movements, it also opens new avenues for exploring the neural correlates of hierarchical language processing.

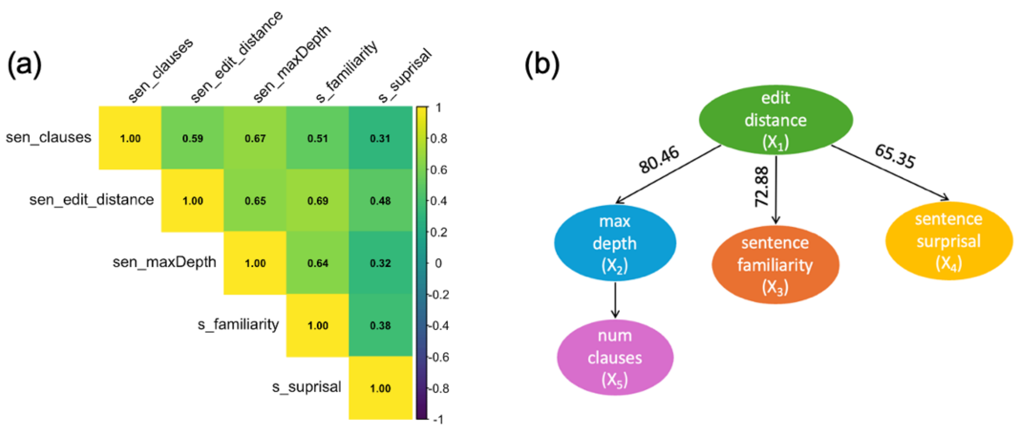

Figure 1. (a) dependency between the five variables; (b) the learned bayesian network using Hill-climbing algorithm

Table 1. Two metrics used to quantify the weight of influence on edit distance

	Edge strength	Mutual information
Max depth	80.45	214.82
Familiarity	72.88	199.66
Surprisal	5.27	65.347

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