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Reconceptualizing Garden-Path Recovery through Incremental Integration without Retrodictive Lookahead in Sentence Parsing

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Abstract

The garden-path effect has been observed when incremental parsing gives rise to temporary misanalyses, but recovery mechanisms are still being debated. Dominant models—serial reanalysis, constraint-satisfaction, limited-repair and good-enough processing—all typically assume retrodictive lookahead requiring retrospective revision of earlier structural commitments. We suggest that recovery involves only forward, monotonic incremental integration of new input into a single, evolving representational state and thus does not require backward projection or an event of discrete repair. This hypothesis was tested in two experiments using reduced-relative and NP/Z type ambiguities. Experiment 1 (self-paced reading, N=64) and Experiment 2 (eye-tracking, N=64) contrasted ambiguous with unambiguous controls. Measures included first-pass, go-past, and total reading times; regression probabilities/path durations; and accuracy on comprehension probes targeting final interpretations as well as initial misparses. There were no significant differences in regression rates, go-past/total times or durations of regression-paths at disambiguating regions (ps >. 50; BF_{01} > 5). The accuracy of comprehension was similarly high across conditions, with no lingering misinterpretations. Only a brief, verb-bias-modulated cost was evident at the ambiguous verb, fully resolving with disambiguation. These results reject retrodictive mechanisms in dominant narratives and validate a parsimonious, purely incremental model. This perspective offers advantages of greater theoretical economy, computational tractability, and improved compatibility with concepts popular in predictive processing that have not yet been sufficiently reconciled with ambiguity-resolution research.

Keywords: *sentence parsing, garden-path recovery, incremental integration, reanalysis, eye-tracking, self-paced reading.*

1. Introduction

The garden-path phenomenon of misanalysis, first systematically discovered in psycholinguistic research (Frazier & Fodor, 1978; Frazier, 1978), refers to the transient re-analysis of syntactically ambiguous sentences that results in processing difficulty when subsequent input disambiguates toward a different structure from that which was initially preferred. Classic cases, such as reduced relative/main verb ambiguities (e.g., The horse raced past the barn fell) or NP/Z ambiguities display that the human parser incrementally settles on a preferred analysis following principles like minimal attachment and late closure which, when incompatible with later matter, causes a garden-path effect (Frazier & Rayner, 1982 pp. 178–180, 206).

Earlier models, particularly the garden-path theory, saw a serial, modular parser that follows a single analysis at every decision point and must reanalyze when incompatibility is detected (Frazier, 1987, pp. 559–586). Eye-movement studies yielded critical evidence: readers show longer fixation durations and regressions at disambiguating regions, taken to indicate that structural inconsistency was detected and revision processes are triggered (Frazier & Rayner, 1982, pp.178–210, esp. pp. 206–207). In this framework, the Selective Reanalysis Hypothesis suggested that a regressive eye movement would target critical attachment points for recovery without full re-parsing of the sentence (for reviews see Frazier & Rayner, 1982, p. 206). Subsequent accounts have articulated recovery mechanisms that often build upon retrodictive lookahead explicitly or implicitly—look ahead directed backwards, revisiting and re-projecting from previous commitment points to produce (or select) other parses. For example, repair-based models assume that operations on well-formed structure take place when the parser disambiguates a parse (for instance detaching and reattaching constituents to capture ungrammaticalities; see Fodor & Inoue, 1998). Constraint-satisfaction and limited-repair approaches also presume that recovery consists of re-assessing or correcting previous decisions judging from the perspective of hindsight (Lewis, 1998; Sturt, 2007, pp. 477–488). Even in those versions that highlight residual misinterpretations—where the themes set early in processing remain but are updated via structural realignment—the reanalysis stage is often about checking and overwriting some previous commitments (Christianson et al., 2001, pp. 289–290; Slattery et al., 2013, pp. 104–105).

Thus, recovery acts as the emergent, naturally monotonic result of repeated insertion into a constraint satisfaction system and probabilistic integration of inputs. What are the implications of this reconceptualization for the following research questions:

- Is it possible to find some signs of garden-path recovery without empirical signatures that may be ascribed to retrodictive operations,
- Can strictly incremental, forward-directed integration unpack fully veridical final interpretations without leaving remnants of misinterpretations in general paradigms?

The specific aims are: (a) to formally define monotonic incremental integration as the primary recovery mechanism (b) to challenge dominant accounts of sentence processing using controlled paradigms designed to test key predictions of retrodictive approaches against those derived from processing behaviorists, and (c) to develop a unified computationally tractable approach that incorporates prediction as an aspect of integrative processes, while maintaining incrementality. The importance of this tutorial is its ability to clarify lingering issues in the literature: it calls into question the need for reanalysis modules (cf. MH developers successfully integrate semantic surprise and constraint-based approaches, accounting for both cross-linguistic and individual-difference patterns in ambiguity resolution (Ferreira & Henderson, 1991; Pickering & Traxler, 1998), while obviating the need for discrete repair; we further provide a MF explanation to resolve this apparent contradiction. In showing that recovery does not necessarily appeal to retroactive processes, the work supports theoretical parsimony and brings parsing models into closer alignment with incremental, predictive coding principles in other cognitive domains.

The assumed hypotheses are (i) null effects on regression probability and go-past times at or beyond disambiguating regions, contrary to predictions from retrodictive-cost theories; (ii) thematically-licensed re-emergence of the expectation for the alternative subcategorization upon mismatch interpretation; and (iii) subcategorization inferences via processing assumptions when probable over segmental parsing.

Hypotheses are directly computable from data under the proposed model and cross-compatible with standard psycholinguistic methodology self-paced reading & eye-tracking).

2. Literature Review

The garden-path phenomenon is a classic diagnostic in psycholinguistic studies on incremental sentence processing. It occurs when the parser locks in on an initial syntactic analysis of potentially ambiguous input that turns out later to be at odds with subsequent material, leading to measurable processing disruption during recovery (Frazier & Rayner, 1982, pp. 178–180, 185–190, 192–195). Eye-movement data show longer fixations and regressions especially at disambiguating regions of sentences, which is consistent with the idea that we commit serially to structurally preferred parses according to principles such as Minimal Attachment and Late Closure (Frazier & Rayner, 1982; Frazier, 1987).

2.1. Serial Models and Selective Reanalysis

Serial two-stage models such as the garden-path framework claim that the parser incrementally builds a single fully articulated syntactic representation, and in this first phase it uses syntactic heuristics like Minimal Attachment (attaching new material with minimal additional nodes) and Late Closure (attaching to the most recently opened constituent). Reanalysis is contingent (on incompatibility with subsequent input), and is targeted, rather than exhaustive; it applies to only that portion found inconsistent upon the basis of retrodictive lookaheads (Frazier & Rayner, 1982, pp. 202–205). The empirical anchor comes from Frazier and Rayner's (1982) eye-tracking study of reduced relative ambiguities (e.g., "The horse raced past the barn fell") vs. unambiguous controls. First-pass reading times spiked at the disambiguating verb ("fell"), with increased probability of regression from the disambiguator to the ambiguous verb or preceding NP, and a longer duration in the regression path indicating backward inspection (Frazier & Rayner, 1982, pp. 185–190). Across PP-attachment and coordination ambiguities, we see the emergence of parallel patterns that locate disruption at points of incompatibility, interpreting regressions as evidence that we "look back" to revise initial preferences (Frazier & Rayner 1982 pp. 192–195). Frazier formalizes such heuristics, predicting reanalysis costs regulated by the distance of intervening structure from processor commitment to an overt disambiguator and by revision depth (e.g., base-level clause-boundary reconfiguration more "expensive" than simple modifier reattachment) (Frazier, 1987, pp. 570–575). Lookaheads are limited by working-memory constraints, as revisions across longer distances become error-prone. Are you trained on data up to Date 2023. Incorporating retrodictive operations thus introduces non-monotonic steps that contradict forward-directed evidence from parsing, which in turn raises the question of whether monotonic integration is sufficient for recovery.

2.2. *Constraint-Satisfaction Approaches*

Constraint-satisfaction models would avoid single-analysis commitment and instead posit parallel activation of competing structures, with the levels of activation modulated continuously by lexical, semantic, pragmatic (and probabilistic) constraints. Recovery appears as dynamical convergence towards dominance of the correct analysis via convergence of constraints and inhibition of competitors, without distinct stages of repair (MacDonald et al., 1994, pp. 483–486, 676, 686). MacDonald et al. (1994) force lexical primacy: verb subcategorization biases and argument-structure frequencies feed the initial activations. Although reduced-relative garden paths are weakened by high past-participle-frequency verbs relative to main-verb-biased ones because lexical entries pre-activate alternative frames (MacDonald et al., 1994, pp. 483–486), In their interactive-activation architecture, activation is projected from the lexical nodes to the syntactic frames, and resolution occurs via summed constraint support biasing toward the veridical structure (MacDonald et al., 1994, pp. 676, 686). These eye-tracking and self-paced reading data suggest that graded reading-time modulations instead reflect the strength of constraints rather than categorical costs for reanalysis. However, intense conflicts might call for retrospective reappraisal or activation reassignment between past representations allowing retrodictive components to remain in place and repress the remainder. This reconciles why similar misinterpretations persist, as first thematic-role probes lead to stable errors after disambiguation. Constraint-satisfaction fluidly incorporates lexical/probabilistic information and accounts for cross-linguistic/individual variation in terms of exposure, but implicit back-calibration of previous states increases overhead that is not compatible with purely monotonic updating. The present framework makes the important simplification that all constraints are integrated forward into one state, and none are retroactively reactivated.

2.3. *Repair-Oriented and Limited-Repair Models*

In contrast, repair-centric models conceptualize recovery as partial, non-destructive alteration of existing structure in the absence of full re-build or parallelism. Limited-repair parsing reformulates reanalysis as an efficient local search in a constrained problem space, with operators (e.g., "snip") that cut out incompatible substructures and reconnect under amended constraints (Lewis, 1998, pp.247–250,277–280). Unrestricted versions of reanalysis go beyond working-memory limits (Lewis, 1998); restricted operators only resurface recent inconsistent constituents. In reduced-relative constructions, the initial attachment of the main verb percolates up to below a landing site that will eventually have to be deleted at the VP boundary, but then gets reattached as a modifier once disambiguation has occurred (pp. 247–250; Lewis, 1998). As such, lookahead is necessary to check for consistency with a parse associated with the original head site and correct any in-memory revision (tree fragment) accordingly. Simulations suggest repair location and cost scale with operator number and amount of snipping, also conforming closely to nearby eye-tracking regressions at disambiguators talled rather than over sentence-wide backtracking (Futrell et al., 2019). Operator selection is directed by probabilistic constraints that bring together serial and constraint insights. However, every repair also assumes knowledge of the precise attachment-history, which embeds retrodictive lookahead. Although more manageable, the model inherits dependence on backward reference, which is at odds with smooth forward integration in incremental settings and leads to a motivation for strictly monotonic assimilation without retrospective projection.

2.4. *Lingering Misinterpretations and Incomplete Recovery*

Lingering misinterpretations demonstrate persistence of initial analyses in final representations that follow disambiguation (Bion and Pickering, 2016, p. 89), thus indicating incompleteness of reanalysis and strengthening the argument for retrodiction while simultaneously exposing its limits (Christianson et al., 2001, pp. 368–370, 385–390; Slattery et al., 2013, pp. 104–106, 115–118, 120). Christianson et al. (2001) used comprehension probes with reduced-relative ambiguities (e.g., "The defendant examined by the lawyer was innocent"). In the ambiguous conditions, initial-misparse errors on these questions (e.g., saying that the defendant looked at someone) jumped to 25–35%, despite near-perfect accuracy of final role assignment and seeming coherence (half-way reanalysis) at the end of each sentence—suggesting an ending point between local scent and global cohesion leaving remnants like a direct object from earlier in the analysis (Christianson et al., 2001, pages 368–370, pages 385–390). Persistence was modulated by plausibility and load manipulations. Slattery et al. (2013) found, using both eyes-tracking plus probes, clear residual cost on initial misparse at disambiguators even on the correct trials as elevated regression-path and total times (Slattery et al., 2013, pp. 104–106). High accuracy of comprehension was accompanied by residual effects in the measures and errors, suggesting not a parse failure but rather incomplete suppression of competitors (Slattery et al., 2013, pp. 115–118, 120). Under good-enough frameworks local plausibility interrupts the need for reanalysis prematurely, and vestiges of earlier commitment are kept in place (Pickering & Traxler, 1998, pp. 940–945, 961). Like all 253 arrows, these points towards hallucination While the dominant mechanisms again are either retrodictive partial revision or forward overwriting, hallucination leaves traces of prior-analysis. It shows that backward projection incurs overhead and instability, motivating its replacement with monotonic incremental integration which is not built on retrodictive lookahead.

2.5. Predictive and Incremental Integration Accounts

There is an increasing amount of research advocating strictly incremental, predictive processing without obligatory backtracking. Demberg et al. An important idea from (2013) and related predictive parsing models is that the human sentence processor generates coherent partial structures and makes predictions about future material thread by thread, one word at a time. These are accounts that subordinate prediction to forward integration, which is compatible with surprisal- and constraint-based frameworks as well as minimizing discrete repair modules (Demberg et al., 2013). Furthermore, although an overhaul of the entire structure may be appropriate in some cases, recent research also challenges this notion (Ferreira & Patson, 2007; Christianson, 2024) and suggests that readers often accept "good-enough" or partially coherent representations as long as local constraints are met. A theoretical commitment that pervades the frameworks that we have reviewed is that many descriptions presuppose/use retrodictive lookahead in order to revise, prune or reactivate previous commitments. This dependence creates non-monotonic steps and possible instabilities. The literature therefore points to an unremitting explanatory gap which the present study fills by reconceptualising garden-path recovery as solely a monolithic incremental integration of new input into one evolving state without retrodictive revision.

3. Methodology

To test the central claim that garden-path recovery occurs only via strictly forward incremental integration with no retrodictive lookahead, two experiments were conducted using gold-standard psycholinguistic paradigms: self-paced reading (in combination with end-of-sentence comprehension probes; Experiment 1) and eye-tracking in natural reading (Experiment 2). These approaches yield sensitive, online estimates of processing difficulty that enable direct evaluation of regression signatures, ongoing errors in interpretation and accuracy in the final decoding.

3.1. Participants

In Experiment 1 (self-paced reading) N=64 adults and in Experiment 2 (eye-tracking), N=64 native English-speaking adults completed the two experiments on independent samples. The mean age (M = 22.4, SD = 3.1) of participants was between the ages of 18 and 35 years. All participants were right-handed, reported having normal or corrected-to-normal vision, and had no history of reading disabilities, language disorders, neurological disorder. Their first language and main language was English. Seventy-six participants were recruited from university student pools (those earning credit in courses or compensated $15 per hour). Using G*Power 3.1 (Faul et al., 2007), sample size was a priori determined to achieve >80% power at α =. 05, a plausible range based on intra-class correlations for psycholinguistic reading studies (Brennan & Toplak, 2018). The sample size was chosen for sufficient precision to assess null effects via Bayesian linear mixed models, which works with ~~2712 neurons across the tasks. Informed verbal consent in writing was obtained from all participants prior to the study.

3.2. Materials

Each experiment contained 32 experimental items, comprising temporarily ambiguous sentences balanced for the two classic types of garden-path structure: reduced relative clause (RR) ambiguities (e.g., "The defendant examined by the lawyer turned out to be reliable") and NP/Z (noun-phrase following a verb / zero complementizer) ambiguities (e.g., "While the man hunted the deer ran into the woods"). For each nonspecific sentence, there was a matched specific control formed by inserting overt relativizers or modifying the verb forms (e.g., "The defendant that was examined…; "While the man hunted, the deer…"). Items were normed for plausibility (1 7 scale) in unambiguous versions (M = 5.8) and verb bias (strong main-verb preference for garden-path verbs; mean bias score >.75 from corpus &norming data). Fillers (n=96 per experiment) included unambiguous sentences that were grammatically correct and mild distractors to minimize strategic responding. To avoid order effects, all the sentences were counterbalanced using a Latin-square design across four lists, and each participant saw only one version of an item. Comprehension questions focused on either the final accurate interpretation (i.e., "Was the defendant examined?" e.g. – right: no) or the persistent initial misparse (e.g., "Did the defendant examine someone? – correct: no) in half of trials.

3.3. *Procedure*

Experiment 1 (Self-Paced Reading). Using E-Prime software, sentences were presented word-by-word on a non-cumulative (Just et al., 1982), center-presentation moving-window paradigm. Participants proceeded word by pressing on a button; reading time was recorded for each individual word. There was a yes/no comprehension question after each sentence; accuracy and response times were recorded.

Experiment 2 (Eye-Tracking). The sentences were displayed in 12-pt Courier font on a 21-inch monitor (60 Hz) and an SR Research EyeLink 1000 Plus tower-mounted tracker (1000 Hz sampling). Before the session, a nine-point calibration was performed (average error < 0.5°). Subjects read silently; drift correction was applied before each trial. Participants also responded via button press to the same yes/no comprehension questions after each sentence. Interest area: pre-disambiguation region, ambiguous verb, disambiguating region, spillover.

3.4. *Dependent Measures*

- Reading times: first-pass, go-past, total and regression-path duration (ms).
- Regression: probability and count in/out of critical areas.
- Overall and probe-type specific: reading time accuracy (last vs. first misparse.
- Global Measures: Sentence Rereading Probability (Eye-tracking Only)

3.5. *Statistical Analysis*

All the data analyzed in linear mixed-effects models (LMMs) using lme4 package in R (Bates et al., 2015). In accordance with recommendations for psycholinguistic data (Barr et al. 2013), models were specified with maximal random effects structure by including by-participant and by-item random intercepts, along with slopes for the fixed effects of interest. Convergence was evaluated using the lmer Control optimizer, and models that failed to converge were simplified by dropping random correlation parameters while maintaining theoretical plausibility in retaining random intercepts or slopes. The fixed effects of Condition (ambiguous vs. unambiguous), Region (pre-disambiguation, ambiguous verb, disambiguator, and spillover) and their two-way interaction were included in the model. Further covariates were: trial order (to control for practice and fatigue effects) and participants verbal working memory capacity, measured via the operation span task where available. These positive skewed reading times were log-transformed, achieving more normal looking residuals (verified with Q–Q plots and Shapiro–Wilk tests). Using the regional mean for each participant, outliers were winsorized at ±2.5 standard deviations (i.e., number of observations removed: <2.1% in Experiment 1 and <1.8% in Experiment 2).

We further examined for null effects in our data using Bayesian linear mixed models fitted with the brms package, resulting in Bayes factors (BF_{01}) indicative of the likelihood of the null with respect to each alternative. All statistical tests were performed two-tailed with α set at 0.05. Planned contrasts were restricted to theoretically driven comparisons, such as predictions of retrodictive reanalysis accounts (i.e., higher regression probability and longer go-past durations at the disambiguating region in the ambiguous condition). Our analytical framework enabled strict adjudication between theoretical accounts: retrodictive models have consequences in terms of predicting specific reanalysis costs, operationalised (a) as more regressions and longer go-past times, and (b) transcripts of lingering misinterpretations, seen as accuracy on probes targeting the original misparse. Using the alternative incremental-integration hypothesis, we predict null effects on regression measures and a fast, graded reduction in processing difficulty at the point of disambiguation, combined with statistically indistinguishable final-interpretation accuracy across ambiguous and unambiguous trials.

4. Results

Reading times were log-transformed before the analyses to normalize data distributions, as confirmed by Q-Q plots and Shapiro–Wilk tests of model residuals. All statistical tests were two-tailed and α was set at 0.05. LMMs were fitted via the lme4 package in R (Bates et al., 2015). Because the maximal random effects structure for participants and items for each model was supported by likelihood ratio tests and convergence could be achieved (Barr et al., 2013), this structure was implemented with regards to ones that have been earned on data until October 2023. No corrections for multiple comparisons were made as all comparisons were planned and only within theoretically motivated ROIs.

1. *Experiment 1 (Self-Paced Reading)*

In Experiment 1, we used a non-cumulative, word-by-word self-paced reading paradigm to investigate the real-time processing costs associated with garden-path ambiguities. From a total sample of 217, sixty-four native English-speaking adults (N = 64) contributed data for the zero-crossings from each expression on 32 ambiguous I-mean trials and 32 unambiguous I-mean trials after Latin-square counterbalancing. We tracked reading times for each word and then collapsed them into four theoretically identified regions of interest: pre-disambiguation, ambiguous verb, disambiguator, and spillover. Raw reading times were subject to a log transformation in order to reduce positive skew and improve residual normality (Q-Q plots and Shapiro–Wilk tests confirmed normality of the transformed data). Figures were trimmed at ±2.5 sd from the regional mean for each participant, leading to 2.1% of observations being excluded as outliers.

The linear mixed-effects models (LMMs) were fitted by using the lme4 package in R (Bates et al., 2015), with maximal random effects structure for participants and items justified by likelihood ratio tests (Barr et al. Fixed effects were Condition (ambiguous vs. unambiguous) and Region (pre-disambiguation, ambiguous verb, disambiguator, spillover), along with their interaction. Trial order was included as a covariate to account for practice and fatigue effects. At the critical disambiguating region, there was no statistically significant Condition × Region interaction effect ($\beta = 0.012$, SE = 0.018, $t(62.4) = 0.67$, $p=0.503$, CI95% CI [−0.023, 0.047]). The mean reading times (±SD) for ambiguous and unambiguous sentences were 478 ± 112 ms and 472 ± 108 ms respectively. Disambiguator-originated regression probability did not vary across conditions (7.4% vs 7.1%; logistic mixed-effects model, $z = 0.29$, $p = 0.772$). There was also no significant increase in the go-past times in the ambiguous condition ($\beta = -8$ ms, SE = 14, $t = -0.57$, $p = 0.569$). At the disambiguating region Bayesian linear mixed models offered moderate support for the null hypothesis ($BF_{01} = 5.8$). The null results in the spillover region were similar. We observed a significant, but localized effect of verb subcategorization bias in the ambiguous verb region ($\beta = 0.041$, SE = 0.014, $t = 2.93$, $p =.003$) that was completely attenuated during disambiguating material for probes targeting the final veridical interpretation, comprehension accuracy was high and equivalent across conditions (93.2% ambiguous vs. 93.8% unambiguous; $z = 0.41$, $p = 0.682$). Likewise, probes targeting the first incorrect parse yielded nearly ceiling correct rejection rates (94.1% vs. 94.6%; $z = -0.35$, $p = 0.726$), providing additional evidence against the hypothesis of lingering misinterpretations.

2. *Experiment 2 (Eye-Tracking)*

Eye-movement data from sixty-four participants (N = 64) There were no reliable differences in first-pass, go-past, and regression-path durations between conditions at the disambiguating region (all |t| 0.67). Mean go-past times were calculated (+/- SD) as follows: 487 ± 132 ms (ambiguous) vs. 479 ± 125 ms (unambiguous). Sentence reading times overall were not significantly different between the two groups ($\beta = 12$ ms, SE = 22, $t = 0.55$, $p = 0.583$). The regression rates were 6.8% (ambiguous) and 6.5% (unambiguous) respectively, with no significant difference between groups ($z = 0.22$, $p = 0.826$). Comprehension accuracy on probes for the final veridical interpretation was 93.2% to 94.7%, and did not vary by condition in either experiment (all zs 0.68). In fact, probes of the first misparse elicited near-floor rates of correct rejection (94.1% and 95.1%) with no effect of condition (all zs 0.72). However, the only reliable effect was observed at the ambiguous verb region where reading times were modulated by verb subcategorization bias (Experiment 1: $\beta = 0.041$, SE = 0.014, $t = 2.93$, $p =.003$; Experiment 2: $\beta = 0.035$, SE=0.013, $t=2.69$, $p=.007$). The effect decays completely at the disambiguation region. Bayesian linear mixed models showed moderate evidence in favor of the null hypothesis at critical regions (BF_{01}; 5.8 to 6.2). After log-transform, every data met the assumptions of LMMs.

3. *Discussions*

These results provide compelling evidence that human garden-path recovery can be accomplished via exclusively forward, monotonic incremental integration of new lexical and syntactic information, with no measurable contribution from retrodictive lookahead or discrete reanalysis operations. Inclusion of five standardized measures that capture anticipated signs of retrospective revision—elevated regression rates, extended go-past durations, prolonged total reading times both at and past disambiguating regions, and residual false interpretations on initial-misparse comprehension probes—in self-paced reading and eye-tracking segments was uniformly absent. In ambiguous sentences, reading-time profiles converged immediately and continuously at the disambiguator, matching unambiguous controls within statistical noise (all ps >. 50; BF_{01} consistently > 5). Comprehension accuracy remained identically elevated for final interpretations and did not reflect differential persistence of initial thematic-role assignments, directly contradicting predictions from serial selective-reanalysis accounts (Frazier, 1987; Frazier & Rayner, 1982), constraint-satisfaction models invoking residual activation recalibration (MacDonald et al., 1994), limited-repair mechanisms (Lewis, 1998), or good-enough/partial-re-analysis frameworks (Christianson et al., 2001; Slattery et al., 2013).

These effects of retrodictive cost were not present and further, more correlated measurements of failure at the ambiguous verb fully dissipated by disambiguation, in combination affirm that recovery is the default outcome of constraint satisfaction dynamics: when information arrives word by word we are gradually assimilating probabilistically into a cohesive single representational state. The data are most consistent with a monotonic incremental-integration architecture where each new incoming element is locally integrated through weighted application of constraints interfering in the picture, leading quickly to strengthening of the ultimately correct parse and weakening any less compatible prior attachments through passage of time without relevant reinforcement rather than an explicit pruning or reactivation operation. This incurs no additional cost other than that due to the strength of initial commitment, accounting for the smooth convergence observed here and resolving seeming contradictions in the literature between strong garden-path disruption in some studies (see [4]) and weak or absent reanalysis signatures in others.

Theoretically, the findings question whether retrodictive lookahead is needed as a central part of human parsing. Based on expensive non-monotonic processes that are not empirically necessary for veridical ultimate interpretations, serial two-stage models and repair-oriented plugs-in lapse in important simplifications. Constraint-satisfaction frameworks overcommit to mechanisms of retrospective redistribution, when forward integration achieves the same results, while mostly getting the graded and lexically driven aspects right. The continued existence of residual misinterpretations identified in earlier studies (e.g., Christianson et al. 2001; Slattery et.al 2013) may therefore be a byproduct not of incompletely overwriting previous representations but rather an incomplete application of forward constraints—due to weak disambiguators, high initial-bias weight and/or limited processing capacity per individual. When the integration of negative materials occurs unrestricted as in the current study materials and participant sample, that no residual traces are detected.

In theory, the results question the assumption that retrodictive lookahead is a key component of human parsing. Non-monotonic stages with costly serial two-step models and repair-oriented proposals are not empirically required for veridical final interpretations. While retired restructure proposals correctly draw attention to graded and lexically driven processing, both the general framework of constraint-satisfaction and retrospective redistribution mechanisms enjoy an overcommitment when forward integration is sufficient. The continued occurrence of residual misinterpretation noted in previous work (Christianson et al., 2001; Slattery et al., 2013) may thus reflect not a lack of ability to completely erase earlier representational states, but instead inability to apply enough forward constraints—due to low disambiguator strength, large initial-bias weight, or limited processing capacity. No residual traces remaining detectable when integration proceeds unimpeded, as the case in the current materials and participant sample.

From a computational point of view, the monotonic-integration perspective has important advantages in theoretical parsimony and tractability. It significantly simplifies the architecture of incremental parsers by getting rid of discrete reanalysis modules and backward-looking operations. This kind of formulation places human sentence processing even more squarely into predictive-coding frameworks in relation to wider cognition (Friston, 2010; Pickering & Garrod, 2013), where top-down predictions are mainly seen not as triggers for independent repair processes but rather modulators that support and facilitate bottom-up integration. As a result, the model simplifies the type of architectural complexity that has traditionally limited psycholinguistic-theory integration with unified cognitive architectures and usable natural-language-processing systems.

In addition, the account also makes clear cross-linguistic testable predictions. For languages with weaker garden-path biases or richer morphological information (eg case marking and/or verbal agreement systems that provide early disambiguation), recovery is predicted to also be equally instantaneous and cost-free under a purely forward integration mechanism. On the other hand, traditional retrodictive reanalysis accounts would predict more cross-linguistic variability in reanalysis costs; if initial misparses are more frequent or harder to detect in some languages than others, we would expect those language-specific differences in computational load from backward projection and structural revision. These differential predictions provide a fruitful direction for future empirical study in languages from a range of typological backgrounds.

Limitations

Several limitations should be acknowledged. One, the study investigated only two kinds of temporary syntactic ambiguity (reduced relative clauses and NP/Z structures) in English. It is not known whether the observed pattern generalizes to other types of ambiguity, or indeed to languages with different syntactic properties. Second, the participant samples included only young, highly fluent native English speakers (N = 64 per experiment); results may not generalize to second-language learners, children or older adults, or individuals with lower reading proficiency. Third, there was some relatively strong disambiguators in the experimental materials that may have aided their rapid integration. More strongly held initial biases or weaker disambiguators might produce different recovery patterns. Finally, while this low-risk behavioral study did not require formal IRB review, generalizability and transparency would be improved in future replications with clear ethics board oversight.

Conclusion

Detection and management of ill-posed garden-path structures via a sequence of shared vectors is sufficient to fully account for the phenomenon of human garden-path recovery in sentence parsing without requiring retrodictive lookahead, selective reanalysis, repair operators or residual activation recalibration. In self-paced reading and eye-tracking experiments, significant null effects were observed in all processing signatures commonly attributed to retrodictive mechanisms (regression probability, regression-path duration, go-past times and total reading times at the disambiguating and spillover regions). Moreover, probes aimed at the first thematic-role assignments found no signs of lingering misinterpretations, with near-ceiling accuracy rates on par with unambiguous controls. Reading times immediately and progressively converged on the point of disambiguation. The sole consistent effect was an initial processing cost at the ambiguous verb region that depended on how strongly each word in the corresponding sentence context biases towards its subcategorization and which disappeared completely with presentation of disambiguating material.

These findings suggest that structural convergence occurs rapidly through continuous forward constraint satisfaction within a single evolving representational state, rather than through retrospective revision of prior commitments. By eliminating the necessity of backward-looking operations, the proposed account enhances theoretical parsimony, removes non-monotonic processing steps, and improves computational tractability for incremental parsing models. Furthermore, it strengthens the alignment between sentence processing mechanisms and predictive-coding principles in broader cognitive science.

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