Syntactic Reanalysis Across the Adult Lifespan: Evidence From Eye Movements

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Abstract

This study examines the influence of age-related cognitive decline on the time course of syntactic reanalysis in Dutch NP/S-coordination garden-path sentences using eye tracking. 110 native Dutch speakers (30-80 years) read ambiguous sentences and comma-disambiguated controls. Garden-path costs were strongest at the ambiguous noun and smaller at the disambiguating verb, with no spillover effects. To further investigate age-related variability, we related garden-path effects to individual differences in cognitive abilities. Principal Components Analysis identified two components reflecting working memory and cognitive flexibility. Together with reading experience and associative learning, we tested these predictors of garden-path costs. Working memory, reading experience and associative learning moderated early garden-path effects, consistent with efficient encoding and rapid updating upon encountering ambiguity. Cognitive flexibility emerged as the most consistent predictor of late garden-path costs, suggesting a role in flexibly managing competing parses and supporting syntactic reanalysis.

Keywords: garden-path effects; syntactic reanalysis; cognitive decline; aging

Introduction

Language comprehension unfolds against a backdrop of a slow but steady decline in domain-general cognitive abilities that is characteristic of healthy aging. This raises a central theoretical question: how is real-time sentence processing affected by age-related changes in cognitive resources? Accounts that link sentence processing to cognitive control predict that age-related changes should be most visible under revision demands, when readers must override an initial parse, retrieve earlier material, and update the developing representation in response to disambiguating input (Novick et al., 2005; Hsu & Novick, 2016). These demands are especially evident in garden-path processing.

Garden-path sentences induce a temporary misinterpretation that must be revised once disambiguating information becomes available. Research using offline and online measures indicates that this reanalysis is often effortful, with processing difficulty typically emerging at or shortly after the point of disambiguation. Eye-tracking studies have reported longer reading times and more regressive eye movements in these regions, consistent with the processing demands associated with abandoning an initially preferred parse and constructing an alternative interpretation (Frazier & Rayner, 1982; Rayner, 1998).

One construction that has been widely used to study garden-path processing is NP/S-coordination ambiguity, as examined by Hoeks et al. (2006). In this structure, readers may initially interpret an upcoming noun phrase as part of a coordinated object, while an alternative analysis treats the same material as the subject of a new clause. For example, in the sentence *The man hugged his child and his wife petted the dog during a picnic*, the sequence *his child and his wife* can initially be parsed as a coordinated object of *hugged*. When the verb *petted* appears, this interpretation becomes incompatible with the sentence structure, requiring readers to reinterpret *his wife* as the subject of a second clause. Using a region-by-region eye-tracking approach, Hoeks et al. localized processing difficulty at the verb and spillover regions and found that regression-based measures were particularly sensitive to reanalysis demands.

However, the time course of garden-path effects remains debated. Hoeks et al. (2006) reported little evidence of disruption prior to disambiguation, whereas alternative accounts propose that readers may begin committing to a preferred analysis during the ambiguous region itself, such that competition between parses emerges before the disambiguating verb forces revision (Staub, 2007; Tabor & Hutchins, 2004). Under this view, garden-path effects reflect incremental competition during ambiguity rather than a repair process triggered only by syntactic failure.

In addition to variation across sentence types and structures, garden-path recovery also varies across readers. Studies comparing younger and older adults suggest that older adults are more likely than younger adults to maintain initial misinterpretations in garden-path sentences, even when later information contradicts the initial parse (Christianson et al., 2006; Malyutina & den Ouden, 2016). These findings point to age-related differences in revision outcomes, but they do not specify when during reading processing difficulty arises or which aspects of reanalysis are most affected.

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Online measures such as eye tracking are well suited to address these questions because they provide fine-grained temporal indices of commitment and revision, including regressions and rereading. Prior work suggests that garden-path effects may persist longer in older readers, potentially reflecting slower or less efficient recovery from misanalysis (Kemper et al., 2004; Payne et al., 2014). At the same time, chronological age is a coarse summary variable that aggregates multiple mechanisms relevant to language processing, and more specific measures of cognitive ability often provide a better account of individual differences in performance (Kwong et al., 1995).

The present study uses eye tracking to examine garden-path processing in Dutch NP/S-coordination sentences across a wide adult age range. We test when and where garden-path effects emerge during ambiguity resolution and how strongly they vary across readers. Using an individual-differences approach, we model these effects as a function of cognitive abilities. We derive working memory and cognitive flexibility indices from a cognitive battery using Principal Components Analysis and test these alongside reading experience and associative learning as continuous predictors of reanalysis costs.

Hypotheses

We predicted that garden-path effects would be region-specific, with processing difficulty localized to the ambiguity-resolution window, emerging at or around the disambiguating region and potentially extending into the spillover region. We further predicted systematic variation in the magnitude of these effects across readers. We expected individual differences in cognitive resources, particularly working memory and cognitive flexibility, to explain this variability, such that stronger cognitive abilities would be associated with smaller processing costs.

Methods

Participants

A total of 110 native Dutch speakers were tested across adulthood (between 20-25 participants per decade; ages 30–80). All had normal or corrected-to-normal vision and reported no history of neurological or language disorders. Written informed consent was obtained prior to testing, and participants received a small gift as compensation.

Design and Materials

The stimuli were drawn from the Dutch NP/S-coordination ambiguity materials of Hoeks et al. (2006). We selected 44 items (22 ambiguous; 22 matched controls). In each item, the noun phrase following *en* (e.g., *zijn vrouw* 'his wife' in the example below) was constructed to be plausible as a continuation of the object of the first verb. This supports an initial NP-coordination analysis in the ambiguous condition (e.g., *zijn kind en zijn vrouw* 'his child and his wife' as the coordinated object of *knuffelde* 'hugged'). In the control condition, a comma marks S-coordination and removes the temporary ambiguity.

To promote natural reading and situate the manipulation in discourse, each target sentence was preceded by a single-sentence context introducing a plausible scenario and relevant discourse referents. Contexts were designed to remain neutral with respect to the competing syntactic interpretations.

For region-based analyses, sentences were segmented into five ROIs: (1) Object noun, (2) Ambiguous noun (the post-conjunction noun), (3) Disambiguating verb, (4) Early post-disambiguation (the two words following the verb), and (5) Late post-disambiguation (the final three words). Function words such as conjunctions and possessive adjectives were not analyzed as separate ROIs, as the present segmentation was designed to target the lexical positions most directly associated with the emergence and resolution of syntactic ambiguity.

Hoeks et al.'s corpus analysis showed that, in the matched construction used here, any *en*-driven preference for NP-coordination is weak. Both NP- and S-coordination continuations are rare (≈1%), so frequency alone is unlikely to explain the garden-path effect.

Example
Context: Terwijl de familie in het park genoot van een zonnige dag, spreidden ze hun kleed uit. ("While the family enjoyed a sunny day in the park, they spread out their blanket.")

Target: De man knuffelde zijn kind (,) en zijn vrouw aaide de hond tijdens een picknick. ("The man hugged his child (,) and his wife petted the dog during a picnic.")

Procedure

Eye movements were recorded monocularly at 1000 Hz using an EyeLink 1000 Plus (SR Research Ltd., 2013). Participants sat ~60 cm from the monitor with head position stabilized by a chin rest and completed a 9-point calibration. Sentences were presented in full for natural reading.

The study consisted of two sessions. In Session 1, participants completed the eye-tracking experiment, which was divided into five blocks with short breaks. The session included 88 trials in total, of which 44 were NP/S-coordination items analyzed here (22 ambiguous, 22 control). These items were embedded within a larger experiment and interspersed with idiomatic and literal filler sentences. Each trial began with a fixation cross and a gaze-contingent trigger box at sentence onset. The context and target sentence appeared after fixation in the trigger box for 100 ms, and participants advanced through the trial via keypress. Items were Latin-square counterbalanced such that each participant saw only one version of each item, and each list contained equal numbers of ambiguous and control sentences.

In Session 2, participants completed a cognitive battery. Working memory was assessed using Reading Span and Digit Span tasks; executive control was assessed with Flanker, set-shifting, and Go/No-Go tasks. Reading experience was measured with the Dutch Author Recognition Test (Brysbaert et al., 2020), and associative learning was assessed with an adaptive paired-associate learning task implemented in Memory Lab (Van Rijn et al., 2009; Sense et al., 2016). Scores from each task were used as participant-level predictors in the analyses.

Eye-tracking Measures

Processing difficulty was assessed using standard region-based eye-movement measures (Rayner, 1998; Clifton et al., 2007). For each region, we computed first fixation duration (FFD; duration of the first fixation in the region), gaze duration (GD; sum of fixations from first entering the region until leaving it), total reading time (TRT; sum of all fixations in the region, including rereading), and regression path duration (RPD; time from first entering a region until the gaze moves to the right of it, including regressions). FFD and GD primarily index early processing at first encounter, whereas TRT and RPD are more sensitive to rereading and reanalysis.

Data Preparation

From the 110 recorded eye-tracking sessions, five were aborted due to poor calibration or tracking quality (e.g., due to glasses), leaving 105 participants for analysis. All trials from the full experiment were manually inspected in EyeLink Data Viewer. A total of 98 trials (1.06%) were excluded due to poor tracking quality, missing data, or technical issues (e.g., black screens). These exclusions were applied uniformly and were not specific to the garden-path items. Garden-path trials were then exported and segmented into regions of interest based on cumulative word position (e.g., object noun, ambiguous noun). First-fixation durations shorter than 80 ms or longer than 800 ms were treated as missing. Outliers in GD, TRT and RPD were trimmed within participants (±2.5 SD), and all duration measures were log-transformed prior to modeling.

Principal Components Analysis

To reduce multicollinearity among cognitive predictors, we conducted a Principal Components Analysis (PCA) on six participant-level scores (z-scored): reading span, digit span, Flanker interference, switching cost, mixing cost, and Go/No-Go accuracy. PCA was performed on one observation per participant. Sampling adequacy was modest but acceptable (KMO = .56), and Bartlett's test of sphericity indicated that the correlation matrix differed from an identity matrix, χ^2 (15) = 38.27, p = .001.

Two components were extracted and varimax-rotated. The rotated solution accounted for 48.84% of the total variance (Component 1: 27.32%; Component 2: 21.52%). Based on the loading pattern (Table 1), Component 1 was interpreted as Working Memory, with strongest loadings from reading span, digit span, and Go/No-Go accuracy (and an inverse relation with Flanker interference). Component 2 was interpreted as Cognitive Flexibility, with strongest loadings from task switching and mixing costs. Component scores were computed for each participant, rescaled to a 0–1 range, and used as continuous predictors in the mixed-effects models.

Table 1: PCA loadings for cognitive measures

Measure	C1	C2
Reading span score	0.647	
Digit span score	0.741	
Flanker interference	-0.489	
Task switching cost		-0.788
Task mixing cost		0.798
Go/No-Go accuracy	0.594	

Note. Values are varimax-rotated component loadings from z-scored task measures. Larger absolute values indicate stronger loadings; negative values indicate an inverse relation. Switching and mixing are cost measures (higher values reflect poorer performance).

Analyses

Analyses were conducted in R (R Core Team, 2025) using linear mixed-effects models fit with lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017). Model diagnostics were assessed with DHARMa (Hartig, 2022), and multicollinearity was evaluated using VIFs from performance (Lüdecke et al., 2021).

We first fit baseline models for each eye-movement measure with fixed effects of Condition, Region of Interest (ROI), and their interaction, and random intercepts for participants and items. Age effects were tested by adding age as a continuous moderator. Finally, individual-differences analyses were conducted in the critical window (ambiguous noun, disambiguating verb, post-disambiguation region) by comparing age-controlled baseline models to models including interactions with centered cognitive predictors (PCA-derived Working Memory and Cognitive Flexibility, reading experience, and associative learning), entered separately to limit multicollinearity. This allowed us to test whether cognitive predictors explained variance in garden-path costs over and above chronological age. The mixed-effects models included random intercepts for participants and items. More complex random-effects structures were tested but led to convergence failures and/or singular fits, so we retained random intercepts only (Bates et al., 2015).

Results

We first report differences between conditions across ROIs for each eye-movement measure. Figure 1 shows model-based predicted reading times across sentence regions in the Ambiguous and Control conditions. Because of space constraints, the figure focuses on Gaze Duration (GD) and Regression Path Duration (RPD), which capture early and late processing stages, respectively.

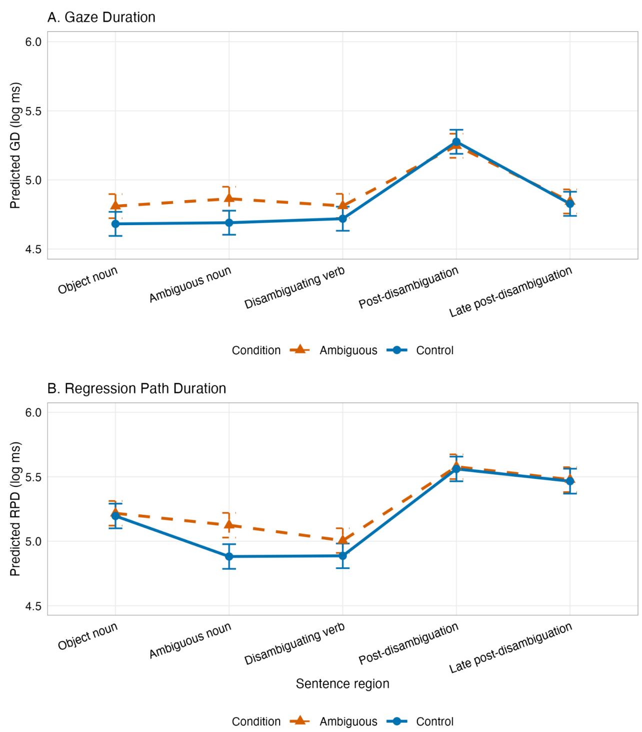

Figure 1. Baseline reading-time measures across sentence regions for Ambiguous and Control sentences (GD, top; RPD, bottom).

Object noun

FFD showed a small, marginal Ambiguous–Control difference ($\beta = -0.011$, $p = .051$). GD and TRT were slightly longer in the Ambiguous condition than in the Control condition (GD: $\beta = -0.063$, $p = .013$; TRT: $\beta = -0.071$, $p = .010$). RPD showed no garden-path effect at the object noun ($\beta = -0.010$, $p = .728$).

Ambiguous noun

At the ambiguous noun, garden-path effects were strong across measures. FFD was longer in the Ambiguous condition ($\beta = -0.011$, $p = .020$). GD and TRT showed clear costs in the Ambiguous condition (GD: $\beta = -0.084$, $p < .001$; TRT: $\beta = -0.098$, $p < .001$). RPD was also reliably longer in the Ambiguous condition than in the Control condition ($\beta = -0.119$, $p < .001$).

Disambiguating verb

Effects were present but smaller than at the ambiguous noun. FFD was reliably longer in the Ambiguous condition ($\beta = -0.015$, $p < .001$). GD and TRT also differed between conditions, but the effects were modest (GD: $\beta = -0.049$, $p = .044$; TRT: $\beta = -0.052$, $p = .049$). RPD showed an Ambiguous–Control difference ($\beta = -0.061$, $p = .019$), indicating a weak continuation of the garden-path cost at disambiguation.

Post-disambiguation region

In the immediate post-disambiguation region, there was no evidence of condition effects for any measure (FFD: $\beta = -0.00025$, $p = .952$; GD: $\beta = 0.015$, $p = .461$; TRT: $\beta = 0.016$, $p = .455$; RPD: $\beta = -0.0065$, $p = .786$). In the late post-disambiguation region, condition effects also remained non-significant (FFD: $\beta = -0.00271$, $p = .572$; GD: $\beta = -0.013$, $p = .635$; TRT: $\beta = -0.0081$, $p = .772$; RPD: $\beta = -0.012$, $p = .727$).

Age effects

Adding age terms did not improve model fit for FFD, GD, or RPD (all *p's* > .06), although it did improve fit for TRT ($\chi^2(10) = 21.65$, $p = .017$). Crucially, across measures, condition × age interactions were not significant, suggesting that the magnitude and timing of reanalysis costs did not vary systematically with age. Instead, age effects emerged as ROI × age interactions independent of condition, reflecting region-specific differences in overall reading time. These effects were most evident for FFD in the immediate post-disambiguation region and for TRT. As shown in Figure 2, age was also associated with systematic variation in cognitive abilities, motivating the individual-differences analyses reported next.

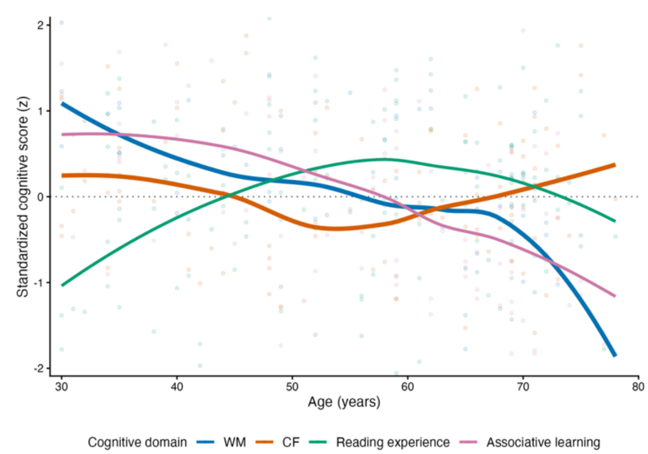

Figure 2. Cognitive abilities across age.

Individual differences analyses

We next tested whether garden-path effects in the critical window (ambiguous noun, disambiguating verb, post-disambiguation) were moderated by individual differences in cognitive abilities, while controlling for chronological age. Specifically, we tested Working Memory (WM), Cognitive Flexibility (CF), Reading Experience, and Associative Learning as predictors of condition × ROI effects. Across measures, chronological age did not modulate the magnitude of the garden-path effect, although some ROI × age effects emerged independently of condition. Overall, cognitive predictors explained variance in garden-path processing beyond chronological age. Figure 3 illustrates early effects in FFD, whereas Figure 4 shows a late TRT effect moderated by Cognitive Flexibility.

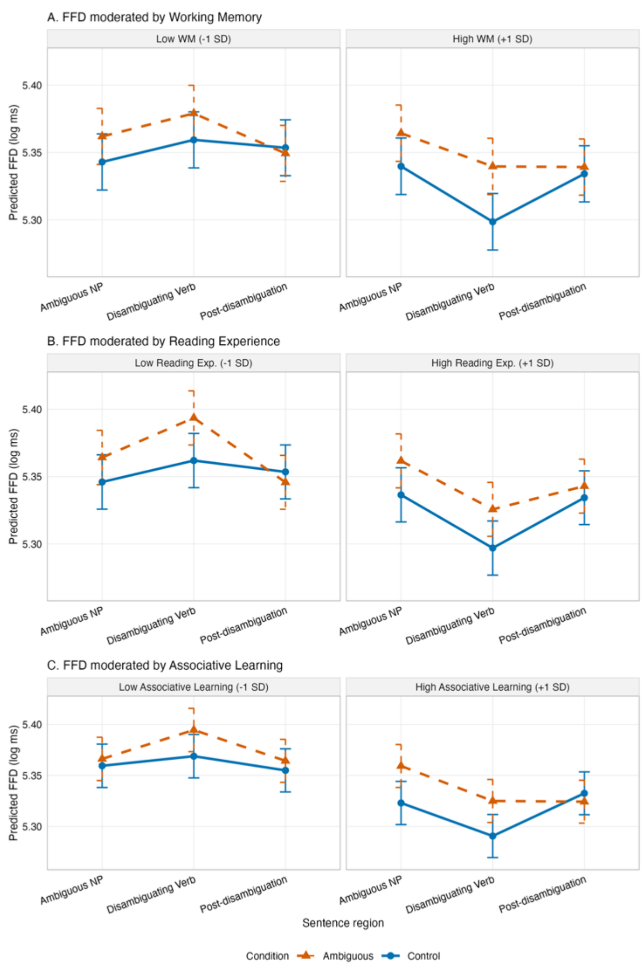

Figure 3. Predicted First Fixation Duration (FFD) across sentence regions as a function of condition (Ambiguous vs. Control) and cognitive ability.

Early measures

First Fixation Duration (FFD) was longer in the Ambiguous than Control condition ($\beta = 0.022$, $p = .019$; N = 12,197). Relative to the age-controlled baseline model, early processing was modulated by multiple cognitive predictors. Adding WM improved model fit ($\chi^2(6) = 13.76$, $p = .032$), with further improvements observed for Reading Experience ($\chi^2(6) = 25.80$, $p < .001$) and Associative Learning ($\chi^2(6) = 18.23$, $p = .006$). In contrast, CF did not improve model fit ($p = .858$). Gaze Duration (GD) was longer in the Ambiguous than Control condition ($\beta = 0.172$, $p < .001$; N = 13,668). Relative to the age-controlled baseline model, only CF improved model fit ($\chi^2(6) = 15.93$, $p = .014$), whereas WM, Reading Experience, and Associative Learning were not supported (p's $\geq .15$).

Late measures

Total Reading Time (TRT) was longer in the Ambiguous than Control condition ($\beta = 0.202$, $p < .001$; N = 13,663). Model fit improved when adding CF ($\chi^2(6) = 21.48$, $p = .002$), while WM, Reading Experience, and Associative Learning did not improve fit (p's $\geq .10$). Regression Path Duration (RPD) was greater in the Ambiguous than Control condition ($\beta = 0.241$, $p < .001$; N = 13,578). Adding CF improved model fit ($\chi^2(6) = 14.70$, $p = .023$). Adding WM, Reading Experience, and Associative Learning did not improve fit (p's $\geq .44$).

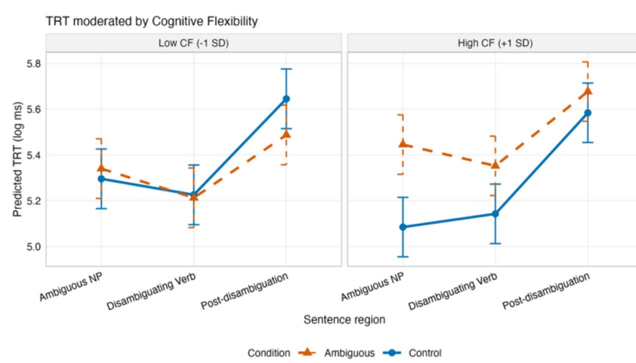

Figure 4. Predicted Total Reading Time (TRT) across sentence regions as a function of condition (Ambiguous vs. Control) and cognitive ability.

Discussion

The present study used eye tracking to investigate garden-path processing in Dutch NP/S-coordination sentences across a broad adult age range, with the goal of clarifying how cognitive aging affects real-time language processing. Building on Hoeks et al. (2006), we localized processing difficulty across sentence regions during ambiguity resolution and extended prior work in two critical ways: first, by adopting a lifespan design in which age was treated as a continuous predictor, and second, by shifting the explanatory focus from chronological age per se to individual differences in cognitive abilities. Specifically, multiple cognitive-task measures were integrated via Principal Components Analysis (PCA) to derive latent Working Memory (WM) and Cognitive Flexibility (CF) dimensions, which were then used to explain variability in ambiguity-related processing.

At the sentence level, garden-path effects were robust but region-specific. Processing costs emerged earliest at the ambiguous noun, where the coordination ambiguity becomes available, were smaller at the disambiguating verb, and did not persist into post-disambiguation regions. This pattern is consistent with relatively rapid resolution once disambiguating information is encountered, and provides little evidence for spillover effects. Any condition differences observed at the object noun should be interpreted cautiously: because this region precedes the ambiguity, such effects cannot reflect reanalysis and are more plausibly attributable to low-level differences associated with the comma manipulation distinguishing conditions.

The early emergence of costs at the ambiguous noun, rather than exclusively at disambiguation, aligns with accounts in which ambiguity immediately induces competition between alternative parses, and relative commitment to one analysis strengthens incrementally as input accumulates, rather than being triggered only by outright syntactic failure (Tabor & Hutchins, 2004; Staub, 2007). On this view, garden-path effects reflect online competition between alternative parses that begins as soon as ambiguity is encountered, rather than a discrete repair process initiated only after disambiguation.

Critically, although cognitive abilities declined with age in our sample, chronological age itself did not modulate the magnitude or timing of the garden-path effect. Instead, age-related effects primarily appeared as ROI × Age interactions independent of condition, reflecting region-specific changes in overall reading time rather than selective amplification or attenuation of ambiguity-related costs. This pattern is consistent with general age-related slowing and redistribution of processing effort across the sentence, rather than with age-specific impairments in syntactic reanalysis.

Shifting the explanatory focus to cognitive resources revealed a stage-dependent pattern of moderation. Early in processing, garden-path effects in First Fixation Duration were moderated by WM, reading experience and associative learning, with associative learning showing the largest improvement in model fit. This pattern suggests that, when encountering ambiguity, individual differences primarily affect efficient early encoding and rapid updating of an intermediate structural analysis (cf. Daneman & Carpenter, 1980; Payne et al., 2014).

CF emerged as the most consistent moderator, predicting garden-path costs in Gaze Duration and also in Total Reading Time and Regression Path Duration. This pattern suggests that successful ambiguity resolution and recovery from misanalysis depend on the ability to flexibly revise and update an evolving syntactic representation rather than on inhibitory control alone. In particular, readers with greater cognitive flexibility appear better able to shift between competing structural interpretations, down-weight an initially preferred parse, and reorganize sentence structure once disambiguating information is encountered.

This pattern is consistent with accounts that view garden-path processing as a dynamic process of competition and incremental updating, in which revision reflects the flexible reweighting of alternative parses rather than a discrete repair operation triggered by syntactic failure.

While the present study provides new insights into language processing across the lifespan, some limitations need to be considered. First, the NP/S-coordination items were embedded in a larger processing experiment that used discourse-embedded materials, and the broader experimental context may have influenced reading strategies. Second, while eye-tracking provides fine-grained temporal information about when processing disruption occurs, it cannot establish readers' final interpretations, leaving open whether early effects reflect completed revision, temporary competition that resolves later, or shallow processing that does not necessarily result in the target interpretation. Third, cognitive predictors were derived from composite measures, which may obscure more specific links between individual abilities and particular stages of reanalysis. A fourth limitation concerns comparisons with prior work on the timing of garden-path effects. Relative to Hoeks et al. (2006), effects in the present study appear to emerge earlier, but our materials were discourse-embedded and our sample differed substantially from their primarily undergraduate participants. Because context and sample composition covary across studies, we cannot attribute this difference to discourse support, population differences, or both.

Future work could address these issues by directly comparing isolated versus discourse-embedded NP/S-coordination materials, incorporating offline interpretation measures to assess final parse commitments, and using more targeted cognitive assessments to clarify which components of memory, cognitive control, and language experience support rapid recovery from misanalysis.

Taken together, the present study provides a lifespan investigation of garden-path processing, shifting the explanatory focus from chronological age to underlying cognitive resources. Despite a substantial age range, chronological age did not account for variability in the garden-path effect. Instead, cognitive abilities showed systematic moderation, with different predictors aligning with earlier versus later measures of processing. This pattern supports the view that apparent "age effects" in syntactic reanalysis are more informatively characterized in terms of underlying cognitive capacities—especially cognitive flexibility for later revision-related costs—rather than age as an overarching explanatory construct.

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