Modeling extralinguistic cognitive constraints on children's sentence processing

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Introduction. Children parse sentences predictively and incrementally, just like adults[1-4]. However, they perform differently from adults with temporarily-ambiguous sentences like (1).

(1) *Put the frog on the napkin in the box.* *(temporarily ambiguous)*

(2) *Put the frog that is on the napkin in the box.* *(unambiguous)*

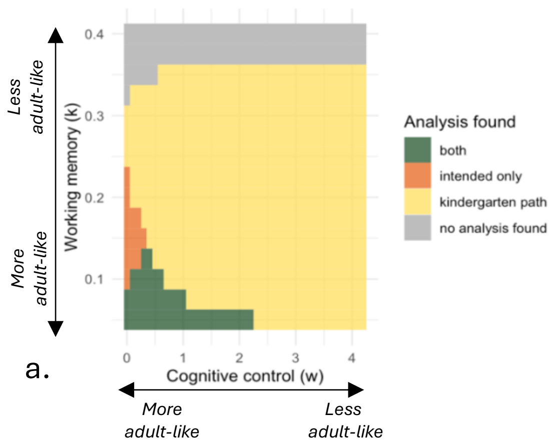
Adults parse (1) such that *in the box* is the destination for the frog, but 5-year-olds persist in their initial analysis of *the napkin* as the destination[5]. Children's parsing of (2) is adult-like, showing no difficulty with these linguistic structures when there is no temporary ambiguity. In cases of temporary ambiguity, as in (1), children seem unable to revise from an initial analysis even after the ambiguity is eliminated. This so-called "kindergarten path" effect has been reproduced across different tasks and ages[5-7]. Here, we develop and evaluate a computational model formalizing how the development of two extralinguistic cognitive systems recruited during sentence processing, **cognitive control** and **working memory**, may be responsible for this effect[8-13].

Method. We implement an incremental and predictive left-corner parser[14-15] with two parameters that model the effects of developing cognitive control and working memory on parsing. These parameters are adjusted individually to isolate the effect of each system as it matures. During parsing, multiple possible analyses of a sentence are maintained on a "beam", on which partial analyses are ranked by a score based on probabilities of linguistic structures in child-directed speech[16]. We model development of the **working memory** system by adjusting beam width, such that at "child-like" settings, only a few of the highest-scoring analyses are maintained, and at "adult-like" settings, additional analyses can be maintained. Developing **cognitive control** is modeled with lagging score-updating, such that at "child-like" settings, the scores of analyses that were previously high-scoring are kept artificially high, allowing them to persist and swamp memory allocated to other analyses. At "adult-like" settings, scores are updated instantly.

Results. In Simulation 1, the parser was evaluated on its ability to model the progression from child-like to adult-like performance with the English sentences in (1-2). At "adult-like" settings of the two parameters, we expect the parser to find the intended analyses for (1-2), while at "child-like" settings, we expect the parser to only find the analysis for (2). We tested the model by incrementally varying each parameter. Fig.1a depicts the model's success in finding (i) the intended analysis (orange regions); (ii) a partial, "kindergarten path" analysis corresponding to *Put the frog on the napkin* (yellow regions); or (iii) both (green regions). We found that limitations in either cognitive control, working memory, or both, could be responsible for children's performance with (1). "Child-like" settings of the parameters led to only the kindergarten path or no analysis found, while the intended analysis is found at "adult-like" settings. Fig. 2 illustrates how the intended analysis is lost over the timecourse of parsing with very limited cognitive control.

In Simulation 2, the parser was evaluated for an interpretation of (1) that has not been considered in previous experiments, in which the destination for the frog is the *[napkin-in-the-box]*. We find that each parameter makes different predictions about the developmental timecourse of when children find this *[napkin-in-the-box]* interpretation and the one previously tested (Fig.1b). Varying cognitive control while holding working memory constant (e.g., left to right along the x-axis), we predict a two-stage developmental trajectory, such that there is a point in development where children can only find the *[napkin-in-the-box]* interpretation (blue region in Fig. 1b), followed by a period where they will find both (green region) as cognitive control matures. Conversely, varying working memory and holding cognitive control constant (e.g., top to bottom on the y-axis) predicts a three-stage trajectory, such that early in development, only the *[napkin-in-the-box]* analysis can be found, followed by a period when only the intended interpretation can be found, and then finally both. This invites future experimental work testing these predictions.

Conclusion. We formally implement an incremental and predictive model of children's parsing. This model parameterized the role of two key extralinguistic systems, thereby (i) isolating the effects of cognitive control and working memory in the developing parser and (ii) generating testable predictions to investigate these systems experimentally.



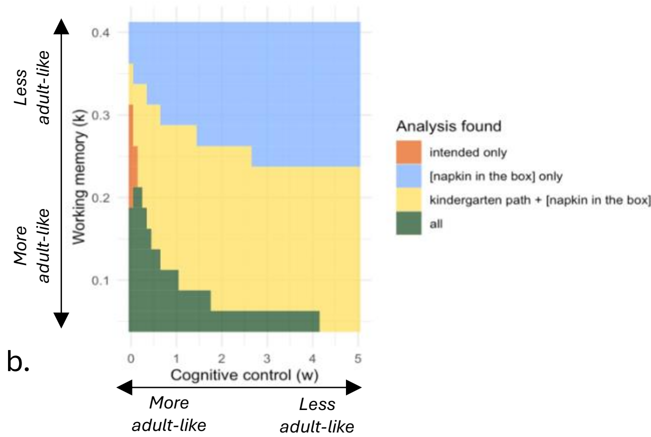


Fig. 1: Analyses found for the temporarily-ambiguous sentence (1) in Simulation 1 (a, left) and Simulation 2 (b, right) with varying values for the cognitive control parameter (w) and the working memory parameter (k). The bottom left corner represents greater maturity in both systems. The intended analysis for (2) is always found.

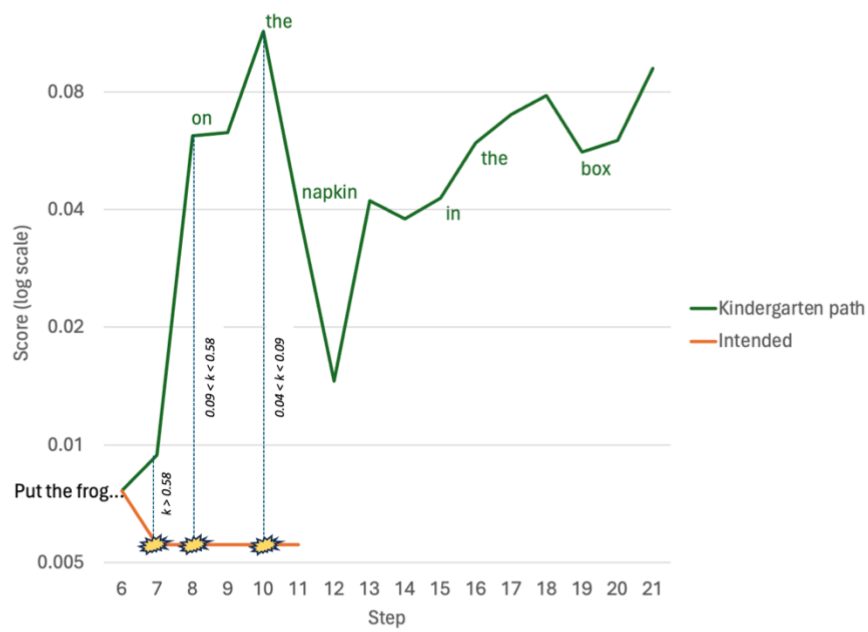


Fig. 2. Illustration of competition between the intended and kindergarten path analyses with immature cognitive control (w = 8). Yellow crash points indicate ranges of the working memory parameter (k) where the lower scoring analysis is lost. Even for adult-like working memory (i.e., a very low value of k), the intended analysis is lost before the word *napkin* is encountered, showing the independent effect of limited cognitive control.

References: **[1]** Frazier and Rayner, 1982 **[2]** Gordon and Chafetz 1990 **[3]** MacDonald et al. 1994 **[4]** Borovsky, Elman, and Fernald, 2012 **[5]** Trueswell et a et al., 1999 **[6]** Snedeker and Trueswell, 2004 **[7]** Omaki et al., 2014 **[8]** Lidz, White, and Baier, 2017 **[9]** Gibson et al., 2000 **[10]** Hsu et al., 2021 **[11]** Lewis, 1996 **[12]** Novick et al., 2005 **[13]** Woodard et al., 2016, **[14]** Demers, 1977 **[15]** Nederhof, 1993 **[16]** Pearl and Sprouse, 2013.