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# Execution of Lexical and Conceptual Processes in Sentence Comprehension among Adult Readers as a Function of Literacy Skill

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**ABSTRACT**

Little is known about conceptual integration processes and their contributions to memory representations that are constructed in sentence comprehension among adults with underdeveloped literacy skills. We measured word-by-word reading time to examine variation of responsiveness to demands of lexical and conceptual processing during sentence comprehension in a sample of adults with reading proficiency ranging from 4th grade through college-level. Relative to those of their more skilled counterparts, the reading times of adults with lower levels of literacy skill were more sensitive to word-level features, but showed a reduced lengthening at sentence-final words ("wrap up"), which has been argued to reflect conceptual integration processing. They also showed poorer sentence memory. However, regardless of literacy level, readers with better overall sentence memory engaged in a reading strategy marked by a larger sentence wrap-up effect. These findings suggest a pathway to intervention for struggling adult readers.

While there is growing recognition that many people arrive at adulthood with underdeveloped literacy skills, the cognitive and linguistic mechanisms underlying these deficiencies are not sufficiently understood to guide intervention (National Research Council, 2012). Significant effort has been devoted to characterizing literacy skill in terms of components presumed to underlie proficient reading based on standardized assessments (e.g., Landi, 2010; MacArthur, Konold, Glutting, & Alamprese, 2010; Mellard, Fall, & Mark, 2009; Mellard, Fall, & Woods, 2010; Sabatini, Sawayi, Shore, & Scarborough, 2010). However, reading is a complex mental activity requiring the coordination of an array of processes to create mental representations that show dynamic change in ongoing comprehension (Rapp & van den Broek, 2005), and less is known about how such dynamics might vary with literacy skill (cf. Ng, Payne, Steen, Stine-Morrow, & Federmeier, 2017; Ng, Payne, Stine-Morrow, & Federmeier, 2018; Steen-Baker et al., 2017).

Fluent reading relies on both incremental processing, in which meaning is activated and sculpted as the text unfolds, and segmental processing, in which meanings in context are resolved, concepts are integrated, and the message-level representation is consolidated (Rayner & Clifton, 2009; Stine-Morrow, Miller, & Hertzog, 2006; Stine-Morrow & Payne, 2016). Among adults with intact literacy skills, the extent of segmental processing has been related to verbal ability, and segmental processing is predictive of subsequent memory for text (e.g., Chin et al., 2015; Payne, Gao, Noh, Anderson, & Stine-Morrow, 2012; Stine-Morrow, Milinder, Pullara, & Herman, 2001; Stine-Morrow, Miller,

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Gagne, & Hertzog, 2008; Stine-Morrow, Noh, & Shake, 2010). The current study aimed to examine segmental processing among adult readers with even more extreme variation in verbal skill than typically studied, including adults with very low levels of literacy proficiency, and its implications for text memory.

### *Incremental processing and segmentation in language comprehension*

The key problem that models of language processing must solve is how readers (or listeners) create mental representations of meaning as the surface form unfolds in time within a limited-capacity working memory (Kintsch, 1988, 1998; Kintsch, Welsch, Schmalhofer, & Zimny, 1990; van den Broek, 2010; van den Broek & Helder, 2017). One general solution to this problem is to assume that there are relatively passive meaning-activation processes that are conducted on the fly, as well as slower meaning-resolution processes. The former are incremental, in the sense that grammatical information and semantic features are activated as the surface form unfolds (Lewis, Vasishth, & Van Dyke, 2006; McElree, Murphy, & Ochoa, 2006; Van Petten & Kutas, 1991). However, language comprehension is also segmental: information from the surface form and output from ongoing computations are temporarily buffered, usually at syntactic boundaries, where the semantic representation is consolidated (Aaronson, 1976; Aaronson & Scarborough, 1976; Haberlandt & Graesser, 1989a). Segmentation serves three functions. First, it affords the opportunity for the surface form, which can tax working memory resources and is less likely to be needed after a message-level representation has been constructed, to decay (Glanzer, Fischer, & Dorfman, 1984). Second, language is inherently ambiguous and segmentation enables the comprehender to resolve the meanings of individual words in the context of syntactically coherent units (Daneman & Carpenter, 1983). Third, it gives the reader an opportunity to integrate concepts to consolidate the representation of meaning (Aaronson & Scarborough, 1976; Haberlandt, Graesser, Schneider, & Kiely, 1986).

Incremental processes tend to be fast and automatic, such that each incoming unit is rapidly attached and integrated to the grammatical structure and semantic representation. Semantic integration processes that underlie segmentation tend to be, to some extent, under strategic control (Just & Carpenter, 1992; Stine-Morrow et al., 2010; van den Broek & Helder, 2017), as suggested by the impact of instructions and reading goals (Aaronson, 1976; Stine-Morrow et al., 2001).

Incremental and segmental processes are complementary, contributing to the efficiency in language comprehension given the limited processing capacity of a reader. No reader can represent all aspects of a text; thus it is up to the reader to allocate attention to a selective subset of computations to meet the goals at hand (Stine-Morrow et al., 2006; Stine-Morrow, Shake, Miles, & Noh, 2006). Texts vary along multiple dimensions, including lexical features such as vocabulary familiarity, and sentence-level features such as informational density, and readers routinely adjust their reading patterns so as to accommodate the demands of the text (Stine-Morrow et al., 2008): they linger longer when the words are unfamiliar, or when the ideas are complex for message assembly. The modulation of reading times in response to these features can serve as a measure of attentional, or resource, allocation to related processing demands (Stine-Morrow & Miller, 2009; Stine-Morrow et al., 2008, 2010).

The well-replicated effects of word length and frequency on reading time (Barton, Hanif, Eklinder Bjornstrom, & Hills, 2014; Schilling, Rayner, & Chumbley, 1998; Taylor & Perfetti, 2016) largely reflect incremental processes specific to decoding and lexical retrieval, respectively. However, word frequency effects can also be due to integration, inasmuch as it can be more difficult to integrate infrequent words into the context (Rayner & Duffy, 1986; White, Warrington, McGowan, & Paterson, 2015). Increases in reading time for the introduction of new noun concepts relative to already established concepts (Stine-Morrow et al., 2001) reflect the incremental processes of instantiation of concepts in context and their ongoing integration as the text unfolds. On the other hand, organization and integration of meanings and ideas also engage segmental processes. In fact, reading times are typically longer for words at clause and sentence boundaries relative to non-boundary words, especially as the semantic processing load of the prior segment is increased (Haberlandt & Graesser, 1989b; Haberlandt et al., 1986; Sharkey & Sharkey, 1987), a phenomenon termed "wrap-up" (Just & Carpenter, 1980, 1987). During wrap-up, ideas in the text are connected and a mental representation of the situation is constructed (Just & Carpenter, 1980; Kuperman, Dambacher, Nuthmann, & Kliegl, 2010; Payne et al., 2012; Rayner, Kambe, & Duffy, 2000; Schad, Nuthmann, & Engbert, 2012; Tiffin-Richards & Schroeder, 2018).

## *Individual differences in comprehension, memory, and language computations*

Individuals vary in processing capacity, knowledge, and reading skill, all of which contribute to the execution of incremental and segmental processes (Chin et al., 2015; Schroeder, 2011; Stine-Morrow, Gagne, Morrow, & DeWall, 2004; Stine-Morrow et al., 2008). Readers with lower verbal ability tend to be more sensitive to word-level features (Kuperman & Van Dyke, 2011; Stine-Morrow et al., 2008; Taylor & Perfetti, 2016), often showing concomitant decreases in conceptual integration processes (Yang, Perfetti, & Schmalhofer, 2007). According to the Lexical Quality Hypothesis (Perfetti, 2007; Van Dyke & Shankweiler, 2013), when the readers's lexical representations are of poor quality, cognitive resources are diverted to the incremental demands of decoding and lexical access, at a cost to higher level semantic processes. Thus, wrap-up as an indicator of semantic integration may decrease, in part, because of variation in the automaticity of accessing lexical representations (cf. Gao, Levinthal, & Stine-Morrow, 2012; Gao, Stine-Morrow, Noh, & Eskew, 2011). However, that is not the only source of variation.

Comparisons of younger and older readers have illuminated how individuals can adjust attentional allocation to language computations to accommodate individual differences in processing capacity and task demands, and how attentional allocation to different component processes contributes to good text memory. As people age, sensory functions, working memory (WM), and processing speed decline, while vocabulary skills are likely to remain strong (Hartshorne & Germine, 2015), at least among those who engage in sustained literacy practices (Stanovich, West, & Harrison, 1995). Older adults read more slowly, but like their younger counterparts, they are sensitive to word-level and text-level features (Smiler, Gagne, & Stine-Morrow, 2003; Stine-Morrow et al., 2008). However, the reading times of older adults with relatively better text memory have been found to be differentially sensitive to text variables reflecting conceptual processing, including wrap-up (e.g., Stine-Morrow et al., 2008). In fact, individual differences in time allocated to wrap-up show good reliability, and are generally predictive of subsequent memory for sentence content (Miller & Stine-Morrow, 1998; Stine-Morrow et al., 2001, 2008).

Regardless of age, less skilled readers generally show poorer text memory, relative to their proficient counterparts, and show reduced appreciation for the relative importance of information, with less differentiation in recalling major points versus details (Smiley, Oakley, Worthen, Campione, & Brown, 1977; Stine & Wingfield, 1988). This phenomenon has also been demonstrated among older, relative to younger, adults using a relative memorability analysis in which age groups are directly compared on text unit recall. Such an approach has been used to show that older adults show a selective decrease in recall of more memororable (presumably the more important, or otherwise salient in the memory system) text units, as informational density increases (Stine & Wingfield, 1988). Manipulations that suppress conceptual integration, measured as wrap-up, have been shown to selectively impair memory for more memorable ideas, especially among older adults (Gao et al., 2012, 2011). Collectively, these findings suggest that readers' variation in processing capacity, knowledge, and reading experience is manifested in particular patterns of attentional allocations to the demands of incremental and segmental processing.

## *The current study*

While there are considerable data on adult readers' comprehension processes as a function of skill, this has been examined largely among college students, who have been selected into that population by virtue of their well-developed literacy skills. Less proficient readers, who are less likely to cross the threshold of college but who would benefit the most from reading research, are ironically often excluded from research participation. As a result, little is known about how they engage processes in reading and how their reading patterns might affect comprehension (National Research Council, 2012). Thus, a deeper understanding of the cognitive underpinnings of reading difficulty in adulthood has tremendous implications for education and social development.

Earlier work using event-related brain potentials (ERPs), which are highly sensitive to incremental processing, has suggested that adults with underdeveloped literacy skills show intact semantic priming in visual and auditory modalities (Ng, Payne, Stine-Morrow, & Federmeier, in preparation), but make less use of predictive mechanisms in reading (Ng et al., 2017, 2018), suggesting that they may not be able to immediately integrate sentence meaning as language unfolds. While ERPs tend to be insensitive to the demands of segmental processing, at least to the extent tested (Stowe et al., 2018), reading times are (e.g., Aronson and Scarborough, 1976; Haberlandt et al., 1986; Stine-Morrow et al., 2001, 2008, 2010). Thus, the current study examined resource allocation to incremental and segmental processes in reading as a function of literacy proficiency. Our interest was not only in the differences in reading engagement among adults with varying levels of reading ability, but also whether there are engagement pathways through which less proficient readers could attain good memory performance. We predicted that the reading times of less proficient readers would be more sensitive to word-level features, reflecting the need to allocate more attention to lexical processing, given their more fragile word decoding skills. The *key questions*, however, were (1) whether these readers would also show reduced sentence wrap-up, reflecting the neglect of conceptual integration, and (2) whether variation in wrap-up within this group was predictive of text memory.

## Method

### Participants

Participants ($N$ = 80; 43 identified as women; 37, as men) were recruited from the local community through bus ads and word-of-month and received monetary compensation for participation. They were 18–64 years of age, and had received 7.5–16 years of formal education. An additional 4 participants were tested but their data were eliminated due to excessive missing data (> 50% of sentence recall), incomprehensible recall, a missing sound file, and an excessive number of reading times excluded as outliers in the sentence-final positions (i.e., > 40%) so that wrap-up effects could not be reliably estimated. A battery of neuropsychological tests was administered before the experimental session (Table 1).

Reading level was estimated as the mean of the grade-equivalent scores of the Slosson Oral Reading Task (SORT) (Slosson & Nicholson, 1990) and the Woodcock Johnson (WJ) Reading Fluency task (Schrank, Mather, & McGrew, 2014). The SORT, a measure of vocabulary recognition, requires participants to read aloud a list of words of increasing difficulty. This test consists of lists of 20 words each, with each list corresponding to a grade level (test-retest reliability = .99; criterion-related validity with the WJ Word Identification subtest = . 90; Davis, Michielutte, Askov, Williams, & Weiss, 1998). The WJ Reading Fluency task required participants to verify within three minutes the truthfulness of as many simple sentences as possible from a list of 98 items (test-retest reliability = . 93). Our sample was diverse in reading skill ($M$ = 9.4 grade level; range = 4.1–12.3) and distributed across the range (n = 11, <6$^{th}$g; n = 29, 7$^{th}$–<9$^{th}$g; n = 16, 9$^{th}$–<12$^{th}$g; n = 19, ≥12$^{th}$g).

The sample was also characterized in terms of vocabulary and fluid ability (Wechsler Abbreviated Scale of Intelligence (WASI); Wechsler, 1981). WM was assessed with the listening (Daneman & Carpenter, 1980; Stine & Hindman, 1994) and counting (Case, Kurland, & Goldberg, 1982) span tasks. In the listening span task, participants were required to determine the truthfulness of auditorily presented sentences while also remembering the last word of each sentence. In the

**Table 1.** Participant characteristics.

| | | Correlations (*r*) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (range) | *SD* | Ed | RL | SORT | WJ RF | Voc | Fluid | WM | RT | Acc |
| Age | 41.7 (18–64) | 12.8 | 0.23 | 0.06 | 0.15 | −0.03 | 0.14 | −0.21 | −0.05 | 0.11 | 0.07 |
| Education level (yrs) | 12.1 (7.5–16.0) | 1.6 | – | **0.31** | **0.27** | **0.28** | **0.41** | 0.11 | **0.34** | −0.08 | 0.14 |
| Reading Level (gl) | 9.4 (4.1–15.3) | 3.0 | | – | **0.86** | **0.92** | **0.64** | **0.50** | **0.57** | **−0.47** | **0.52** |
| SORT (gl) | 9.6 (3.8–12.5) | 2.9 | | | – | **0.60** | **0.60** | **0.45** | **0.51** | **−0.42** | **0.59** |
| WJ Reading Fluency (gl) | 9.3 (3.2–18) | 3.8 | | | | – | **0.55** | **0.44** | **0.52** | **−0.43** | **0.37** |
| WASI Vocabulary | 27.8 (14.0–43.0) | 6.5 | | | | | – | **0.57** | **0.59** | **−0.36** | **0.61** |
| WASI Fluid Ability | 21.4 (5.5–42.5) | 8.8 | | | | | | – | **0.53** | **−0.39** | **0.53** |
| Working Memory | 4.4 (1.6–7.0) | 1.0 | | | | | | | – | **−0.32** | **0.42** |
| Reading time (ms/word) | 966 (253–2592) | 478 | | | | | | | | – | −0.07 |
| Recall Accuracy (%) | 54.5 (7.5–90.6) | 18.5 | | | | | | | | | – |

*SORT = Slosson Oral Reading Test; WJ = Woodcock-Johnson; WASI = Wechsler Abbreviated Scale of Intelligence. gl = grade-level equivalent score. Working Memory = mean of listening span and counting span. Numbers in **bold** indicate statistically significant correlations, $p < 0.05$.*

counting span task, participants counted and remembered the number of dots in a series of dot arrays. For both span tasks, participants were prompted to recall the words or numbers in their exact order after a set of stimuli. The number of items increased across trials, and the span score was the highest level at which recall was perfect plus the fraction of items correct on the next level.

Several points deserve notice in Table 1. First, although our participants encompassed adults of a wide age range, age was not correlated with education or reading level. Second, there was a moderate correlation between education and reading level, but the latter was a more powerful predictor of reading time and recall accuracy. Unsurprisingly, there were moderately strong correlations of reading level with vocabulary, fluid ability, and WM.

### Stimulus materials

Stimuli were 25 two-sentence expository passages adapted from Stine-Morrow et al. (2001) so as to be appropriate for the range of skill in our sample. Texts covered diverse topics in science, nature, and culture with generally unfamiliar content (e.g., *Romans once thought baldness could be cured with pig's fat and seahorse ashes. Today seahorses are still used for science.*). The first sentence was the target sentence for which reading time and recall were measured. The second sentence was a filler to assure that reading time on the last word of the target sentence would not be contaminated by preparation for recall; therefore, any increment in processing time would reflect wrap-up in the ordinary course of reading in preparation to move forward in the text. Table 2 shows the characteristics of the stimuli and

**Table 2.** Characteristics of words, sentences, and word-level reading times.

| | Descriptive Statistics | | | | Correlations | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | SD | WF | Cum NNC | NNC | SntB | RT[a] |
| *Word-level Properties* | | | | | | | | | |
| Word Length (WL) | 1 | 10 | 4.0 | 1.7 | **−0.72** | 0.09 | **0.47** | **0.23** | **0.60** |
| Log Word Frequency (WF) | 4.0 | 17.0 | 12.2 | 3.1 | | **−0.12** | **−0.65** | **−0.25** | **−0.70** |
| Cumulative NNC (CumNNC) | 0 | 7 | 2.6 | 1.3 | | | **0.29** | **0.44** | **0.20** |
| New Noun Concept (NNC) | 0 | 1 | .31 | .46 | | | | **0.33** | **0.63** |
| Sentence Boundary (SntB) | 0 | 1 | .07 | .27 | | | | | **0.57** |
| *Sentence-level Properties* | | | | | | | | | |
| | 13 | 16 | 14.1 | 1.0 | | | | | |
| Number of Propositions (#P) | 4 | 9 | 7.0 | 1.3 | | | | | |
| Reading Grade Level (RGL) | 2.8 | 4.9 | 4.4 | 0.5 | | | | | |
| *Reading Time (log ms/word; RT)* | 2.0 | 3.2 | 2.8 | 0.1 | | | | | |

*Numbers in **bold** indicate a statistically significant correlation, $p < 0.05$.*
[a]*Median log-transformed reading time per word*

their correlations. Importantly, target sentences were within the skill level of participants, with a mean Flesch-Kincaid reading grade level of 4.4 (range: 2.8–4.9), as calculated in Microsoft Word.

CPIDR (Computerized Propositional Idea Density Rater) was used to identify the propositional content in each target sentence for scoring (Brown, Snodgrass, Kemper, Herman, & Covington, 2008). A proposition is an idea, defined as a set of related concepts (Kintsch & van Dijk, 1978). Because CPIDR identifies propositions based on part-of-speech tagging, we corrected the output for certain minor, but systematic, errors introduced by this algorithm: an attributive adjective or noun that modifies another noun (e.g., *turmeric rice*), treated by CPIDR as a compound word, was counted as a modifier proposition; phrasal verbs (e.g., *knock down*), were counted as one, rather than two, propositions; and comparative adjectival phrases (e.g., *as much as*) were considered as two, rather than three, propositions. This changed fewer than 3% of the propositions. Recall scoring was coded manually based on these propositions.

## Procedure

Participants were tested individually in a quiet room. They were instructed to read the passages one word at a time with a self-paced moving-window presentation, controlled by a button press on a response pad. A "READY?" prompt, displayed at the center of the monitor, preceded each passage, and was replaced by the first word of a passage with the button press. The passage was left-aligned in an invisible rectangular frame centered on the monitor. Each subsequent word replaced the previous word to its left by a button press. A passage was arranged in a paragraph format. Words appeared in Arial 50-point black font on a white background.

A question mark followed each passage to signal the participant to orally recall the sentence. Participants were instructed to recall as much information as they could remember from the passage they had just read, both main ideas and details. They were explicitly told that it was not necessary to recall the text word for word. There was no time limit on reading or recall. Recall was digitally recorded for later analysis. A short practice with 5 passages preceded the study. The experimental passages were randomized for each participant. The whole reading task took approximately 25 minutes. The neuropsychological battery was administered on a separate day and took about one hour.

## Data processing and analysis

Each word in the target sentence, excluding the sentence-initial word, was coded for its text characteristics (Table 2). We selected text features as predictors in our linear modeling so as to represent incremental and segmental processes while also avoiding problems of multicollinearity created by highly correlated variables (see Wurm & Fisicaro, 2014, for discussions). At the lexical level, we were interested in decoding difficulty and lexical access, as represented by word length (in characters, WL) and word frequency (WF), respectively (Balota et al., 2007). Word frequency was based on the HAL written corpus of US English (Lund & Burgess, 1996).[1] In English, lower frequency words tend to be longer words, and in our dataset WL and WF were strongly correlated ($r = 0.72$), and when both were included the models did not converge, so we only included WF as a predictor variable in statistical modeling. Overall results did not change if WL, rather than WF, was in the models.

At the text-level, we were interested in conceptual integration as an end-of-sentence wrap-up process, operationalized as a dummy code for whether or not the word was in a sentence-final position (SntB). We also considered examining ongoing conceptual processing in two ways: (a) as conceptual instantiation when a new concept was introduced, represented by a dummy code for whether a word introduced a new noun concept in the sentence (NNC), and (b) as an ongoing conceptual integration process as new concepts were introduced, operationalized as the cumulative new noun concepts at each word in a sentence (CumNNC). Because NNC was a stronger predictor of reading time and showed a slightly smaller correlation with SntB relative to CumNNC (cf. Table

2), this was the variable we selected to estimate ongoing conceptual processing.[2] Thus, in the final models, the predictors were WF, a continuous variable, and NNC and SntB, which were both categorical variables. Using the R function *vif.lme*, variance inflation factors for the fixed effects were all less than 3, suggesting that interpretation of our effects is not compromised by multicollinearity.

The dependent variable was word reading time, measured as the interval between button presses in self-paced reading. Reading times longer than 10 sec or shorter than 100 ms were excluded from analysis, which accounted for 0.92% of the reading-time data. Reading times were log-transformed to normalize their distributions and reduce the effect of extreme data points. Mixed-effects linear regression modeling was employed for data analysis using the lme4 package for R version 3.4.0 (R Core Team, 2017). A null model was fit to the data that included random intercepts for subjects and items. We found that the variance due to subject intercepts was larger than the variance due to item intercepts. When we fit a model with a random intercept for sentences, the variance due to sentences was zero. Thus, every word in each sentence was considered as an independent item. Models with both by-subject and by-item random slopes for each of the predictors did not converge. The final models therefore included random intercepts for both subjects and items plus only random slopes for subjects, using the restricted maximum likelihood (REML) method of estimation.

The *p*-values for each predictor variable were obtained using the ImerTest package for R (Kuznetsova, Brockhoff, & Christensen, 2017), which uses Satterthwaite approximation of degrees of freedom. Our modeling of the data focused on relating reading patterns, operationalized as reading times per word, and recall accuracy to text characteristics and participants' literacy levels. We included line break as a covariate in all models to control for its effect on reading times.

Recordings of recall were transcribed and manually scored by three trained research assistants for the propositions accurately recalled using a gist criterion (Turner & Greene, 1978). Interrater reliability across pairs of raters ranged from .84 to .87. Sentence recall was considered missing if the participant did not utter a word after the sentence, which accounted for 15% of trials. If the participant produced any words that did not include scorable ideas, it was assigned a zero value.

## Results

### *Recall accuracy*

Recall accuracy was calculated as the proportion of correct propositions recalled relative to the total number of propositions a participant attempted to recall (i.e., recall from missing protocols was excluded). The average recall accuracy was 54.5% (*SD* = 18.5).[3] Recall accuracy was unrelated to overall reading rate (cf. Table 1).

### *Resource allocation in reading*

Recall that our key research questions were (1) whether resource allocation would differ as a function of literacy skill, particularly with respect to conceptual integration as measured by wrap-up, and (2) to the extent that wrap-up was engaged by less-proficient readers, whether it would be predictive of recall. We report the results of models to address these questions in Table 3. Model 1 characterizes the general allocation policy to reading in terms of the effects of text variables on reading time, as well as the independent effects of individual differences on overall reading speed. Models 2a and 2b specifically address the first research question by probing whether the allocation policy in reading varied with literacy skill. Model 3 addresses the second research question by examining whether high recall accuracy was engendered by a distinctive allocation policy. For each one, variances in the random intercepts by items and by subject are presented in the top rows. Parameter estimates are presented at the bottom.[4]

**Table 3.** Linear mixed-effects models predicting reading time from text features, literacy level, and recall accuracy.

| | Model 1 | | | | Model 2a | | | | Model 2b | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\sigma^2$ | β | SE | p | $\sigma^2$ | β | SE | p | $\sigma^2$ | β | SE | p | $\sigma^2$ | β | SE | p |
| Random intercept by Items | 0.001 | – | – | – | 0.001 | – | – | – | 0.001 | – | – | – | 0.001 | – | – | – |
| Random intercept by subjects | 0.052 | – | – | – | 0.051 | – | – | – | 0.049 | – | – | – | 0.052 | – | – | – |
| Residual | 0.040 | – | – | – | 0.040 | – | – | – | 0.040 | – | – | – | 0.040 | – | – | – |
| Intercept for fixed effects | – | 3.289 | 0.060 | **< .001** | – | 3.433 | 0.091 | **< .001** | – | 3.546 | 0.119 | **< .001** | – | 3.199 | 0.088 | **< .001** |
| Line Break | – | 0.031 | 0.007 | **< .001** | – | 0.031 | 0.007 | **< .001** | – | 0.031 | 0.007 | **< .001** | – | 0.031 | 0.007 | **< .001** |
| Log Word Frequency (WF) | 0.000 | −0.011 | 0.001 | **< .001** | 0.000 | −0.022 | 0.004 | **< .001** | 0.000 | −0.026 | 0.005 | **< .001** | 0.000 | −0.010 | 0.003 | **0.004** |
| New Noun Concept (NNC) | 0.002 | 0.045 | 0.009 | **< .001** | 0.002 | 0.047 | 0.022 | **0.032** | 0.003 | 0.019 | 0.032 | 0.547 | 0.002 | 0.026 | 0.020 | 0.194 |
| Sentence Boundary (SntB) | 0.028 | 0.142 | 0.021 | **< .001** | 0.027 | 0.032 | 0.064 | 0.624 | 0.024 | −0.071 | 0.083 | 0.396 | 0.025 | −0.007 | 0.058 | 0.904 |
| Literacy Level (Lit) | – | −0.027 | 0.006 | **< .001** | – | −0.043 | 0.009 | < **.001** | – | −0.061 | 0.015 | **< .001** | – | −0.027 | 0.006 | **< .001** |
| Subj Recall Accuracy (%) (SubjAcc) | – | 0.000 | 0.001 | 0.619 | – | 0.000 | 0.001 | 0.620 | – | 0.000 | 0.001 | 0.976 | – | 0.001 | 0.002 | 0.442 |
| WF x Lit | – | – | – | – | – | 0.001 | 0.000 | **0.003** | – | 0.002 | 0.001 | **0.004** | – | – | – | – |
| NNC x Lit | – | – | – | – | – | 0.000 | 0.002 | 0.902 | – | 0.004 | 0.004 | 0.333 | – | – | – | – |
| SntB x Lit | – | – | – | – | – | 0.012 | 0.006 | 0.073 | – | 0.025 | 0.010 | **0.012** | – | – | – | – |
| WF x SubjAcc | – | – | – | – | – | – | – | – | – | – | – | – | – | 0.000 | 0.000 | 0.720 |
| NNC x SubjAcc | – | – | – | – | – | – | – | – | – | – | – | – | – | 0.000 | 0.000 | 0.317 |
| SntB x SubjAcc | – | – | – | – | – | – | – | – | – | – | – | – | – | 0.003 | 0.001 | **0.008** |

The $\sigma^2$ values by the text features are the variances from the by-subject random slopes.
*Each p-value less than 0.05 is in bold.*

### Model 1: allocation policy, and effects of literacy skill and recall accuracy on overall speed

This model established whether the reading times of our community sample, who showed considerable variation in age and reading abilities, could be modeled in terms of attention allocation to word and text-integration processes. We also examined whether overall reading time varied with reading level and subsequent sentence recall performance.[5] Similar to the samples of college students tested in much of the previous literature, community-based adult readers took longer to read lower frequency words, words introducing new noun concepts, and sentence-final words. Thus, these results replicated previous findings and confirmed the suitability of our paradigm for a heterogeneous community sample. In addition, higher literacy skill engendered a faster reading rate, but those with better recall accuracy did not read reliably faster or slower relative to those with poor recall.[6]

### Model 2a: effects of literacy skill on resource allocation

This model examined how adults with different levels of literacy attainment allocated attention to different processes. Figure 1 shows the estimates of log reading time as a function of each of the three text features and literacy levels. Readers with lower levels of literacy skill took differentially longer to read low-frequency words, relative to readers with well-developed literacy skill. The effects of new noun concepts on the reading times were insensitive to reading abilities.

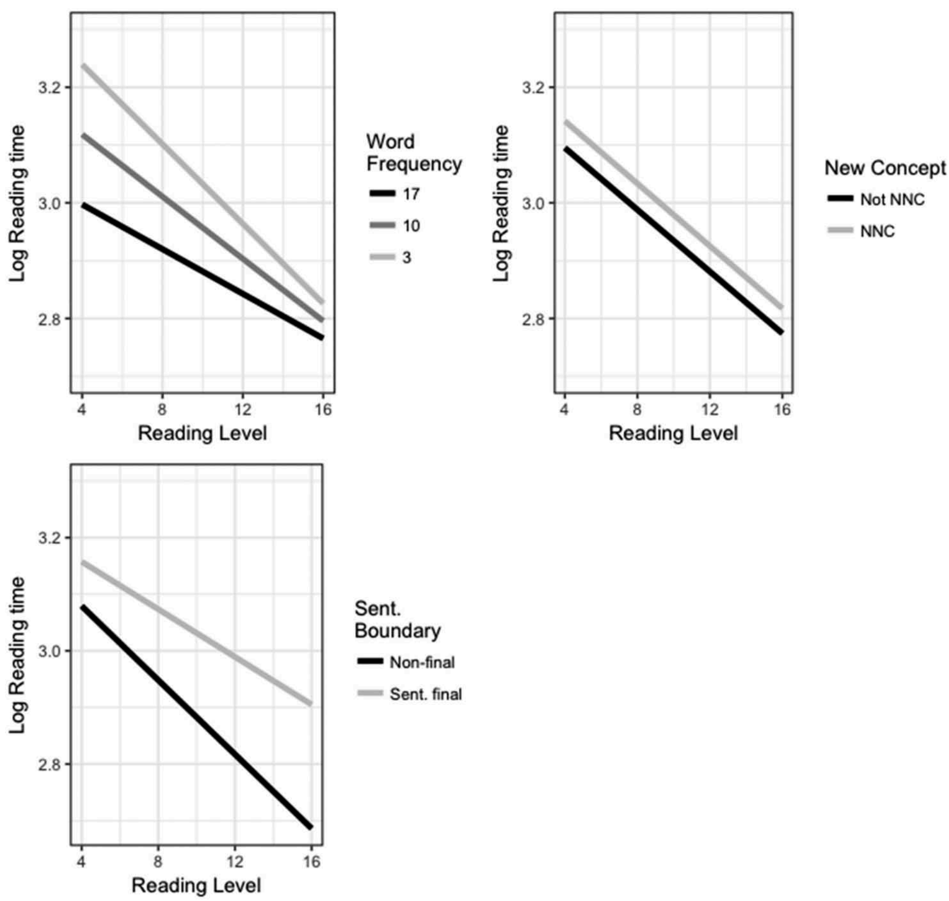


**Figure 1.** Mean fitted values from Model 2 for the reading times as a function of the text features (Word frequency, new noun concept and sentence boundary) and reading level.

As shown in Figure 1, the regression lines are virtually parallel. Finally, there was a numerical trend for greater sentence wrap-up with increasing literacy skill, as indexed by the marginal SntB x Reading Level interaction.

### *Model 2b: effects of literacy skill on resource allocation (reading grade level ≤12)*

Given the well-replicated correlation between verbal skill and sentence wrap-up among relatively proficient readers (Payne et al., 2012; Stine-Morrow et al., 2008), the marginal SntB x Reading Level interaction was a surprise. To explore this effect further, we examined the plot of SntB BLUPs (Best Linear Unbiased Predictions) of each participant as a function of reading level (see Online Supplement). This plot suggested a nonlinear effect such that the most proficient readers showed relatively reduced levels of sentence wrap-up. Reasoning that our materials (written at about a 4$^{th}$-grade reading level) may have simply not been challenging enough for participants with college reading skills, we wondered if the effect might emerge if we excluded those readers. In fact, among proficient readers, wrap-up has been shown to decrease when demands of integration are reduced (e.g., Miller & Stine-Morrow, 1998). In Model 2b, we refit the model with data only from participants who read at or below the 12th grade level. In this case, the SntB x Reading Level interaction was robust.

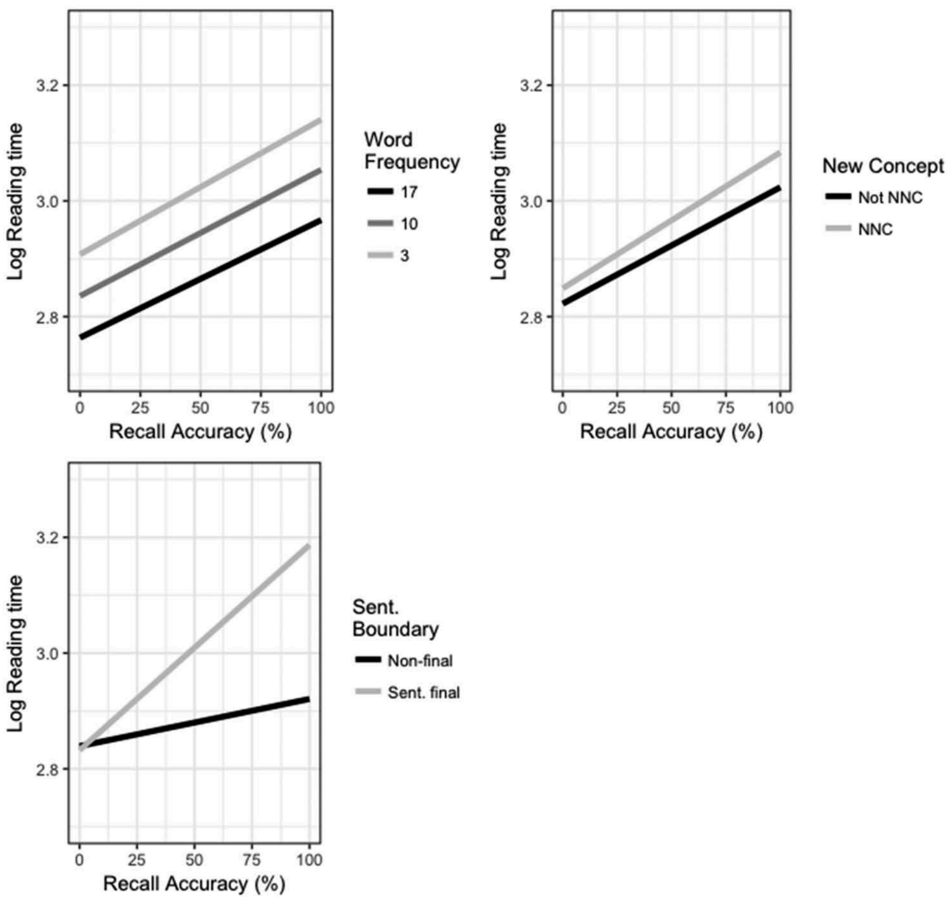


**Figure 2.** Mean fitted values from Model 3 for the reading times as a function of the text features (Word frequency, new noun concept and sentence boundary) and recall accuracy.

### Model 3: patterns of resource allocation that lead to good text memory

This model aimed to examine reading pattern associated with better text memory (regardless of participants' literacy attainment). It showed that while neither allocation to word-level processing nor immediate conceptual processing varied as a function of subsequent recall performance, allocation to conceptual integration did. Figure 2 shows reading time as a function of the three text features and recall accuracy. Thus, sentences with high levels of recall were specifically preceded by greater allocation to process sentence-final words. An additional model was fit to examine the interactions of each text feature with Reading Level and Recall Accuracy. None of the 3-way interactions was significant.

## Exploratory analysis of recall quality

As noted earlier (cf. Table 1), recall accuracy was moderately related to reading level. Here, we consider the qualitative difference in recall as a function of literacy proficiency (Smiley et al., 1977) to examine group differences not just in how many ideas were recalled, but which ideas were recalled. Here, we used a relative memorability analysis (Stine & Wingfield, 1988), in which we compared the memorabilities (i.e., probabilities of recall) of individual idea units for participant groups with high- and low-literacy skill. Many factors contribute to the differential memorability of particular items (e.g., importance, concreteness). An analysis based on memorability is agnostic with respect to the specific factors that contribute to recall, but at a general level, memorabililty reflects selectivity of ideas to be retained in memory. A high correlation of item memorabilities across participant groups suggests comparable processes in the selection of ideas for retention in memory (Stine & Wingfield, 1988, 1990). On the other hand, the slope of the relationship can reflect differences in the extent to which those factors come into play. A slope of unity suggests that both groups reflect high similarity in the differentiation of items in memory; enhanced selectivity for more memorable items by the target group relative to the reference group will be reflected in a slope greater than unity; and reduced selectivity for more memorable items (i.e., reduced discrimination among items) will be reflected in a slope less than unity (Stine & Wingfield, 1988).

Based on a median split of reading level, we divided participants into high- (RL>$9^{th}$g) and low- (RL<$9^{th}$g) literacy groups (n = 40 in each group). These groups did not differ in age (M = 41.5 yrs,

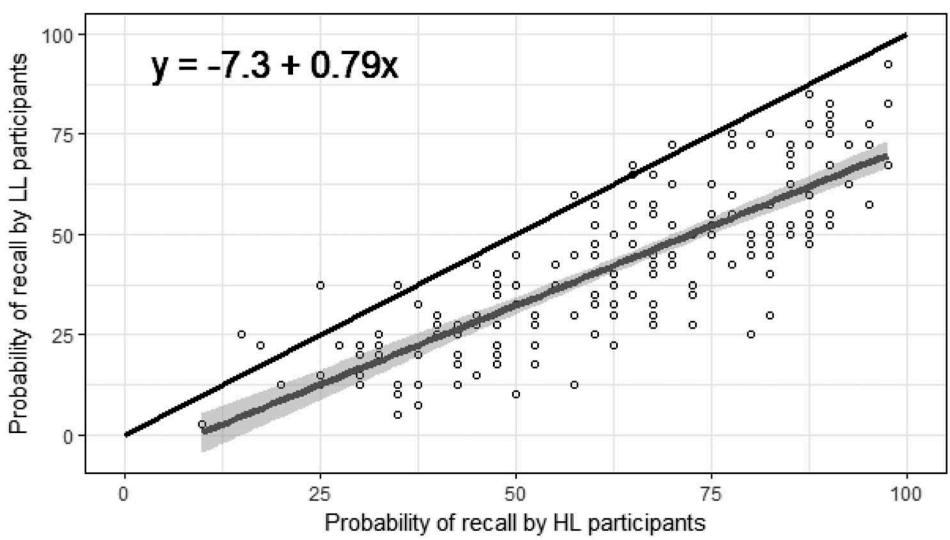


Figure 3. The correlation between the proportions of higher literacy (HL) and lower literacy (LL) participant groups who accurately recalled a proposition. The black line indicates the hypothetical perfect correlation when a proposition is recalled by the same proportion of participants from the two groups.

SD = 12.2; and M = 41.9 yrs, SD = 13.6, respectively), but the better readers had about one more year of formal education (M = 12.5, SD = 1.5; range: 8–16) than the poorer readers (M = 11.6, SD = 1.7; range: 7.5–16), t(78) = 2.64, $p$ = .01); otherwise, the groups differed in all of the measures shown in Table 1, $p < .01$. Figure 3 plots the probability of propositional recall among the low-literacy adults as a function of that among high-literacy adults. In fact, the two groups showed a moderately high correlation between unit recall probabilities ($r = .81$, $p < .001$), suggesting a qualitative similarity in the mechanisms underlying the selection and retention of ideas in sentence memory, as a function of literacy skill. A line with a slope of 1 and y-intercept of 0 (reflecting identical performance between the two groups) is plotted for comparison against the regression line of $y = -7.3 + 0.79x$. Adults with underdeveloped reading skills showed poorer recall overall relative to the skilled group (a negative intercept). However, the slope of the regression line was less than 1, $t(171) = 4.67$, $p < .001$, suggesting that less proficient readers were especially less likely to remember the ideas that were most memorable for the proficient readers, showing reduced discrimination among idea units in their memory for text information[7].

## Discussion

The current study examined attentional allocation to reading processes among adults with varying levels of literacy attainment, and identified reading patterns contributing to better text memory. This sample showed considerable range in reading level with some adults reading at the equivalent of about a 4th grade reading level. Much like the samples of college students that have been more extensively investigated, these readers were sensitive to both lexical and text-level features in sentence processing. They took longer to read low-frequency words, sentence-final words, and words that introduced new noun concepts, suggesting that the core processing mechanisms underlying sentence processing are intact. However, literacy proficiency modulated the extent of resource allocation: readers with underdeveloped reading skill spent disproportionate resources on lexical processes and relatively less on segmental processing that supports text integration (cf. Payne et al., 2012). Consistent with the Lexical Quality Hypothesis (Perfetti, 2007), these findings lend support to the idea that more effortful decoding and lexical retrieval among less skilled readers may deplete the attentional resources needed to perform conceptual processing, contributing to reduced memory performance not only in terms of the amount of content retained in memory but also in terms of item discriminability. These findings contribute to the literature along three lines.

First, our findings suggest that wrap-up is reduced among less proficient readers, supporting the idea that this is a process engendered by reading experience. Within our sample, the relationship between reading proficiency and wrap-up was only reliable among those reading up to the 12$^{th}$-grade level. We speculate that this was due to the low level of difficulty of our reading materials, which were not challenging for adults with college-level reading skills. Further research titrating text difficulty to reader competence is needed to confirm this interpretation. If this turned out to be the case, it would not only lend evidence to the proposal that adult readers' attention allocation at sentence boundaries is modulated by the semantic and linguistic demands of reading materials (e.g., Miller & Stine-Morrow, 1998; Stine, 1990), but also suggest that how taxing these demands scale to reader competencies.

Second, we have replicated the relationship between attention allocation to sentence wrap-up and recall accuracy (Payne & Stine-Morrow, 2016; Stine-Morrow et al., 2001, 2008) across a wider range of reading skill than has heretofore been investigated. This finding supports the idea that segmental processes related to conceptual resolution and consolidation are engaged at wrap-up, contributing to text comprehension and retention. There has been some debate as to whether sentence wrap-up actually reflects such integration processes, or rather, low-level mechanisms, such as prosodic simulation or simply punctuation-induced hesitation. Consistent with an integration account, wrap-up increases with the conceptual load of the sentence (e.g., Aaronson & Scarborough, 1976; Haberlandt et al., 1986; Stine, 1990) or demands for resolving ambiguity (Daneman & Carpenter, 1983; Miller & Stine-Morrow, 1998); decreases with manipulations that induce wrap-up earlier in the sentence, suggesting that the mental workload of wrap-up can be distributed (Millis & Just, 1994; Stine-Morrow et al., 2006); reduces the parafoveal processing benefit, suggesting that wrap-up is attentionally demanding (Payne & Stine-Morrow, 2012); and as just mentioned, is related to subsequent recall performance (Stine-Morrow et al., 2008). On the other hand, reading time is increased by punctuation, such as a comma or period even when processing demands are held constant (Hirotani, Frazier, & Rayner, 2006; Payne & Stine-Morrow, 2012; Stine-Morrow et al., 2010), an extreme case being a direct address preceding a command (e.g., David, leave me the key, vs. David left me the key; Hirotani et al., 2006), which is consistent with an implicit prosody interpretation. Importantly, using eye-tracking, it can be shown that such an effect occurs as early as the first fixation (Hirotani et al., 2006; cf. Warren, White, & Reichle, 2009), which is implausibly early to reflect integration processes.

In fact, the time allocated to sentence-final words is likely due to both implicit prosody grounded in language experience, and the engagement of language computations that give rise to comprehension. Findings from a study of sentence processing among older adults with well-developed literacy skills who varied in cognition are instructive (Payne & Stine-Morrow, 2016). In this study, the reading time patterns of both healthy older adults and those with cognitive impairment revealed an increase in reading time at sentence boundaries. Those with cognitive impairment showed smaller reading time increases, but the more dramatic difference was in the functional relationship between wrap-up and subsequent recall. While healthy older adults showed a robust relationship between wrap-up and recall, individuals with the most severe impairment did not show a benefit at all from wrap-up on memory performance. So even though the older adults with cognitive impairment appeared not to engage processes that would produce a memory representation (or at least, not effectively so), they nevertheless, paused briefly at sentence-final words. Thus, the procedural skill of segmentation (likely driven by prosodic mechanisms) that is well engrained among literate adults was retained, even though the cognitive resources to engage the necessary computation for memory were lacking.

In the current case of adults with less well-developed literacy skills, wrap-up was reduced. This could be explained either in terms of reduced prosodic simulation as a consequence of impoverished reading engagement, or as a reduced skill in engagement of conceptual integration processes. Importantly, the functional relationship between wrap-up and recall did not vary with literacy skill, so that it appears that this increased time allocation to end-of-sentence processing produced the same benefits for subsequent memory among adult readers, regardless of literacy skill. This is not to deny the possibility that implicit prosody is also involved, but such a finding makes it difficult to dismiss a computationally important role for wrap-up. Further study is needed to determine whether readers of different levels of literacy skill engage similar or different conceptual processes.

Third, readers of different literacy levels showed a similar rank order in idea memorability (Rubin, 1978; Stine & Wingfield, 1987, 1988). In other words, the ideas that were more likely to be remembered by proficient readers were also more likely to be remembered by less skilled readers. This positive correlation was strong and reflects comparable mechanisms of memory selection in play (e.g., isolation of gist, appreciation of salience). However, our data also indicated that less proficient readers showed reduced discriminability of the ideas, relative to their proficient counterparts. To the extent that wrap-up reflects conceptual integration in which the semantic representation of the sentence is consolidated, the reduced wrap-up among the less proficient readers implies that they might have a more fragmented semantic representation of the reading material that does not accurately distinguish between small details and larger ideas. The relative memorability analysis was consistent with that in suggesting not only a deficit in overall recall among readers with underdeveloped literacy skill, but also in the organization of ideas in memory.

These findings have instructional implications for teaching adults to read. Regardless of an individual's reading ability, more resources allocated to concept instantiation and conceptual integration predicted higher accuracy in recall, whereas attention allocated to word-level features did not. Nevertheless, it is certainly plausible that the lack of automaticity in word recognition and the quality of lexical representation might contribute to a processing bottleneck among developing adult readers that indirectly impairs integrative semantic processing (e.g., Perfetti, 2007). Thus, the fundamental question is whether difficulty in decoding and lexical retrieval consumes disproportionate attentional resources among lower-literacy adults, which causes their inability to adjust their reading pattern in response to text-level demands; or instead, their segmental processing mechanisms are inefficient. If the former were the underlying cause, increasing the efficiency in word recognition may automatically promote deeper conceptual processing. If the latter turned out to be true, instructions on integrative segmental processes (e.g., amalgamating semantic units to form a coherent message, constructing a situation model, connecting the key nouns or concepts, distinguishing foreground and background information, and resolving ambiguities) may improve reading comprehension. Future research should examine whether facilitated lexical retrieval (e.g., through pre-exposure to vocabulary before reading), would improve sensitivity to text-level features, and relatedly, whether improved skills in segmental processing can compensate for delayed or deficient incremental processes.

In conclusion, adults with underdeveloped reading skill are sensitive to both word-level and text-level features. They also remember similar ideas as adults who are proficient readers. Thus, their language processing mechanism for written input is generally intact and efficient. The main difference among adults with varying reading abilities is that less proficient readers are more sensitive to lexical features but less so to text-level features. Our data show that readers who allocate greater time to concept instantiation and conceptual consolidation show improved text retention after reading. Considerations may therefore be given to integrate conceptual processing into adult reading programs.

## Notes

1. For our target words, the correlation between log frequencies based on the HAL and SUBTL corpora was .956, so the selection of corpus was arbitrary.
2. It should be noted that clause boundary has also been used as a predictor for reading times to examine organizational processing within sentences (e.g., Haberlandt & Graesser, 1989b; Payne et al., 2012). However, in the current materials set, sentences were relatively short and simple, affording little opportunity to separate out the effects of intra-sentence wrap-up. Additionally, while resource allocation coefficients in sentence processing show fairly reliable individual differences, clause boundary wrap-up tends to be less so (Stine-Morrow et al., 2001). Thus, even though clause wrap-up has been shown to be differentially preferred by some readers with reduced WM capacity (e.g., older adults), its effects were not evaluated in the current study.
3. We only report recall for ideas in the target sentence, for which we analyzed reading times. Propositional recall from the target sentence and whole passage was highly correlated, $r = .95$, suggesting that recall accuracy on the target sentence was representative of recall of the whole passage.
4. As shown in Table 3, the variance estimates for the by-subject random slope of Word Frequency in each model are zero. Removing this random effect from all models did not change the overall findings. For the sake of consistency, we kept them in the models.
5. The parameter estimates did not change if these two individual difference variables were excluded from the model.
6. Adults with lower levels of reading skill also showed lower scores on working memory (WM) span ($r = 0.57$) and fluid ability ($r = 0.45$). When we fit an additional model including these factors, WM did not predict reading time, but fluid ability did; the effect of reading level remained robust even with these variables in the model. However, in subsequent models with interaction terms, neither fluid ability nor its interactions reached significance.
7. It appears in Figure 3 that the low-proficiency readers may have been at floor for the least memorable propositions. To confirm that it was not just a floor effect that was driving the reduced slope, we analyzed the data including only the propositions that were recalled by more than 40% of the proficient readers. The regression line was $y = -13.4 + 0.87x$, with a slope still less than 1, $t(147) = 2.03$, $p < .05$.

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## Conflict of interest

The authors declare no conflict of interest.

## Informed Consent

All participants provided informed consent.

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