The effects of print exposure on sentence processing and memory in older adults: Evidence for efficiency and reserve

Brennan R. Payne [a] [b], Xuefei Gao [a] [b], Soo Rim Noh [e], Carolyn J. Anderson [b] [c] [d] & Elizabeth A. L. Stine-Morrow [a] [b] [c]

[a] Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

[b] Department of Educational Psychology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

[c] Department of Psychology, University of Illinois at Urbana-Champaign, Urbana, IL, USA

[d] Department of Statistics, University of Illinois at Urbana-Champaign, Urbana, IL, USA

[e] Department of Psychology and the Volen National Center for Complex Systems, Brandeis University, Waltham, MA, USA

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The effects of print exposure on sentence processing and memory in older adults: Evidence for efficiency and reserve

**Brennan R. Payne[1,2], Xuefei Gao[1,2], Soo Rim Noh[5],
Carolyn J. Anderson[2,3,4], and Elizabeth A. L. Stine-Morrow[1,2,3]**

[1]Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[2]Department of Educational Psychology, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[3]Department of Psychology, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[4]Department of Statistics, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[5]Department of Psychology and the Volen National Center for Complex Systems, Brandeis University, Waltham, MA, USA

ABSTRACT

The present study was an examination of how exposure to print affects sentence processing and memory in older readers. A sample of older adults ($N = 139$; Mean age = 72) completed a battery of cognitive and linguistic tests and read a series of sentences for recall. Word-by-word reading times were recorded and generalized linear mixed effects models were used to estimate components representing attentional allocation to word-level and textbase-level processes. Older adults with higher levels of print exposure showed greater efficiency in word-level processing and in the immediate instantiation of new concepts, but allocated more time to semantic integration at clause boundaries. While lower levels of working memory were associated with smaller wrap-up effects, individuals with higher levels of print exposure showed a reduced effect of working memory on sentence wrap-up. Importantly, print exposure was not only positively associated with sentence memory, but was also found to buffer the effects

of working memory on sentence recall. These findings suggest that the increased effi-
ciency of component reading processes that come with life-long habits of literacy buffer
the effects of working memory decline on comprehension and contribute to maintaining
skilled reading among older adults.

Reading is an important activity for maintaining intellectual capacity and
exercising cognitive function across the lifespan (Manly et al., 1999; Manly,
Schupf, Tang, & Stern, 2005; Manly, Touradji, Tang, & Stern, 2003; Stern,
2009) with higher rates of literacy-related behaviors predicting greater levels
of memory for text (Hartley, 1986; Rice & Meyer, 1985, 1986), attenuated
longitudinal decline in memory more generally (Manly et al., 2005), and
resistance to late-life cognitive pathology (Wilson et al., 2000). Sustained lit-
eracy habits also cultivate crystallized abilities (Stanovich, West, & Harrison,
1995), such as vocabulary (Verhaghen, 2003) and general world knowledge
(Ackerman, 2008) that can be well preserved into very late life, and to
some extent offset declines in processing capacity (Meyer & Rice, 1989).
However, less is known about how the accumulated experience of reading
contributes to the capacity to learn from text or the moment-to-moment pro-
cesses underlying text comprehension, the fluent experience of which would
likely contribute to continued reading (cf. Payne, Jackson, Noh, & Stine-
Morrow, 2011). In the current study, we investigated whether individual
differences in exposure to print, a measure of reading-related engagement,
contributes to sentence processing and memory among older readers.

Reading and Aging

The mechanisms underlying the comprehension of written language
are complex, involving the active processing and integration of information
as the reader controls pacing through the text. At the word level, readers
encode orthographic and lexical information. At the sentence level, read-
ers parse sentences into syntactic constituents (Pickering & van Gompel,
2006) and construct a semantic representation of the integrated ideas given
by the text (Kintsch & Keenan, 1973; McKoon & Ratcliff, 1980, 2008).
This textbase representation of the sentence is resilient relative to the sur-
face form and is the basis for text memory (Kintsch, Welsch, Schmalhofer,
& Zimny, 1990). One method that has been used by researchers to measure
the moment-to-moment allocation of attention to word and textbase pro-
cesses is the *resource allocation* approach (Aaronson & Scarborough, 1977;
Graesser, 1981; Just & Carpenter, 1980; Lorch & Myers, 1990; Millis, Simon,
& tenBroek, 1998; Schroeder, 2011). This approach involves recording mil-
lisecond reading times (in a word-by-word or segment-by-segment self-paced

paradigm or with eye-tracking) and using statistical techniques (e.g., random regression or mixed effects modeling) to decompose these reading times into process-specific components. For example, when a random regression approach (Lorch & Meyers, 1990) is used to model how individuals' reading time is affected by particular linguistic features, the resulting coefficients represent each individual's attentional allocation policy in engaging the text demands online.

A number of studies have used this approach to examine age differences in reading strategies during sentence and text processing (e.g., Stine-Morrow, Miller, & Leno, 2001; Stine-Morrow, Miller, Gagne, & Hertzog, 2008). Collectively, these studies have found that age differences in text memory can be explained to some extent by a reduced allocation of attentional resources to textbase processing during reading. However, older readers appear to be able to achieve relatively high levels of performance, in part by allocating disproportionately more time to textbase processes, such as conceptual integration (see Stine-Morrow, Miller, & Hertzog, 2006; Stine-Morrow & Miller, 2009 for reviews).

A hallmark of language comprehension is the ability to construct a coherent representation in memory of the conceptual relationships given by a text (Kintsch, 1998; Kintsch et al., 1990). There is substantial evidence suggesting that elaborated semantic and conceptual analysis occurs at clause and sentence boundaries (i.e., across input cycles; see Kintsch, 1998). This phenomenon is called wrap-up and is characterized by peaks in reading time at clause and sentence boundaries (Just & Carpenter, 1980; Rayner, Kambe, & Duffy, 2000; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989). Wrap-up effects have been found to be one particular textbase process associated with higher levels of memory performance among older adults (Stine, 1990; Stine-Morrow, Miller, et al., 2001, 2008), suggesting that greater attention to conceptual integration during reading serves an essential compensatory function in engendering high levels of comprehension with advancing age.

Print Exposure, Verbal Efficiency, and Language Processing

Even within literate populations, there is a great deal of variability in how much people read in everyday life. Stanovich and co-workers (Cunningham & Stanovich, 1992; Stanovich & West, 1989) have coined the term *print exposure* to describe the habitual investment in reading and literacy activities. The Author Recognition Test (ART; Stanovich & West, 1989) was developed as a performance-based measure of print exposure that avoids common issues with self-report data (Paulhus, 1984; Stanovich & West, 1989). In the ART, participants are given a checklist containing authors and foils and are asked to indicate which names they recognize as authors. An overall discriminability score is calculated to adjust for false alarms. The logic of this measure is that people who read widely develop a familiarly with the names of

authors even if they have not read their work. Across multiple studies, both the reliability and construct validity of the ART have been established (Acheson, Wells, & MacDonald, 2008; Cunningham & Stanovich, 1992; Stanovich & West, 1989; Stanovich, West, & Harrison, 1995; West, Stanovich, & Mitchell, 1993), with scores on the ART relating highly to both subjective (e.g., activity preference, self-reported time) and objective (e.g., observed reading in natural environments) measures of reading habits.

Researchers have long been interested in the role that print exposure plays in vocabulary development, cognitive ability, and word-identification processes in children and young adult readers (Cunningham & Stanovich, 2003; see Long, Johns, & Morris, 2006). In developing readers, for example, higher levels of print exposure (as measured by the ART) uniquely predict facilitation in visual word recognition (Cunningham & Stanovich, 1990). Interestingly, the impact of print exposure on word recognition processes is maintained into college age, suggesting that individual differences in print exposure still affect orthographic and lexical processing even among young adult readers, long after they have developed into skilled readers (Chateau & Jared, 2000; Stanovich & West, 1989; Unsworth & Pexman, 2003). These effects are maintained even when accounting for general vocabulary ability (Chateau & Jared, 2000), suggesting that print exposure contributes to word recognition processes over and above reading-related gains in vocabulary.

According to verbal efficiency theory (Perfetti, 1985, 2007), this increased efficiency in the retrieval of orthographic and lexical codes that comes with accumulated reading experience may free up resources to be available for higher-level language processes. For instance, Ruthruff, Allen, Lien, and Grabbe (2008) found that visual word recognition shows evidence of increased automaticity among more highly skilled readers. A similar effect is also found among older adults, who were assumed to have greater cumulative experience in lexical processing than younger readers (Lien et al., 2006). It is important to note that this age-related benefit in visual word recognition would be expected only for older readers with relatively stronger literacy habits. That is, automaticity in lexical processing would not be assumed to come 'for free' with age. Rather, there is a great deal of individual variability in lexical efficiency among older adults that may, in part, be explained by individual differences in exposure to print.

There is also evidence that efficient word-level processing leads to the greater availability of resources for more elaborative semantic processing. Gao, Stine-Morrow, Noh, and Eskew (2011) found evidence for this word-level/textbase-level tradeoff predicted by verbal efficiency theory. They presented text in varying levels of visual noise in order to manipulate the difficulty of word-level encoding and found that when visual noise was high, participants allocated more time to word-level processing (i.e., greater time

spent at less frequent and longer words), but this came at the cost of reduced attentional allocation to textbase processes and poorer memory for text.

Collectively, these studies suggest that greater experience with skilled reading may result in more efficient lexical processing that may, in turn, free up resources for more demanding textbase processing. Given the cognitive profile of older adults, who typically have reduced cognitive capacity but at the same time incur the benefits of an accumulated lifetime of reading experience, individual differences in exposure to print would be expected to play an important role in sentence processing and memory within this group of readers.

A distinct but related possibility is that an increased efficiency in lexical processing would serve a compensatory function in sentence processing and memory particularly for older adults with diminished cognitive abilities. Age-related deficits in verbal working memory (vWM) are robust (Bopp & Verhaghen, 2005) and have been argued to be an important mechanism responsible for declines in sentence and text comprehension (Borella, Ghisletta, & de Ribaupierre, 2011; Daneman & Merikle, 1996; Just & Carpenter, 1992; Just, Carpenter, & Keller, 1996). While the empirical evidence for effects of vWM on online language processing are mixed (Caplan, DeDe, Waters, Michaud, & Tripodis, 2011; Caplan & Waters, 2011; Gordon, Hendrick, & Johnson, 2001; Fedorenko, Gibson, & Rohde, 2006; Just & Carpenter, 1992; Kemper, Crow, & Kemtes, 2004; Kemper & Liu, 2007; MacDonald & Christiansen, 2002; Stine-Morrow, Ryan, & Leonard, 2000; Waters & Caplan, 1996, 2001, 2005), there is a great deal of evidence that vWM impacts sentence memory and reading comprehension (Daneman & Merikle, 1996; DeDe, Caplan, Kemtes, & Waters, 2004; Friedman & Miyake, 2004; Waters & Caplan, 2005; Stine-Morrow, Miller, et al., 2008).

At the same time, certain factors have been shown to buffer the impact of vWM on text processing and memory among older readers. For example, if older adults have sufficient prior contextual knowledge of the information to be read, they show greater efficiency during reading and minimal effects of vWM on recall, suggesting that readers can use domain knowledge to buffer against capacity declines during reading (Miller, 2009; Miller, Cohen, & Wingfield, 2006). In a similar vein, it may be that increased practice with reading serves to alleviate the impact of capacity limitations on text processing and memory for text. To the extent that individual differences in print exposure reflect differences in the practice of a highly skilled activity that continues to accrue benefits over time (cf. Ericsson, Charness, Feltovich, & Hoffman, 2006), then engagement in reading-related activities may have beneficial effects on text processing and memory, even among older adults with reduced cognitive capacity.

The Current Study

The current study addressed two particular mechanisms through which individual differences in print exposure might impact sentence processing and memory performance among older readers. First, to the extent that greater print exposure leads to facilitated orthographic and lexical processing that frees up resources for semantic integration, we hypothesized that those with higher levels of print exposure would be facilitated in word-level processing during reading, but would show increased allocation to higher-level textbase processing and improved sentence memory. We call this the *efficiency* hypothesis. Second, although individual differences in vWM have been shown to impact sentence comprehension, it is not known how print exposure and vWM jointly determine text processing and recall. Thus, we examined the moderating effect that print exposure has on sentence processing and memory among older adults with varying levels of verbal working memory. We reasoned that higher levels of print exposure might operate as a compensatory 'reserve' mechanism by buffering against the impact of capacity limitations on sentence processing and memory. Specifically, any effects of vWM on textbase processing and sentence recall should be diminished among individuals with greater exposure to print. We call this the *reserve* hypothesis.

METHOD

Participants

Participants were 139 community-dwelling older adults. These data are reported from the Senior Odyssey project (Stine-Morrow, Miller, et al., 2008; Stine-Morrow, Parisi, Morrow, Greene, & Park, 2008), an ongoing community-based field experiment investigating the effects of intellectual engagement on cognition, and are based on pretest measures, before participants were randomly assigned to an experimental or control group. Participants ranged in age from 64 to 92 years (mean = 72.03, $SD = 7.94$), and had an average of 15.41 years of education ($SD = 2.67$). The participants had normal or corrected-to-normal vision and were screened for incident dementia or other major cognitive impairment, such that all participants in the sample scored above a 23 on the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975).

Measures

Print Exposure

Print exposure was measured with the ART (Stanovich & West, 1989) as described earlier. Participants were instructed to select the authors they knew

and were discouraged from guessing. A discriminability score was calculated as hits minus false alarms. In this sample, the ART was highly correlated with each of the major variables of interest in the current study (see Table 1), as well as with a number of other key variables that were collected, confirming the validity of the ART in this sample. ART scores were correlated with a self-report of the number of hours per week spent reading books, $r = .42, p < .001$, and with performance on the comprehension subtest of the Nelson–Denny Reading Test, a timed measure of general reading comprehension, $r = .26$, $p < .001$. Additionally, the ART was positively associated measures of psychomotor speed (letter and pattern comparison tasks, Salthouse & Babcock, 1991; and the identical pictures test, Ekstrom, French, & Harman, 1976; $\alpha = .84$), $r = .23, p < .001$, and reasoning (letter sets, number series, letter series, word series tasks, Ekstrom et al., 1976; and the everyday problem solving task; Marsiske & Willis, 1995; $\alpha = .90$), $r = .20, p < .01$, which is in line with prior research finding positive relationships between reasoning, fluid cognition, and print exposure (Siddiqui, West, & Stanovich, 1998; Stanovich, West, & Harrington, 1995).

Vocabulary

The advanced vocabulary and extended range vocabulary tests from the Educational Testing Service Kit of Factor Referenced Cognitive Tests (Ekstrom et al., 1976) were used to measure vocabulary. Both tests are timed and similar in that, for each item, participants are asked to choose a correct synonym of a target word from a list of five possible words. Because of the high correlation between these two measures ($r = .82, p < .001$), they were combined into one composite measure of vocabulary for each subject. This composite showed high rank-order stability, with a test–retest reliability correlation of .78 ($p < .001$).

Verbal Working Memory (vWM)

The loaded reading span task, as described in Stine and Hindman (1994) was used to measure verbal working memory. Participants read a set of sentences silently and were asked to immediately make true/false judgments after each sentence. After reading all of the sentences in a group, the participants were asked to recall all of the target words (the last words of each sentence in that group) in order. The number of sentences per set increased with progress through the task (until eight sentences per set or when the participant could no longer recall each of the target words in a set successfully). The participants' final score was the number of target words recalled within the highest set in which they did not make an error, plus a fraction for the number of correctly recalled words on the set in which they erred. This measure showed modest test–retest reliability in this sample, $r = .40, p < .001$.

Sentence Materials

Each participant read a set of 24 sentences adapted from the stimuli in Stine-Morrow, Milinder, Pullara, and Herman (2001). Each sentence contained 18 words and was followed by a filler sentence to ensure that retrieval planning did not contaminate reading times on the sentence-final word. These filler sentences were not analyzed. This resulted in $18 \times 24 = 432$ total words read per subject. Each of these words was coded for a set of five variables reflecting resource allocation to text processing demands. Word-level variables included: (1) the number of syllables (Syll) and (2) the natural logarithm of word-frequency (lnWF), using norms from Francis and Kucera (1982). These two variables reflect time spent on orthographic decoding and lexical access, respectively. Textbase level variables included: (3) whether a word introduced a new concept in the sentence (NC), (4) whether the word marked the end of a clause or other minor syntactic boundary (IntSB), and (5) whether the word occurred at a sentence boundary (SB). Readers spend more time on words that introduce new concepts (Haberlandt, Graesser, Schneider, & Kiely, 1986) and readers allocate more time to processing words at the end of clause and sentence boundaries (i.e., wrap-up). These variables have consistently been shown to affect reading times (see Stine-Morrow, Milinder, et al., 2001; Stine-Morrow, Miller, et al., 2008) for both younger and older readers. In the analyses reported in this study, the number of syllables and word frequency were treated as continuous predictors and the remaining text variables were dummy coded (0/1) for the absence or presence of each effect.

Procedure

Participants completed the battery of measures in the current study as part of a larger group testing session lasting approximately 2 hours. Participants were later administered the sentence reading task in a larger individual laboratory session also lasting approximately 2 hours. For the reading task, the two-sentence passages were presented on a 19 inch (48.3 cm) Dell M782 monitor set to a resolution of 1024×768 pixels, controlled by a Dell 3.20 GHz computer. MATLAB software (Mathworks, Inc., Natick, MA) was used to control presentation and record millisecond reading-times.

Participants read each passage word-by-word, using the moving window method (Aaronson & Ferres, 1984). Each sentence began with all punctuation intact, as well as a set of underscores representing each word in the sentence visible to the participant. The initial press of the space bar produced the first word of the sentence. Succeeding space bar presses produced the next word while concurrently removing the prior word. On a fixed but randomly selected one-third of the sentences, an indicator was presented at the close of the sentence instructing the participants to recall aloud what they had just previously read. Oral recall was recorded and transcribed for later scoring.

Analyses

Analyses on the reading time data were performed using generalized linear mixed effects models (GLMM), with subjects and words specified as crossed random effects. The sentence memory data were analyzed with logit mixed-effects models, with subjects and sentences specified as crossed random effects (see Jaeger, 2008). SAS (version 9.2) procedure MIXED was used to fit the reading time models and procedure GLIMMIX was used to fit the sentence memory models.[1]

Similar to the recent use of mixed effects modeling instead of traditional subject (F1) and item (F2) analyses in experimental psycholinguistic research, the resource allocation (RA) approach is also amenable to mixed effects modeling. In the classic RA approach, within-participant reading times are regressed onto item-level predictors and the resulting regression coefficients are submitted to a separate analysis across subject-level effects (see Lorch & Myers, 1990). Much in the way that GLMM draw strength by being able to combine F1 and F2 analyses, GLMM can also model the subject analyses and item-level regressions in RA simultaneously, resulting in more precise estimates, correct standard errors, and valid statistical tests of effects (see Baayen, Davidson, & Bates, 2008 for results from a simulation study). Furthermore, it is possible to simultaneously model interactions between predictors of subject and item variance.

The reading time models were based on maximum likelihood estimation and the sentence memory models were based on maximum likelihood estimation through the Laplace approximation. Significance tests for fixed effects were conducted using likelihood ratio tests (Agretsi, 2002; Snijders & Bosker, 1999). This test statistic is calculated as the difference between –2 times the natural logarithm of the likelihood for a full model and a nested model (without the predictor being tested) and follows an approximate χ^2 distribution with degrees of freedom (df) equal to the difference in parameters between the full and nested models. For random effects, significance tests are conducted using a likelihood ratio test statistic where the sampling

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[1]The use of mixed-effects modeling has been prevalent in social science, education, and behavioral research for some time (Singer, 1998; Snijders & Bosker, 1999). Recently, these modeling techniques have begun to gain ground in psycholinguistic and cognitive psychology research as well (Baayen, Davidson & Bates, 2008; Jaeger, 2008; Locker, Hoffman, & Boviard, 2007; Quene & van den Bergh, 2004, 2008). In conventional psycholinguistic experiments, the use of GLMM incurs several benefits, such as allowing the researcher to analyze fixed and random effects across subjects and items simultaneously, which avoids the need for separate F1 (by-subjects) and F2 (by-items) analyses. Additionally, GLMM are capable of (1) modeling predictors of subject and item level variability simultaneously, (2) modeling both discrete and continuous variables simultaneously, (3) modeling unbalanced designs, and (4) explicitly modeling variances and covariances, allowing for violations of sphericity and homogeneity of error variance (Snijders & Bosker, 1999).

distribution of the test statistic is a mixture of two χ^2 distributions, df $= 0$ and 1 (Self & Liang, 1987; Stram & Lee, 1994, 1995; Verbeke & Molenburghs, 2000).

RESULTS

Table 1 presents the means and standard errors for age, educational level, vWM, vocabulary, and sentence memory, and their intercorrelations.

Effects of Print Exposure on Online Sentence Processing

There were 60,048 total observations (432 observations per subject × 139 subjects) for the reading time (RT) analyses. The natural logarithm (ln) of RTs was calculated to transform the distribution to normality. These RTs were then trimmed about each individual's mean, such that RTs over three standard deviations were replaced with the value at the third standard deviation. This constitutes a very conservative trimming procedure, resulting in less than 0.02% replacement of the data.

Based on the unconditional means model (see Equation 1 in the Appendix), we entered predictors of reading time sequentially in 5 models. First, in Model 1, we examined only the item-level predictors of reading time. It was specified as seen in Equation 2 in the Appendix and represents the fixed effects of the word and textbase characteristics on reading time. All parameters in this model were significant (see Table 2), replicating findings using the random regression resource allocation approach (see Stine-Morrow, Milinder, et al., 2001; Stine-Morrow, Miller, et al., 2001, 2008). On average, readers allocated significantly more time to words that were more orthographically complex, to words that were lower in word frequency, to the immediate instantiation of new concepts, and to wrap-up at clause and sentence boundaries.

TABLE 1. Means, standard errors, and correlations among age, educational level, verbal working memory, vocabulary, print exposure, and sentence memory

	M (SE)	1	2	3	4	5
1. Age	72.30 (0.65)					
2. Ed	15.40 (0.22)	0.01				
3. vWM	3.92 (0.08)	−0.14†	0.15†			
4. Vocab	0.00[a](0.09)	0.03	0.49**	0.22*		
5. ART	10.20 (0.43)	−0.18*	0.30**	0.20*	0.62**	
6. Recall	0.51 (0.01)	−0.12	0.28**	0.34**	0.46**	0.34**

Note: †p <.10; *p <.05; **p <.01. *M,* Mean; *SE,* Standard error; Ed, Educational level; vWM, Verbal working memory; Vocab, Composite of extended range vocabulary and advanced vocabulary; ART, Author Recognition Test; Recall, Sentence memory.
[a]Mean is equal to 0 because it is based on a composite of two standardized measures.

TABLE 2. Estimates and standard errors from linear mixed effects models of reading time

	Model 1		Model 2		Model 3		Model 4		Model 5	
	Est	SE	Est	SE	Est	SE	Est	SE	Est	SE
Intercept	6.493***	0.039	6.764***	0.066	6.691***	0.317	6.736***	0.317	7.142***	0.432
Fixed item effects										
Syll	0.049***	0.01	0.068***	0.011	0.066***	0.012	0.062***	0.015	0.117***	0.033
logWF	−0.051***	0.001	−0.058***	0.007	−0.057***	0.007	−0.054***	0.009	−0.047**	0.019
NC	0.058***	0.017	0.084***	0.020	0.086***	0.020	0.071*	0.028	0.123*	0.061
IntSB	0.040**	0.015	0.064***	0.019	0.066***	0.019	0.016	0.029	−0.079	0.064
SB	0.479***	0.028	0.458***	0.039	0.454***	0.033	0.258***	0.047	−0.271***	0.099
Fixed subject effects										
ART	–	–	−0.026***	0.005	−0.019**	0.007	−0.019**	0.007	−0.055*	0.028
Age	–	–	–	–	0.001	0.004	0.001	0.004	0.001	0.004
Vocab	–	–	–	–	−0.046	0.038	−0.047	0.037	−0.046	0.037
vWM	–	–	–	–	−0.028	0.029	−0.038	0.030	−0.134	0.077
vWM × ART	–	–	–	–	–	–	–	–	0.009	0.006
Two-way cross-level interactions										
ART × Syll	–	–	−0.002***	0.001	−0.002***	0.001	−0.002**	0.001	−0.007**	0.003
ART × logWF	–	–	0.001*	0.000	0.001	0.000	0.001	0.000	0.000	0.002
ART × NC	–	–	−0.002*	0.001	−0.002**	0.001	−0.003**	0.001	−0.008	0.005
ART × IntSB	–	–	0.002*	0.001	0.002*	0.001	0.003*	0.001	0.003	0.005
ART × SB	–	–	0.003	0.002	0.002	0.002	0.000	0.002	0.050***	0.008
Two-way cross-level interactions										
vWM × Syll	–	–	–	–	–	–	0.001	0.003	−0.012	0.008
vWM × logWF	–	–	–	–	–	–	−0.001	0.002	−0.002	0.004
vWM × NC	–	–	–	–	–	–	0.004	0.006	−0.009	0.014
vWM × IntSB	–	–	–	–	–	–	0.023***	0.006	0.038*	0.015
vWM × SB	–	–	–	–	–	–	0.055***	0.009	0.185***	0.023

(*Continued*)

TABLE 2. (Continued)

	Model 1		Model 2		Model 3		Model 4		Model 5	
	Est	SE	Est	SE	Est	SE	Est	SE	Est	SE
Three-way cross-level interactions										
ART × vWM × Syll	–	–	–	–	–	–	–	–	0.001	0.001
ART × vWM × logWF	–	–	–	–	–	–	–	–	0.000	0.000
ART × vWM × NC	–	–	–	–	–	–	–	–	0.001	0.001
ART × vWM × IntSB	–	–	–	–	–	–	–	–	−0.001	0.001
ART × vWM × SB	–	–	–	–	–	–	–	–	−0.012***	0.002
Random effects										
τ^2	0.122***	0.015	0.091***	0.011	0.089***	0.011	0.089***	0.011	0.087***	0.011
ψ^2	0.014***	0.001	0.014***	0.001	0.014***	0.001	0.014***	0.001	0.014***	0.001
σ^2	0.167***	0.001	0.169***	0.001	0.168***	0.001	0.165***	0.001	0.169***	0.001
Model fit (−2 log likelihood)	64428.51		63063.12		57969.68		57851.11		5795.82	

To examine individual differences in resource allocation as a function of PE, we added performance on the ART as a predictor, as well as the cross-level interactions between ART and each of the five item-level predictors (see Equation 3 in the Appendix). In this model, Model 2, the interaction terms represent the degree to which print exposure moderates the effects of each of the item-level predictors of reading time.

Figure 1 plots the partial effects of each significant interaction parameter in this model at conditional levels of print exposure, where low print exposure is one *SD* below the mean and high print exposure is 1 *SD* above the mean. The significant interactions between ART and the text features (Syll, lnWF, NC, and IntSB) revealed that older adults who had greater levels of print exposure were facilitated in orthographic processing, lexical access, and in the immediate instantiation of new concepts, but allocated disproportionally more time to clause wrap-up. While the ART × SB interaction was in the predicted direction, it did not reach significance ($p = .20$). Collectively, these findings are largely consistent with the verbal efficiency hypothesis (Perfetti, 1985, 2007) in suggesting that those with higher levels of print exposure were more efficient in orthographic decoding and lexical processing, but also showed larger end of clause wrap-up effects, which are associated with

FIGURE 1. Partial effects plots of significant interactions in Model 2 at conditional levels of print exposure (low print exposure = 1 *SD* below the mean; high print exposure = 1 *SD* above the mean). *Note:* PE, Print exposure; NC, New concept. Word frequency is plotted in reverse to show effect from high frequency to low frequency.
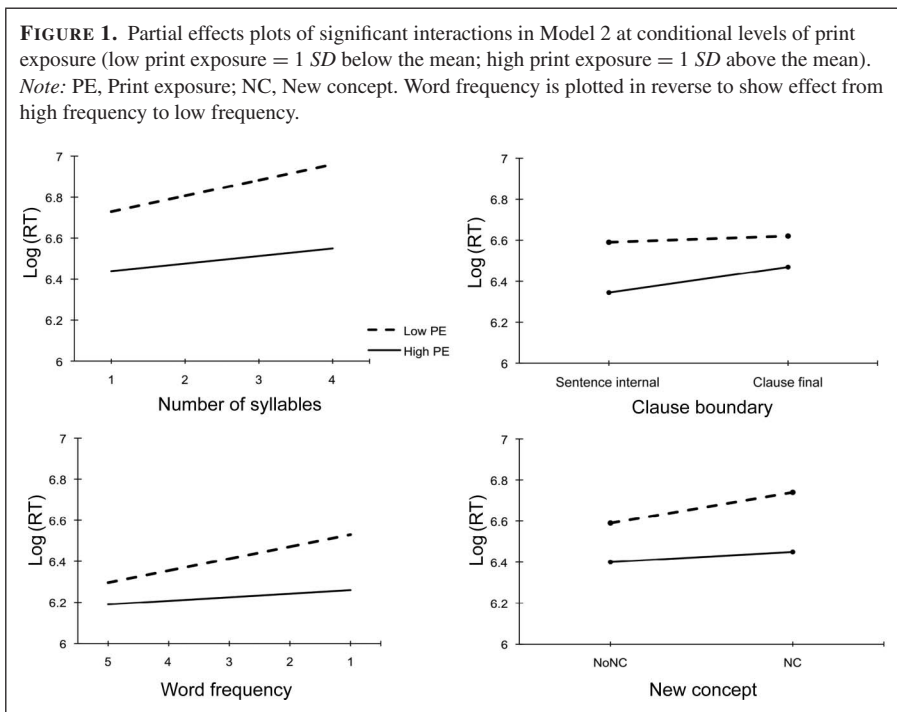
demanding semantic integration processes (Payne & Stine-Morrow, in press; Rayner et al., 2000; Stine-Morrow et al., 2010).

In Model 3, we added age, vocabulary, and vWM as covariates in order to assess the unique effects of print exposure after accounting for these individual differences. In our sample, individuals with better vocabulary read more (see also Stanovich & West, 1989) as suggested by the fact that vocabulary was correlated with both print exposure and a self-report of the number of hours per week spent reading books ($r = .62$; $r = .23$, respectively), and it is possible that vocabulary performance is a stronger determinant of resource allocation (Stine-Morrow, Miller, et al., 2008) than print exposure. This raises the possibility that the correlation between print exposure and any online measure of sentence processing might arise because of shared covariance between print exposure and vocabulary (see also, Chateau & Jared, 2000). Likewise, as there exists a moderate correlation between vWM and PE, and vWM often predicts processing time during reading (though not necessarily as a function of processing difficulty; Caplan & Waters, 1999), we also included this as a covariate in the analysis. Examining differences in exposure to print that are independent of vocabulary and vWM constitutes a very conservative test (Chateau & Jared, 2000) because we are partialing out variability in abilities that are likely developed and sustained by greater exposure to print. Thus, the findings we present in Model 3 represent the unique effects of print exposure on online reading comprehension even after it has been "robbed of some of its rightful variance" (p. 265; Cunningham & Stanovich, 1991).

Model 3 was specified by adding the three subject-level covariates to Model 2 (see the Appendix, Equation 4). If age, vocabulary, or verbal working memory were responsible for the relationships between print exposure and resource allocation, then adding these would be expected to reduce or eliminate the significant interactions found in Model 2. After covarying for age, vocabulary, and vWM, all parameters that were significant from Model 2 were largely unchanged in Model 3 (see Table 2), with all parameter estimates remaining relatively stable and significant, with the exception of the ART $\times$ lnWF interaction that became marginally significant ($p = .07$) in Model 3. These findings suggest that the observed effects in Model 2 were largely unique to print exposure and could not be explained by individual differences in age, vocabulary, or vWM.

Next, we report evidence for the reserve hypothesis in online sentence processing, that greater print exposure serves as a compensatory mechanism particularly for individuals with lower cognitive capacity. To test this hypothesis, in Model 4 we examined whether individual differences in vWM affected resource allocation and in Model 5 whether print exposure moderated the effects of vWM on resource allocation.
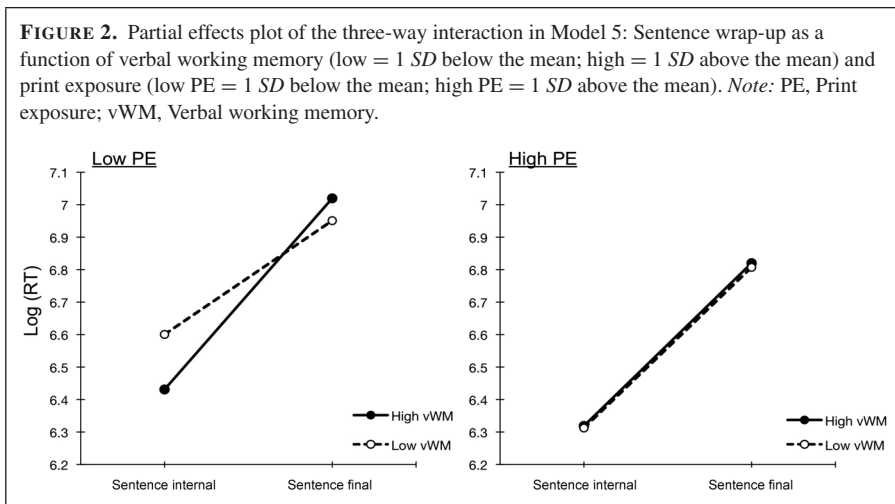
Model 4 was specified by adding all two-way interactions between vWM and the item-level predictors to Model 3 (see Equation 5 in the

Appendix). Table 2 shows that two significant two-way interactions were found between vWM and the item-level variables. While vWM did not significantly moderate the Syll, logWF, or NC effects, there were reliable interactions between vWM and the clause wrap-up effect (IntSB $\times$ vWM) and vWM and the sentence wrap-up effect (SB $\times$ vWM). Older adults with higher working memory showed exaggerated clause and sentence wrap-up relative to those with lower working memory, suggesting that working memory afforded processing resources for consolidating and integrating semantic information at syntactic boundaries.

If print exposure contributes to compensation during online sentence processing, then the negative effects of poor working memory on resource allocation should be reduced among individuals with higher scores on the ART. In Model 5, this was tested by adding all three-way interactions between vWM, ART, and the item-level predictors to Model 4 (see Equation 6 in the Appendix). The findings revealed only some evidence for the reserve hypothesis in online reading times. Of the three-way interactions of interest that were added in Model 5, the ART $\times$ vWM $\times$ SB effect was reliable. Figure 2 presents this three-way interaction, plotting the reading times for sentence internal and sentence final words as a function of print exposure and vWM.

To decompose this three-way interaction, test statistics for differences in the simple slopes presented in Figure 2 were calculated (see Aiken & West, 1991; Dawson & Richter, 2006; Bauer & Curran, 2005).[2] For individuals

FIGURE 2. Partial effects plot of the three-way interaction in Model 5: Sentence wrap-up as a function of verbal working memory (low = 1 *SD* below the mean; high = 1 *SD* above the mean) and print exposure (low PE = 1 *SD* below the mean; high PE = 1 *SD* above the mean). *Note:* PE, Print exposure; vWM, Verbal working memory.

[2]It is important to note that, while these methods for decomposing continuous interactions were originally designed in the context of ordinary least squares regression, these methods are also appropriate and equivalent in the context of GLMM, since we are only probing a parameter from the fixed portion of the model.

with lower print exposure (mean − 1 *SD*), reduced working memory was associated with reduced allocation of time to sentence wrap-up ($t = 4.98$, $p < .001$). However, for those with higher levels of print exposure (mean + 1 *SD*), working memory was not systematically related to sentence wrap-up ($t = 0.02$).

These findings are in line with the reserve hypothesis in suggesting that print exposure served to alleviate the influence of working memory capacity on the more cognitively demanding (Payne & Stine-Morrow, in press) sentence wrap-up effect. To the extent that wrap-up represents the time allocated to conceptual integration across sentences (Just & Carpenter, 1980; Stine-Morrow, Miller, et al., 2008; Stine-Morrow et al., 2010), these results suggest that print exposure can buffer against the effects of working memory (cf. Miller et al., 2006). That older readers with lower print exposure and lower working memory showed less evidence of wrap-up suggests that they engaged in less end-of-sentence semantic and conceptual integration, which would result in a more fragmented representation of the sentence in memory. This is examined directly in the next section, where we examine the effects of print exposure and working memory on sentence recall.[3]

Effects of print exposure on sentence memory

Transcribed recall protocols were scored, using a gist-based criterion, for the proportion of propositions correctly recalled from each of the eight sentences that were probed (Turner & Greene, 1978). Two trained independent raters who were blind to participant characteristics (e.g., age, cognitive scores) assessed a subset of the protocols. Estimates between the two raters showed good inter-rater reliability ($r = .93$). Based on this procedure, the measure of sentence memory was the number of correct propositions recalled for each sentence by each participant. One participant's verbal recall protocol was lost due to recording error, so analyses were based on $N = 138$ participants.

To investigate the effects of print exposure on sentence memory, we first fit a logit mixed-effects model to the data, with subjects and sentences as crossed random effects. This model treats each proposition in each sentence as a trial of a binomial random variable, where remembering a proposition
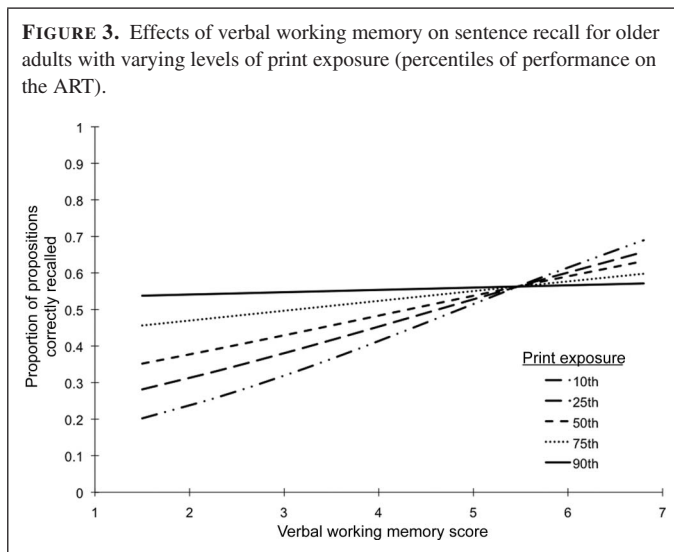
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[3] Although our analyses focused on verbal working memory as the major indicator of individual differences in processing capacity, similar effects were found for the reading time models when speed of processing was used in place of vWM as a proxy of fluid cognition. That is, re-fitting the reading time models while replacing speed with vWM revealed that processing speed was a significant predictor of reading time ($p < .001$) and interacted with sentence and clause wrap-up (SB × Speed, $p < .001$; IntSB × Speed, $p < .001$). Importantly, the effects of processing speed on sentence wrap-up were buffered by print exposure (ART × SB × Speed, $p < .001$), much in the same way that the effects of vWM were buffered by greater print exposure. Thus, it appears that individual differences in processing speed acted in a similar fashion to vWM as an indicator of cognitive capacity among older adults.

is a success. This model included ART, vWM, and the interaction between vWM and ART as predictors and is presented in Equation 7 in the Appendix.

Both vWM $(\hat{\gamma}_{10} = .49, SE = 0.17; \chi^2(1) = 7.73, p < .001$, odds ratio (OR) $= 1.63)$ and ART $(\hat{\gamma}_{20} = .15, SE = 0.06; \chi^2(1) = 6.02, p < .05;$ OR $= 1.16)$ emerged as positive predictors of sentence memory. Thus, in line with the efficiency hypothesis, individuals with higher overall scores on the ART showed greater sentence recall. Importantly however, the interaction was also significant $(\hat{\gamma}_{30} = -.03, SE = 0.01; \chi^2(1) = 4.17, p < .05,$ OR $= 0.97)$, suggesting that print exposure moderated the effects of vWM on sentence recall. This interaction is presented in Figure 3, which plots the effect of vWM on the proportion of propositions recalled at varying levels of performance on the ART. Older adults with lower print exposure showed strong effects of vWM on sentence recall, while older adults with higher print exposure showed no systematic relationship between vWM and sentence memory. These results support the reserve hypothesis in suggesting that higher levels of print exposure serve to buffer against the effects of vWM capacity on sentence memory.

To test the unique effects of print exposure on sentence recall, we fit a model based on the above model that included both age and vocabulary as covariates (see Equation 8 in the Appendix). Unlike the reading time analyses, adding the covariates to the sentence memory models did reduce the effects of ART, leading to a non-significant main effect for ART and a non-significant vWM by ART interaction. Entering the age and vocabulary covariates sequentially revealed that, while age did not impact the main effect of ART nor the vWM × ART effect, adding vocabulary as a covariate did reduce both effects

FIGURE 3. Effects of verbal working memory on sentence recall for older adults with varying levels of print exposure (percentiles of performance on the ART).

to non-significance. This suggests that the positive effects of print exposure on recall may be due in part to growth in crystallized verbal ability that comes with greater exposure to print.[4]

DISCUSSION

The findings from the current study suggest that sentence comprehension among older adults may be partially determined by the degree to which they expose themselves to text and habitually engage in skilled reading. Specifically, we found evidence in support of several mechanisms by which print exposure affects reading comprehension. In line with the efficiency hypothesis, we found that higher print exposure was associated with (a) more efficient lexical and orthographic processing, (b) greater allocation of attention to clause wrap-up, and (c) better sentence recall. Importantly, greater print exposure also appeared to act as a compensatory mechanism for individuals with lower working memory capacity, in support of the reserve hypothesis. Specifically, (a) working memory had less of an impact on sentence wrap-up effects for those with higher print exposure and (b) print exposure appeared to buffer against the effects of working memory capacity limitations on sentence recall.

The online reading time findings are consistent with studies demonstrating facilitation in visual word recognition for individuals with higher print exposure (Chateau & Jared, 2000; Sears, Siakaluk, Chow, & Buchanan, 2008; Stanovich & West, 1989). Our results extend these findings by examining effects in a population of older readers, as well as in a sentence reading task. By examining effects on sentence processing, we not only showed that higher print exposure is associated with more efficient word-level processing, but also that this efficiency was important in allowing a greater availability of resources to be allocated to more demanding textbase processes, an effect which was particularly valuable for older adults with lower working memory.[5]

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[4]Unlike the reading time models (see footnote 3), using processing speed in place of vWM revealed that speed did not uniquely predict sentence recall ($p = .20$) nor was its effect on recall moderated by print exposure ($p = .21$). The robust effects of processing speed on the reading time models may reflect the fact that psychomotor speed is a stronger predictor of reaction time variables than those based on memory processes. Given that speed did not predict recall, while vWM did (and was influenced by print exposure), this suggests that working memory has broader predictive power for measures of language comprehension, perhaps because complex span measures tap multiple abilities (e.g., executive attention, processing capacity, and resistance to proactive interference; Lustig, May, & Hasher, 2001; Whitney, Arnett, Driver, & Budd, 2001; Engle, 2002) that underlie language comprehension.

[5]Verbal working memory, like most measures of fluid cognition, shows monotonic declines across the entire lifespan. However, within this sample, the correlation between age and vWM was only marginally significant. This is due largely to the restricted age range in the current study (64–92). Nevertheless, there was a great deal of variance in vWM among the older adults, suggesting that our older sample showed substantial individual differences in cognitive ability.

Earlier studies (Hartley, 1986; Rice & Meyer, 1985, 1986) have demonstrated positive relationships between self-reports of reading engagement and text memory among older adults. These early studies suggest that the habitual reading of older adults can be an important and unique contributor to the ability to learn and retain information from text. However, to our knowledge, this effect had not been previously estimated using an objective measure of reading engagement, as was done in the current study. Using this performance-based measure, we presented evidence that higher rates of literacy were associated with resilience in language memory in older adulthood. Importantly, we found that print exposure moderated the relationship between vWM and sentence recall. This suggests that higher rates of print exposure are beneficial to memory for text, especially in the face of capacity declines. Consistent with cognitive reserve theory (Manly et al., 1999, 2003; Stern, 1999, 2009), increased literacy appears to serve as a compensatory mechanism. Cognitive reserve theory is predicated on the view that certain factors (such as education, activity engagement, and literacy) are partially responsible for "individual differences in how tasks are processed that can allow some people to cope better than others with brain changes in general and aging in particular" (p. 2027; Stern, 2009). Given that working memory is a basic cognitive ability: (1) that shows normative age-related declines, (2) that subserves complex performance in a number of domains, and (3) of which the neural substrates show both structural and functional age-related change (Reuter-Lorenz, et al., 2000), the current study suggests that literacy habits serve as a source of cognitive reserve in buffering against the effects of cognitive decline on language processing and memory for text among older readers.

Interestingly, while the effects of print exposure on online processing appeared to be independent of vocabulary, this was not the case when examining the effects on recall. Adding vocabulary as a covariate reduced the effects of print exposure on recall to non-significance. To the extent that vocabulary performance is an index of general verbal knowledge and crystallized ability (Baltes, 1997; Schaie, 1994), this suggests that increases in crystallized knowledge that come with greater print exposure appear to be an active mechanism contributing to the positive effects on recall. At the same time, greater practice with reading appears to impact the efficiency of online processing over and above its effect on vocabulary (Chateau & Jared, 2000).

Similar to a great deal of the educational and psychological research on literacy, the current study is cross-sectional and correlational, limiting the ability to make causal claims. In fact, as mentioned in the introduction, there likely exists a reciprocal relationship between the cognitive processes underlying text comprehension and rates of print exposure (Cunningham & Stanovich, 1997; Stringer & Stanovich, 2000). However, the development of more sophisticated analyses allows for greater flexibility in making well informed inferences about the effects of reading experience on the component

processes of reading (Stanovich & Cunningham, 2004). Thus, while certain limitations exist in terms of experimental manipulation (i.e., one cannot manipulate a lifetime of literacy activities), researchers can still test hypotheses that may not be easily and directly amenable to experimentation. Future research using converging methodologies, designs, and analytical strategies are key to addressing complex questions in the cognitive aging and psycholinguistic literature, such as the effects of literacy on language processing across the lifespan.

Examining the influence of expertise on the efficiency of the cognitive processes that subserve complex performance is an active field of study that cuts across multiple domains (Charness, 2009; Clancy & Hoyer, 1994; Morrow et al., 2009). Consistent with much of this literature on the development of expert performance and deliberate practice (see Ericsson et al., 2006), our results suggest that continued engagement in practicing the highly skilled activity of reading has beneficial effects on sentence processing and memory, even among older adults with reduced processing capacities. Thus, our data are largely in support of the notion that experiential factors, such as engagement in reading-related activities, play a large role in sculpting the cognitive system to perform effectively even in the face of declines.

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APPENDIX

This appendix contains technical information regarding the generalized linear mixed effects models and general model fitting approach used in the current paper.

SECTION 1: READING TIME ANALYSES

The Unconditional Means Model

The unconditional means model (i.e., no predictors) was fit to the data to assess random effects of subject and item variability on reading time; that is,

$$\ln(Y_{ijk}) = \gamma_{000} + U_{0j0} + V_{00k} + e_{ijk} \tag{1}$$

where $\ln(Y_{ijk})$ is the log transformed reading time for subject j and word k, γ_{000} is the intercept; U_{0j0} is the random effect for subject j distributed as $N \sim (0, \tau^2)$; V_{00k} is word k random effect distributed as $N \sim (0, \psi^2)$; and the e_{ijk} is the residual term that is assumed to be independent and distributed as $N \sim (0, \sigma^2)$. Unsurprisingly, there was significant variability accounted for by both subjects ($\hat{\tau}^2 = .12$; $SE = 0.014$; $\chi^2 (0/1) > 5000$, $p < .001$) and words ($\hat{\psi}^2 = .05$, $SE = 0.004$, $\chi^2 (0/1) > 5000$, $p < .001$). The proportion of total variance in reading time accounted for by subjects was 35% and the proportion of total variance in reading time accounted for by words was 15%.

Resource Allocation Model

$$\ln(Y_{ijk}) = \gamma_{000} + \gamma_{001}(\text{Syll})_k + \gamma_{002}(\text{lnWF})_k + \gamma_{003}(\text{NC})_k + \gamma_{004}(\text{IntSB})_k$$
$$+ \gamma_{005}(\text{SB})_k + U_{0j0} + V_{00k} + e_{ijk} \tag{2}$$

where Syll is the number of syllables; lnWF is the natural log of word-frequency; NC is whether a word introduced a new concept in the sentence, IntSB is whether the word marked the end of a clause or other minor syntactic boundary, and SB is whether the word occurred at a sentence boundary.

Effects of Print Exposure on Resource Allocation

$$\ln(Y_{ijk}) = \gamma_{000} + \gamma_{001}(\text{Syll})_k + \gamma_{002}(\text{lnWF})_k + \gamma_{003}(\text{NC})_k + \gamma_{004}(\text{IntSB})_k$$
$$+ \gamma_{005}(\text{SB})_k + \gamma_{010}(\text{ART})_j + \gamma_{011}(\text{ART})_j (\text{Syll})_k + \gamma_{012}(\text{ART})_j (\text{lnWF})_k$$
$$+ \gamma_{013}(\text{ART})_j (\text{NC})_k + \gamma_{014}(\text{ART})_j (\text{IntSB})_k + \gamma_{015}(\text{ART})_j (\text{SB})_k$$
$$+ U_{0j0} + V_{00k} + e_{ijk}$$
$$\tag{3}$$

where ART is the score on the author recognition task for print exposure.

Unique Effects of Print Exposure on Resource Allocation

$$
\begin{aligned}
\ln(Y_{ijk}) =\ & \gamma_{000} + \gamma_{001}(\mathrm{Syll})_k + \gamma_{002}(\ln\mathrm{WF})_k + \gamma_{003}(\mathrm{NC})_k + \gamma_{004}(\mathrm{IntSB})_k \\
& + \gamma_{005}(\mathrm{SB})_k + \gamma_{010}(\mathrm{ART})_j + \gamma_{020}(\mathrm{Age})_j + \gamma_{030}(\mathrm{Vocab})_j \\
& + \gamma_{040}(\mathrm{vWM})_j + \gamma_{011}(\mathrm{ART})_j\,(\mathrm{Syll})_k + \gamma_{012}(\mathrm{ART})_j\,(\ln\mathrm{WF})_k \\
& + \gamma_{013}(\mathrm{ART})_j\,(\mathrm{NC})_k + \gamma_{014}(\mathrm{ART})_j\,(\mathrm{IntSB})_k + \gamma_{015}(\mathrm{ART})_j\,(\mathrm{SB})_k \\
& + U_{0j0} + V_{00k} + \mathrm{e}_{ijk}
\end{aligned}
$$

$$(4)$$

Unique Effects of Print Exposure and Working Memory on Resource Allocation

$$
\begin{aligned}
\ln(Y_{ijk}) =\ & \gamma_{000} + \gamma_{001}(\mathrm{Syll})_k + \gamma_{002}(\ln\mathrm{WF})_k + \gamma_{003}(\mathrm{NC})_k + \gamma_{004}(\mathrm{IntSB})_k \\
& + \gamma_{005}(\mathrm{SB})_k + \gamma_{010}(\mathrm{ART})_j + \gamma_{020}(\mathrm{Age})_j + \gamma_{030}(\mathrm{Vocab})_j \\
& + \gamma_{040}(\mathrm{vWM})_j + \gamma_{011}(\mathrm{ART})_j\,(\mathrm{Syll})_k + \gamma_{012}(\mathrm{ART})_j\,(\ln\mathrm{WF})_k \\
& + \gamma_{013}(\mathrm{ART})_j\,(\mathrm{NC})_k + \gamma_{014}(\mathrm{ART})_j\,(\mathrm{IntSB})_k + \gamma_{015}(\mathrm{ART})_j\,(\mathrm{SB})_k \\
& + \gamma_{041}(\mathrm{vWM})_j\,(\mathrm{Syll})_k + \gamma_{042}(\mathrm{vWM})_j\,(\ln\mathrm{WF})_k + \gamma_{043}(\mathrm{vWM})_j\,(\mathrm{NC})_k \\
& + \gamma_{044}(\mathrm{vWM})_j\,(\mathrm{IntSB})_k + \gamma_{045}(\mathrm{vWM})_j\,(\mathrm{SB})_k + U_{0j0} \\
& + V_{00k} + \mathrm{e}_{ijk}
\end{aligned}
$$

$$(5)$$

where Vocab is the score on the vocabulary composite and vWM is the score on the reading span task for verbal working memory.

Print Exposure Moderates the Effect of Working Memory on Resource Allocation

$$\ln(Y_{ijk}) = \gamma_{000} + \gamma_{001}(\text{Syll})_k + \gamma_{002}(\ln\text{WF})_k + \gamma_{003}(\text{NC})_k + \gamma_{004}(\text{IntSB})_k$$

$$+ \gamma_{005}(\text{SB})_k + \gamma_{010}(\text{ART})_j + \gamma_{020}(\text{Age})_j + \gamma_{030}(\text{Vocab})_j$$

$$+ \gamma_{040}(\text{vWM})_j$$

$$+ \gamma_{050}(\text{ART})_j \, (\text{vWM})_j + \gamma_{011}(\text{ART})_j \, (\text{Syll})_k + \gamma_{012}(\text{ART})_j \, (\ln\text{WF})_k$$

$$+ \gamma_{013}(\text{ART})_j \, (\text{NC})_k + \gamma_{014}(\text{ART})_j \, (\text{IntSB})_k + \gamma_{015}(\text{ART})_j \, (\text{SB})_k$$

$$+ \gamma_{041}(\text{vWM})_j \, (\text{Syll})_k + \gamma_{042}(\text{vWM})_j \, (\ln\text{WF})_k + \gamma_{043}(\text{vWM})_j \, (\text{NC})_k$$

$$+ \gamma_{044}(\text{vWM})_j \, (\text{IntSB})_k + \gamma_{045}(\text{vWM})_j \, (\text{SB})_k$$

$$+ \gamma_{051}(\text{ART})_j \, (\text{vWM})_j \, (\text{Syll})_k + \gamma_{052}(\text{ART})_j \, (\text{vWM})_j \, (\ln\text{WF})_k$$

$$+ \gamma_{053}(\text{ART})_j \, (\text{vWM})_j \, (\text{NC})_k$$

$$+ \gamma_{054}(\text{ART})_j \, (\text{vWM})_j \, (\text{IntSB})_k + \gamma_{055}(\text{ART})_j \, (\text{vWM})_j \, (\text{SB})_k$$

$$+ U_{0j0} + V_{00k} + e_{ijk}$$

$$(6)$$

SECTION 2: SENTENCE MEMORY ANALYSES

Effects of Print Exposure and Working Memory on Sentence Recall

$$\frac{\pi_{jk}}{1 - \pi_{jk}} = \exp[\gamma_{00} + \gamma_{10}(\text{vWM})_j + \gamma_{20}(\text{ART})_j + \gamma_{30}(\text{vWM})_j \, (\text{ART})_j + U_{j0} + V_{0k}]$$

$$(7)$$

where π_{jk} is the probability of correctly recalling a proposition.

Unique Effects of Print Exposure and Working Memory on Sentence Recall

$$\frac{\pi_{jk}}{1 - \pi_{jk}} = \exp[\gamma_{00} + \gamma_{10}(\text{vWM})_j + \gamma_{20}(\text{ART})_j + \gamma_{30}(\text{vWM})_j \, (\text{ART})_j$$

$$+ \gamma_{40}(\text{Age})_j + \gamma_{50}(\text{Vocab})_j + U_{j0} + V_{0k}]$$

$$(8)$$